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The Vessel for Autonomous Research Underwater (The VARUNA)

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ENTITLED

The Vessel for Autonomous Research Underwater (The VARUNA)

BE ACCEPTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREES OF

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The Vessel for Autonomous Research Underwater
(The VARUNA)

By

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SENIOR DESIGN PROJECT REPORT

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ABSTRACT

Humans are intimately connected to the Earth's ocean, and yet only 5% of it has been explored. Learning more about marine life and ocean chemistry can only improve our stewardship efforts. The addition of an Autonomous Underwater Vehicle to the Santa Clara University Robotic Systems Laboratory's collection of marine robots will contribute to this quest for knowledge. It will assist researchers by providing a low-cost, easy-to-use, portable, reliable, and safe alternative to operator-controlled vehicles. This report describes our motivations for this project, the decisions we made in the design and manufacturing of the VARUNA, and tradeoff analyses of possible options. We also include descriptions of the subsystems, an account of testing, a summary of our accomplishments, and suggestions for the future of the project.

Keywords: Autonomous Underwater Vehicle, Marine Research, Control Systems, Robotic Systems Lab, Continuing Project, AUV, ROV, Submarine

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We would also like to thank the members of the Robotic Systems Lab (RSL) and our advisors Dr.'s Chris Kitts, Sally Wood, Walter Yuen, and Timothy Hight. Without the RSL, we would not have had a space that the VARUNA could call home, and without our advisors we would have had a difficult time getting our thrusters turning.

Next, we would like to thank Don and Calvin at SCU's Mechanical Engineering Machine Shop and Orville from Anchor Electronics for helping us find the tools and methods best suited for the tasks at hand.

Special thanks go out to our industry advisors: Killian Poore, a recent SCU grad student, and Bill Kirkwood and Geoff Wheat, both of whom associated with the Monterey Bay Aquarium Research Institute (MBARI). They all provided great feedback and advice and lent us the MBARI testing tank. Their help was integral during our ideation and testing phases.

Some final and very special thanks go out to our team's families. Between providing machining advice, logo designs, and test pools and boats, our families were there for us when we needed them.

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Acronyms

AUV Autonomous Underwater Vehicle

CFD Computational Fluid Dynamics

CTD Conductivity, Temperature, and Depth

ESC Electronic Speed Controller

GUI Graphical User Interface

IMU Inertial Measurement Unit

MBARI Monterey Bay Aquarium Research Institute

MUV Manned Underwater Vehicle

ROV Remotely Operated Vehicle

RSL Robotic Systems Lab

SCU Santa Clara University

VARUNA The Vessel for Autonomous Research UNderwAter

Chapter 1 - Introduction

1.1 - Background and Motivation

One of the most unique things about our Earth compared to the other planets in our solar system is our oceans. While water covers almost 72 percent of Earth's surface, no other planet that humans have found contains quantities of liquid water as great [1]. This water is of critical importance to humans because it enabled life to begin, and it enables life to continue. Today, half of the world's population lives in coastal regions [2]. Our oceans provide food and energy, among other resources, and help regulate weather patterns and climate change [3]. The ocean produces over half the oxygen in the atmosphere and is the largest absorber of carbon in the atmosphere [2]. Clearly, knowledge about the ocean is both valuable in learning more about Earth's history and in making sure that we are keeping this vital piece of our existence safe and healthy. Yet, 95 percent of the ocean remains unexplored.

The limitations to the scope of human exploration of the world's aquatic environments are a product of the environments themselves. The ocean is about 2.3 miles deep on average. Much of it is inaccessible to humans due to ice caps or treacherous conditions. Many of these limitations, however, are surpassed with the aid of robotic systems. Most undersea operations are carried out using Manned Underwater Vehicles (MUVs) or Remotely Operated Vehicles (ROVs). Each of these has its benefits. MUVs enable operators to actually be in the field with them. However, this is potentially dangerous, and it limits the length and thus the scope of the operation. ROVs can be used for longer periods of time, but they still require the full attention of the operator throughout the entire mission time. Additionally, their requirement for a ship from which to operate makes ROV missions very costly. Autonomous Underwater Vehicles (AUVs), however, can be operated without a ship and function without an operator during the entirety of the mission.

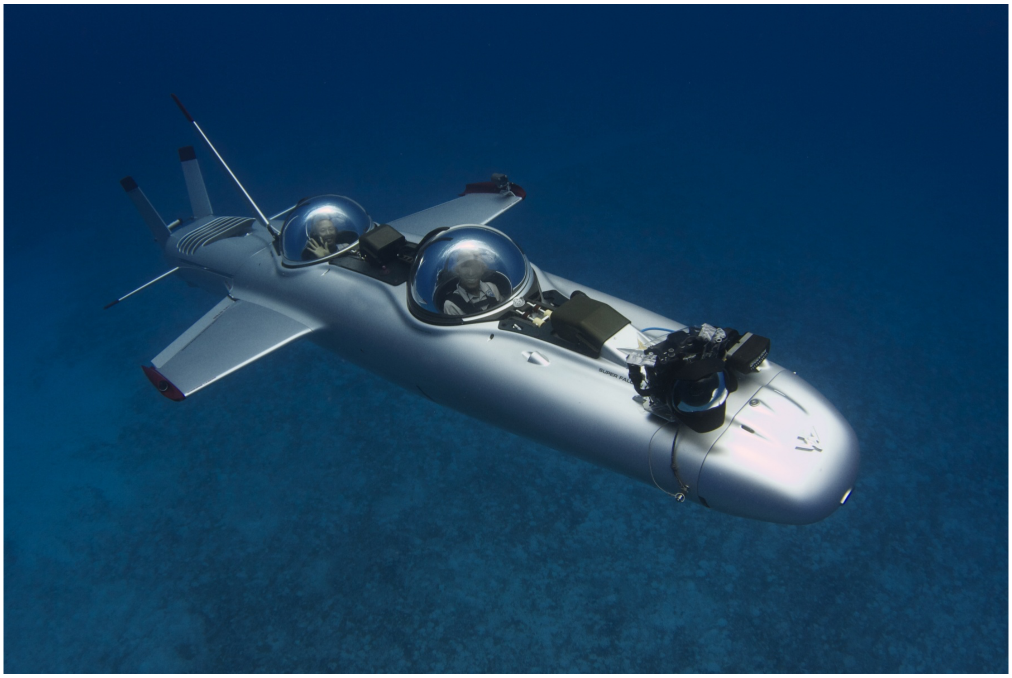

Figure 1: DeepFlight Super Falcon, an MUV (Photo: DeepFlight)

A major benefit of an AUV in comparison to an MUV or ROV is to have a robotic solution to the challenge of marine exploration that is more feasible for smaller research teams who may not have the means to launch an MUV or ROV expedition. However, as we will mention later, most AUVs on the market are quite expensive. Our motivation behind building The Vessel for Autonomous Research Underwater, or the VARUNA, was to make marine exploration for all scientists more feasible by designing a relatively low-cost solution to the difficulties of underwater research. The VARUNA will be operated and maintained by the RSL.

1.2 - Reviews of Field Literature

This section reviews several sources of literature on AUVs. Here we examine journal articles and books to discuss some of the design options and challenges that others have identified in building an AUV.

1.2.1 - *Intelligent Autonomy for Unmanned Marine Vehicles* [4]

This book by Carlos Insaurralde explains that undersea operations are carried out using MUVs or ROVs. Each of these has its upsides. MUVs are good because operators are able to be in the field with them. However, this can be dangerous, and it can limit the scope of the operation being performed because humans can only be underwater for a few hours at a time.

ROVs have the upside of being able to be used for longer periods of time, but they still need to be operated by someone. Additionally, they are attached by an umbilical to a ship. This requires a ship to be used the entire time an ROV is used. These factors lead to very high costs of using ROVs and leaves a clear space in the market for a vehicle that does not require the full-time attention of an operator.

To fill this space in the market AUVs were introduced. As implied by their title, AUVs are a class of underwater vessels that are controlled by a system that does not require human interaction once it enters the water. AUVs have become increasingly popular since their inception in the late 1950s.

1.2.2 - *Practical Robotics and Mechatronics: Marine, Space, and Medical Applications* [5]

The beginning of this book, by Ikuo Yamamoto, provides a brief overview of a "long-distance cruising AUV." It outlines the specifications of an older model AUV from Japan called the Urashima. Some of our ideas about the geometry of our AUV were shaped by the geometry of the Urashima, which has a long cylindrical body that enables it to glide through the water in a fashion similar to a torpedo. It utilizes vertical thrusters to help with pitch correction, horizontal thrusters along with rudders to control directional movement, and vertical rudders to further aid with motion control. At a length of 10 meters and equipped with devices out of the scope of our project, the Urashima is more complex than anything that we envisioned. Our mission to create a smaller, more versatile marine vehicle design that is cost effective and can still travel long distances draws from design and control concepts presented in this book.

1.2.3 - *Autonomous Underwater Vehicles: "Fully Coupled 6 Degree-of-Freedom Control of an Over-Actuated Autonomous Underwater Vehicle"* [6]

One of the many difficult parts of this project has involved the design of the controls that will govern the motion of the AUV as it makes its underwater trek. A very popular method for governing the movement of the AUV that has continually resurfaced throughout our research is the utilization of PID controllers interfaced with some sort of guidance system. This article, written by Matthew Kokegei, Fangpo He and Karl Sammut and edited by Nuno Cruz, explains a PID control system that many AUVs employ. The authors go through the dense theory and fundamentals of the PID control, explaining the error-adjustment cycle that the system goes through.

1.2.4 - *AUVs as research vessels: the pros and cons* [7]

This article examined the pros and cons of using AUVs in marine science applications. The article identifies several potential applications for AUV use, although primarily focusing on the use of acoustics. For instance, the article introduced the potential capability of using AUVs to examine fish population in fisheries as well as applications under ice. The primary benefits of AUVs mentioned in the article are the ability to operate without the restriction of a tether, low levels of noise emission, and the ability to operate at various depths and collect data over a large range. More importantly, the article discusses the potential challenges of using an AUV as a marine sampling vessel. An AUV is not tethered, therefore its range of operation is limited by its power source, which introduces further difficulties in weight and volume. This article is useful as it was important to consider and address the pros and cons of AUVs as we proceeded through the design process.

1.2.5 - *Mechanical Design for a new Autonomous Underwater Vehicle (AUV)* [8]

This article examined the designs and assembly of the major mechanical design components of an AUV. This article is particularly helpful as it breaks down the various subsystems in AUV mechanical design, and provides problem statements, solutions, and explanations for the majority of components. This is a particularly helpful resource with respect to the design process of an AUV as it details advantages and disadvantages of various solutions, providing scoring tables, as well as detailing the assembly process and hierarchy. Additionally, the article provides a helpful list of components, multiple drawings to reference for different solutions, and many necessary definitions and calculations for the theoretical design considerations involved in building an AUV. As a whole, this paper addresses nearly all the design considerations involved in designing an AUV and serves as a good example for the design process of an AUV.

1.2.6 - *Hull shape optimization for autonomous underwater vehicles using CFD* [9]

Hull shape is an important element in the mechanical design of an AUV, as minimizing drag is paramount in maximizing battery efficiency, and maximizing volume is needed in order to house the many electrical components and sensors needed in marine sampling applications. This article discusses various hull shapes and attempts to identify the optimal design through Computational Fluid Dynamic (CFD) analysis. As CFD analysis and design of the hull is integral in the mechanical design of an AUV, this resource is particularly helpful as it provides various mathematical models and definitions necessary in performing this analysis. Additionally, the article examines the experimental testing and results of each hull design, comparing and optimizing drag and volume. According to the article, a long nose, minimal mid-section, and a reasonably sized tail section provided the best results. The CFD analysis and experimental results provided in this article helped direct us in our own CFD analysis and consideration of hull shapes.

1.2.7 - *Remote environmental measuring units* [10]

This article provides insight into the system design of the REMUS underwater vehicles. It examines the challenges and criteria in designing the hull shape of an AUV, addressing the issues of volume and drag with respect to hull design. Furthermore, the article presents the projected vehicle performances for various conditions and speeds, as well as the estimated cost of such a design, providing useful benchmark material. The article also addresses the design of heading, depth, and roll control, as well as sensors, propulsion, and power systems. The REMUS vehicles are considered to be successful low-cost AUVs used in a variety of scientific marine applications, and insight into their design is valuable as our team's design shares many of the same constraints and criteria.

1.3 - Existing Products

This section takes a look at a few of the different AUVs on the market. Understanding what was available was important for us in considering the specifics of our design and how we could make something new.

Table 1: Existing Product Specifications

Product Name	**REMUS 100**	**MBARI Dorado**	**Bluefin Sandshark**	**Sparus II**
Dimensions: Length & Diameter	L=1.7 m D=0.19 m	L=2.4 - 6.4 m D=0.53 m	L=1.1 - 2.0 m D=0.124 m	L=1.6 m D=0.23 m
Mass	36 kg	475 kg	5 kg	50 kg
Depth rating	100 m	6000 m	200 m	200 m
Payloads	Configurable	Imaging, mapping, water sampling	Configurable	Configurable
Cost	$$$$	$$$$	$$	$$$$

1.3.1 - REMUS 100

The REMUS 100 was developed by the Woods Hole Oceanographic Institution. With a length of 1.7 meters and hull diameter of 19 centimeters, the Remus 100 is a relatively small vehicle with respect to other AUV models. Additionally, it weighs 35 to 40 kilograms, which, in combination with its small size, makes it relatively easy to deploy with a smaller team. Like other REMUS models, the REMUS 100 features a torpedo shape. The REMUS 100 has seen widespread use, and its involvement on many missions has led it to be regarded as one of the most dependable AUV products on the market. Its configurability with respect to sensors and payload options contributes to its widespread use as it is capable of supporting many different sensors to meet the needs of many missions. With a potential twelve-hour operation time and capability of operating up to a 100-meter depth, the REMUS 100 is capable of handling many different mission scenarios.

Figure 2: The REMUS 100 being prepped for an expedition (Photo: Wikimedia)

1.3.2 - MBARI Dorado

MBARI's Dorado class AUVs have a long, successful track-record as the first vehicle performed its first mission in 2001, and subsequent models have been conducting missions regularly since 2002. While the REMUS model is configurable and capable of supporting many different sensors, the Dorado class AUVs offer three different models: imaging, seafloor mapping, and upper-water column AUVs. Capable of operating for twenty hours, each model excels at its designed task. For instance, the seafloor mapping AUV is capable of operating up to a depth of 6000 meters. Each model features 53.3-centimeter hull diameter, but vehicle lengths range from 2.4 meters to 6.4 meters.

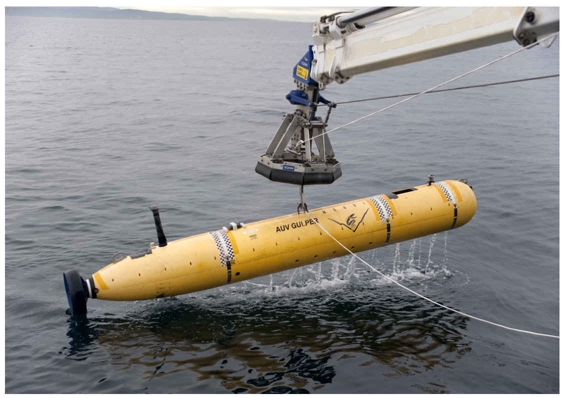

Figure 3: The MBARI Dorado Class AUV Gulper being deployed (Photo: MBARI)

1.3.3 - Sparus II

The Sparus II is an AUV model designed for hovering capability in shallow waters. It was first designed by the Underwater Robotics Research Center at the University of Girona. With its lightweight body, torpedo shaped hull, and hovering capabilities, the Sparus II is highly maneuverable, featuring a three-thruster design. It's length of 1.6 meters, diameter of 23 centimeters, and weight of approximately 50 kilograms make it easily deployable by a team of two. Additionally, it's payload section is configurable, allowing it to handle a variety of different missions.

1.3.4 - Bluefin Sandshark

The Bluefin Sandshark is a very small, highly modular AUV model. The primary vehicle components are stored in the tail section, and modular payload sections are connectable, allowing the Sandshark to be highly configurable. With a 12.4-centimeter hull diameter, the length of the tail section being approximately 0.5 meters, and the modular payload section ranging from 0.6 meters to 1.5 meters based upon custom configuration, the Sandshark has a very small size with respect to other AUV models. With its tail section weighing only 5 kilograms, the Sandshark is lightweight and deployable by a single person. It also features a lithium-ion battery, allowing it to operate for over five hours.

Figure 4: The Bluefin Sandshark being deployed (Photo: Bluefin)

1.4 - Project Partnerships

Throughout this project we partnered with the RSL, which is led by our advisor Dr. Christopher Kitts. The RSL has several marine robots, however all of their vehicles are either ROVs or surface vehicles. The type of data that such vehicles are capable of acquiring is either pinpointed underwater data or surface data only. Thus, there is need for a vehicle that can autonomously travel underwater and scan large volumes of water to bring new types of engineering and scientific research opportunities to the RSL.

1.5 - Project Objectives

Given our relationship with the RSL and knowledge of different types of AUVs on the market, we developed a mission statement to drive our project: To build the foundation of an autonomous marine robot capable of scanning large volumes of water not always accessible by ROVs or surface vehicles, as the beginning of a multi-year project that will be carried on in the

RSL. The 5-year vision for the project is a vehicle that uses a set of user-defined waypoints to move back and forth, effectively scanning an area for data, then move to another depth to repeat the process. After scanning various depth levels, the VARUNA will return to the surface, and broadcast its position for easy retrieval. Our goal was to create a small vehicle, capable of increased transportability compared to what is currently on the market. Potential future applications of this AUV will be numerous, as the onboard sensor package will be modifiable based on the interests of the user.

The requirements for our team, the first iteration of this multi-year project, were narrower in scope. Our goal was to design and build the first version of the mechanical and electrical systems of an AUV with basic heading and depth control, as well as a basic conductivity, depth and temperature (CTD) sensor package. Chapters 2 and 3 describe the decisions we made in designing and fabricating the submarine, and Chapter 4 details our testing processes and summarizes our achievements.

Chapter 2 - System Overview

This chapter provides an overview of the project. It discusses the customer needs of the product and various system tradeoffs. It provides a layout of the main functions and subsystems of the AUV that were developed in response to the needs of our customer.

2.1 - Customer Needs

To collect data about the needs of potential users of the AUV we developed a questionnaire. The questionnaire is attached in Appendix D. The contacts in the study included a scientist working in the research industry, research-conducting graduate students from SCU's Graduate School of Engineering, a practicing marine engineer for the Moss Landing Marine Laboratories, and the RSL director. We were also able to conduct phone calls and maintain email correspondences with a professor from Purdue University who uses aquatic vehicles in his research and a scientist from MBARI. As possible users of our product, our contacts provided information that helped us to identify some of the essential needs of our customers.

Table 2: Solutions to the needs of the customer based off of the Survey responses.

Customer Need	**Design Consideration for Need**	**Priority Factor**
Sensors: water quality, acoustic mapping, video feed, ambient water current reader, chemical concentration, pH	Make a modular design capable of accommodating a multitude of sensors.	3
Battery life	Create an AUV that can last for a minimum of 4.0 hours	6
Maneuverability	Ensure a turning radius of 20 meters or less	5
Data Acquisition	Provide data acquisition at 1 to 2 Hz	2
Depth Capabilities	300 to 500 ft	4
Easily deployable	Make a model that is between 3 and 5 ft and weighs less than 80 lbs	1

From the pool of information we were able to collect, we created a list of different customer needs and created a hierarchy for those needs based on the scope of our product. Each need and its importance relative to the other needs is listed in Table 2. To read the questionnaire and the responses, refer to Appendix D.

2.2 - System Level Overview

This section gives an outline of the main features and functions of the VARUNA. Here, we break the entire system into several subsystems, and address issues we faced and basic functional decisions we made early on in the design process.

2.2.1 - System Overview

The main function of the AUV is to serve as an instrument for volumetric data collection. The vehicle can be programmed to cover a specific area at a specific depth, taking data points at programmable intervals as it goes along. The ideal mission profile for the VARUNA, as laid out in section 1.5, Project Objectives, is illustrated in Figure 5. Its directional movement in planes of the same depth is controlled by differential steering using the two thrusters at the back. Later iterations of the VARUNA will be able to travel to multiple depths before resurfacing and sending out its location to be picked up. Its depth is controlled by the vertical thruster at the front. Figure 6 shows the design at which we arrived for VARUNA.

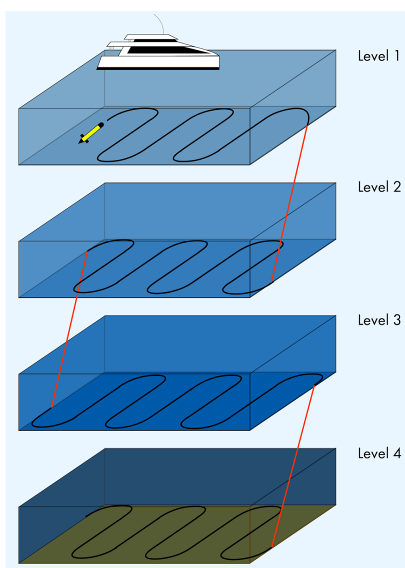

Figure 5: Ideal operation profile

To define a mission, the operator will enter the parameters into a GUI and send the code to the AUV, as explained in more detail later. In its first year of operation, the AUV will be equipped with conductivity, temperature, and depth sensors, as well as a pressure sensor, an accelerometer and gyroscope, and a timer to provide navigational information to determine the location of the points at which data was taken. In the future, the AUV will be able to be customized to include ultrasonic and photographic imaging capabilities, sensors for water clarity, and additional payload as desired.

2.2.2 - Mechanical Overview

The AUV is broken down into the following subsystems:

- Exoskeleton
- Pressure Vessels
- Propulsion
- Power
- Navigation Sensors and Processing
- Payload

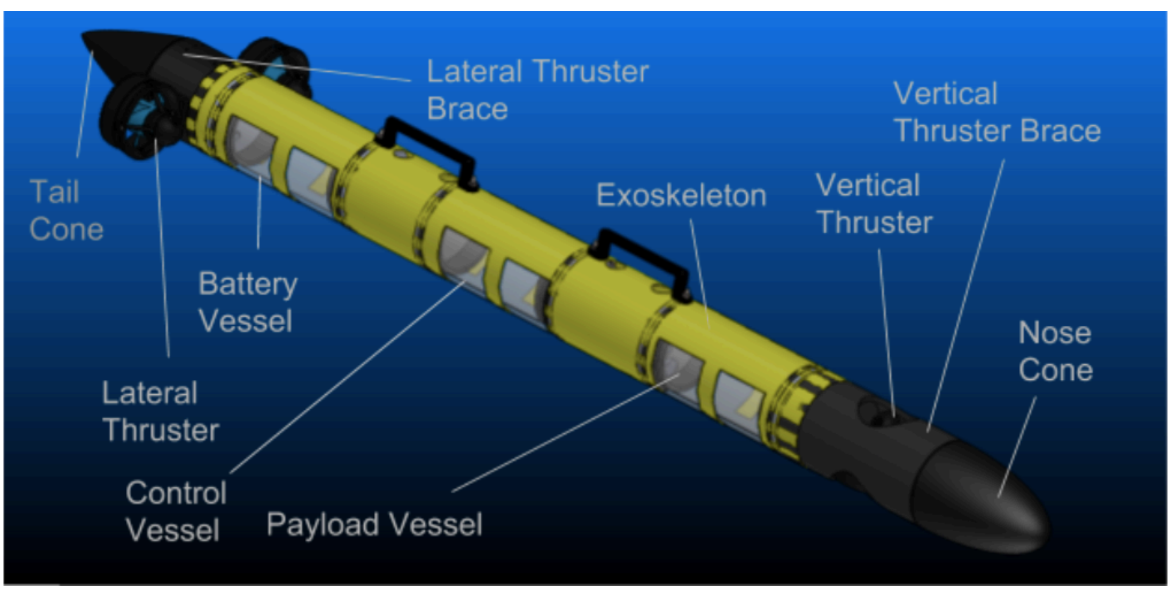

Figure 6: Mechanical layout of the VARUNA

Figure 6 provides a mechanical layout of the final VARUNA design. The exoskeleton is the outer shell of the VARUNA, which holds the pressure vessels, the vertical and lateral thruster assemblies, and the nose and tail cones of the vehicle together. The exoskeleton main assembly consists of the aluminum shell and the cones. The pressure vessels are watertight bottles that hold the innards of the AUV. They are modular units, one containing the power subsystem, one containing the navigation sensors and processing subsystem, and one containing the payload electronics. Modularity was a driving principle of our design because it adds flexibility and potential for customization for future users. Propulsion consists of the rear thrusters to control direction and the vertical thruster to control depth, as well as the subassemblies that house the thrusters. Power includes the battery, fuses, and converters. The sensors and processing subsystem includes the CTD sensor package, the magnetometer and gyroscope, the clock, the onboard computer, and the main controls system, along with how the operator communicates with the AUV to set the parameters of the mission. Each of the subsystems is explained in depth in Chapter 3.

Another system level decision that was made right off the bat was to keep the buoyancy of our vehicle constantly positive. Having a fixed positive buoyancy allows, in the situation that a failure during testing occurs, the vehicle to float to the surface and be retrieved.

2.2.3 - Electronics Overview

Figure 7 shows the level zero block diagram for the AUV. The green arrows represent inputs while yellow arrows represent outputs. The figure depicts the rudimentary, ground-level design of the vehicle's movement. The AUV receives input from a compass, pressure sensor, and a clock, and the vehicle will move according to the information it receives from these components.

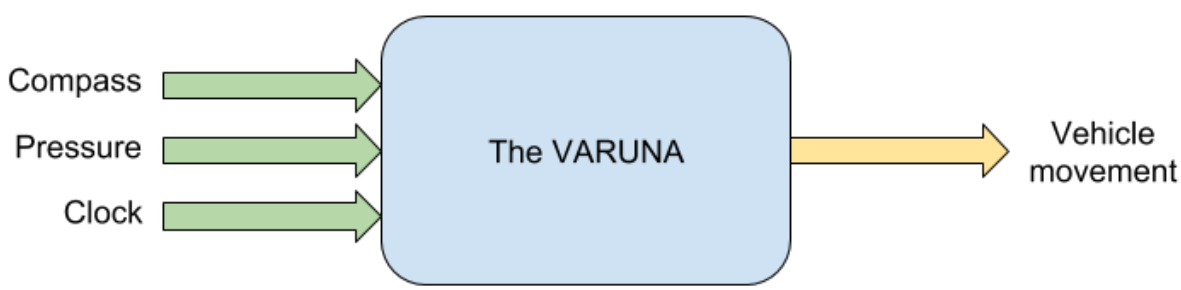

Figure 7: A level zero block diagram of the VARUNA's system.

Figure 8 shows a more in depth functional block diagram featuring the electrical components and instrumentation of the vehicle. The components are separated into three watertight pressure vessels. Represented by green bubbles in the diagram, the power components are held in the battery pressure vessel. In order to protect the other components, the battery is connected to a fuse. It then supplies power to the motor drivers. The battery also connects to a DC/DC converter in order to lower the voltage, which is appropriate to power the on-board computer. Lines designating power flow are shown in red. The primary electrical components necessary to moving and controlling the robot are housed in the control electronics pressure vessel and are represented by orange bubbles. As shown in Figure 8, the on-board computer receives input from an IMU/compass and pressure sensor and uses this information to provide direction to the motor drivers based on its programming. Lastly, the payload pressure vessel contains the designated sensor package needed for the desired mission; these components are represented by purple bubbles. The sensor package connects to the on-board computer to allow for data collection. Lines showing communication between electronics are colored blue.

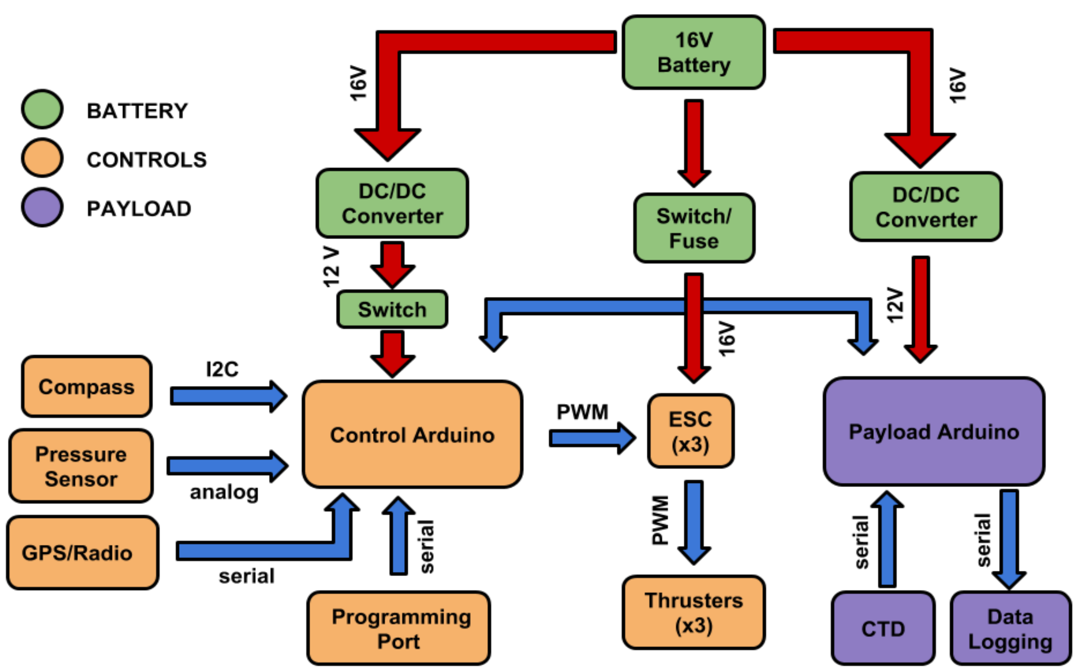

Figure 8: An in-depth workflow block diagram of the VARUNA with the division of the components with respect to the pressure vessels

2.2.4 - Programming Overview

The next few figures delve into the basic programming structure of the AUV. Figure 9 shows the main controls flowchart.

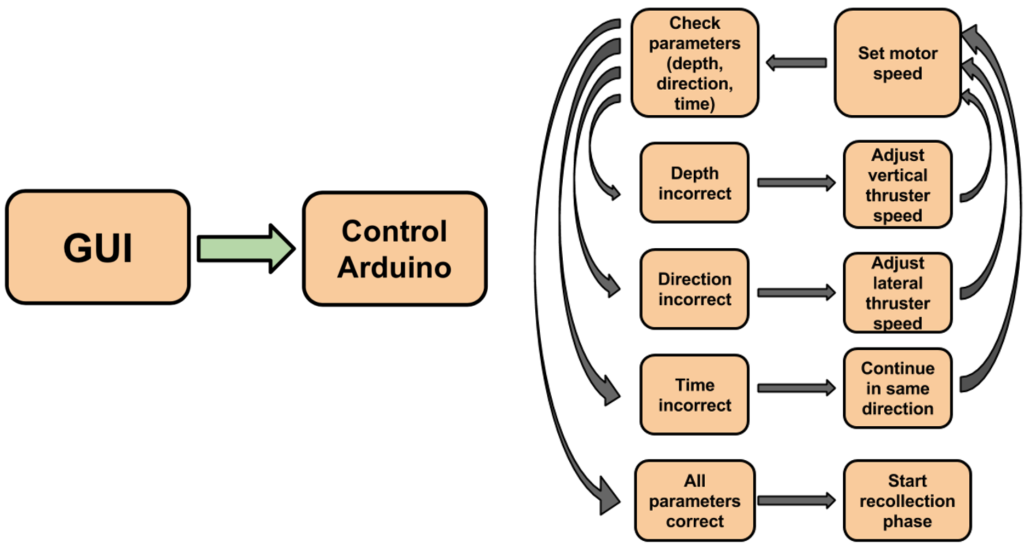

Figure 9: Main Controls Flowchart

The flowchart starts with asking for the mission parameters, which are input by the researcher in a computer downloadable GUI, which is sent to the controls Arduino through a serial port connection. Once the AUV receives the parameters, it will begin the main controls loop. In this loop, three sensors are constantly checked: the current depth, direction, and time. If one or more of these are incorrect, the AUV will tell the motors to adjust accordingly. Once the AUV has completed its mission--that is, it has mown the lawn across the final depth--it will begin the recollection phase, where the motors will turn off and it will float to the top. A more in-depth look at the controls system can be found in section 3.5.

The last major section of note is the controls-to-payload communication, as shown in Figure 10. The AUV is a modular design, and it was decided that the sensor payload would be controlled by its own Arduino. Because of this, it was important to have clear information from the controls Arduino to command the payload Arduino. The two Arduinos communicate over the onboard serial ports, and at certain times (determined by the control parameters) the controls Arduino will send a string of data that contains the AUV's current x-coordinate, y-coordinate, and depth. When the payload Arduino receives this, it will read all the sensors in the payload and print all of the information to a data logger. This gives researchers payload sensor data at specific distance intervals.

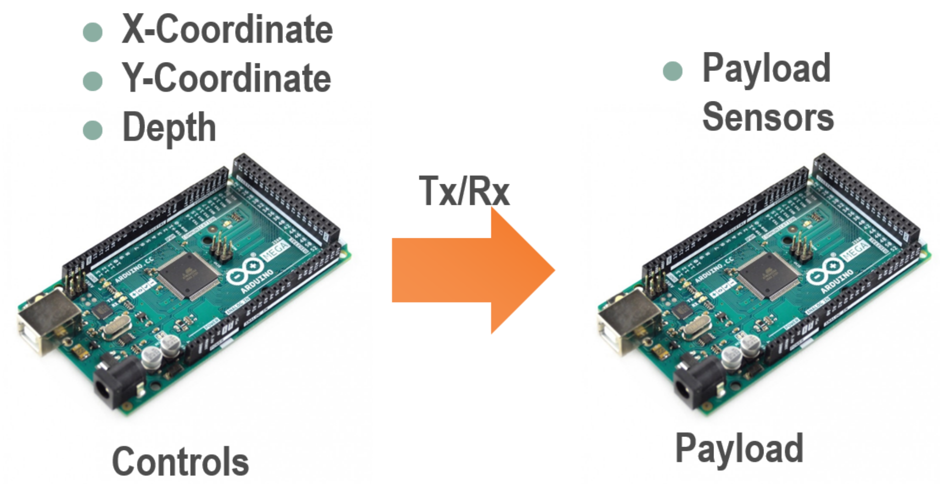

Figure 10: Controls and Payload Communication

2.3 - Summary

Our project is designed to be the first of a multi-year ongoing project in the RSL. The primary customer needs that we considered were those of future students affiliated with the RSL and industry partners such as MBARI that have a long-standing history with the RSL. Creating a low-cost option became the driving principle of our design. The mission profile we developed for the VARUNA is a mow-the-lawn pattern at incrementally larger depths, eventually compiling a cube of volumetric ocean data. We broke the overall system into mechanical, electronics, and programming subsystems.

Chapter 3 - Subsystems

This chapter explains the subsystems in more depth. It details the requirements of each system, as well as the design options and our rationale for the choices we made.

3.1 - Hull

This section details the requirements and design decisions for the outer body of the AUV.

3.1.1 - Requirements

The hull is what houses all of the parts of the AUV, our design used an exoskeleton to hold the entire body, thrusters, and nose and tail cones together. The shape and dimensions of the cones with the aluminum exoskeleton determines how hydrodynamic the vehicle is, which in turn affects how much power it needs. Thus, it is important that the shape is optimized to be as hydrodynamic as possible. Another important aspect of the hull is that it holds the pressure vessels, which contain all of the electronics. We have worked to keep the design of our electronics modular and configurable, so it is important that the exoskeleton was made with those goals in mind.

3.1.2 - Options

Here, we discuss the options we faced when designing and manufacturing the exoskeleton and the nose and tail cones.

3.1.2.1 - Exoskeleton Manufacturing

The overall shape of the AUV was determined hand-in-hand with the thruster arrangement, as described in section 2.2.2 and Appendix E. We opted for a torpedo-shaped design to make the AUV as streamlined and hydrodynamic as possible. This meant that the main body of the vehicle, which holds the electronics and motors together, had to be shaped like a long tube to grasp the bottles that contain the electronics. We discussed the option of having a larger hull that would contain the elements of the AUV, but since early on we decided to purchase watertight bottles to contain the electronics, having a watertight hull would be difficult and redundant. Because of this, we opted for a tube-like ribs to cage everything. The decision of the shapes for the nose and tail cone is explained in greater depth in the following section. The image below shows a first sketch of the shape we imagined for the exoskeleton.

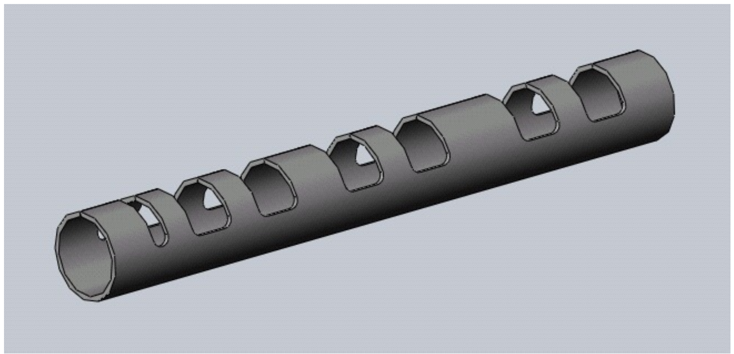

Figure 11: Initial exoskeleton design

Several materials were considered for the exoskeleton. The following table shows some of the mechanical properties of a few materials considered for the hull.

Table 3: The Material Properties of Potential Hull Candidates

Material	**Yield Strength**	**Fracture Toughness**	**Cost**
Al 5052	193 MPa	29 MPa-$m^{1/2}$	$2-$8/kg
PVC	55.2 MPa	3.9 MPa-$m^{1/2}$	$0.46/kg
Acrylic	50 MPa	N/A[1]	$2-$4/kg

Steel was not considered because of its weight and poor corrosion resistance. The pressure under 150 meters of water is about 1.6 MPa. Thus, all of the materials in Table 3 above are strong enough with large factors of safety.

Our first idea was to use an ABS pipe, which has similar properties to PVC, and cut sections out of it to make the shape we desired. Unfortunately, the largest diameter of ABS or PVC pipe that we could find that was not too large had the same diameter as the watertight bottles we purchased and was too stiff to bend to fit the bottles inside it.

We moved from ABS to sheet aluminum, because sheet aluminum is relatively cheap, easy to come by, and rollable into the tube shape we desired. We used 5052 aluminum because it is better than other alloys for rolling. At first, we made the exoskeleton out of several rolled

[1] Little to no information was available for the fracture toughness of Acrylic.

rectangles of aluminum riveted together. For the final exoskeleton, we had once piece of aluminum water jet cut to the exact shape and rolled to the proper diameter. This was then powder coated to protect from corrosion caused by salt water.

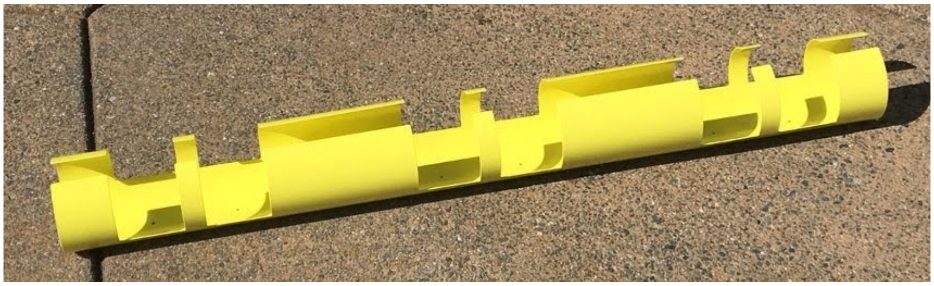

Figure 12: Aluminum exoskeleton with powder coating for corrosion protection

3.1.2.2 - Nose and Tail Cones: Computational Fluid Dynamic Simulations and Results

The profile and shape of an AUV's body is very important when analyzing the resultant forces that the AUV experiences while travelling through water. These resultant forces are studied to understand the system's hydrodynamics, or behavior of the fluid-structure interaction. To develop a quantitative study of the hydrodynamics of the system, the team ran CFD simulations on a model of the VARUNA. The main goal of our CFD simulations were to optimize the nose and tail cone geometries and to validate our thruster selection.

When an object glides through a fluid, the fluid will push back on the object, creating a resultant force. This resultant force is known as the drag force. The drag force is the sum of two types of drag: the pressure drag and the viscous or friction drag. The pressure drag is a phenomenon that occurs when there is a pressure difference between the front face and the back end of an object moving through a fluid. The displacement and the compression of the fluid particles at the front face, or the frontal stagnation point, creates a high pressure. The back end, or the rear stagnation point, experiences a low pressure due to the separation of those particles. [11]. The viscous drag occurs from the resistance the surface of an object exerts on the fluid. This resistance, caused by friction, along with the pressure difference from the pressure drag act to impede the motion of an object immersed in a fluid. This impedance of motion prompts the need for an increase in the battery power output to the thrusters in the case of an AUV.

According to fluid mechanics theory, a blunted or rounded nose cone and a streamlined tail cone is ideal for decreasing the overall drag force [11]. This is portrayed in Figure 13, which displays the drag coefficients of four different object shapes moving through water. The lowest drag coefficient, which is a dimensionless measurement of the drag force, is created by Figure 13(c). Basing our study of the hydrodynamics of the VARUNA off the published fluid mechanics theory in Figure 13, we aimed to decrease the needed power output to the thrusters using CFD simulations.

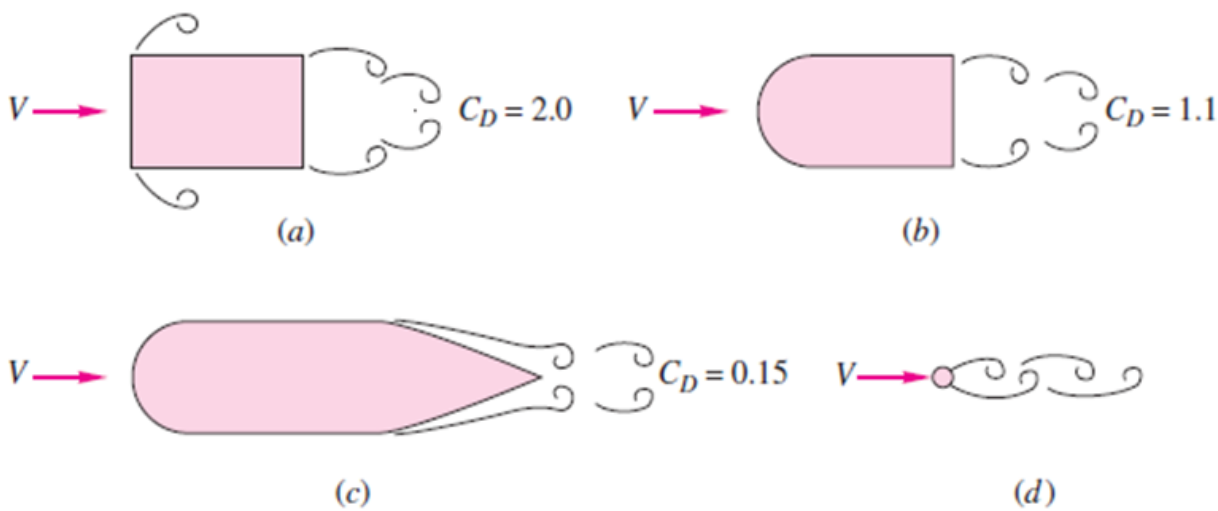

Figure 13: Published experimental drag coefficient values for four different object geometries

The CFD simulations and the ensuing analyses of the drag force exerted on the AUV by the surrounding water were crucial to the design of the nose and tail cones. To model the VARUNA gliding through the water, we used the COMSOL Multiphysics CFD simulation environment. Our model, displayed in Figure 14, was a rectangular prism with the designed geometry of the VARUNA model cut away from the inside of the prism. In the simulation, the right face of the prism was the inlet, with water coming in at various speeds, while the left face was the outlet. We ran our simulations assuming steady state and no-slip boundary conditions at the boundary of the VARUNA model cutaway, and that the flow was incompressible and laminar. We also assumed that the Mach number was much less than 1.

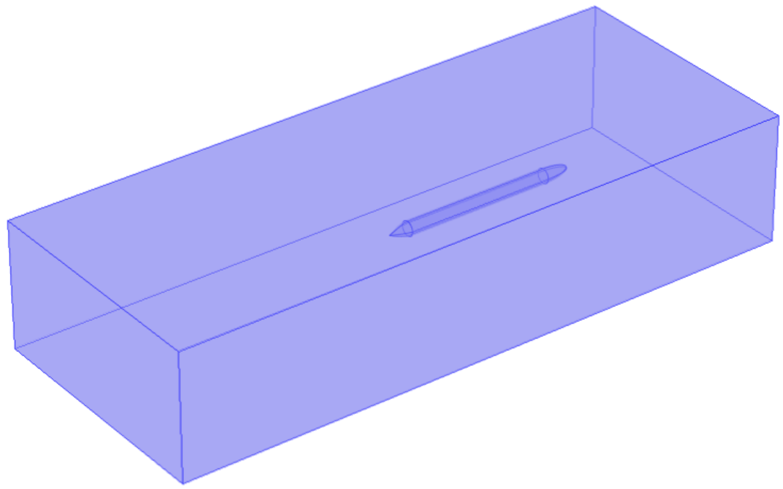

Figure 14: The model used for simulating the VARUNA's hydrodynamics

By running multiple models with different nose and tail cone designs and combinations, we were able to find the nose and tail cones that created the least pressure drag. Referring to Figure 15 below, one can see the four combinations of nose and tail cone geometries. Comparing the initial simulation results between each of the figures, Figure 15(a) resulted in the minimum drag force, and was deemed the most hydrodynamic. After finding that the drag force was the least for Figure 15(a) at 1.0 m/s, we ran simulations for Figure 15(a) at speeds from 0 to 3.0 m/s at increments of 0.25 m/s. More details on the methods and the validation of the CFD simulations can be found in Appendix F.3.

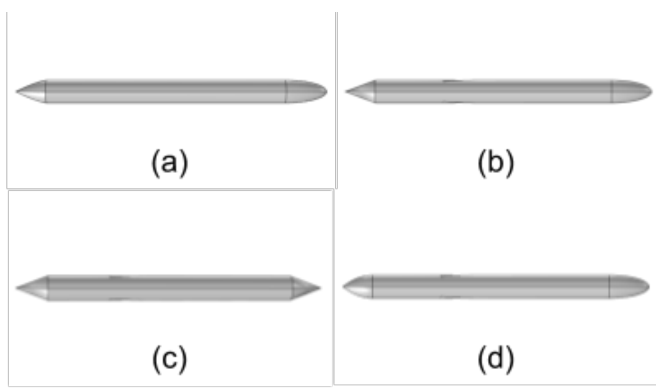

Figure 15: The models used to run the CFD simulations

The results from our simulations were highly informative. Referring to Figures F-3 and F-4 in Appendix F.3, one can see the pressure and viscous drag force and drag coefficients acting on the model at multiple travel speeds. Note that the drag contributions in the drag force graph of Figure F-3 are very low below 1.0 m/s. During our field testing following the CFD simulations, we operated the VARUNA at a test speed of about 0.75 m/s, so the drag according to the simulations was relatively low. This validated our choice of thruster, the Blue Robotics T200. More information on our thruster choice can be found in the Systems Integration section in Chapter 4. Referencing Figure F-6 in Appendix F.3, which displays the pressure distribution across the surface of the model, one can see the high pressure at the front stagnation point on the nose cone and the low pressure at the back stagnation point on the tail cone.

The CFD simulations helped to inform us of crucial information. Our simulations were able to find an optimal nose and tail cone profile and were able to validate our thruster choice. The simulations also gave us more information than we had previously thought. An analysis of the simulations we ran for the VARUNA informed us that operating our AUV at speeds below 1.0 m/s results in very minimal drag forces. Because of this, we ran the VARUNA at about 0.76 m/s during all of our tests. Running missions at this speed would theoretically extend battery life, and thus extend mission longevity. Understanding and knowing the drag force values acting on the body of the VARUNA can also help improve the control systems of the future iterations of the VARUNA in later years.

3.2 - Pressure Vessels

This section describes the pressure vessels used in the AUV. The subsystem features three watertight enclosures at atmospheric pressure. The environmental challenges, the subsequent requirements, and the different options that were available to us are also detailed below.

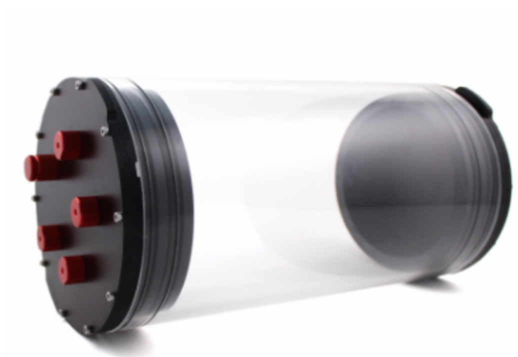

Figure 16: A Blue Robotics 6” series watertight enclosure (Photo: Blue Robotics)

3.2.1 - Requirements

The subsea terrain is a very hazardous environment for any electronic system. The pressure vessels needed to provide protection for all of the mission critical electronics. This includes the batteries, the payload sensor package, both onboard processors, the IMU, the pressure sensor, and all other electronic systems within each vessel. Overall, the pressure vessels need to be a reliable, watertight system. There also needs to be a watertight interface between each of the three pressure vessels so as to ensure that all of the systems were connected to the power source and to each other without any water leakage.

3.2.2 - Options

The main decision that we faced in this subsystem was whether to manufacture our own pressure vessels, send them to a third party with dimensions to machine for us, or to purchase them from a vendor. Research into the fabrication of O-Ring fitted interfaces revealed to us that the tolerances needed were an order of magnitude higher than we were capable of meeting. Because of the time and precision, it would have taken us to manufacture a reliable pressure vessel, we voted that idea off early on.

We also posed the idea of sending fully dimensioned part sketches and/or computer aided drawings to a machinist and having custom pressure vessels manufactured for us. This would be an ideal scenario for later iterations of the AUV because at that point all dimensions of the craft will have been decided. The nature of the design and prototyping stage of this project called for adjustments to the dimensions of the craft if an issue is found, making a pricey custom-machined pressure vessel illogical.

In the end, we settled on ordering a pre-made watertight enclosure from Blue Robotics. Because of the relatively fast turnaround with shipping and the fact that they are already tested and can withstand the high pressure sub-aquatic environment, our team decided that this would be the fastest and safest choice. Although it is more expensive than manufacturing our own with a homemade seal, we decided that the more reliable option was worth the extra money. The pressure vessels that best fit our needs were the acrylic, 8-inch-long, 4.5-inch outer diameter series watertight enclosures from Blue Robotics.

Using Blue Robotics's pressure vessels was convenient and safe, but it also led to another problem. The endcaps of the pressure vessels were manufactured to only allow for use with other Blue Robotics products. Some of the watertight electrical connectors that were donated to us were not from Blue Robotics. These connectors for vessel to vessel power and signal transmission were incompatible with the end cap hole dimensions. To solve this, we manufactured our own custom end caps to fit securely around the connectors that we used.

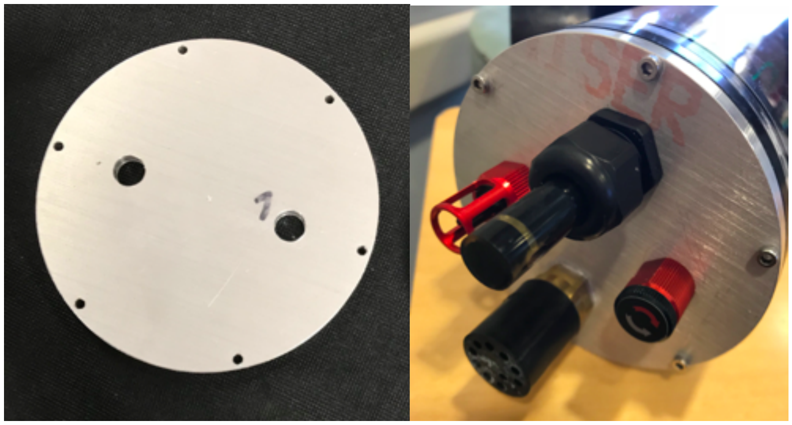

Figure 17: Custom manufactured aluminum end caps

3.3 - Propulsion

This section provides details on the motion control system of the robot, discussing the manner in which pitch, yaw, and roll are controlled or addressed in the design.

3.3.1 - Requirements

The propulsion and steering system needs to be small and cost-effective with respect to the vehicle's overall dimensions and the project budget. Additionally, the propulsion and steering system must have low power consumption in order to maximize vehicle operation time. Similarly, the propulsion and steering configuration must be hydrodynamic in order to reduce drag and maintain power efficiency. Lastly, the propulsion and steering configuration must have high waterproof ability in order to ensure a reliable waterproof system and reduce design and construction time.

3.3.2 - Options

3.3.2.1 - Thruster Configuration

After considering many options with respect to propulsion and steering, the team closely examined five potential solutions that were deemed viable. Each option was criticized based upon the requirements mentioned above. The matrix in section E.2 of Appendix E compares each option with respect to weighted criteria, and Table 4 below provides a simpler breakdown on the pros and cons for each solution.

Table 4: Pros and Cons for Motion Control Options

	1. One Thruster w/ actuators	**2. Two Thrusters w/fixed wing**	**3. Three Thrusters**	**4. Two Thrusters w/ actuators**	**5. Five Thrusters**
Pros	-Power draw -Drag	-Thrust -Power draw -Waterproofability	-Thrust -Maneuverability -Waterproofability -Drag	-Thrust -Maneuverability -Drag	-Thrust -Maneuverability -Waterproof-ability
Cons	-Waterproof-ability -Thrust	-Maneuverability	-Power draw	-Waterproof-ability	-Power draw -Drag -Mass

In general, using actuator-controlled fins for pitch and yaw control is very power efficient and reliable with respect to maneuverability. However, the off-the-shelf waterproofed servos necessary to achieve this design were not highly accessible and did not match the budget requirements. Additionally, creating our own custom waterproof servos was deemed not viable due to time constraints with respect to designing and building. Furthermore, the team was dubious of the reliability of waterproofing in regard to a custom waterproof servo.

The three-thruster design met nearly every design requirement, providing a reliable maneuverable design while minimizing drag. The use of thrusters allows for the design to be easily waterproofed but increases power draw. To offset the increased power draw in the future, the possibility of a fixed wing idea presented in option 2 could be added later. As the third thruster is used for depth control, the wings would be fixed so as to aid the third thruster in moving the vehicle downward. In this design, the effects of potential roll would be addressed through ballasting.

3.3.2.2 - Thruster Choices

There are a number of waterproof thrusters the team could choose from, but we are very thankful to RSL for providing us with Blue Robotics's T200 Thrusters. At nearly 170 dollars per thruster, the T200 Thrusters are very budget-friendly. With a potential eleven pounds of forward thrust and the capability to operate in reverse, the T200 Thrusters meet our requirements with respect to thrust and maneuverability. With an approximate length and diameter of 13 centimeters and 10 centimeters respectively, these thrusters also match requirements with respect to the vehicle's size.

Figure 18: Blue Robotics T200 Thrusters

3.4 - Power

This section details the electric power needs of the system. This includes the power source and the connections between components.

3.4.1 - Requirements

The battery is the life source of this vehicle, so it is important to carefully budget for all electric power needs in order to make the right choice. The main power requirements of the system are defined by the thrust needed to propel the vehicle forward. The battery also needs to provide power to the electronic control devices and sensors. The maximum voltage and power draw of the T200 Blue Robotics thrusters is 20V and 350W, respectively. Through testing of the vehicle, we determined that half speed is more than sufficient to move forward, requiring a total of 240W for all three thrusters. The details of our power budget analysis can be found in Appendix F.1. The recommended input voltage of the microprocessor is 7-12V, which means that we used a DC/DC converter to step down the battery voltage. We used a 12V 4.5A UBEC 2-5S LiPo (7.2-21V) for each Arduino Mega because it can accept a large input voltage and handle a large amount of current.

After deciding which power source to use for the VARUNA we next had to consider the methods available for connecting our components together. When selecting connectors for power and signal distribution it is important to consider the safety of the user and the security of the system. Thicker gauge wires are needed when large amounts of current are being dispersed, such as the wires delivering power to the ESCs and thrusters. In the case of power connections, it is also best to use mated connectors that mechanically inhibit the user from connecting power and ground incorrectly to other components. To limit mechanical stress on our connections we implemented a method of strain relief for each connector.

3.4.2 - Options

There are several battery types available for consideration. Based on the assessment provided in Table 5 below and our power capacity needs we selected to use a 14.8V 4S 20000mAh LiPo battery as our power source.

Table 5: Battery Type Comparison

	Lead Acid	**Nickel-Metal Hydride (NiMH)**	**Lithium-ion Polymer (LiPo)**
Pros	-Inexpensive	-Safe -Reliable	-Light -Short charge time -Low maintenance
Cons	-Heavy -High toxicity -Long recharge time	-Heavy	-Expensive -Requires extra circuitry

Figure 19 is an artistic rendition of some of the wire connectors we chose to use in our power and signal distribution design. In order to easily connect with the LiPo's existing connector we used XT60 connectors. We also implemented quick disconnect crimp connectors and bullet connectors so that so that we could easily troubleshoot and manipulate the system without compromising the integrity of the design.

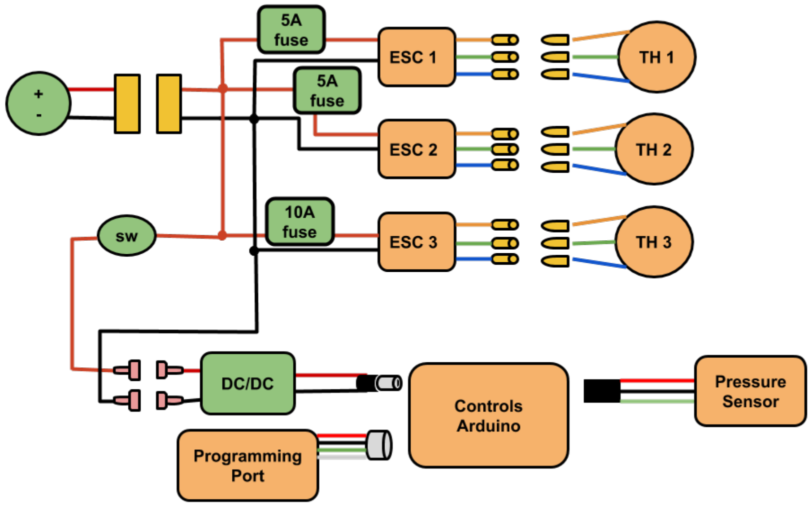

Figure 19: Electrical connections between components

3.5 - Navigation Sensors and Processing

This section outlines the sensors for that the VARUNA uses to navigate itself throughout a mission.

3.5.1 - Requirements

The navigation of the vehicle relies on three sensor inputs: heading, pressure, and time. The magnetometer provides the vehicle's directional heading, the pressure sensor provides depth, and a combination of the commanded speed and time allows the AUV to estimate distance traveled. Our budget does not allow for more sophisticated instruments for inertial guidance, so this combination of sensor inputs offers a low-cost alternative for navigation control. Therefore, an accurate compass and pressure sensor are essential to the navigation of the robot.

The on-board computer in the navigation system is also crucial to the control of the vehicle's movement. The processor must be able to intake sensor input, compare it to the user's parameters, and change the speed and direction of the thrusters accordingly.

3.5.2 - Options

Fortunately, there are affordable and accurate sensors that are compatible with common microcontrollers, such as Arduino. We decided to use the BNO055 Absolute Orientation Sensor as our directional sensor because it includes a gyroscope, an accelerometer, and a geomagnetic sensor. The included gyroscope can help our heading measurement account for the tilt of the vehicle. To measure depth, we chose an automotive pressure sensor because of its affordability and reliability. Previous projects within the RSL have successfully used this pressure sensor at similar depths.

A decision that needed to be made was whether to use an Arduino Mega or a Raspberry Pi as the onboard processor. Table 6 shows the pros and cons of each. It was quickly decided that an Arduino Mega would be used due to the team's familiarity with the device and its compatibility with the sensors we were using. If future teams were to decide that a Raspberry Pi would be better suited for the scope of the project, they can implement that instead.

Table 6: Microprocessor Comparison Chart

	Arduino	**Raspberry Pi**
Pro	-Familiarity with device -Inexpensive -Readily available -Compatibility with sensors	-Powerful
Con	-Less powerful	-More complex -More expensive

An important aspect of the design was how the researchers would communicate with the Arduino. Having to deconstruct the AUV and open the controls bottle to communicate with the main Arduino is tedious at best, especially during testing where code was being changed frequently. We decided on using a wired connection.

Table 7: Computer-to-Arduino Connection Comparison

	Wired Connection	**Xbee Wireless Connection**
Pro	-Direct connection	-No extra hole in end cap
Con	-An extra hole in the end cap -The required connector would need maintenance and upkeep	-Would require a small component to work, easily losable -Loss of signal integrity through air and bottles

Another decision we had to make was whether to use one Arduino or two to implement the navigation and payload functions. If we used one Arduino, the controls and the data collection would be working together. In general, Arduinos do not function well when having to do more than one thing at once. Using two Arduinos would 1) allow for less constrained timing parameters in the controls and 2) allow researchers to change the payload without needed to change anything in the controls Arduino. In keeping with the idea of a modular design, we chose to use two Arduinos, one that would perform the controls functions and one that would manage the payload.

Finally, we needed to consider how the AUV will be retrieved after finishing its mission. Currently, we have not implemented any of the proposed options, though GPS sensors and transmitters have been bought and are ready for use when future teams continue with the design process.

Table 8: Recollection Communication Comparison

	Strobe Light	**GPS Transmitter**	**Satellite Communication**
Pro	-Inexpensive	-Affordable -Mid range	-High range
Con	-Short range	-Weather dependent	-Expensive -Weather dependent

3.5.3 - Sensors

There are two main sensors for the navigation and controls of the AUV: an “EYourLife 300PSI” pressure sensor, an “Adafruit 9-DOF Absolute Orientation” IMU. Code integration for these sensors can be found in Appendix G.

3.5.3.1 - Pressure

The pressure sensor uses an analog pin to send voltage levels to the Arduino. At the time of writing, a datasheet for this sensor has not been found, so an equation for turning the voltage levels into pressure was found through linear estimation. The sensor gives a voltage range of

0.5V to 4.5V and it goes a pressure range of 0 psi to 300 psi. Using these numbers, a very rough linear graph was created, as seen in Figure 20, and this is the equation that is used in the code. It is recommended for future design teams to buy a more accurate pressure sensor, such as the pressure sensor from Blue Robotics.

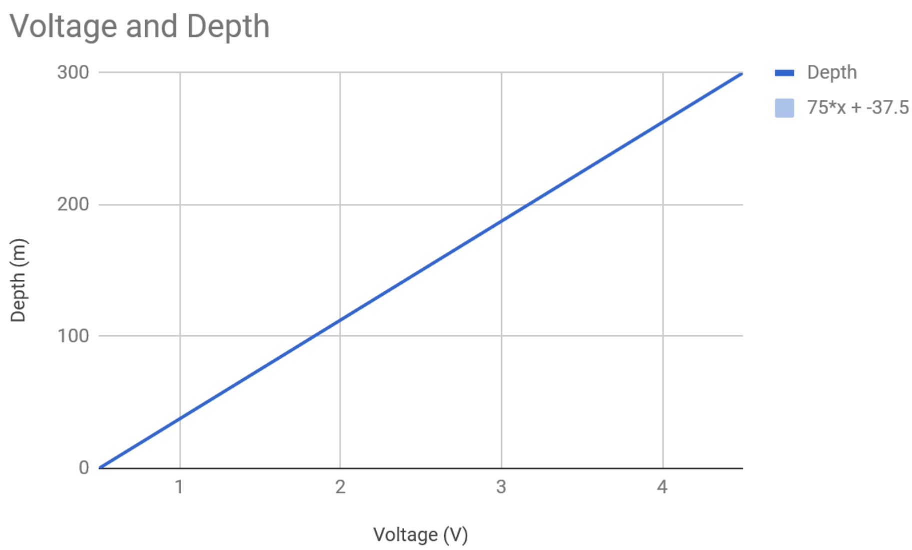

Figure 20: Linear Graph for Pressure Sensor

3.5.3.2 - IMU

The IMU has many capabilities for the future design of the AUV, but as of now it is only being used for the onboard magnetometer's heading data. The heading data collected is in degrees, and the compass translation is show in Figure 21. It should be noted that this is an inverted unit circle, and the controls must be built to reflect this.

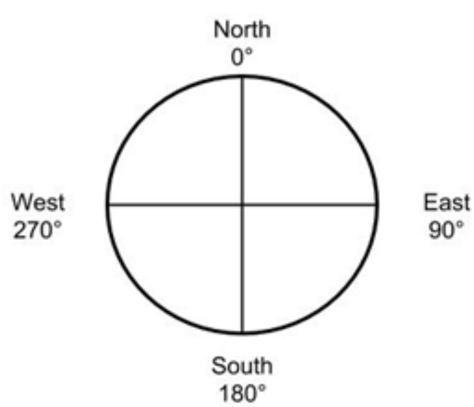

Figure 21: Unit Circle Model of IMU

The AUV's main mission has it moving back and forth, and in order to stay on this path we are using "North" and "South", or 0 degrees and 180 degrees. The IMU's heading readings are sensitive to movement and are heavily affected by induced magnetic fields, though the amount this affects the data readings have not been tested. Because of this, we are unsure how the motors affect the heading data, so it is recommended that testing be done for this in the future. The IMU is also very sensitive to roll and pitch.

The IMU must be calibrated every time the AUV is turned on. To do this, picking up the AUV and spinning it in figure eight patterns will allow it to find magnetic north. The calibration is not perfect, so it is not guaranteed that the "north" the IMU finds during calibration is necessarily magnetic north. It is assumed for the needs of the mission that it is not required that the IMU's north is magnetic north, just that it stays constant throughout the mission.

3.5.4 - Main Program

It's important to note that at this stage of development the VARUNA is still in the testing phase, so a complete control system has not been implemented though there is a basic structure. The controls system uses three sensors: a pressure sensor, a magnetometer, and a timer. There are two parts of the main program: the first section details how the program structures the missions and the second section details the main controls system for the thrusters.

3.5.4.1 - Mission Structure

The program starts by asking for the parameters of the mission. This is done through a GUI (See 3.5.5), and after parsing the data from the GUI the program receives six parameters: its total X Distance (xTotal), total Y Distance (yTotal), the final depth to survey (dTotal), how often data is taken in the X direction (xIncrement), how often data is taken in the Y direction (yIncrement), and the depth changes (dIncrement). A visual representation of this can be seen in Figure 22. The total distance and the increments are both exact numbers: for example, a researcher would say "I want to go a total of 100 meters in the x-direction, while taking data at 10-meter intervals." "100" and "10" would be the information the program receives. After receiving the data, a time variable called "time2" is created which determines the time between data points in milliseconds. This is found by multiplying the xIncrement distance with a "rate", which is determined from testing. Currently the AUV has been tested to go 0.75m/s at its baseline quarter speed.

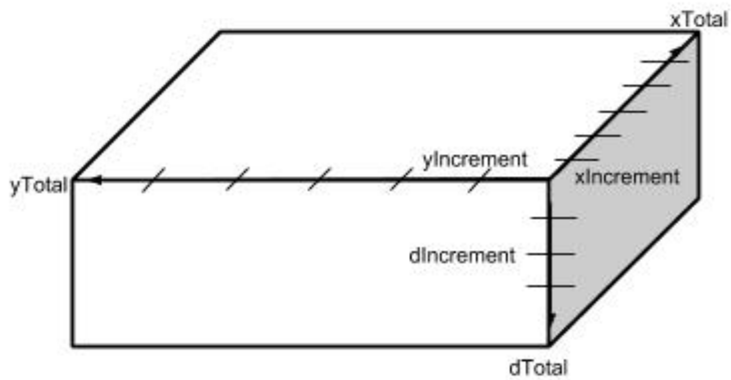

Figure 22: Mission Parameters

The main loop starts, and the Arduino's internal timer begins. The AUV starts moving in the "X" direction, which is "North" on the IMU. Three variables are created to help the program understand where it is in space: xCurrent, yCurrent, and dCurrent, which initialize to zero. Every 100 milliseconds, the AUV checks its heading and pressure to determine if any motor changes need to be made to stay on course. More on this will be detailed in 3.5.4.2 - Controls. Figure 23 shows the mission control flowchart. When the current time in milliseconds is greater or equal to time2, i.e. it has reached an increment point, the payload will collect data and the program will increment xCurrent by adding xIncrement to it. If xCurrent is greater than or equal to xTotal, then the AUV will turn to face the opposite direction and set xCurrent to zero, while incrementing yCurrent by adding yIncrement. While turning, the AUV will move a distance approximately equal to the yIncrement distance [note: turning radius has not been tested yet, so more testing must be done in order to implement this]. Once both xCurrent and yCurrent are equal to or greater than xTotal and yTotal, this indicates that scanning across the depth has been completed and the AUV can move to the next depth. The AUV turns in place to face the opposite direction and then dives to a new depth which is determined by its dCurrent plus dIncrement. xCurrent and yCurrent are set to zero, and the procedure goes through the new depth. Once all three parameters have been completed (dCurrent, xCurrent, and yCurrent are greater than or equal to xTotal, yTotal, and dTotal), then the mission is complete, and the AUV returns to the surface.

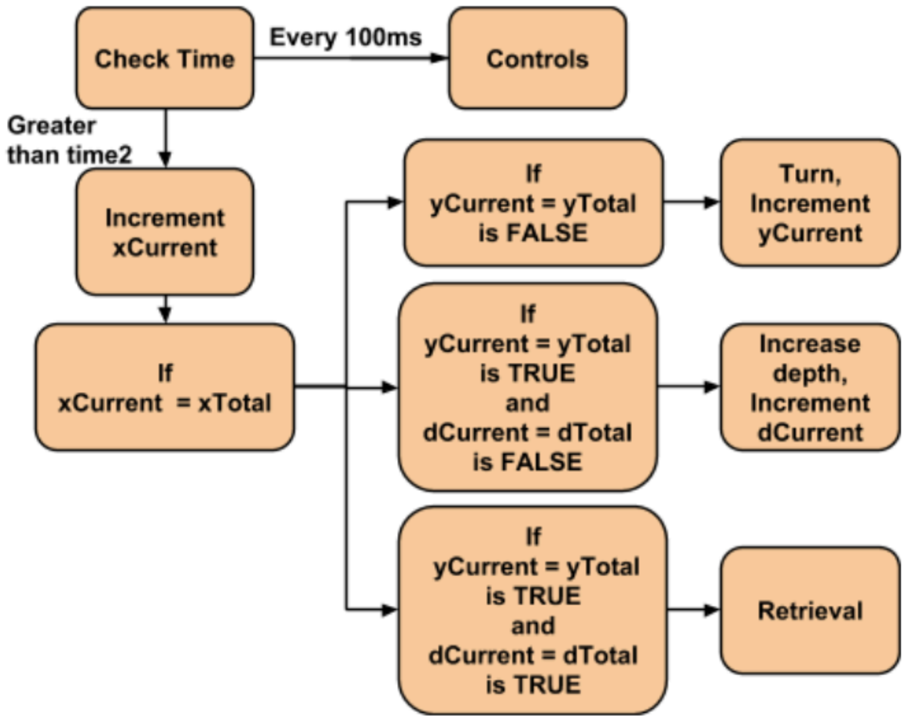

Figure 23: Timing Controls Flowchart

3.5.4.2 - Controls

Every 100 milliseconds, the program runs the main controls system which checks the pressure sensor and magnetometer. If the depth is not within a range (currently a range of plus/minus one meter of the desired depth), the vertical thruster will change its speed to compensate. If the heading is not within a range of plus or minus 15 degrees of the desired direction, the lateral thrusters change their speed to compensate. By how much the thrusters will change to compensate has not yet been decided on, as the testing is ongoing. Currently two types of controllers have been tested: a proportional controller and a half-proportional controller.

For the heading control, the proportional controller would take the actual heading, subtract that from the desired heading, multiply the result by a constant, and add or subtract it to the thrust of the motors. Ideally, this type of controller would evolve into a PID controller. There are a few issues that the controller runs into currently. First, the thrusters are limited to a range of 100ms (1600ms being baseline, and 1700ms being max), so the constant for the controller must be limited to consider this. Currently, the proportional constant is suggested to be between 1 and 0.5. The maximum deviation the heading controller would see is 180, so if one wanted to use a full proportional controller, the constant would have to be less than 0.55 to not blow a fuse. To go off of this, there is an issue that presents itself when trying to use a full proportional controller: when the two lateral thrusters go in opposite directions at higher speeds, the AUV is highly likely to flip. The half-proportional controller has been suggested as a way to keep the AUV from flipping until a solution to roll has been found.

The half-proportional controller checks the heading and if it is off, it adds the change to one thruster according to the same specifics as the proportional controller. The other thruster remains at the constant baseline speed. This helps roll as in no case do the thrusters turn backwards, but it is limiting for mobility. Examples of both controllers can be seen in Appendix G.

3.5.5 - GUI

In order to keep the VARUNA user-friendly, a downloadable GUI has been developed to simplify mission programming (Figure 24). The mission begins with asking the user what their desired mission parameters are. There are seven fields that need to be filled: X-Distance, Y-Distance, Total Depth, X-Increments, Y-Increments, Depth Increments, and water type. This is packaged with a character separator between each field and sent through the serial port to the receiver (in the current case, an Arduino) when the “Send Data” button is pressed.

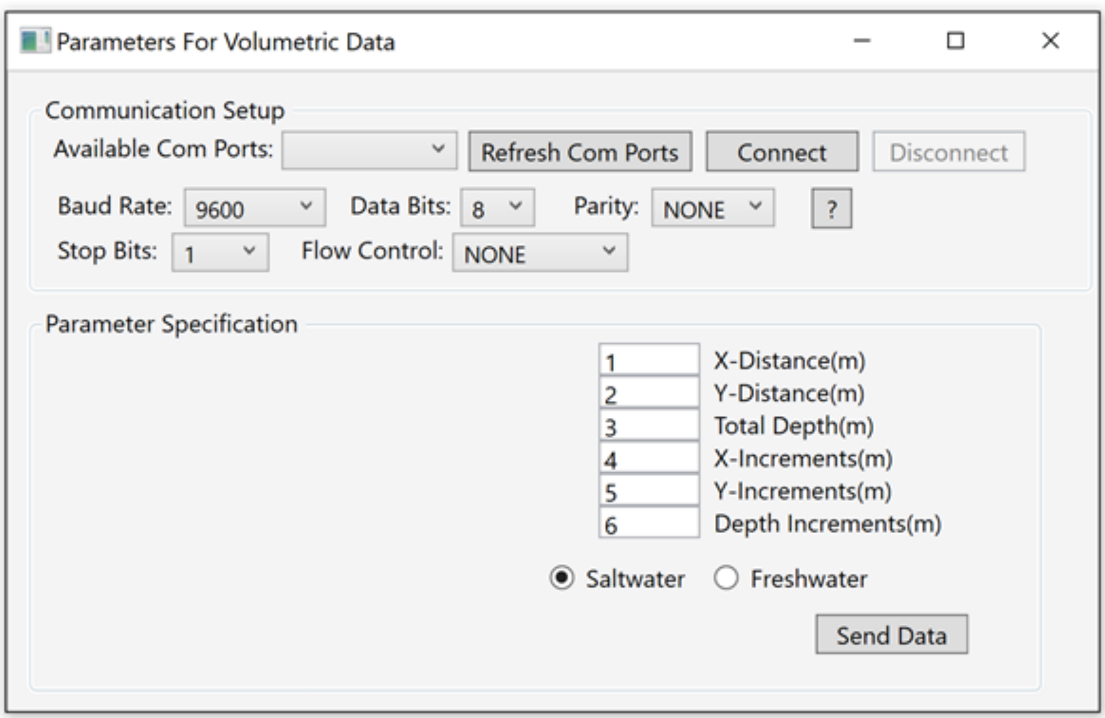

Figure 24: GUI

The Communication Setup section is there for users to modify if they so desire. It autofills the boxes with the suggested parameters, so unless a change to the receiver is made the user does not have to worry about it. The GUI is built in Visual Studios using C#, and the source code can be downloaded and modified with new parameters in the future, such as sensor choices, starting from a specific point in the mission, and mission length based on the inputs.

3.6 - Payload

3.6.1 - Requirements

The payload component of this vehicle is customizable. The main requirements for the system are sensors that probe the vehicle's surroundings and a processor that has the capability to log this data at various intervals.

3.6.2 - Options

There were a multitude of possible options for payload Sensors. We decided to go with a general CTD Sensor: conductivity, temperature, and depth sensor. Depth is given from the controls Arduino, so we decided on a temperature sensor and a conductivity sensor for the payload.

3.6.3 - Sensors

The vehicle includes payload sensors that are responsible for collecting data from the area of study. Our design carries a minimal payload of a temperature and conductivity sensors, but the long-term vision includes a modular system where the user can easily connect their preferred sensors to the system. The current payload set-up consists of the Celsius Fast-Response Temperature Sensor from Blue Robotics and the Conductivity Probe K 1.0 from Atlas Scientific.

3.6.3.1 - Temperature

The Celsius Fast-Response Temperature Sensor from Blue Robotics is designed to work with underwater vehicles. Blue Robotics has a downloadable library to use with the sensor. This made it easy to integrate with the AUV and makes programming for the sensor easy and quick. The sensor cannot be plugged into the Arduino, as it requires a DC-to-DC level converter, otherwise the sensor is damaged. The sensor uses the I2C port on the Arduino and is currently the only payload sensor that does so. If any sensors are implemented in the future that use I2C, the internal payload Arduino code will need to be modified to accompany more than one sensor on the I2C bus.

3.6.3.2 - Conductivity

Conductivity sensors are most often used to determine the salinity levels in water samples. This is done by applying a voltage across two parallel electrodes and measuring how quickly the electrons move through the water between them. This particular sensor has a response time of 90% in 1 second and functions in depths up to 1,125 ft. Use of this sensor requires a 2-point calibration using the solutions provided with the probe. Along with the conductivity probe we also purchased the EZO-EC™ Embedded Conductivity Circuit so that the data collected could easily communicate with the Arduino. Using UART mode the conductivity circuit communicates the salinity values directly to the Arduino.

3.6.4 - Payload Functionality

The controls Arduino and the payload Arduino communicate through the Arduino Mega's onboard serial ports. The payload Arduino waits for input from the serial port from the controls Arduino. The controls Arduino at the increments described in section 3.5.4.1 sends a package of data "xCurrent, yCurrent, dCurrent," to the payload Arduino. Once it receives this, the payload runs its sensors and prints all of the information to a data logger. Example data package would be "xCurrent, yCurrent, dCurrent, temperature_data, conductivity_data". The data logger stores the information as a text file on a microSD card, and future programs used to process the data uses the commas as separators. This gives researchers sensor data at a specific point in the mission. At the time of writing, it has not been tested how much data can be ultimately stored. Missions with high data resolution are recommended to use higher capacity microSD cards.

3.7 - Summary

Our team designed and built a complicated robotic system by dividing the system into smaller, more manageable subsystems. The structural components were comprised of the hull, pressure vessel, and propulsion systems. The electrical components fell into either the power management or the sensor and processing subsystems. The design decisions we made in each of these categories led to the final assembly of the VARUNA. Structurally, we chose to use an aluminum exoskeleton for our hull, three separate pressure vessels with custom end caps, and a propulsion configuration of two rear thrusters and a single vertical thruster in the front of the vehicle. Electrically, we decided to use a 20mAh 14.V LiPo battery to power the entire system, using DC/DC converters to provide appropriate voltage levels to the on-board sensors and processors. Our current control sensors are pressure and compass heading. Operators use our GUI to input their desired parameters into the control processor. These parameters dictate the cube of volumetric data that is collected and stored by the payload processor.

Chapter 4 - System Integration, Testing, and Results

This chapter details the work that went into integrating the subsystems of the VARUNA. It also describes how we tested our vehicle and what we accomplished.

4.1 - Systems Integration and Bench Testing

This section details the processes by which we ensured that each of the VARUNA's subsystems came together to execute the overarching functionality of our design.

4.1.1 - Electronic Systems Bench Testing

There are many functionalities of the VARUNA that can be tested in the lab before it ever nears the water. First, we verified the individual functionality of each component in our system to ensure that they worked as expected. Next, we integrated the components into a larger electronic system and verified that everything worked when connected together.

4.1.1.1 - ESCs and Thrusters

One of the first things we needed to test was whether or not our ESCs could successfully control the speed of our thrusters. This system set-up also verified that all necessary components were receiving the appropriate amount of power. As pictured in Figure 25, power and ground from the battery branch off to power the ESCs and also to a DC/DC converter to step the voltage down before powering the Arduino Mega.

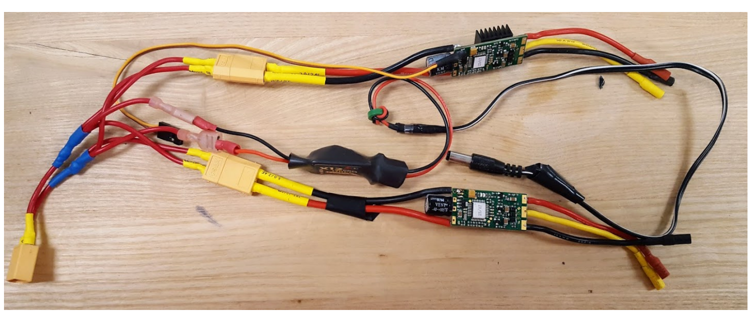

Figure 25: Early iteration of the electronics testing set-up

This wiring set-up was implemented in order to safely and quickly test the behavior of our ESCs and thrusters and was not optimized for magnetic interference removal or economical use of space. To verify the behavior of the thrusters we programmed the Arduino with simple test code that used different pulse width modulation (PWM) values between the 1100ms (full speed backwards) and 1900ms (full speed forwards) levels in increments of 50ms. The motors performed as expected, going the correct directions and speeds as defined in the code.

4.1.1.2 - Pressure and Temperature Sensors

We tested two of the main sensors, the pressure and temperature sensors. Due to the nature of the sensors, we could not fully test them to determine their range and accuracy. Through wiring to the Arduino, we were able to see that they could take accurate values of the area. Small tests were done to see if the sensors could change according to the stimulus we applied. When blowing into the pressure sensor, the pressure reading increased, and when placing our fingers on the temperature sensor, the sensed temperature increased.

Figure 26: Pressure sensor (left) and temperature sensor (right)

4.1.1.3 - Arduino to Arduino Communication

An important part of the programming was making sure that the two Arduinos could communicate effectively. The controls Arduino needed to be able to send a string of data, which the payload Arduino needed to be able to receive and print to a serial port. To test this, we had the controls Arduino send a word once a second and had the payload Arduino print it out to a computer's serial port. This worked as expected.

4.1.1.4 - Compass Reading and Thruster Response

The initial tests for the IMU compass were done by itself. After hooking it up, we spent time practicing initialization and plotting the relative degrees with the compass directions. Then to test control code, we set up some LEDs as placeholder motors and watched as the LEDs lit up to determine which direction the motor was going to "fix" the heading back to the wanted heading. Then, when we finished the thruster setup, we combined everything and experimented with motor response to the IMU's heading. Overall, this has been rather successful outside of water.

4.1.2 - Ballasting

Ballasting for marine robots is incredibly important. The locations of the centers of gravity and buoyancy affect how the vehicle moves in the water. For torpedo-shaped vehicles, the center of mass should be directly below the center of buoyancy. If they are too close, the vehicle will not know which side of itself is up; if they are too far apart, however, the vehicle will resist diving. Thus, adding weights in the right places to bring the centers of mass and buoyancy to the correct location is an important and delicate process. To keep track of the location of the centers of mass and of buoyancy, we made a spreadsheet that noted each item in the AUV and its location, volume, and mass. The spreadsheet calculated the moments each component in the AUV contributed and summed them to find an approximation of the locations of the centers of mass and buoyancy. The spreadsheet can be viewed in Appendix F.2.

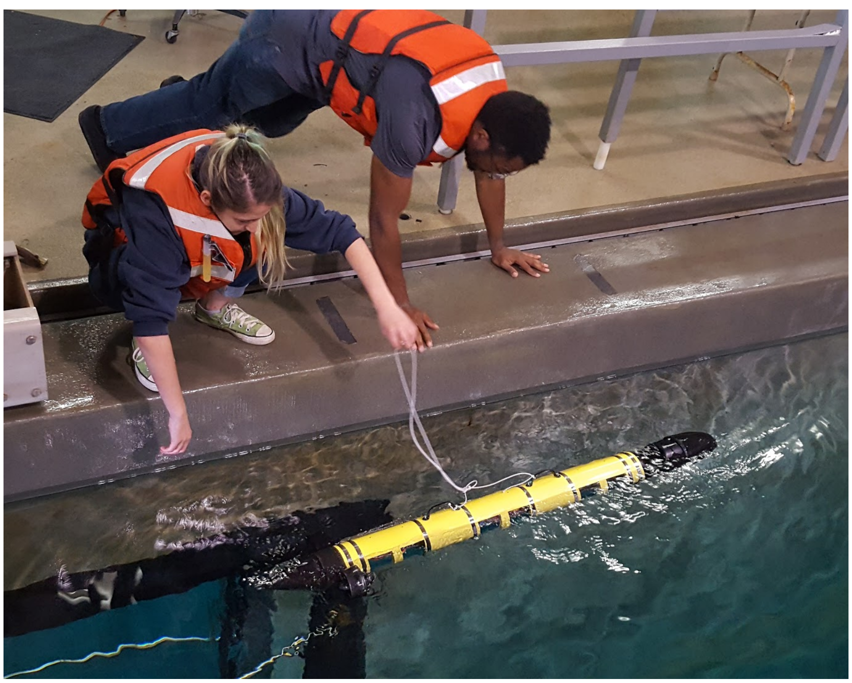

Figure 27: Ballasting the VARUNA

Before testing and after the approximate locations of the ballast points were found using the mass spreadsheet, the VARUNA had to be experimentally ballasted until the centers of mass and buoyancy were lined up correctly. In the early stages of testing, our design did not include easy ways to add or remove weights. This drove us to redesign the nose and tail cones to include threaded rods on the inside that could hold disc-shaped weights. With improved designs, experimental waterside ballasting tests were much easier to complete. The image below shows us testing the ballast of the VARUNA in MBARI's test tank.

During MBARI test days we also discovered a problem with our method of 3D printing our end cones and coating them with fiberglass. We discovered that there were small pockets of air within the structure of the end cones that were compressed as VARUNA dove deeper into the tank. The compression of these air pockets allowed water to enter the cones and sink the vehicle. Due to this realization, the cones were redesigned once again and will now be manufactured from a ultra-high molecular weight plastic.

4.2 - Field Tests

This chapter details the testing processes and the results of our work in the field. Our understanding of the system was greatly enhanced by our experiments in test pools and lakes.

4.2.1 - Thruster Verification

In order to gain a better understanding of the T200 thrusters, we implemented a moment arm with a spring scale attached to one end and a thruster attached to the other. We methodically incremented the signal pulse length by 50ms and measured the force required to keep the moment arm vertical. Figure 28 shows our experimental set-up and Figure 29 shows our resulting data, which verified the plots available on the Blue Robotics datasheet.

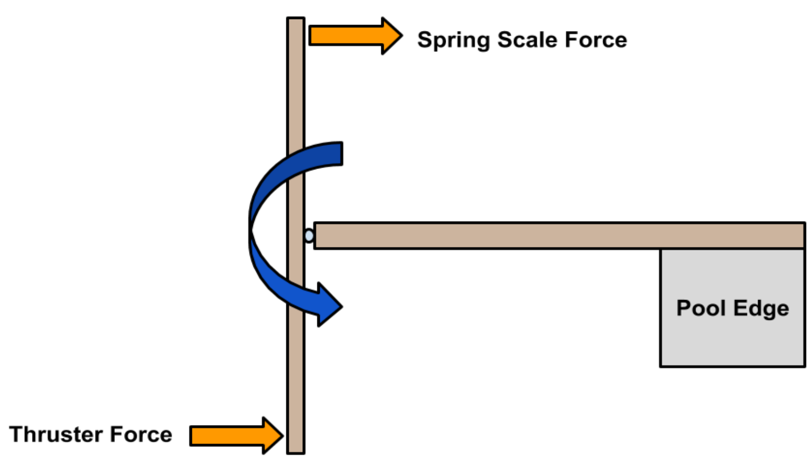

Figure 28: Thruster verification testing set-up

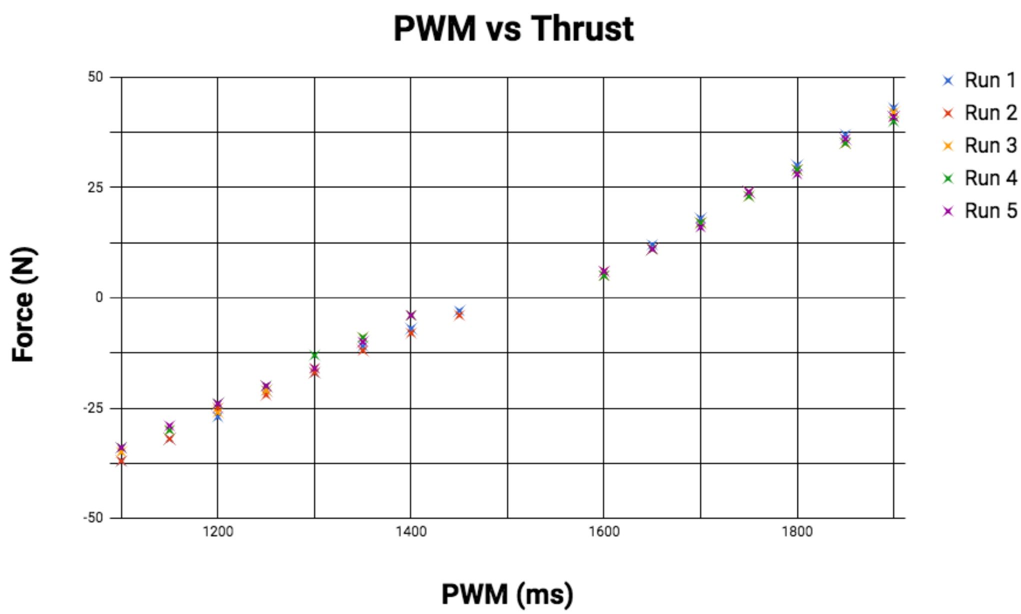

Figure 29: Force of thrusters due to length of signal pulse

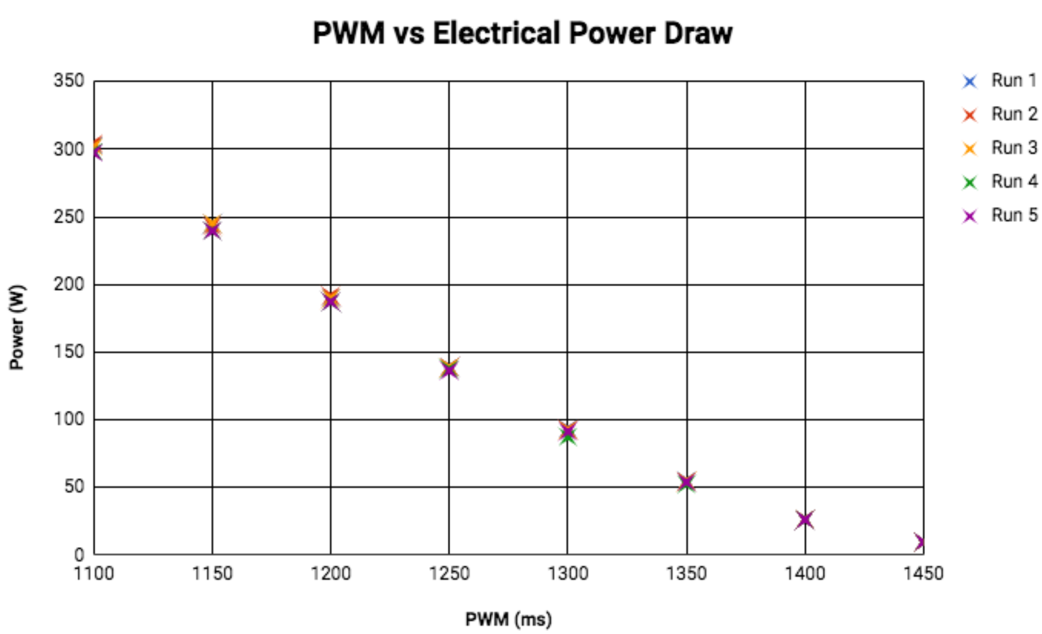

Figure 30: Relationship between signal pulse length and electrical power

We also connected a current meter to our set-up to measure the amount of current necessary to run the motors at different speeds. We combined this data with the input voltage to determine the power needed to move the motor at various speeds. Figure 30 shows this data for the motor starting at full speed backwards to stopping at neutral.

4.2.2 - The Archimedes

Our preliminary tests called for the use of a rugged design. The need for a quick yet effective model resulted in the manufacture of our first prototype, the Archimedes, or "Archi" (Figure 31). Archi had to maintain an appropriate degree of watertight operation, approximate the general geometry of the finalized craft, and give our team a good idea of the general behavior of underwater craft. Archi featured steel ties screwed into machined aluminum plates that supported our T200 Blue Robotics thrusters. Its hull was manufactured from a 19.25-inch ABS pipe with ABS end caps.

Testing Archi's capabilities was the first step in increasing our understanding of some of the basics of underwater robotic operations. The tests gave us an idea of the underwater travel speed, the behavior of the T200 thrusters near the surface of the water, the importance of ballasting, and the difficulty of programming the control processor without readily operated switches. We were also able to get preliminary directional control data. Directional control verification was perhaps one of the most important moments in the early stages of our proof-of-concept work and will be explored in detail in section 4.2.2.

Figure 31: The Archimedes resting at the bottom of the test pool during the initial field tests.

4.2.3 - The VARUNA

Although testing Archi was a crucial first step in our field work, we could only get an approximation of the general dynamics of our AUV, and we were not able to implement the third vertical thruster into Archi's design. Archi was by no means an ideal representation of this year's finalized AUV.

After realizing this, we built and manufactured the first model of the VARUNA. Figure 32 displays the VARUNA undergoing its first pool deployment. In the later phases of testing the VARUNA, many underlying issues proved to be detrimental to the successful operation and the execution of our mission plan. Two of the issues that arose during testing included unstable roll and compressed air pockets, the latter having been explained in Section 4.1.2.

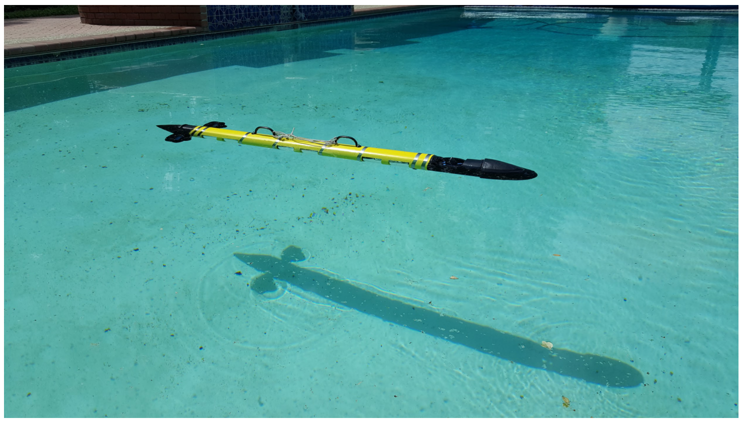

Figure 32: The first pool test of the VARUNA in a fully assembled state

One of the most important aspects of the VARUNA code is making sure the AUV can stay on a directed course in a certain direction. This was difficult to test, as our main testing area was a small pool, and we required a bigger space to get any usable data. The team went out to lake to do these heading tests. The lake, while giving us lots of space, added the variable of waves. This was unfortunate for our initial testing, but it was valuable to see how the AUV interacted with this extra obstacle. A graph of heading over time can be seen in Figure 33.

The AUV was instructed to stay on a “North” course, which is at 0 degrees, for around sixty seconds. The heading had an error buffer of plus and minus 15 degrees. This means that when the heading had exceeded this buffer, the controls system would try to bring the AUV back to zero. We can see from the graph that the sensed heading is very unstable. This can be attributed to the waves from the lake that disturbed the AUV. The important thing to note from the graph is that when the AUV’s heading exceeded its buffer, the AUV took measures to move back towards zero, which can be seen throughout the graph.

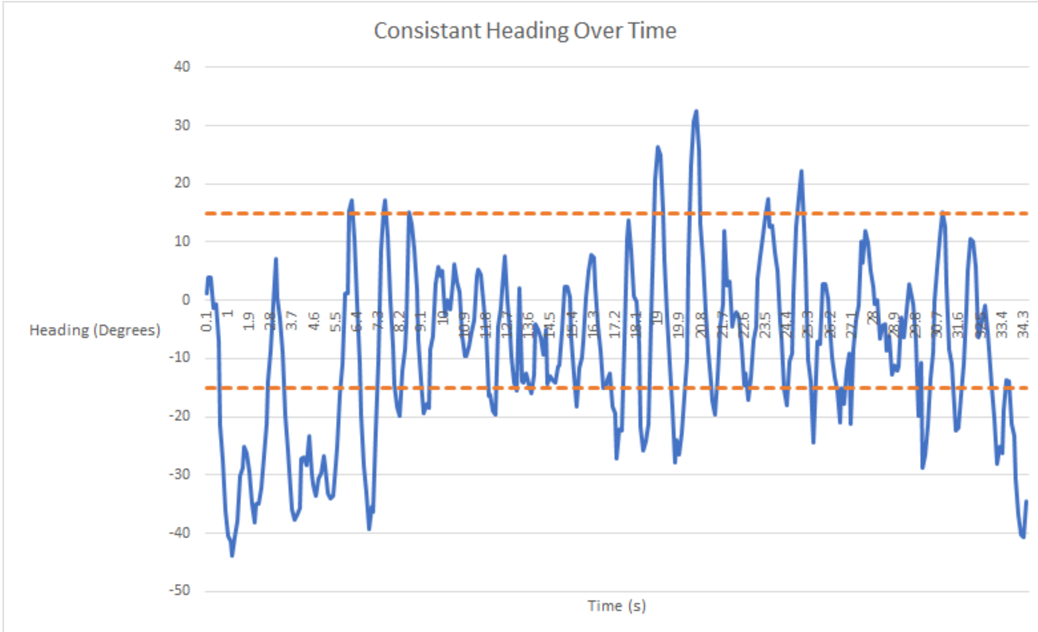

Figure 33: Heading data over time

An AUV cannot truly be called an underwater vehicle if it cannot go underwater and know its current depth. To test this, we asked the AUV to dive to a depth of 3 meters then stop and return to the top. Figure 34 shows the data from this experiment.

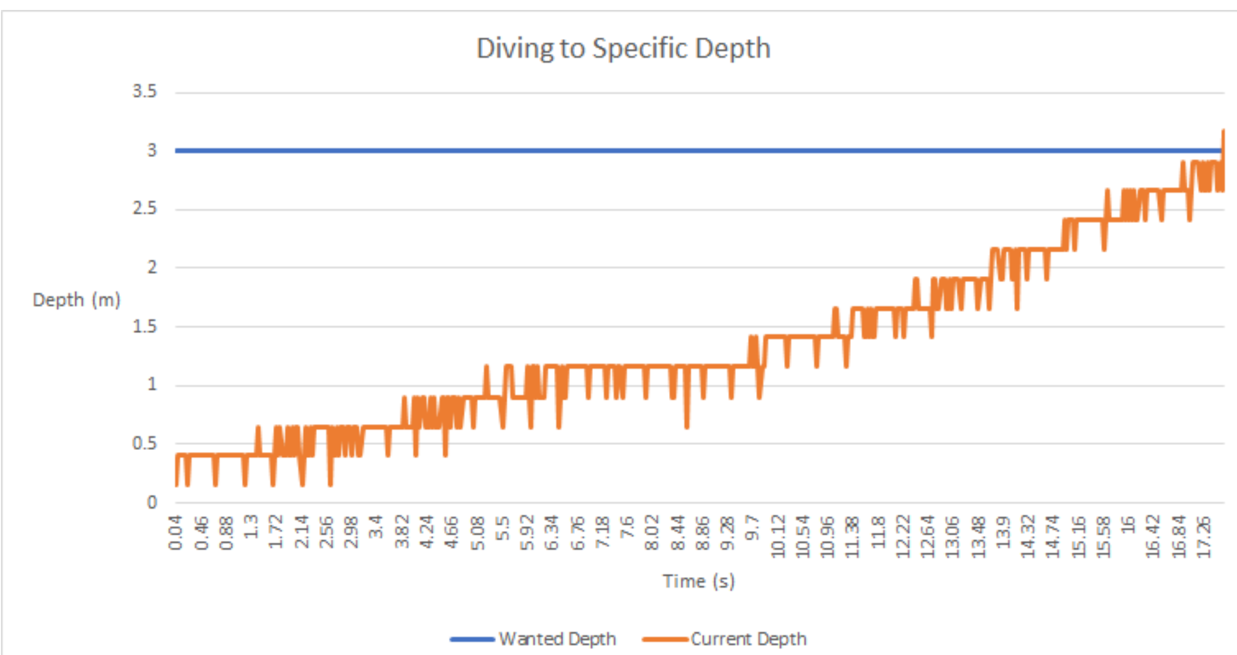

Figure 34: Pressure data over time

The graph shows a steady dive to reach 3 meters, and when it had exceeded 3 meters the AUV stops, which is what we wanted. The next phase of this testing is maintaining a depth, which will be carried on with future teams.

4.3 - Summary

Simulations and analysis are helpful tools in engineering a reliable and fundamentally sound product, but our team found that bench and field testing were critical in our design of VARUNA. First, we individually tested all components for functionality. Next, we integrated these components together and used basic programs to verify the system behavior. Through this testing we were able to determine the ideal PWM commands for VARUNA's typical operation speed. We were also able to generate equations to help us interpret the raw output of the pressure sensor.

Testing with Archi in the pool dramatically increased our understanding of how the thrusters operate in water. For example, we determined the ideal depth below the surface the thrusters needed to be before they stopped pulling air into the water. Testing with the fully assembled VARUNA became an iterative process: we would test something, discover an issue, redesign, and test again. As mentioned in section 4.1.2 the ballasting process became an important part of every field test. At the time of writing we have yet to test our payload processor in the field.

Chapter 5 - Professional Issues

5.1 - Engineering Standards and Realistic Constraints

This section discusses how several professional considerations affected our design decisions. It talks about the relevance of economics, environmentalism, sustainability, manufacturability, and health and safety in the design process.

5.1.1 - Economics

Making a low-cost AUV option for scientists and research groups with limited funding was an important concern of ours. Most of the AUVs on the market are extremely expensive. The sensors and payload are what often drive the price of AUVs so high, with high-end marine sensor packages sometimes costing up to $20,000, which is more expensive than some of the low-cost AUVs themselves. Research laboratories, such as the RSL, do not often have the means of attaining such expensive equipment.

With this in mind, the goal of our project was to achieve a high-value product at a low cost. The capabilities of our robot can be largely improved if the user chooses to include high-grade sensors due to the modularity of our design. However, we believe that our student-level project will meet the needs of other students in the lab. It can also live on for future design teams and they can make adjustments using their available funding. We ordered off-the-shelf components from reliable retailers to ensure that our low-cost model can be easily sustained in future years.

The economic model for our project is similar to that of a non-profit in that we are not expecting to sell our final product for a profit. Our AUV can contribute to the financial success of the RSL by garnering the interest of possible donors and industry partnerships. The economic model of our project does not lend the VARUNA to being self-sustained through mass production and purchasing. We have minimized the effect of the economic sustainability by producing only one robot that will be used for research and products in the future.

5.1.2 - Environmentalism

Consideration of VARUNA's environmental impact is two-fold: (1) the consequences of building, deploying, and disposing of the vehicle and (2) the advancement of environmental knowledge based on data collection during deployments. In this section we consider the effects our design choices may cause to the environment.

5.1.2.1 - Resources for Product, Process, and Service

The impact on the immediate and global environment is largely dictated by the mechanical and electrical components used to create our AUV. We utilized off-the-shelf components, so design and manufacturing costs were included in the cost of purchase. Our mechanical engineering team was responsible for machining the end caps for the watertight enclosures, the polyurethane end cones, aluminum exoskeleton, and 3D printed thruster braces. These processes used the resources of the mechanical engineering department machine shop and donated material from industry partners. To ensure secure electronic connections we used the soldering and crimping resources available in the RSL.

5.1.2.2 - Operational Resources

This is intended to be a long-term project. To that end, once the current team has completed the year, the project will move onto a new team. This means that more material will be used in the future to further the project. Once the AUV is considered finished, it will not require any resources to keep it operational, besides general upkeep requirements. These requirements may include replacement electronics and mechanical parts, in the case that something was to break. There is also an energy requirement for the AUV in the form of rechargeable batteries. The use of rechargeable batteries is beneficial to the environment, as the users do not have to dispose of batteries once they are depleted.

5.1.2.3 - Environmental Impacts of Materials Disposal

Most of the mechanical structure of the AUV is composed of recyclable materials: aluminum, glass, and steel. The electronics will be disposed of using the university's electronic waste collection service when they reach the end of their life. The benefit of using a lithium polymer (LiPo) battery to power our system is that they are landfill safe once they have been properly discharged, so we are not introducing harmful chemicals into the environment once the battery is no longer operational.

5.1.2.4 - Expected Duration of the Product Life

Our goal was to build a vehicle that can be improved upon and used for years within the RSL. A number of updates will need to occur to keep the vehicle operational. The aluminum exoskeleton will need to be replaced eventually because it will experience corrosion in the saltwater environment, the LiPo batteries will need to be replaced, and the sensors could be exchanged as technology improves.

5.1.3 - Sustainability

5.1.3.1 - Benefit to Users

Commercial AUVs are expensive to buy and getting an AUV that does the exact missions you need it for are even more expensive. By designing and building this AUV, SCU's RSL will have the building blocks for future AUV research. Researchers at MBARI have also expressed interest in using VARUNA, which will benefit them greatly as they won't have to develop a costly AUV for their shallow-water research needs.

5.1.3.2 - Articulated "Wants" and "Needs"

The RSL has a clear need to add an AUV to its repertoire. By adding another tool for the students to use and become familiar with, SCU graduates will be more prepared to work in the field with a diverse set of research vehicles. It will also add another avenue of industry partnership for the RSL with environmental scientists. The AUV will also give future students the opportunity of internships and capstone projects as further work is done on it.

5.1.3.3 - Ease of Use and Value for Users

Our design goal was for the AUV to be easy to operate for non-engineers. This means that the RSL could loan the vehicle to a geologist or oceanographer and they would be able to deploy the robot with use of an included user's manual and computer-downloaded GUI. It is small enough to fit inside a large car and light enough for 2 people to pick it up, and it has handles for easy carrying.

The highest risk for physical danger is the misuse of the LiPo batteries. If these batteries are overcharged or mishandled they can explode and cause fire. The safe charging and discharging protocol will be clearly outlined in the user manual so as to avoid any physical harm. We are using mated wire connectors for all wiring connections to ensure safe electronics in the marine environment.

5.1.3.4 - Accessibility for Intended Users

The AUV will stay with RSL, where it will be easily accessible to future design teams. Researchers that have a connection to the RSL can also easily partner with the lab to gain access to the AUV. It is possible that this project will generate new connections between industry professionals and the university, potentially adding new users that we had not originally intended.

5.1.4 - Manufacturability

A design is only successful if it can be manufactured. It was important for our team to think about design options that we could actually fabricate or get machined for us. This impacted the material selection for various parts of the design. One of the major reasons that manufacturability has been an important consideration is that due to our limited budget, we have had to make some specific parts to ensure compatibility with parts that were given to us for free. For example, marine grade connectors are very expensive, so it was important that we chose watertight bottles that could interface properly with the connectors that were donated to us. To deal with this, we purchased watertight bottles from Blue Robotics, but removed the end caps that came with the bottles and machined our own.

Another example where the issue of manufacturability was important was in the material choice of the exoskeleton. The design process for the exoskeleton is explained in greater depth in section 3.1.2.1, but balancing accessibility of material with manufacturability was important. This led us to steer away from making the exoskeleton out of PVC or ABS piping and toward other material options.

5.1.5 - Health and Safety

The health and safety of the users and any bystanders is an essential design consideration when it comes to the VARUNA. When operating the craft, it was important to take into consideration that there will be many potential hazards to the user. Some of these hazards come in the form of the rotating blades of the thrusters, the electrical components and the inherent current-water issue, and the weight of the system. Some possible measures that can be considered in addressing health and safety concerns include covering the thrusters with a light mesh, potting wires, and including ergonomic handles on the VARUNA's hull. For a more comprehensive overview of the health and safety concerns, refer to the Safety Report attached in Appendix D.

5.2 - Proposed Business Plan

This section discusses an in-depth potential business plan for the commercialization of the VARUNA and its accessibility to organizations other than the RSL.

5.2.1 - Goals and Objectives

The goal of the commercialization of our product is to provide small research organizations and educational laboratories access to a relatively low-cost way to build their own autonomous marine vessels. Most AUVs currently on the market are priced starting at upwards of \$10,000, often times with sensors that themselves can cost over \$20,000 and are ordered either preconfigured with sensor packages or can be customized at additional cost. For small scientific and educational groups with low budgets and varying needs in such a vessel, the option for a cheap, bare-bones, build-your-own kit that can be customized by the user to whatever specifications they desire. Selling our product as a kit allows customers to configure it with whatever sensors they desire, bringing the overall price to whatever the customer chooses to pay, given the quality and range of sensors they want driven by the specific needs of their AUV.

5.2.2 - Product Description

The VARUNA features three 4.5”/4.0” outer/inner-diameter modular pressure vessels--one contains the battery, one houses the controls hardware and processor, and one that contains the payload hardware and processor. The pressure vessels feature end cap flanges and end caps that can be machine-customized by the user. We also provide a tube of silicone grease for installing the O-rings along with instructions on the complete mechanical assembly of the VARUNA.

The bottles are held together via a bright yellow aluminum exoskeleton, which is in turn reinforced by 4.0” - 5.0” hose clamps and is complete with two handles for ease of transport. The VARUNA utilizes ultra-high molecular weight polyethylene nose and tail cones that help to reduce the drag forces on the craft’s body. The inside of the cones will contain shafts for adding weight for ballasting the craft. We provide multiple weights of different masses to allow for fine tuning of the ballasting process.

Our product also features three Blue Robotics thrusters--two rear laterally oriented thrusters for forward propulsion and steering, and a third frontal vertical thruster to enable diving and resurfacing. These come complete with electronic speed control components. The user has the ability to modify the wires for the connectors to fit the inner wiring of their AUV. The thrusters were powered by a 20,000 mAh LiPo battery during testing--the user is responsible for purchasing his or her own power source.

The VARUNA comes with a basic sensor package which provides conductivity, temperature and depth readings. The payload pressure vessel contains extra ports and leads for the addition of more sensors. This gives flexibility in sensor selection--depending on the user's need for specific mission data, this design allows for the integration of different sensors or imaging devices.

Within the payload and controls pressure vessels are two microprocessors. We chose to use Arduino Mega 2560s. The control processor is responsible for checking the pressure and compass readings and comparing them to the user-defined parameters. Based on the data resolution rate defined by the user, the control processor will send a signal to the payload processor and instruct it to take payload data measurements. These measurements will then be saved in the microSD card along with the corresponding spatial coordinates and time stamp.

5.2.3 - Potential Markets

The specific market we are trying to reach is one that is often overshadowed by the marine robotics commercial industry: scientific and educational groups, often at universities, who don't have the means to acquire robots on the market. Our AUV kit-selling business will also target small research organizations that may not have the capital to use more high-end equipment. This product also has potential to be utilized by hobbyists that have a desire to get into the world of marine robotics.

5.2.4 - Competition

There are few products on the market that are as low-cost and configurable as a build-your-own AUV kit would be. The biggest competition would be the Bluefin Sandshark, described in section 1.3.4, and the Teledyne Marine Gavia AUV. These products are low cost, but not as configurable as a kit.

Blue Robotics sells parts for ROVs that can be purchased separately and configured, but these fail to meet the needs of an AUV. We are not worried about competition, since no products perfectly suit the needs of low-budget organizations.

5.2.5 - Sales and Marketing Strategies

Since many components of the kit are off-the-shelf products from Blue Robotics, we would partner with Blue Robotics for this business venture. Working with Blue Robotics, we could use their website to sell and advertise the kit as well as replacement parts for the kit.

For additional pinpointed marketing, we would reach out to research organizations, especially at universities, like the RSL, as potential customers. We would also target high school robotics clubs to provide them opportunities for involved educational projects.

We would also market at events like RoboSub, which is a collegiate-level autonomous robotic submarine competition put on by Robonation, and SAUVC, which is a similar competition organized by the Institute of Electrical and Electronics Engineers Oceanic Engineering Society Singapore.

5.2.6 - Manufacturing Plans

Our manufacturing plan will be relatively simple - much of our kit will be composed of off-the-shelf products. The thrusters, pressure vessels, switches, plugs, temperature sensor, and the respective hardware related to the assembly and integration of these parts are from Blue Robotics. The marine grade connectors were purchased from SubConn Company and the exoskeleton hull is braced by hose clamps purchased from a local hardware store. The handles of the kit were also purchased from a local hardware store.

The parts that require manufacture include the nose and tail cones, the vertical and lateral thruster braces, the aluminum end caps, and the exoskeleton. All of these components would be manufactured out-of-house.

5.2.7 - Product Cost and Price

Our team spent approximately $1500 on parts for the VARUNA; however, an estimated $1100 worth of off-the-shelf products and manufacturing services were donated to us. Therefore, we estimate that the sum of all of the parts necessary for the VARUNA comes to approximately $2600. We plan to sell the AUV kit at a market price of $3100, giving us $500 revenue for each kit. We would need some funding from Blue Robotics or another partner to begin but would quickly make it back.

5.2.8 - Service and Warranty

Our product would include a six-month warranty after purchase so that the customer can experiment with the components and configure the AUV in the way they see fit. If there are issues after the expiration of the six-month warranty, we will provide a troubleshooting forum. It will be updated initially by us, and, after we can pay them, by our employees.

5.2.9 - Financial Plan

Our financial plan would require us to initially borrow money from investors with an interest in marine robotics, possibly Blue Robotics. After a period of time, we would turn a profit and reimburse Blue Robotics with added interest in hopes of fostering an ongoing partnership.

Chapter 6 - Project Management

In this chapter, we detail some of the critical aspects of the project related to management. We will discuss challenges we faced unrelated to engineering, working with the time and the budget we had, and ways we managed our team and our working process.

6.1 - Project Challenges

A major challenge we faced in designing this AUV was the interdisciplinary aspect of the project. Many of the hardest design challenges were circular problems, a result of each design choice affecting the best option for other design choices. For example, the more the mass increases, the more thrust and therefore more power is needed. However, larger power requires a larger battery, which increases the mass, and so on. This was especially difficult in managing since the electrical engineers on the team were working on the power budget, while the mechanical engineers were working on the mass budget. Staying updated on what everyone in the team is doing, especially in an interdisciplinary team, is important for efficient group work.

Another challenge in creating the AUV was simply time. Field testing is incredibly important for this project because when so many different parts are being built or purchased and combined, testing needs to be done to see how the whole system works together. The time taken for shipping of parts is important to consider. We faced setbacks when parts would break, and we didn't have extras on hand because we had to wait for new parts to ship before we could finish testing.

6.2 - Budget

The SCU School of Engineering granted our team $2,500 for the completion of the project. For a breakdown of the cost of parts of the AUV, reference Appendix K. Our team spent a total of $1523.68.

6.3 - Timeline

The finite time frame given to the team for completing testing, manufacturing, refining the VARUNA's design and control systems was one of the main hurdles. Because of lead the times for off-the-shelf products and manufacturing, it was necessary for us to create a timeline to plan for the phases of The VARUNA's design process. We defined our outline of ordering, manufacturing, and testing, which can all be found in Appendix J.

6.4 - Design Process

The first step of the design process was identifying the potential opportunities in designing and building an AUV, defining the team's mission statement and goals and determining potential clients. After this phase, research was conducted regarding client needs, potential competition and existing products, and relevant literature. Following this, concepts were generated and developed based upon the information gathered in the previous phase. Then, a concept's architecture was broken down into various sub-levels and the general layout of the system was determined. After the general design of the system was achieved, more detailed planning and design was conducted, providing more concrete details on each part within the system such as dimensions and tolerances.

6.5 - Risks and Management

This being a robot that operates with high speed moving parts underwater, there are several safety concerns to take into account. These safety hazards are present in all stages of the life of the AUV: manufacturing, assembly, test and operation, display, storage, and disposal. The Safety Report in Appendix H details all of the risks and how we mitigated them.

6.6 - Team Management

Working in a multidisciplinary team presented a fair share of challenges to our group. We learned that clear communication of roles and responsibilities is something we need to work on in order to successfully meet our project objectives. Dividing the AUV into mechanical and electronic subsystems made a complicated and large-scale project more manageable. Table 9 shows the general roles that were assigned to each team member.

Table 9: Team member responsibilities

NAME	RESPONSIBILITY	EMAIL
Shae Connor	Leader	sconnor@scu.edu
Anthony Jackson	Recorder	ajjackson@scu.edu
Madeleine Peauroi	Facilitator	mpearoui@scu.edu
Erin Guthrie	Devil's advocate	eguthrie@scu.edu
Tyler Briles	Timekeeper	tbriles@scu.edu

Chapter 7 - Project Summary

In this chapter we review the successes we experienced throughout the quarter and look ahead at what future groups could contribute to improve the functionality of the VARUNA.

7.1 - Achievements

We are very proud of what we accomplished this year working together on the VARUNA. We aimed to build the first iteration of an on-going project in the RSL for the benefit of future students. As the first step in a longer journey, the VARUNA satisfied the requirements we set out to meet. The VARUNA is easily deployable by 1 to 2 operators because it is less than 25 kg (~50 lbs) with the current payload package and it can fit within a car. It is a modular and configurable design that so that specific functions and capabilities can be modified without altering the functionality of the entire system. Lastly, we were able to accomplish our low-cost model by remaining within the $2,500 budget.

Beyond designing and building the VARUNA to our specifications we were also able to test our control methods a number of times. As detailed in section 4.2, we were able to verify our directional control system by causing the VARUNA to correct its thruster speeds when outside of ±15° from 0° (North). We also verified that our diving functionality worked as expected. The VARUNA was instructed to dive to 3m and then stop its motors, which is shown in Figure 35 in section 4.2.

7.2 - Future Work

While we are proud of what we accomplished over the past year, there are improvements that can be made to elevate the VARUNA to the next level. Below are our recommendations for the next group of motivated engineers to implement and test in their time with the VARUNA.

7.2.1 - Structural considerations

The first design choice that should be made is finding a way to prevent the VARUNA from rolling. We recommend adding wings or a keel to stabilize the vehicle during operation. This adjustment will largely improve the functionality of the IMU in the controls bottle.

7.2.2 - Controls system and Sensors

There is lots of work to be done in relation to the controls system and the AUV's sensors. Currently the payload sensors have not been tested in relation to the controls. While basic code has been written for the temperature sensor, future teams will need to test and integrate this and other payload sensor codes into the main testing program. Along with this, the payload and controls Arduino have not been tested together in water tests. They work with test code on the bench, but it is imperative to test the two working together in the water.

The 9-degree-of-freedom IMU sensor is very underutilized, and future groups can use the IMU to enable the AUV to have a more complete understanding of its orientation in space, which will allow for a more robust and complete controls system. It is also suggested that future teams invest in a more accurate and higher resolution pressure sensor - while low depth resolution didn't pose any problems in the testing of the AUV, higher data resolution would be desirable to researchers.

At the time of writing, our control system consists of a proportional gain adjustment of the rear and vertical thruster speeds. Lots of testing needs to be done, as only very basic controls have been implemented. With additional field testing and use of computer simulation programs like Simulink, future groups can implement PID controllers. We think this would improve the vehicle's reaction to depth and directional feedback to account for the drift of the vehicle in environments with currents.

7.2.3 - Electrical system

There are a number of improvements that can be made to the physical wiring of the controls electronics. We were exploring the idea of using terminal blocks that consolidate the common ground and power connections in a connector tab at either end of the enclosure. The amount of physical wires could be reduced so that the electronics could more easily fit in the enclosure bottle.

We also recommend that future groups implement a "kill switch" for the entire system. We have discussed using a magnetic relay switch connected to the battery source so that the entire system can be powered on and off without opening the battery bottle. In the current set-up the battery is always connected to the system and only the Arduinos can be turned on and off with a switch.

Our controls processor is wired to implement a GPS transceiver, but this functionality has not yet been tested. We recommend that future groups utilize this functionality as a way to locate the vehicle at the end of a mission.

There are additional sensors that we also believe would add value to the design of the VARUNA. A voltage sensor that can read the voltage level of the power source and communicate with the controls processors would offer a way to halt movement when the battery is drained to a specified point. A leakage sensor in each bottle could similarly provide input to the controls processor and cause the robot to return to the surface in the case of a leak in the system.

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Appendix A - User Manual

A.1 - GUI User Guide

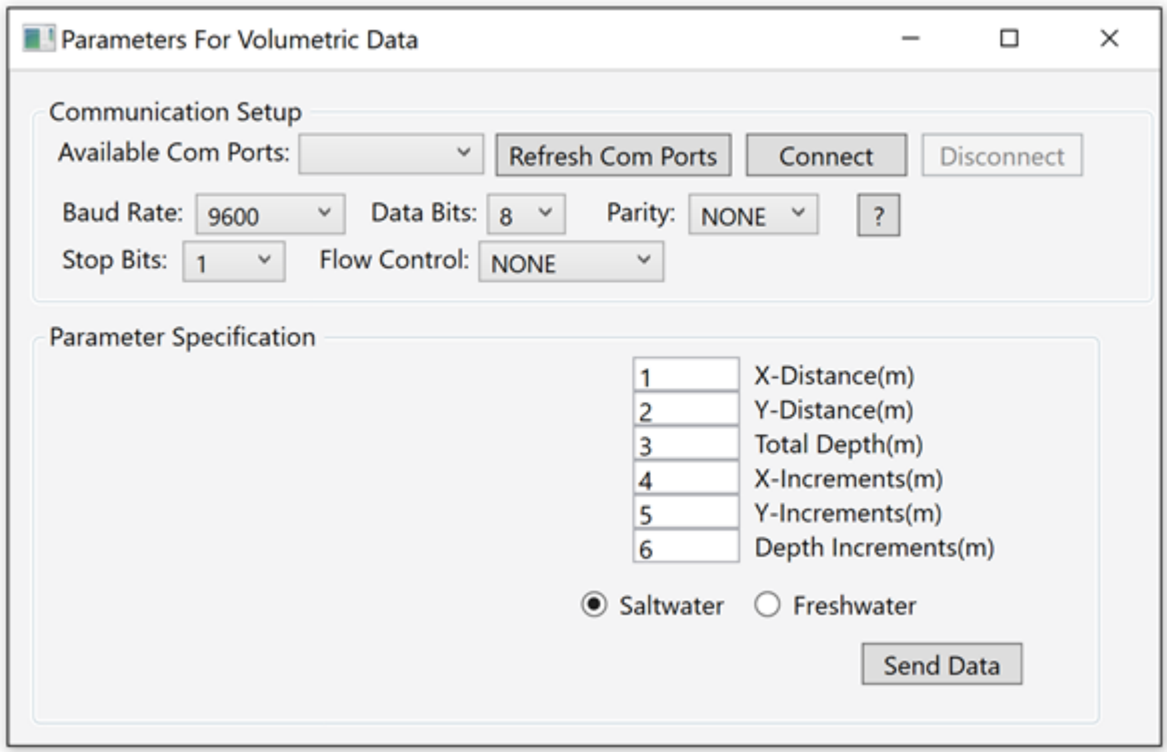


Figure A-1: The GUI

1. Connect the computer to the programming port through the USB wire. (NOTE: The control Arduino will turn on when this happens.)
2. Click "Refresh Com Ports". The port with the Arduino will show up automatically in the "Available Com Ports" box. If this does not happen, check your wired connection and try again.
3. Click "Connect". The GUI will open a connection on the serial port with the Arduino. If an error box appears, check your connection and try again. If the connection is successful, the "Connect" box will be grayed out.
4. Enter in ALL the mission parameters. Only use whole numbers for the parameters! Choose saltwater or freshwater (Saltwater is auto chosen).
5. Once you have entered all your data, click "Send Data". The GUI will send the parameters to the Arduino. If there is an error, fix your mistake and try again.

6. Once you have sent the data, press the "Disconnect" button and unplug the wired connection. Be sure to plug the programming port up!

Notes:

The GUI can only detect certain errors: unfilled boxes and letters. It will point out these errors. It will not point out symbols or other miscellaneous problems.

There is no feedback from the Arduino to the GUI. If the Arduino cannot parse the information, the GUI will not know.

The Baud Rate, Data Bits, Parity, Stop Bits, and Flow Control all autofill with the suggested parameters. These do not need to be edited unless something on the Arduino side has changed.

A.2 - Data Logger User Guide

Over the course of the mission, as long as you are printing information to the Data Logger, it will be storing data. For information on how to do this see Appendix G.1.3. To retrieve data:

1. Remove the microSD card from the Data Logger
2. Connect it to your computer and open the folder
3. There may be multiple text files. Figure out which ones are the ones you require.
4. Open up Excel. Click "Open Other Workbooks", then "Browse", then go to the microSD card folder. Ensure you click "All Files". Open up the Data Logger file you want.

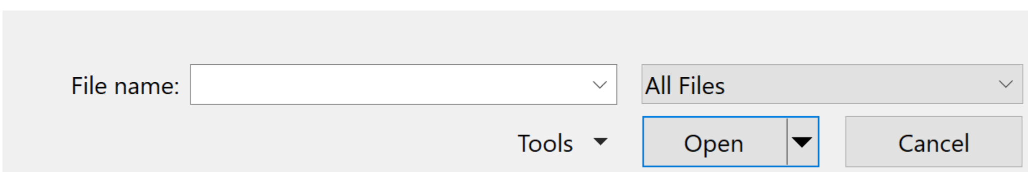


Figure A-2: Excel Browser Tool

5. The "Text Import Wizard" will open. This step will depend on how you programmed the Arduino to send information. If you used commas as is suggested in the programming documentation, click "Delimited", then "Next". Click "Comma" then press "Finish."
6. You now have all of the data in an Excel file, and you can manipulate it however you like.

A.3 - Assembly Guide

A.3.1 - Mechanical Assembly Guide

1. Assemble Lateral Thruster Brace Assembly (PA1). Screw the Lateral Thruster Brackets (P010) onto the Lateral Thruster Tube (P004). The position of the brackets on the tube can be changed based on the desired angle between the lateral thrusters. Screw one thruster onto each Lateral Thruster Bracket, making sure that the rounded center of the thruster points toward the front of the AUV and the pointed center points toward the back. Thread the thruster cables through the holes in the Thruster Tube.
2. Connect the Lateral Thruster Brace Assembly to the back of the Battery Bottle Assembly. Screw the red connectors on the ends of the thruster cables of the two lateral thrusters into the corresponding holes on the Endcap Batteries Aft (PV002).

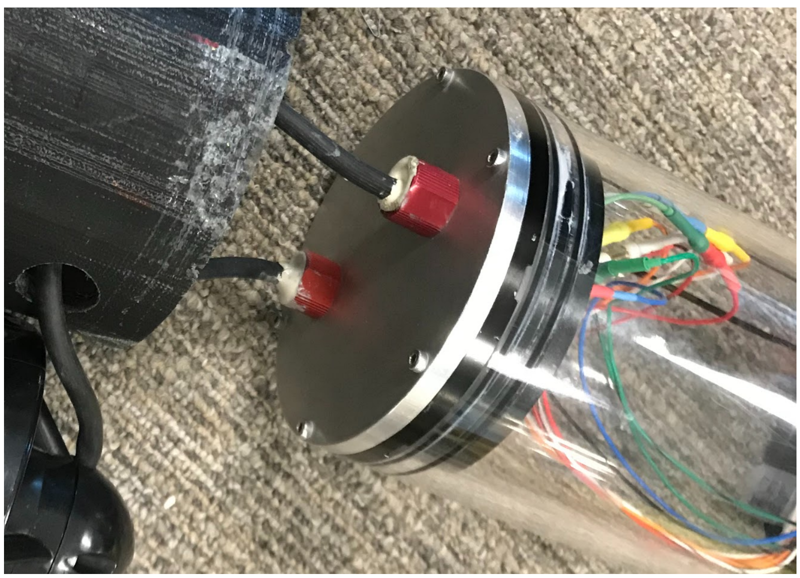


Figure A-3: Lateral Thruster Brace attached to Endcap Batteries Aft

3. Prepare the front of the Battery Bottle Assembly. Screw a Female SubConn 10 Connector (PV014) into the medium sized hole in the Endcap Batteries Fore. Make sure the small hole is plugged with a Red Plug (PV010) or a Vent/plug (PV005).

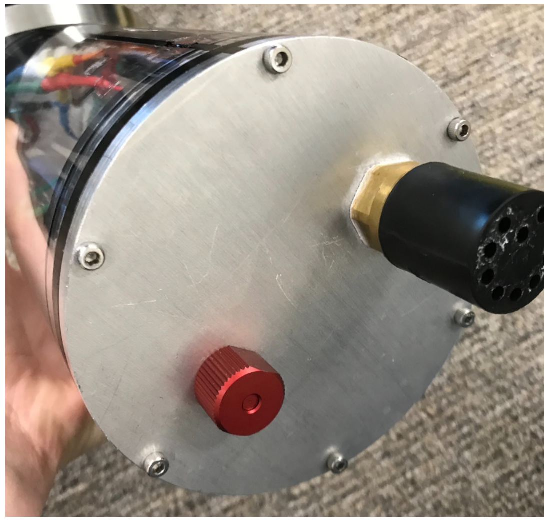


Figure A-4: Endcap Batteries Fore

4. Once battery electronics are assembled as detailed in A.3.2.3, the Battery Bottle Assembly can be completed. Clean and grease four Radial Seal O-Rings (PV017) and slide them into the grooves of two O-Ring Flanges (PV004). Slide the O-Ring Flanges into the ends of the battery Bottle (PV001). Clean and grease two Face Seal O-Rings (PV018) and place them in the grooves on the tops of the O-Ring Flanges. Once the O-Ring Flanges are in the Bottle, screw the Endcap Batteries Aft and the Endcap Batteries Fore into the O-Ring Flanges. Endcaps should be screwed into O-Ring Flanges after the Flanges are already in the Bottle to avoid pressurizing the inside of the Bottle. Make sure to align the black marks on the sides of the Endcaps with the black lines running down the Bottle.
5. Assemble Vertical Thruster Brace Assembly (PA2). Slide the Vertical Thruster Stabilizer Fore (P008) into the front of the Vertical Thruster Tube (P006). Slide the Vertical Thruster Stabilizer Aft (P009) into the back of the Vertical Thruster Tube. Insert the Vertical Thruster Ring (P007) into the hole in the top of the Vertical Thruster Tube and screw it into the Vertical Thruster Stabilizers. Now slide a thruster into the Vertical Thruster Ring and screw it in place from the front end. This may take some finagling. Thread the thruster cable through the hole in the in the Vertical Thruster Stabilizer Aft.

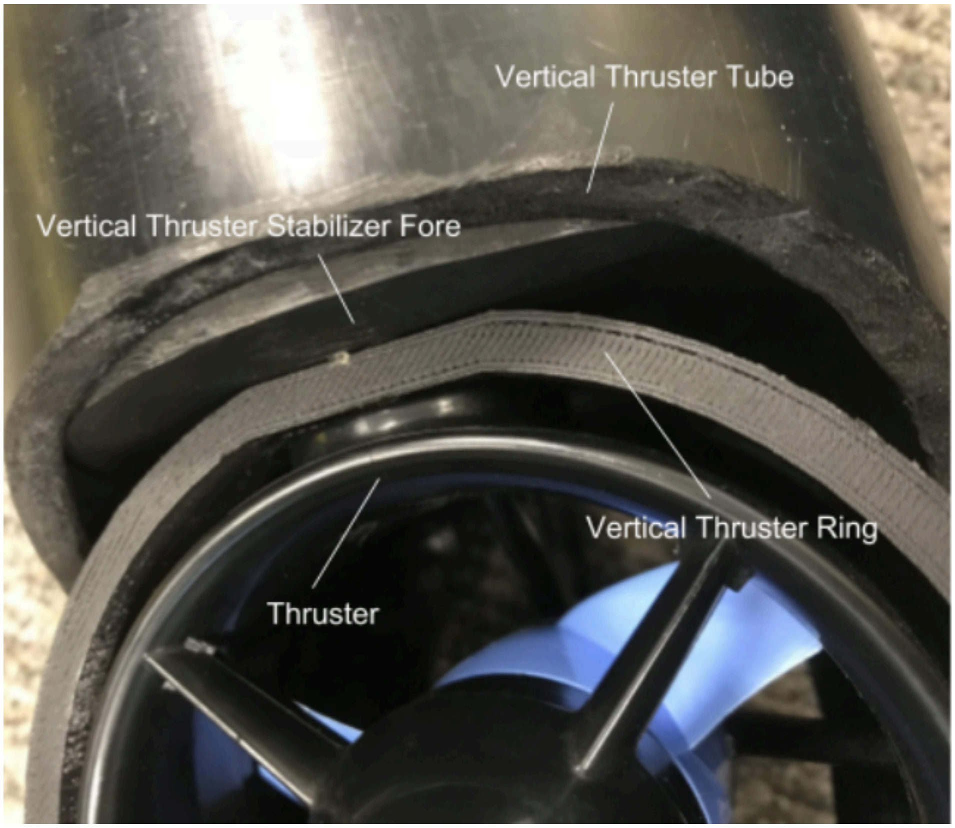


Figure A-5: Assembled Vertical Thruster Brace

6. Connect the Vertical Thruster Brace Assembly to the front of the Payload Bottle Assembly. Screw the red connector on the end of the thruster cable into one of the holes in the Endcap Payload Fore (PV002). Make sure the other hole is plugged with a Red Plug (PV010) or a Vent/plug (PV005).

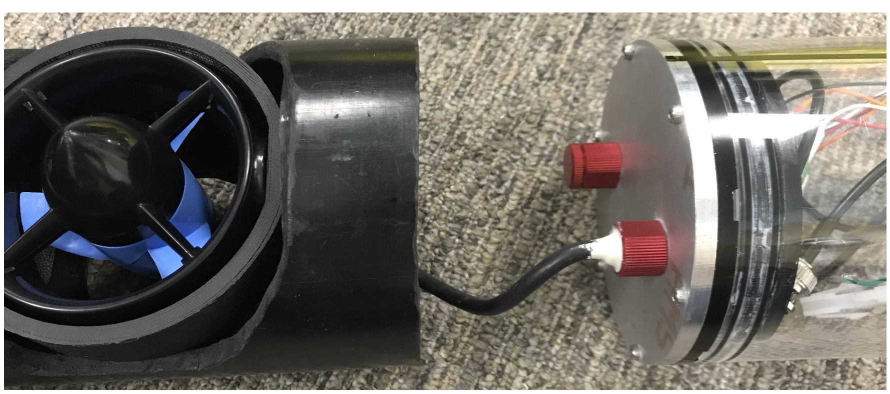


Figure A-6: Assembled Vertical Thruster Brace attached to Endcap Payload Fore

7. Prepare the back of the Payload Bottle Assembly. Screw a Female SubConn 10 Connector (PV014) into the medium sized hole in the Endcap Payload Aft (PV009). Screw a Switch (P012) into one of the small holes in the Endcap Payload Aft. Screw the Temperature Sensor (SP007) into the other small hole in the Endcap Payload Aft. Insert the Conductivity Sensor (SP006) into an Adjustable Connector (PV012). Screw the Adjustable Connector with the Conductivity Sensor in it into the large hole in the Endcap Payload Aft.

Figure A-7: Endcap Payload Aft

8. Once payload electronics are assembled as detailed in A.3.2.2, the Payload Bottle Assembly can be completed. Clean and grease four Radial Seal O-Rings (PV017) and slide them into the grooves of two O-Ring Flanges (PV004). Slide the O-Ring Flanges into the ends of the payload Bottle (PV001). Clean and grease two Face Seal O-Rings (PV018) and place them in the grooves on the tops of the O-Ring Flanges. Once the O-Ring Flanges are in the Bottle, screw the Endcap Payload Aft and the Endcap Payload Fore into the O-Ring Flanges. Endcaps should be screwed into O-Ring Flanges after the Flanges are already in the Bottle to avoid pressurizing the inside of the Bottle. Make sure to align the black marks on the sides of the Endcaps with the black lines running down the Bottle.

9. Prepare the front of the Controls Bottle Assembly. Screw the black connector with the Male SubConn 4 Connector potted into it into one of the small holes in the Endcap Controls Fore (PV008). Screw a Switch (P012) into the other small hole in the Endcap Controls Fore. Insert a Male SubConn 10 Connector (PV013) into an Adjustable Connector (PV012). Screw the Adjustable Connector into the large hole in the Endcap Controls Fore.

Figure A-8: End cap Controls Fore

10. Prepare the back of the Controls Bottle Assembly. Screw the red connector with the Pressure Sensor (SP003) potted into it into the small hole in the Endcap Controls Aft (PV007). Insert a Male SubConn 10 Connector (PV013) into an Adjustable Connector (PV012). Screw the Adjustable Connector into the large hole in the Endcap Controls Aft.

Figure A-9: Endcap Controls Aft

11. Once control electronics are assembled as detailed in A.3.2.1, the Controls Bottle Assembly can be completed. Clean and grease four Radial Seal O-Rings (PV017) and slide them into the grooves of two O-Ring Flanges (PV004). Slide the O-Ring Flanges into the ends of the controls Bottle (PV001). Clean and grease two Face Seal O-Rings (PV018) and place them in the grooves on the tops of the O-Ring Flanges. Once the O-Ring Flanges are in the Bottle, screw the Endcap Controls Aft and the Endcap Controls Fore into the O-Ring Flanges. Endcaps should be screwed into O-Ring Flanges after the Flanges are already in the Bottle to avoid pressurizing the inside of the Bottle. Make sure to align the black marks on the sides of the Endcaps with the black lines running down the Bottle.
12. Now slide the Controls Bottle Assembly into the middle of the Ribs (E001), making sure to align the black lines running down the Bottle with the edges that the ends of the Rib tines make. The middle small tines of the Ribs should grip the center of the controls Bottle. The inside edges of the two large tines of the Ribs should grip the edges of the controls Bottle by an inch on each side. Secure these overlapping edges with Hose Clamps (E002).
13. Slide the front of the Battery Bottle Assembly (which is connected to the Lateral Thruster Brace Assembly) into the back of the Ribs until the Male SubConn 10 Connector mates with the Female SubConn 10 Connector, again making sure to align the black lines

running down the Bottle with the edges that the ends of the Rib tines make. The outside edge of the back large tine of the Ribs and the inside edge of the farthest backward tine of the Ribs should grip the edges of the battery Bottle by an inch on each side. Secure these overlapping edges with Hose Clamps.

14. Slide the front of the Lateral Thruster Brace Assembly up until it touches the back of the battery Bottle. The end of the Ribs should grip the edge of the Lateral Thruster Brace Assembly by about an inch. Secure this overlapping edge with a Hose Clamp.
15. Slide the back of the Payload Bottle Assembly (which is connected to the Vertical Thruster Brace Assembly) into the front of the Ribs until the Male SubConn 10 Connector mates with the Female SubConn 10 Connector, again making sure to align the black lines running down the Bottle with the edges that the ends of the Rib tines make. The outside edge of the front large tine of the Ribs and the inside edge of the farthest forward tine of the Ribs should grip the edges of the battery Bottle by an inch on each side. Secure these overlapping edges with Hose Clamps.
16. Slide the back of the Vertical Thruster Brace Assembly back until it touches the front of the payload Bottle. The end of the Ribs should grip the edge of the Vertical Thruster Brace Assembly by around an inch. Secure this overlapping edge with a Hose Clamp.
17. Slide the Tail Cone (E007) into the back of the Lateral Thruster Brace Assembly and screw it in place.
18. Slide the Nose Cone (E003) into the front of the Vertical Thruster Brace Assembly and screw it in place.

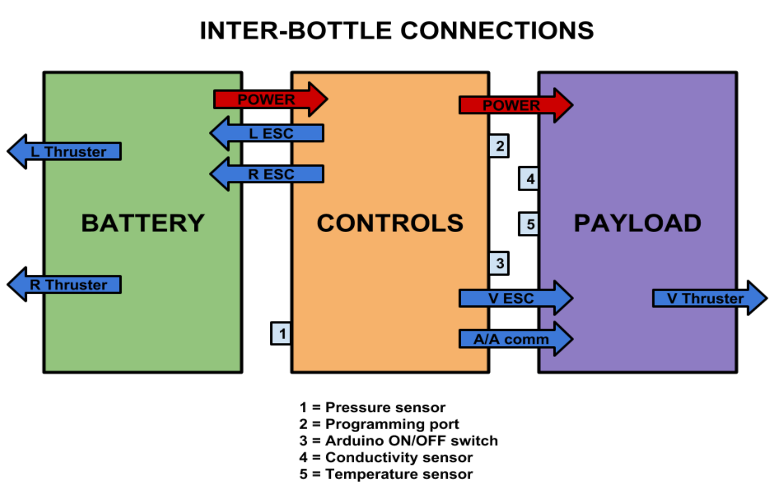


Figure A-10: Diagram of signal and power connections between bottles

A.3.2 - Electronics Assembly Guide

A.3.2.1 - Control Electronics

1. Secure ESCs and fuse holders to one side of the electronics platform with the R and L facing the Controls Aft end cap and the Vertical facing the Controls Fore end cap. The battery bottle is the back (aft) of the vehicle and the payload is considered the front (fore) of vehicle.
2. Secure the Arduino Mega 2560 and the accompanying shield to the other side of the electronics platform, making sure the IMU is towards the Controls Fore end cap.
3. **Note:** Getting all of the control electronics into the bottle is a little tricky. Please exercise patience and caution.
4. Make connections to Controls Aft end cap after the flange and the end cap are attached.
5. Connect power via the XT60 connector.
6. Ensure that the barrel jack is plugged into the Arduino.
7. Attach the pressure sensor to the Arduino shield (see pin-out diagram).
8. Connect left and right ESC bullet connectors to their corresponding connector using the labels L1, L2, L3, etc.

Figure A-11: Bullet connectors

9. Now that the aft end cap connections are made through the flange, slide the electronics platform into the bottle and install the flange into the enclosure. Be careful to keep all wires inside the bottle and keep them from being pinched by the flange. Keep the remaining connections accessible so they can be attached to the Controls Fore end cap.
10. Connect to the switch by pushing the quick connects (black connector at the end of blue wire) onto the button terminals.

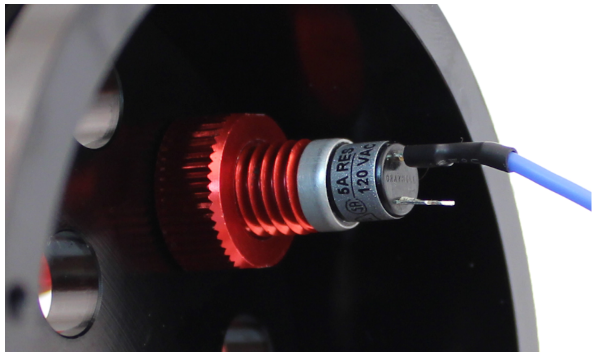


Figure A-12: Switch quick connect

11. Connect programming port of the Arduino to the 4-pin Mini-Fit Jr Connector.
12. Connect power to male Mini-Fit Jr Connector to deliver power to payload electronics.
13. Connect pin 19 (RX) and pin 18 (TX) on the controls shield to the female Mini-Fit Jr Connector.

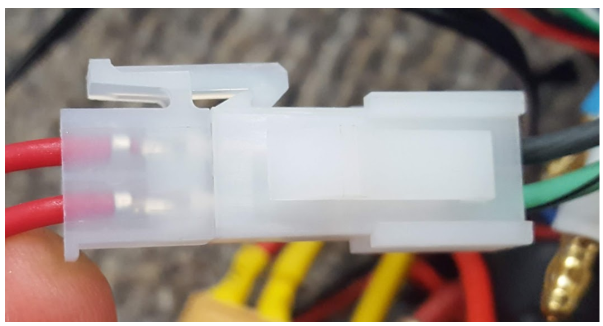


Figure A-13: Mini-Fit Jr Connector

14. The last connection on the Controls Fore end cap is the vertical thruster ESC to the bullet connectors labeled V1, V2, and V3.
15. Now that all connections are made between the control electronics and the end cap connectors, it is time to insert the fore flange into the bottle. The power switch for the Arduino can be used as a pressure vent if the dial is unscrewed enough to create ventilation hole. Once both flanges have been installed (make sure all O-rings are completely within the acrylic pipe) re-tighten the switch dial so as to close the ventilation hole.

A.3.2.2 - Payload Electronics

1. Secure the Arduino Mega 2560 and the accompanying shield to the electronics platform using zip ties. Also secure the DC/DC converter to the other side of the platform.
2. Ensure that there is a microSD card in the datalogger on the Arduino shield.
3. Connect the vertical thruster cables to their corresponding bullet connectors using the label V1, V2, V3.
4. Using the Payload Pin-Out diagram connect the conductivity and temperature sensors to the Arduino shield.
5. Connect the power source using the XT60 connector and plug the barrel jack into the Arduino.
6. Connect pin 17 (RX) and pin 16 (TX) on the controls shield to the 2-pin Mini-Fit Jr Connector.
7. Now all of the payload connections are complete, and the flanges and end caps can be secured to the acrylic tube.

A.3.2.3 - Battery Electronics

1. Plug the voltage sensor/alarm into the LiPo battery as shown in Figure A-10.

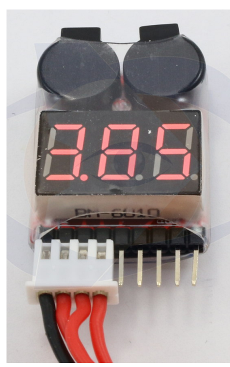


Figure A-14: Voltage sensor

2. Make sure the Arduino switch is off before plugging the LiPo battery into the XT60 connector.
3. Secure the battery to the bottom of the acrylic tube so that it does not shift during operation and cause the vehicle to become unbalanced.

A.3.2.4 - Arduino Pinout Guide

Use figure A-15 and table A-1 as guides for connecting sensors to the controls and payload shields.

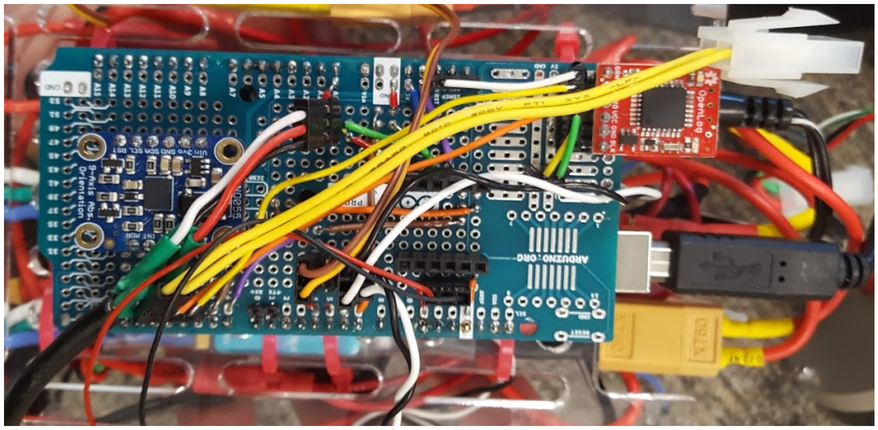


Figure A-15: Wiring of controls shield

Table A-1: Pinout guide for controls and payload Arduino shields

CONTROLS			PAYLOAD		
Pressure Sensor:			**Conductivity Sensor:**		
	Analog Input	A0		TX	17 (RX)
	5V	5V		RX	16 (TX)
	GND	GND		GND	GND
				VCC	5V
				PRB1	BNC1
				PRB2	BNC2
Data Logger:			**Data Logger:**		
	TX	17 (RX)		TX	15 (RX)
	RX	16 (TX)		RX	14 (TX)
	GND	GND		GND	GND
	VCC	5V		VCC	5V
	RESET	RST		RESET	
IMU:			**Temperature:**		
	Vin	5V		Green / SCL	SCL
	GND	GND		Wh / SDA	SDA
	SCL	SCL		Red / 5.5V	5V
	SDA	SDA		GND	GND
Comm w/ PAYLOAD:			**Comm w/ CONTROLS:**		
	TX	19 (RX)		TX	17 (RX)
	RX	18 (TX)		RX	16 (TX)
Piezzo Alarm:	VCC	D11			
	GND	GND			
GPS:	VCC	3.3V			
	GND	GND			
	TX	15 (RX)			
	RX	14 (TX)			

A.4 - Deployment Checklist

A.4.1 - Things to bring

- Allen wrench for end cap screws
- hose clamp screwdriver
- wrench/pliers to tighten gland connectors
- silicone grease for O-rings and SubConn connectors
- extra fuses
- extra M3 screws
- dive/ballasting weights
- USB programming port cable
- fully charged LiPo batteries in safety bag
- tether/buoy
- laptop
- water for post-dive rinsing
- Duct tape

A.4.2 - Pre-deployment Checklist

1. Follow the Mechanical and Electronic Assembly Guides to install a charged battery and fully assemble VARUNA.
2. Check that all O-rings are completely inside the enclosures.
3. Ensure that all SubConn connectors are greased and fully connected.
4. Check the switch on control bottle to make sure it is water tight
5. Check that all gland connectors are tight.
6. Ensure that all hose clamps are tight and all subsections (end cone, thruster braces, and watertight enclosures) are securely connected.

A.4.3 - Post-deployment Checklist

1. Rinse the VARUNA and all components with fresh water to prevent corrosion.
2. Turn off processors using switch on the controls bottle.
3. Remove battery enclosure and disconnect battery, store in LiPo safety bag.

A.5 - Upkeep

Some steps should be followed periodically to prolong the life of the AUV and its parts:

- Remove endcaps and O-ring flanges from bottles. Remove and relubricate O-rings.
- Relubricate small O-rings in the switches, vent/plugs, and connectors.
- Relubricate prongs of SubConn connectors.
- Replace corroding screws and nuts.

Appendix B - Parts List

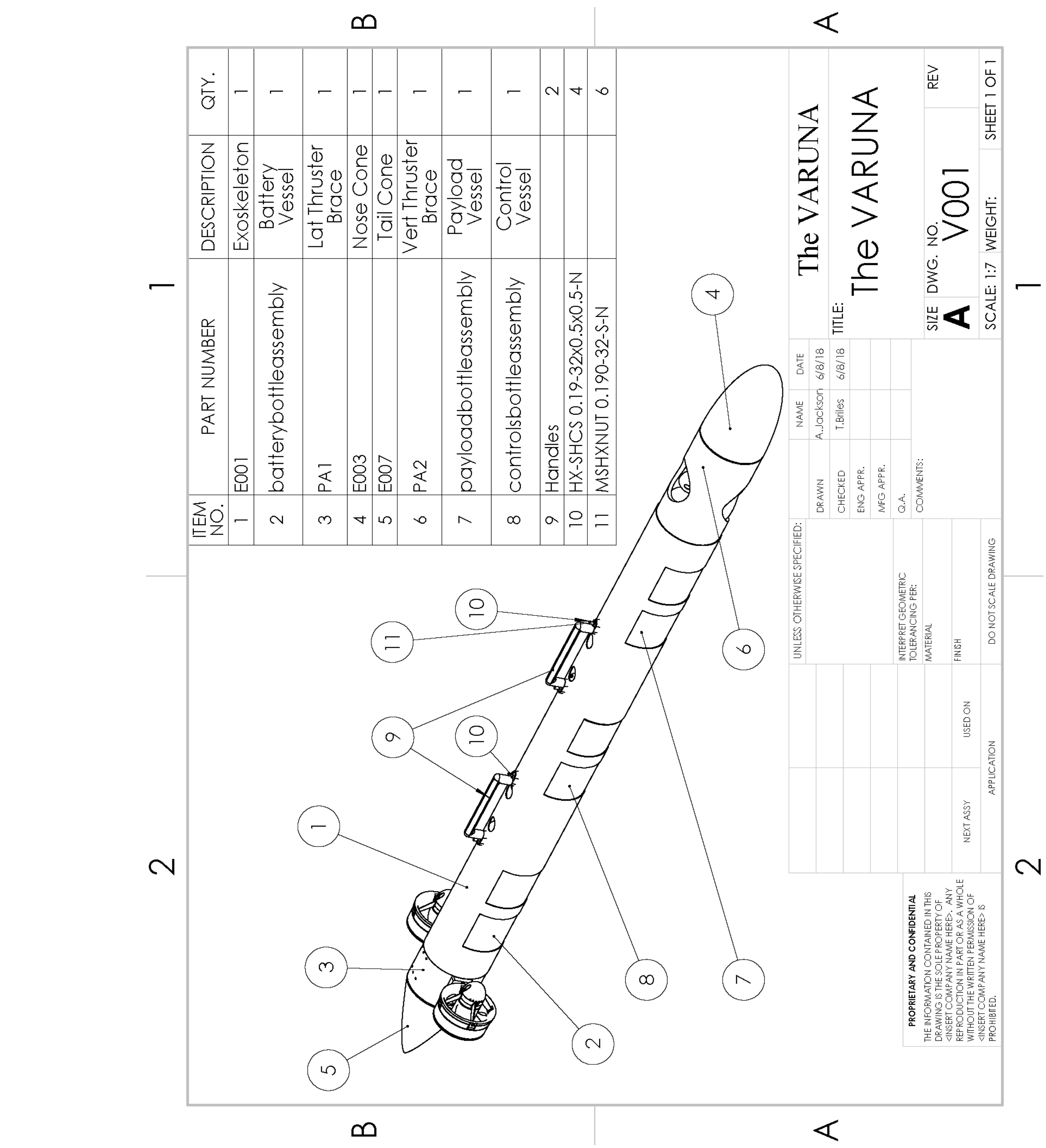
Table B-1: List of parts

Subsystem	Component Description	Part Number	Number of Items	B/M/O	Vendor
Exoskeleton					
	Ribs	E001	1	O	Northwest Precision Sheet Metal
	Hose clamp	E002	8	B	Amazon
	Nose cone	E003	1	O	MBARI
	Handle	E004	2	B	Home Depot
	6-32 x 0.5 in	E005	4	B	Home Depot
	6-32 nut	E006	4	B	Home Depot
	Tail cone	E007	1	O	MBARI
	10-32 x 0.5 in	E008	4	B	Home Depot
	0.5 in wing nut	E009	2	B	Home Depot
Pressure Vessels					
	Bottle	PV001	3	B	Blue Robotics
	Endcap batteries aft, payload fore	PV002	2	M	N/A
	Endcap batteries fore	PV003	1	M	N/A
	O-Ring flange	PV004	6	B	Blue Robotics
	Vents/plugs	PV005	3	B	Blue Robotics
	Red connector	PV006	5	B	Blue Robotics
	Endcap controls aft	PV007	1	M	N/A
	Endcap controls fore	PV008	1	M	N/A
	Endcap payload aft	PV009	1	M	N/A
	Red plugs	PV010	2	B	Blue Robotics
	Black connector	PV011	1	B	Blue Robotics

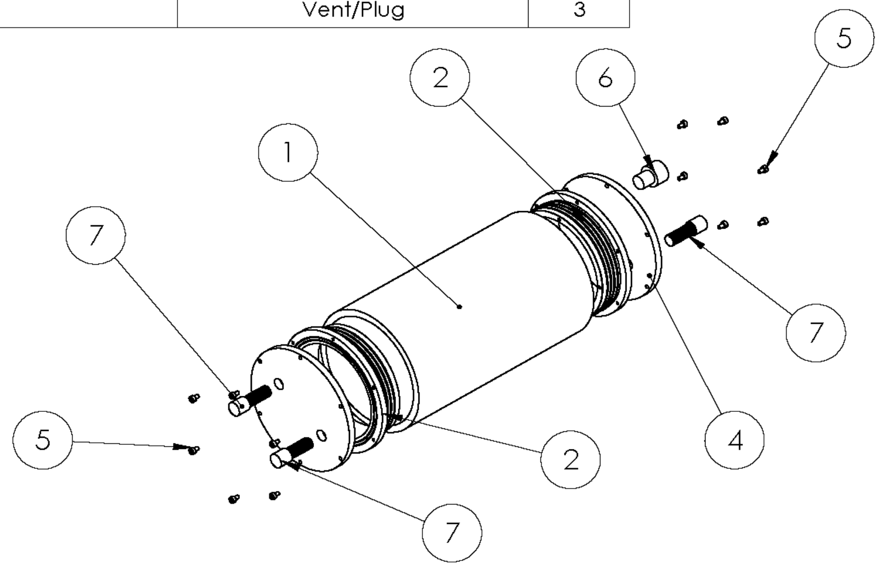
	Adjustable connectors	PV012	3	B	MBARI
	Subconn 10 connector, male	PV013	2	B	SubConn
	Subconn 10 connector, female	PV014	2	B	SubConn
	Subconn 4 connector, female	PV015	1	B	SubConn
	Subconn 4 connector cap, male	PV016	1	B	SubConn
	Radial Seal O-Ring	PV017	12	B	Blue Robotics
	Face Seal O-Ring	PV018	6	B	Blue Robotics
	M3 x 12	PV019	36	B	Blue Robotics
	Electronics shelf	PV020	2	M	N/A
	Battery bottle assembly	**PVA1**	1	M	N/A
	Controls bottle assembly	**PVA2**	1	M	N/A
	Payload bottle assembly	**PVA3**	1	M	N/A
Propulsion					
	M3 x 0.5	P001	15	B	Home Depot
	M3 nut	P002	3	B	Home Depot
	Thruster	P003	3	B	Blue Robotics
	Lateral thruster tube	P004	1	M	N/A
	Electronic Speed Controller	P005	3	B	Blue Robotics
	Vertical thruster tube	P006	1	M	N/A
	Vertical thruster ring	P007	1	M	SCU Maker Lab
	Vertical thruster stabilizer fore	P008	1	M	SCU Maker Lab
	Vertical thruster stabilizer aft	P009	1	M	SCU Maker Lab

	Lateral thruster bracket	P010	2	M	SCU Maker Lab
	6-32 x 1 in	P011	4	B	Home Depot
	Switch	P012	2	B	Blue Robotics
	6-32 nut	P013	4	B	Home Depot
	Lateral thruster assembly	**PA1**	2	M	N/A
	Vertical thruster assembly	**PA2**	1	M	N/A
Electrical Power					
	DC to DC Converter	EP001	2	B	Hobby King
	Battery	EP002	1	B	Hobby King
Navigation Sensors and Processing					
	Arduino Mega	N001	2	B	Hobby King
	IMU/magnetometer	N002	1	B	Adafruit
	Pressure Sensor	N003	1	B	Amazon
	GPS	N004	1	B	SparkFun
	Data Logger	N005	2	B	SparkFun
Payload					
	Conductivity Sensor	PL001	1	B	MBARI
	Temperature sensor	PL002	1	B	Blue Robotics

Appendix C - Mechanical Drawings



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	PV001	Bottle Tube	1
2	PV004	O-ring Flange	2
3	PV002	Battery Aft Endcap	1
4	PV003	Battery Fore Endcap	1
5	PV019	M3 Hex Screw	12
6	PV014	Female Subconn 10 Plug	1
7	Pv005	Vent/Plug	3



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APPLICATION	

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DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±0.01
TWO PLACE DECIMAL ±0.005
THREE PLACE DECIMAL ±0.001

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	T. Briles	6/6/18
CHECKED	M. Peauroi	6/7/18
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

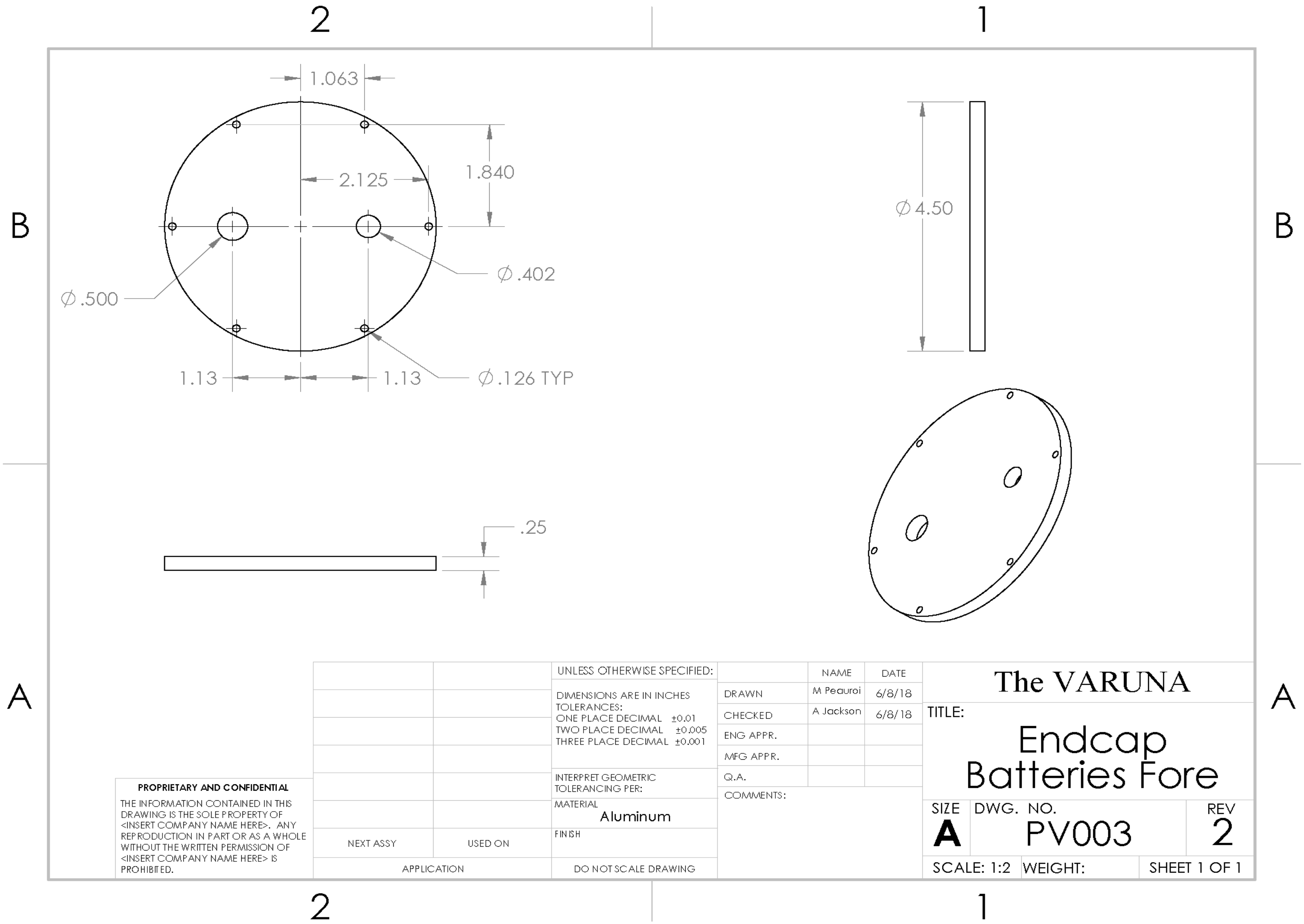
The VARUNA

TITLE:

Battery Bottle Assembly

SIZE A | DWG. NO. PVA1 | REV 2

SCALE: 1:10 | WEIGHT: | SHEET 1 OF 1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A
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∅ .402
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1.13
∅ .126 TYP
∅ 4.50
.25
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APPLICATION
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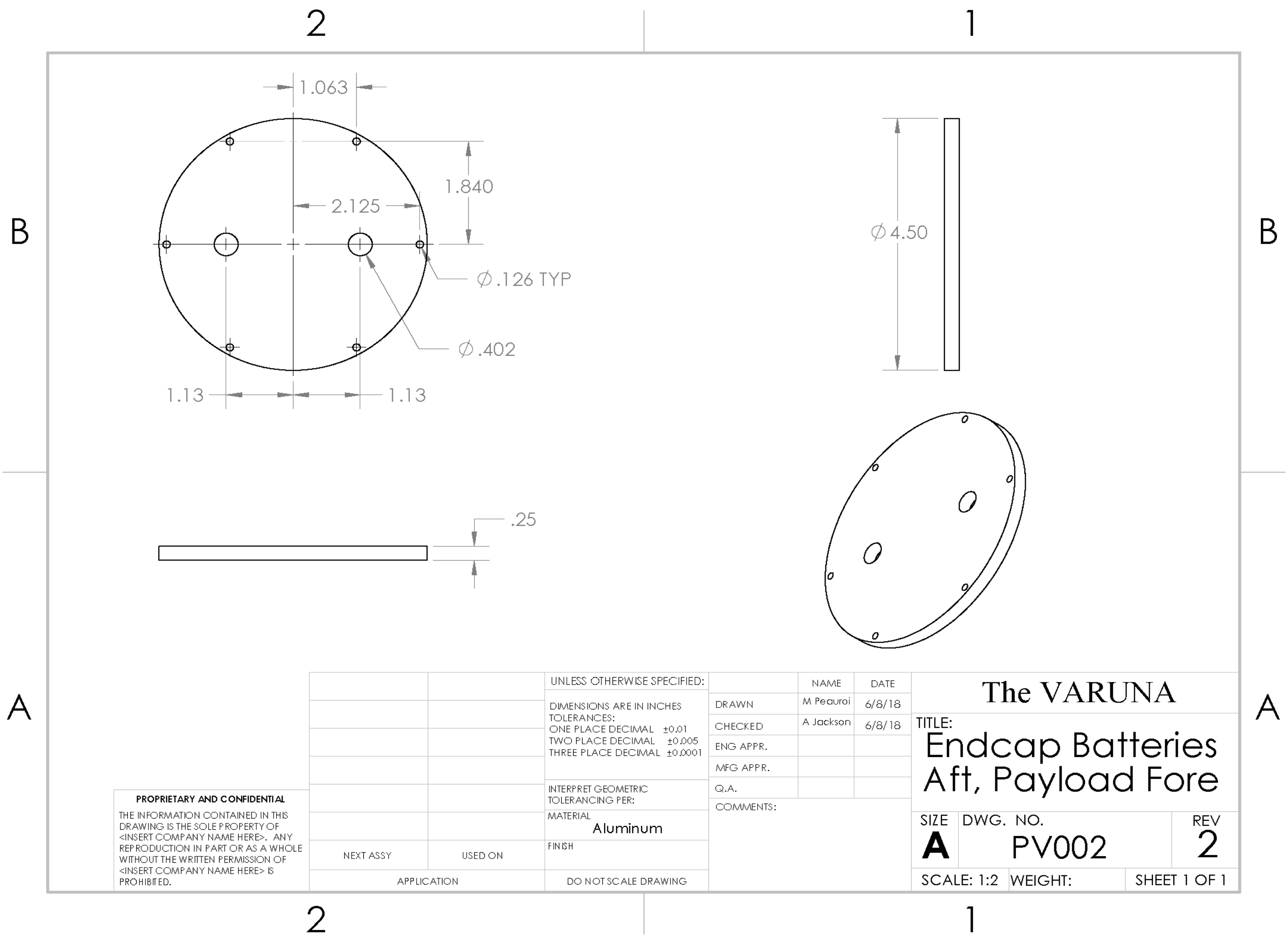
DIMENSIONS ARE IN INCHES
TOLERANCES:
ONE PLACE DECIMAL ±0.01
TWO PLACE DECIMAL ±0.005
THREE PLACE DECIMAL ±0.001
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Aluminum
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
M Peauroi
6/8/18
CHECKED
A Jackson
6/8/18
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
The VARUNA
TITLE:
Endcap Batteries Fore
SIZE
A
DWG. NO.
PV003
REV
2
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1



2
1
B
A
1.063
1.840
2.125
∅.126 TYP
∅.402
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1.13
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.25
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
ONE PLACE DECIMAL ±0.01
TWO PLACE DECIMAL ±0.005
THREE PLACE DECIMAL ±0.0001
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Aluminum
FINISH
NEXT ASSY
USED ON
APPLICATION
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
M Peauroi
6/8/18
CHECKED
A Jackson
6/8/18
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
The VARUNA
TITLE:
Endcap Batteries Aft, Payload Fore
SIZE
A
DWG. NO.
PV002
REV
2
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1
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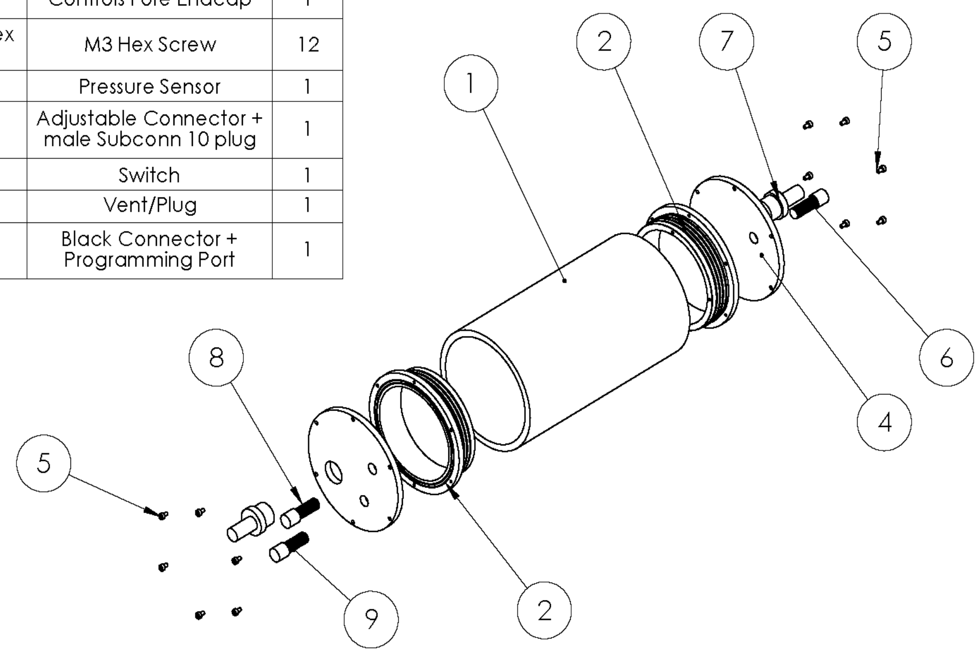
ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	PV001	Bottle Tube	1
2	Flange	O-ring Flange	2
3	endcap_controls_aft	Controls Aft Endcap	1
4	endcap_controls_fore	Controls Fore Endcap	1
5	B18.3.1M - 3 x 0.5 x 5 Hex SHCS -- 5NHX	M3 Hex Screw	12
6	N003	Pressure Sensor	1
7	PV012+PV013	Adjustable Connector + male Subconn 10 plug	1
8	P012	Switch	1
9	PV005	Vent/Plug	1
10	PV011+PV015	Black Connector + Programming Port	1



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±0.01
TWO PLACE DECIMAL ±0.005
THREE PLACE DECIMAL ±0.001

INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING

NEXT ASSY | USED ON
APPLICATION

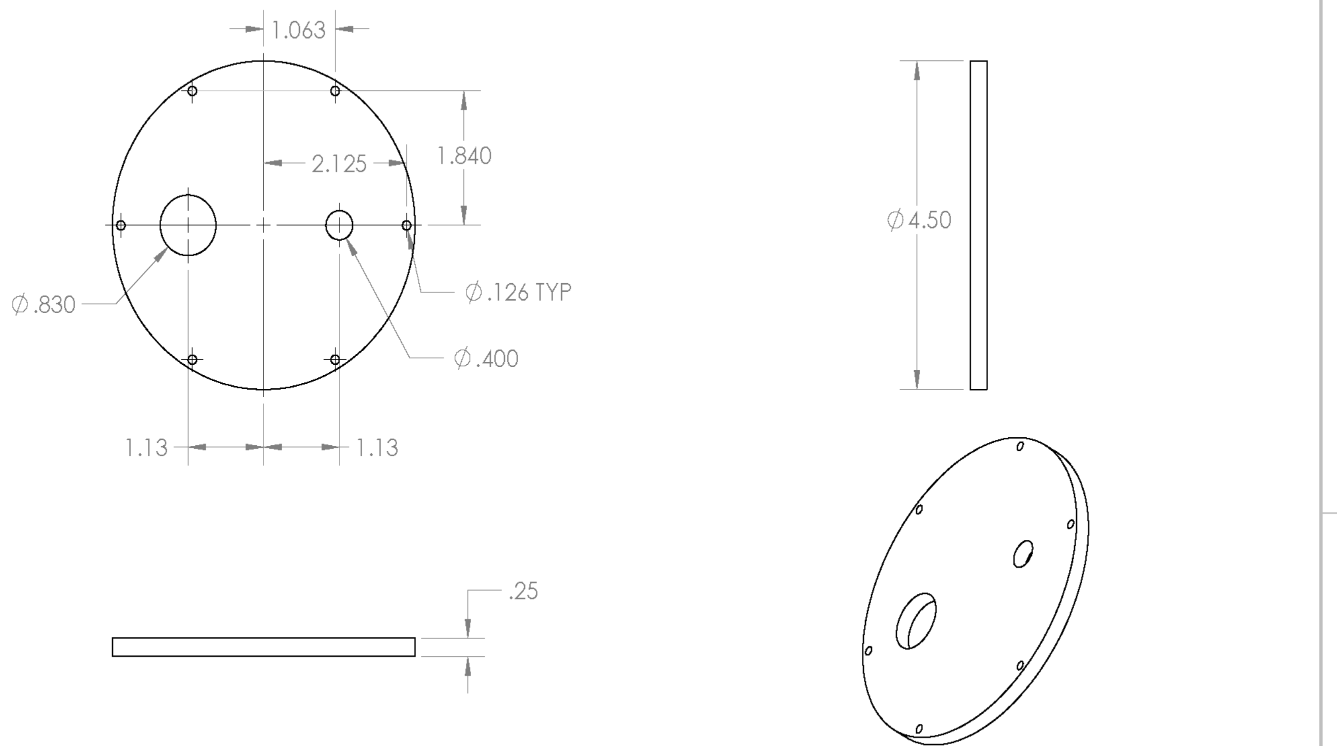
	NAME	DATE
DRAWN	T. Briles	6/6/18
CHECKED	M. Peauroi	6/6/18
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

The VARUNA

TITLE:
Controls Bottle Assembly

SIZE A | DWG. NO. PVA2 | REV 2
SCALE: 1:5 | WEIGHT: | SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:		NAME	DATE	The VARUNA		
DIMENSIONS ARE IN INCHES TOLERANCES: ONE PLACE DECIMAL ±0.01 TWO PLACE DECIMAL ±0.005 THREE PLACE DECIMAL ±0.0001	DRAWN	M Peauroi	6/8/18	TITLE: Endcap Controls Fore		
	CHECKED	A Jackson	6/8/18			
	ENG APPR.					
	MFG APPR.					
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.					
MATERIAL Aluminum	COMMENTS:			SIZE A	DWG. NO. PV008	REV 2
FINISH						
DO NOT SCALE DRAWING				SCALE: 1:2	WEIGHT:	SHEET 1 OF 1

NEXT ASSY	USED ON
APPLICATION	

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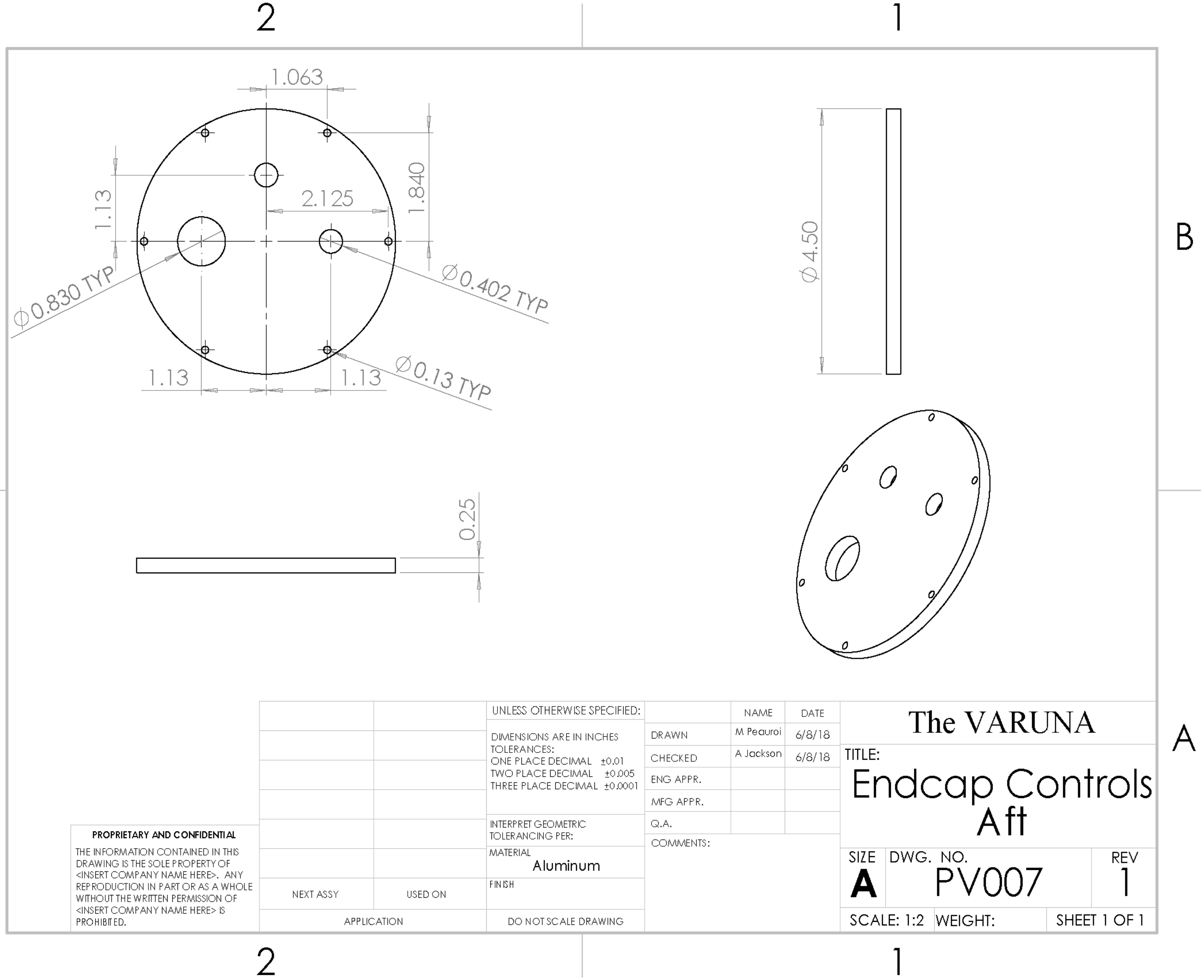
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B
A
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2.125
1.13
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1.13
Ø0.830 TYP
Ø0.402 TYP
Ø0.13 TYP
Ø4.50
0.25
PROPRIETARY AND CONFIDENTIAL
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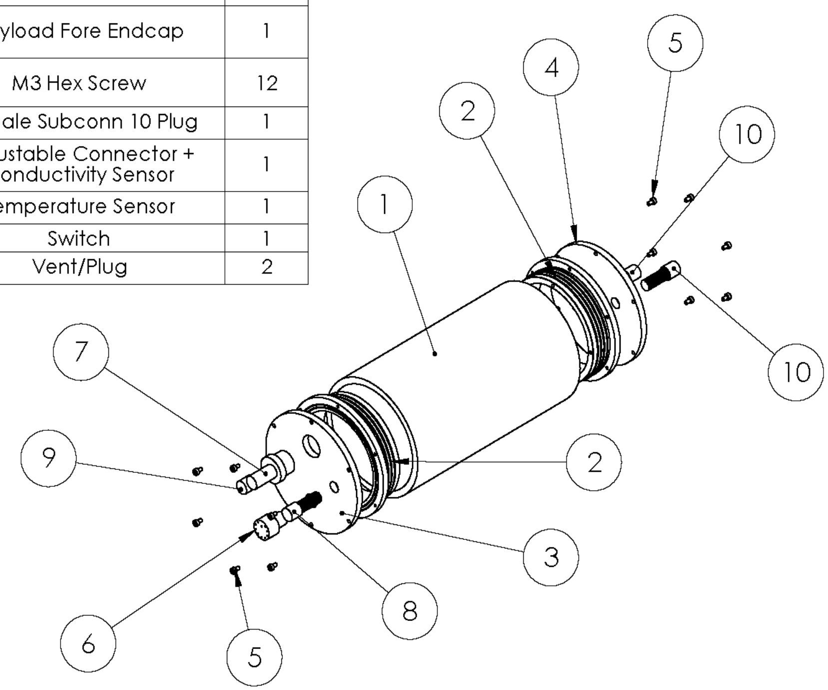
NEXT ASSY
USED ON
APPLICATION
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
ONE PLACE DECIMAL ±0.01
TWO PLACE DECIMAL ±0.005
THREE PLACE DECIMAL ±0.0001
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Aluminum
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
M Peauroi
6/8/18
CHECKED
A Jackson
6/8/18
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
The VARUNA
TITLE:
Endcap Controls Aft
SIZE
A
DWG. NO.
PV007
REV
1
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	AUV tube	Bottle Tube	1
2	Flange	O-ring Flange	2
3	endcap_payload_aft	Payload Aft Endcap	1
4	endcap_batteries_aft_payload_fore	Payload Fore Endcap	1
5	B18.3.1M - 3 x 0.5 x 5 Hex SHCS -- 5NHX	M3 Hex Screw	12
6	PV014	Female Subconn 10 Plug	1
7	PV012+PL001	Adjustable Connector + Conductivity Sensor	1
8	PL002	Temperature Sensor	1
9	P012	Switch	1
10	PV005	Vent/Plug	2



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±0.01
TWO PLACE DECIMAL ±0.005
THREE PLACE DECIMAL ±0.001
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING

NEXT ASSY | USED ON
APPLICATION

	NAME	DATE
DRAWN	T. Briles	6/6/18
CHECKED	M. Peauroi	6/7/18
ENG APPR.		
MFG APPR.		
Q.A.		

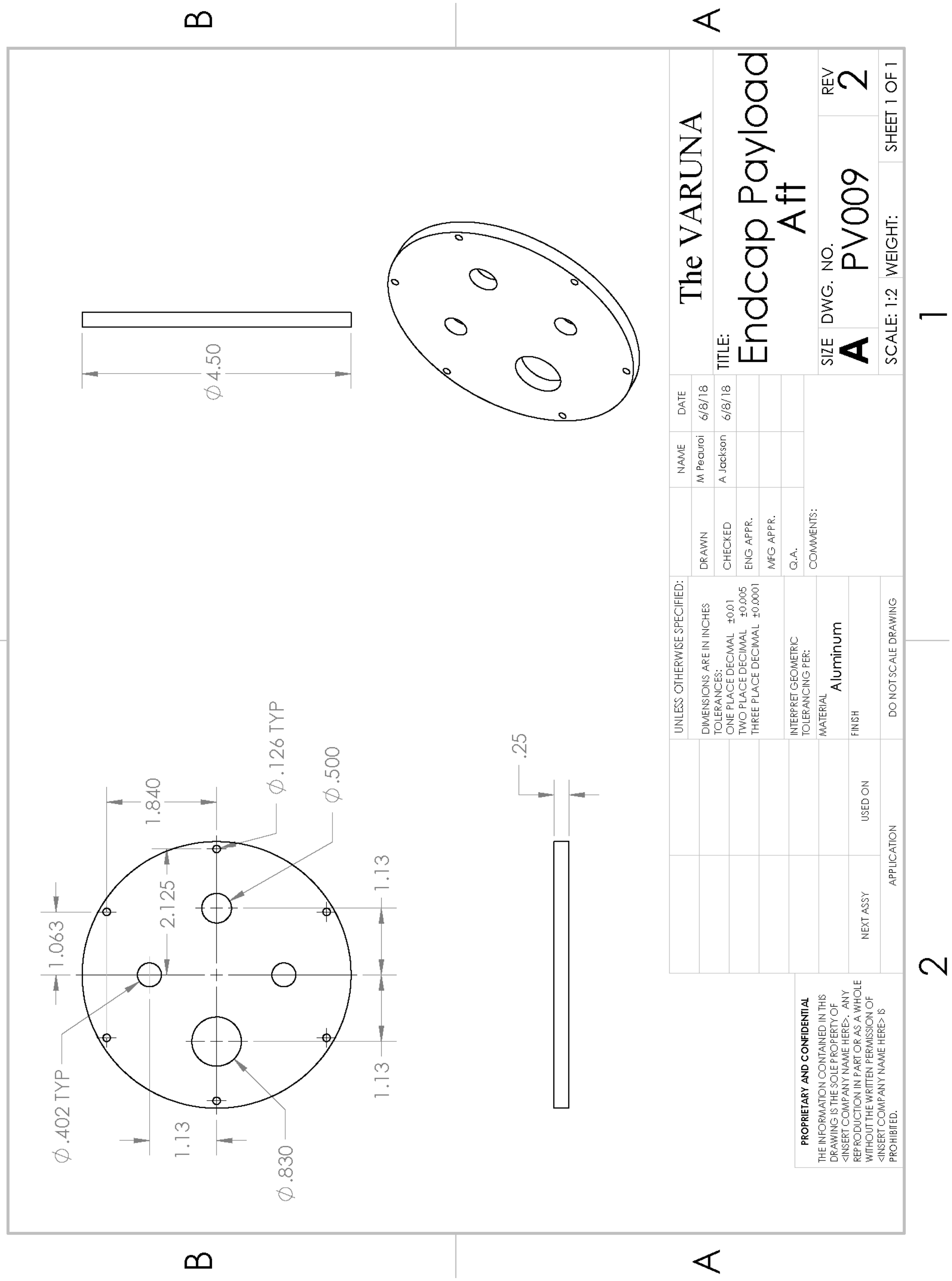
COMMENTS:

The VARUNA

TITLE:
Payload Bottle Assembly

SIZE A | DWG. NO. PVA3 | REV 2

SCALE: 1:10 | WEIGHT: | SHEET 1 OF 1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TITLE:
Endcap Payload Aft
SIZE A
DWG. NO. PV009
REV 2
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
ONE PLACE DECIMAL ±0.01
TWO PLACE DECIMAL ±0.005
THREE PLACE DECIMAL ±0.0001
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Aluminum
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
M Peauroi
6/8/18
CHECKED
A Jackson
6/8/18
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
NEXT ASSY
USED ON
APPLICATION
PROPRIETARY AND CONFIDENTIAL
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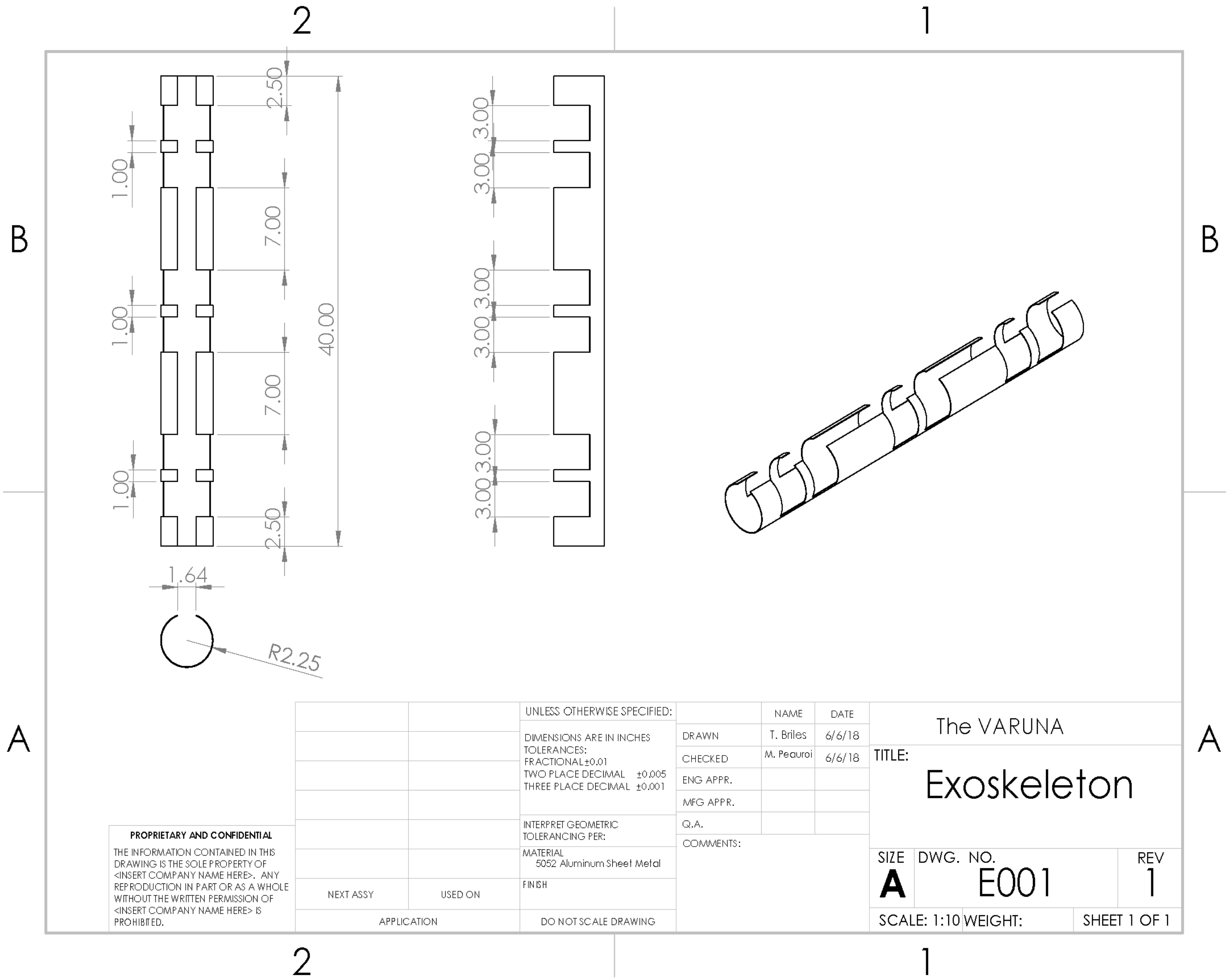

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3.00 3.00
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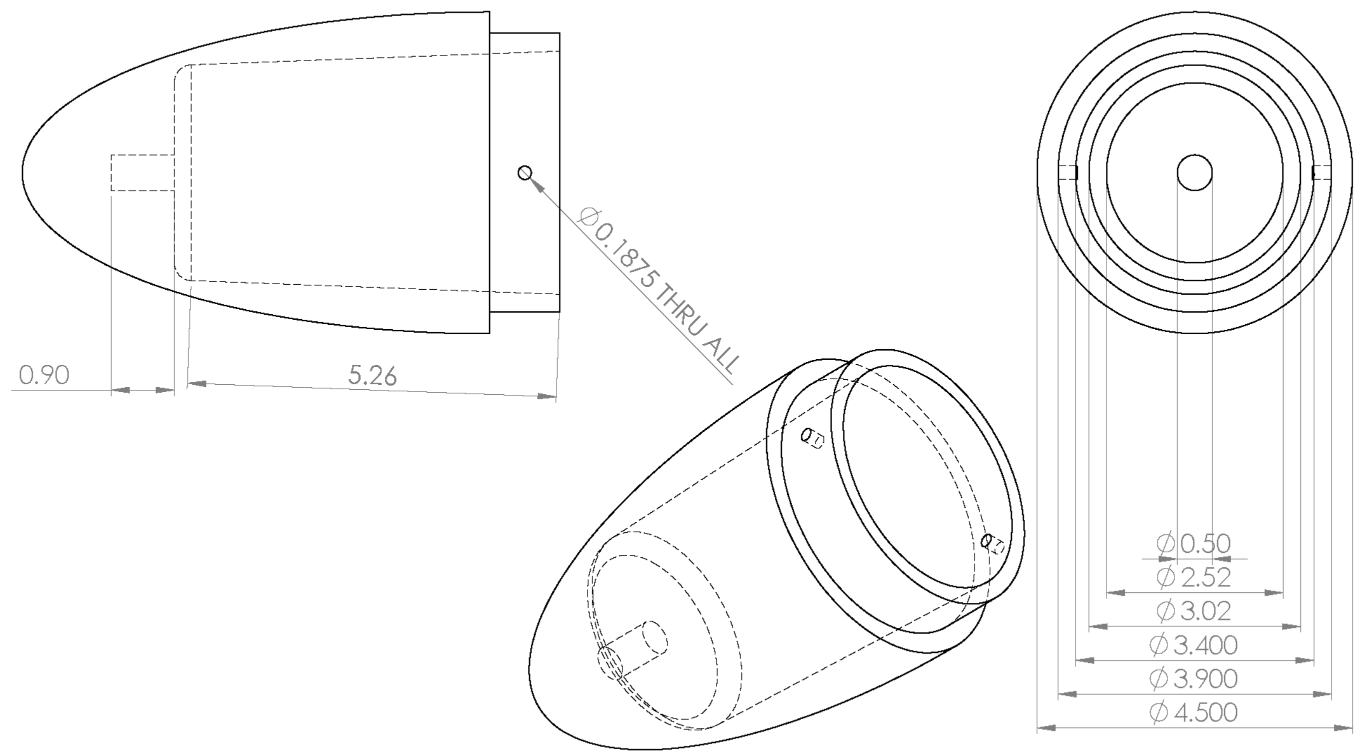
USED ON
APPLICATION
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±0.01
TWO PLACE DECIMAL ±0.005
THREE PLACE DECIMAL ±0.001
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
5052 Aluminum Sheet Metal
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
T. Briles
6/6/18
CHECKED
M. Peauroi
6/6/18
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
The VARUNA
TITLE:
Exoskeleton
SIZE
A
DWG. NO.
E001
REV
1
SCALE: 1:10
WEIGHT:
SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:		NAME	DATE	The VARUNA
DIMENSIONS ARE IN INCHES TOLERANCES: TWO PLACE DECIMAL ± 0.01 THREE PLACE DECIMAL ±0.005 FOUR PLACE DECIMAL ±0.001	DRAWN	A.Jackson	5/16	TITLE: Nose Cone
	CHECKED	M.Peauroi	5/16	
	ENG APPR.			
	MFG APPR.			
INTERPRET GEOMETRIC TOLERANCING PER: N/A	Q.A.			
MATERIAL: Ultra High Molecular Weight Polythylene	COMMENTS: The Profile of the Nose Cone is half of an ellipsoid with a minor radius a = 2.25", major radius b = 6.0". The 0.1875" hole needs to be dimensioned to fit a #10-32 screw .			SIZE A DWG. NO. E003 REV
FINISH				SCALE: 1:2 WEIGHT: SHEET 1 OF 1
DO NOT SCALE DRAWING				

NEXT ASSY	USED ON
APPLICATION	

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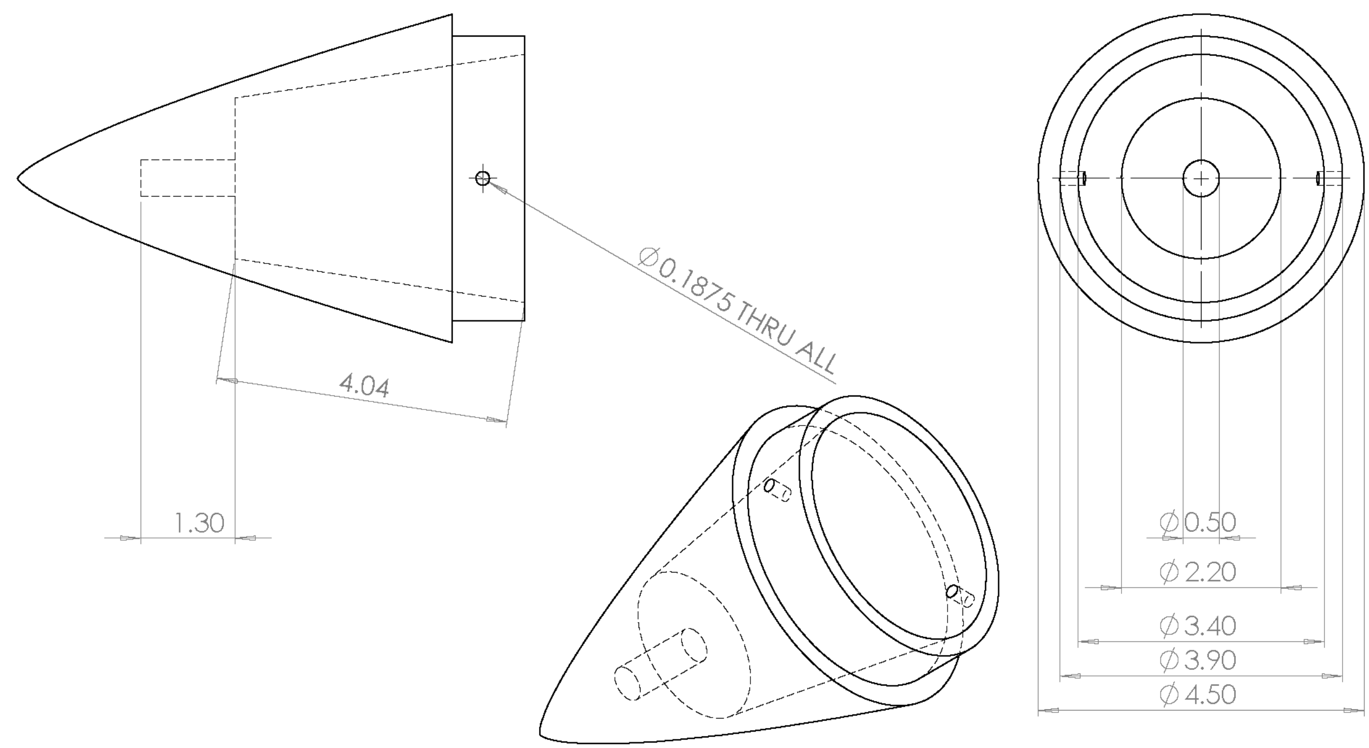


The VARUNA

TITLE: **Tail Cone**

	NAME	DATE
DRAWN	A.Jackson	5/24
CHECKED	M.Peauroi	5/24
ENG APPR.		
MFG APPR.		
Q.A.		

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
TWO PLACE DECIMAL ± 0.01
THREE PLACE DECIMAL ±0.005
FOUR PLACE DECIMAL ±0.001

INTERPRET GEOMETRIC TOLERANCING PER: N/A

MATERIAL: Ultra High Molecular Weight Polythylene

FINISH

DO NOT SCALE DRAWING

NEXT ASSY | USED ON

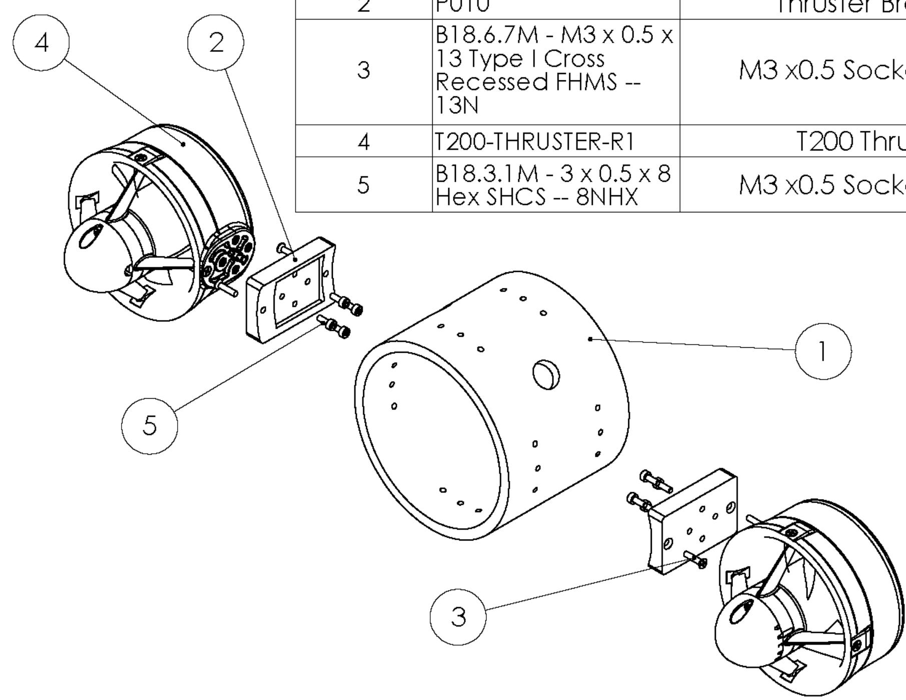
APPLICATION

COMMENTS:
The Profile of the Tail Cone has a profiled of the mirrored equation modeled from x=y^0.75.
The 0.1875" hole needs to be dimensioned to fit a #10-32 screw .

SIZE **A** DWG. NO. **E007** REV

SCALE: 1:2 WEIGHT: SHEET 1 OF 1

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	P004	Thruster Brace	1
2	P010	Thruster Bracket	2
3	B18.6.7M - M3 x 0.5 x 13 Type I Cross Recessed FHMS -- 13N	M3 x0.5 Socket Screw	4
4	T200-THRUSTER-R1	T200 Thruster	2
5	B18.3.1M - 3 x 0.5 x 8 Hex SHCS -- 8NHX	M3 x0.5 Socket Screw	8



UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL

FINISH

NEXT ASSY | USED ON

APPLICATION

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	A.Jackson	6/6/18
CHECKED	M.Peauroi	6/7/18
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

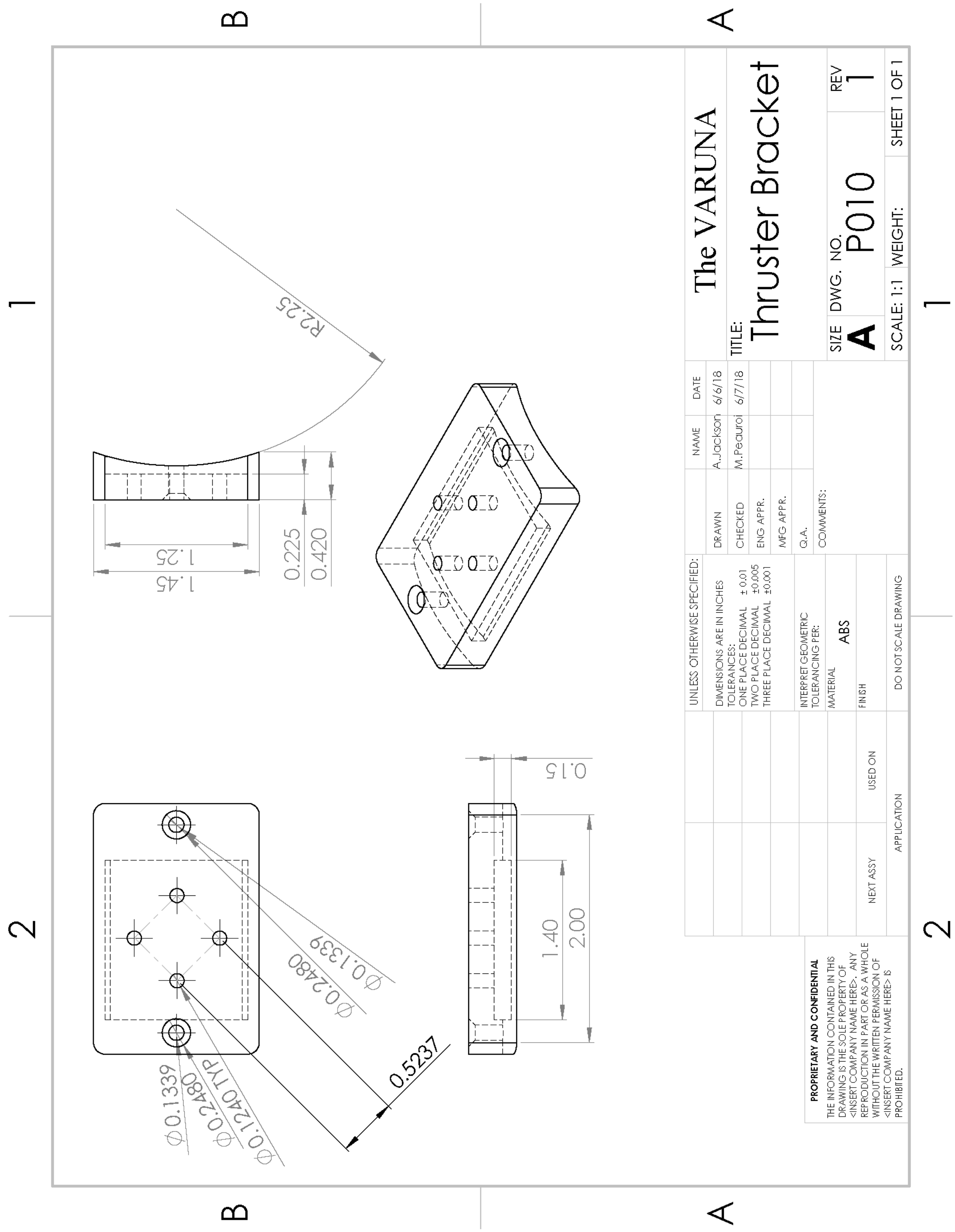
The VARUNA

TITLE:

Lateral Thruster Brace Assembly

SIZE A | DWG. NO. PA1 | REV

SCALE: 1:3 | WEIGHT: | SHEET 1 OF 1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TITLE:
Thruster Bracket
SIZE A
DWG. NO. P010
REV 1
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1
DRAWN A.Jackson 6/6/18
CHECKED M.Peauroi 6/7/18
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
NAME
DATE
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
ONE PLACE DECIMAL ± 0.01
TWO PLACE DECIMAL ±0.005
THREE PLACE DECIMAL ±0.001
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
ABS
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
PROPRIETARY AND CONFIDENTIAL
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R2.25
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1.45
0.225
0.420
0.15
1.40
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⌀0.2480
⌀0.1240 TYP
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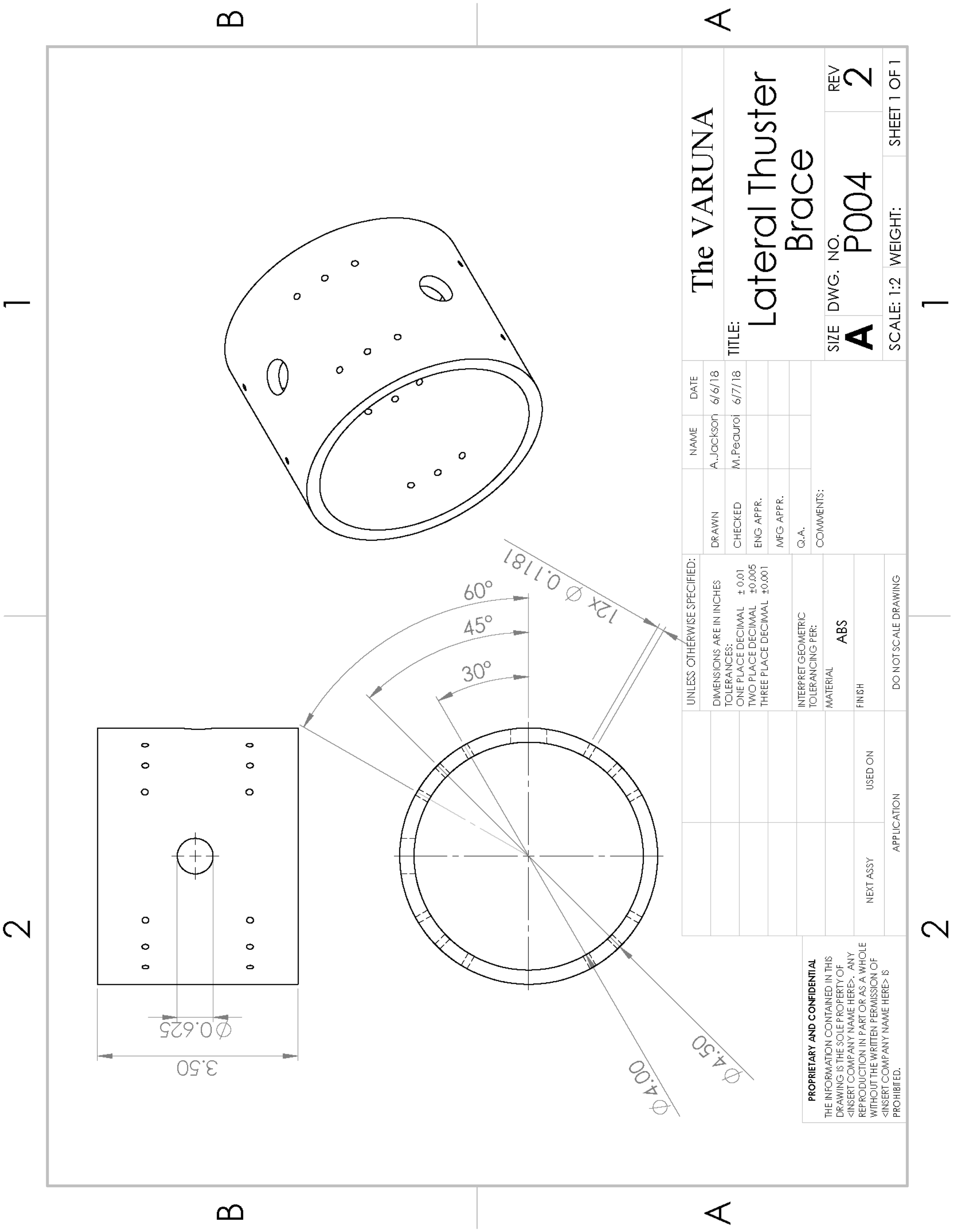
⌀0.2480



The VARUNA
TITLE:
Lateral Thuster Brace
SIZE A
DWG. NO. P004
REV 2
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1
NAME
DATE
DRAWN A.Jackson 6/6/18
CHECKED M.Peauroi 6/7/18
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
ONE PLACE DECIMAL ± 0.01
TWO PLACE DECIMAL ±0.005
THREE PLACE DECIMAL ±0.001
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL ABS
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
PROPRIETARY AND CONFIDENTIAL
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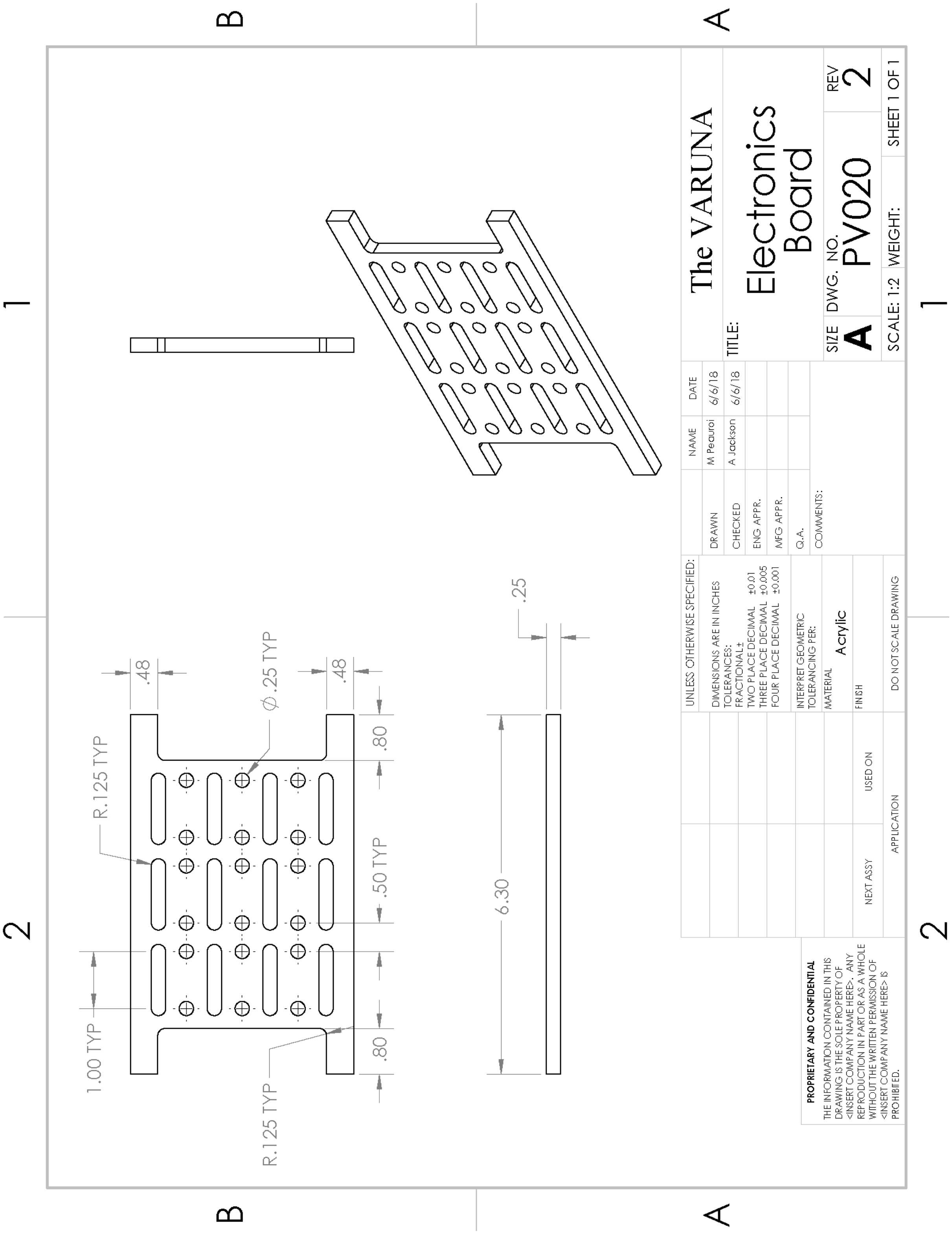
Ø4.00
Ø4.50
12x Ø 0.1181
30°
45°
60°
A
B
1
2



The VARUNA
TITLE:
Electronics Board
SIZE A
DWG. NO. PV020
REV 2
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1
NAME
DATE
DRAWN M Peauroi 6/6/18
CHECKED A Jackson 6/6/18
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
TWO PLACE DECIMAL ±0.01
THREE PLACE DECIMAL ±0.005
FOUR PLACE DECIMAL ±0.001
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL Acrylic
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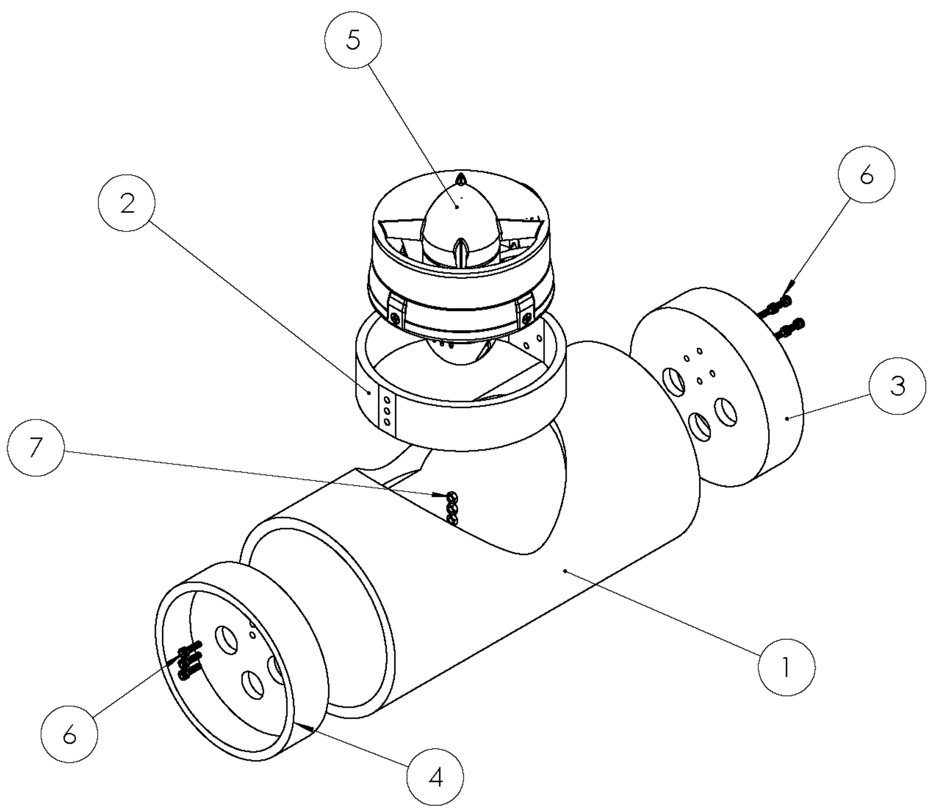
ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	P006	Vertical Thruster Tube	1
2	P007	Vertical Thruster Ring	1
3	P008	Vertical Thruster Stabilizer Fore	1
4	P009	Vertical Thruster Stabilizer Aft	1
5	P003	Thruster	1
6	P001	M3 x 0.5	7
7	P002	M3 nut	3



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DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

MATERIAL

FINISH

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	NAME	DATE
DRAWN	M Peauroi	6/6/18
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

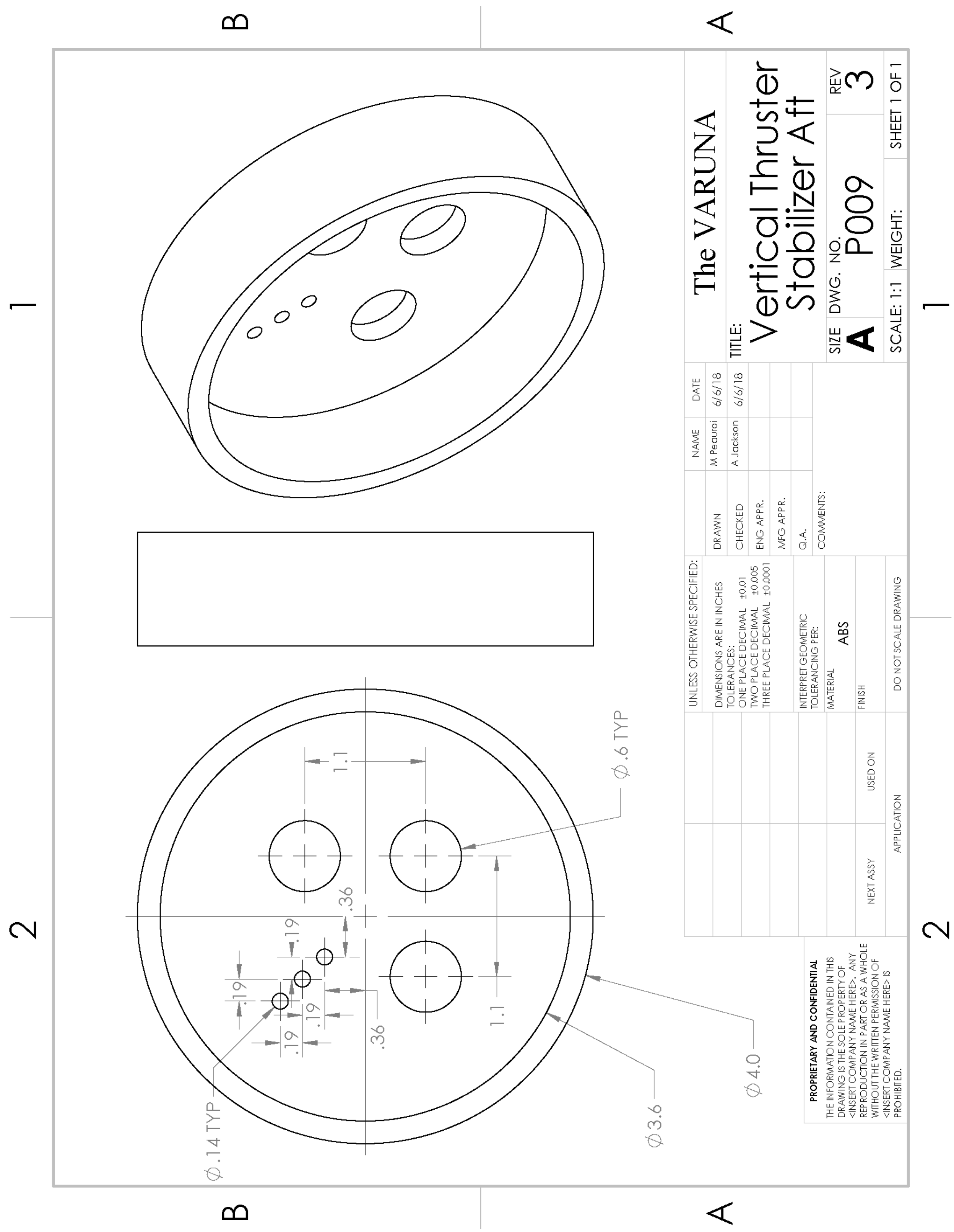
COMMENTS:

The VARUNA

Vertical Thruster Assembly

SIZE A | DWG. NO. PA2 | REV. 2

SCALE:1:3 | WEIGHT: | SHEET 1 OF 1



The VARUNA
TITLE:
Vertical Thruster Stabilizer Aft
SIZE A
DWG. NO. P009
REV 3
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1
NAME
DATE
DRAWN M Peauroi 6/6/18
CHECKED A Jackson 6/6/18
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
ONE PLACE DECIMAL ±0.01
TWO PLACE DECIMAL ±0.005
THREE PLACE DECIMAL ±0.0001
INTERPRET GEOMETRIC TOLERANCING PER:
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FINISH
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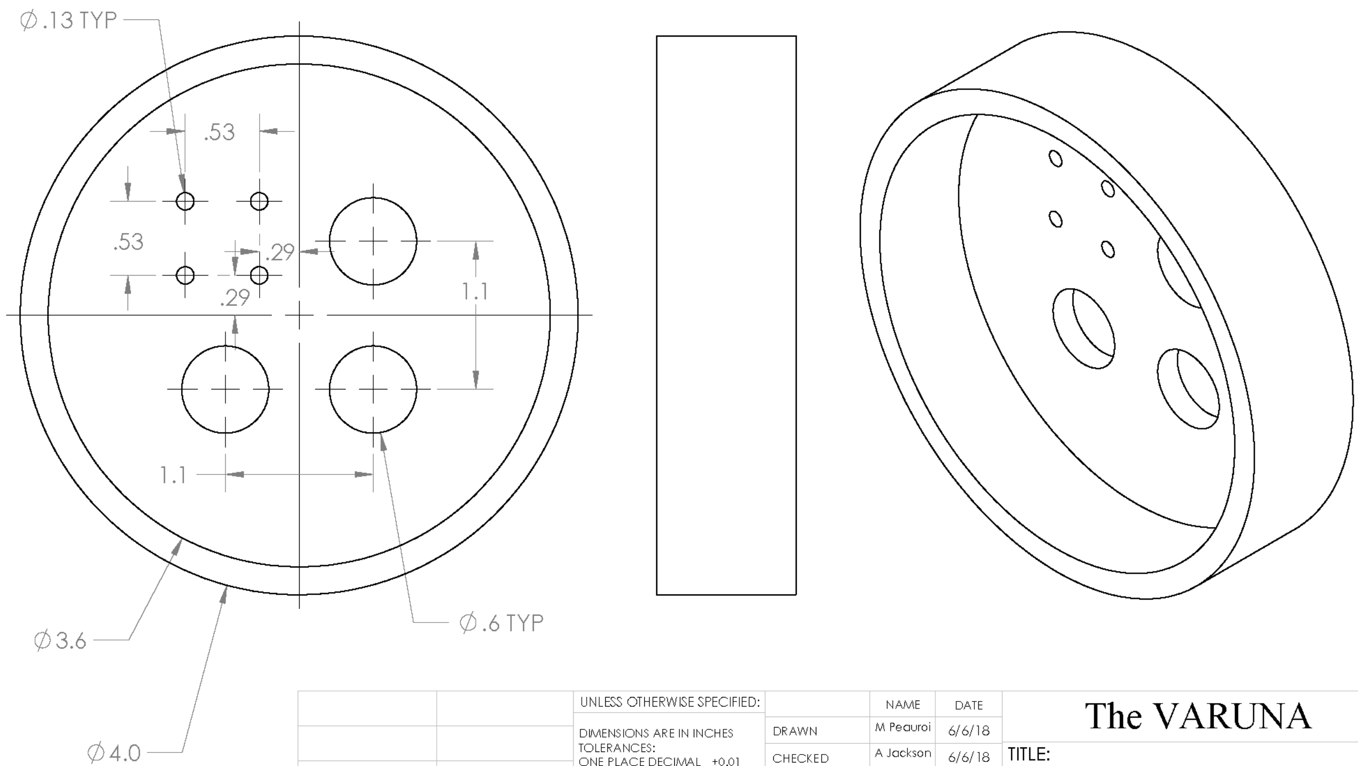

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UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
ONE PLACE DECIMAL ±0.01
TWO PLACE DECIMAL ±0.005
THREE PLACE DECIMAL ±0.0001
INTERPRET GEOMETRIC TOLERANCING PER:
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FINISH
DO NOT SCALE DRAWING

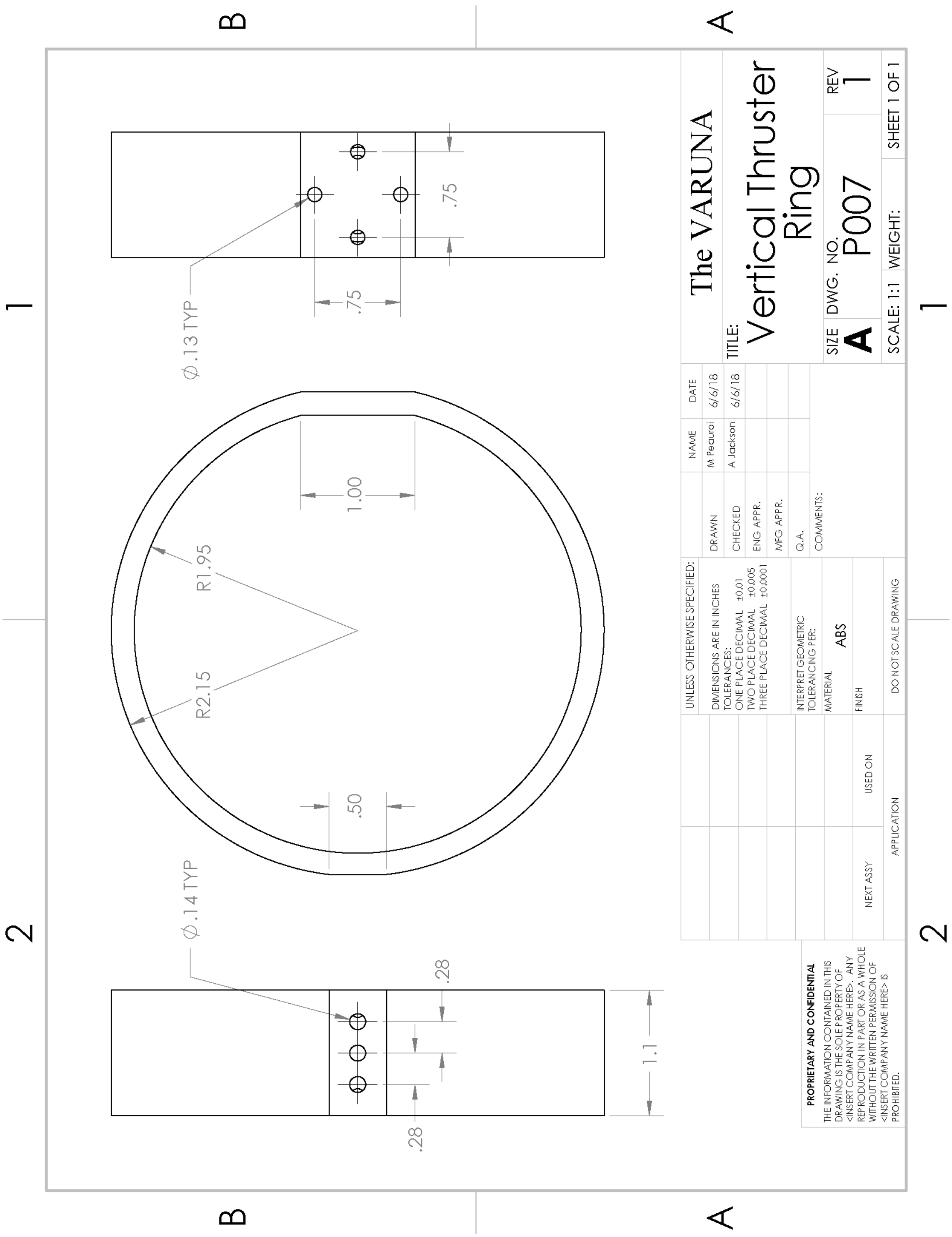
	NAME	DATE
DRAWN	M Peauroi	6/6/18
CHECKED	A Jackson	6/6/18
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

The VARUNA

TITLE:
Vertical Thruster Stabilizer Fore

SIZE A | DWG. NO. P008 | REV 3
SCALE: 1:1 | WEIGHT: | SHEET 1 OF 1


The VARUNA
TITLE:
Vertical Thruster Ring
SIZE A
DWG. NO. P007
REV 1
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
ONE PLACE DECIMAL ±0.01
TWO PLACE DECIMAL ±0.005
THREE PLACE DECIMAL ±0.0001
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL ABS
FINISH
DO NOT SCALE DRAWING
NAME DATE
DRAWN M Peauroi 6/6/18
CHECKED A Jackson 6/6/18
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
NEXT ASSY
USED ON
APPLICATION
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R2.15
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Ø.14 TYP
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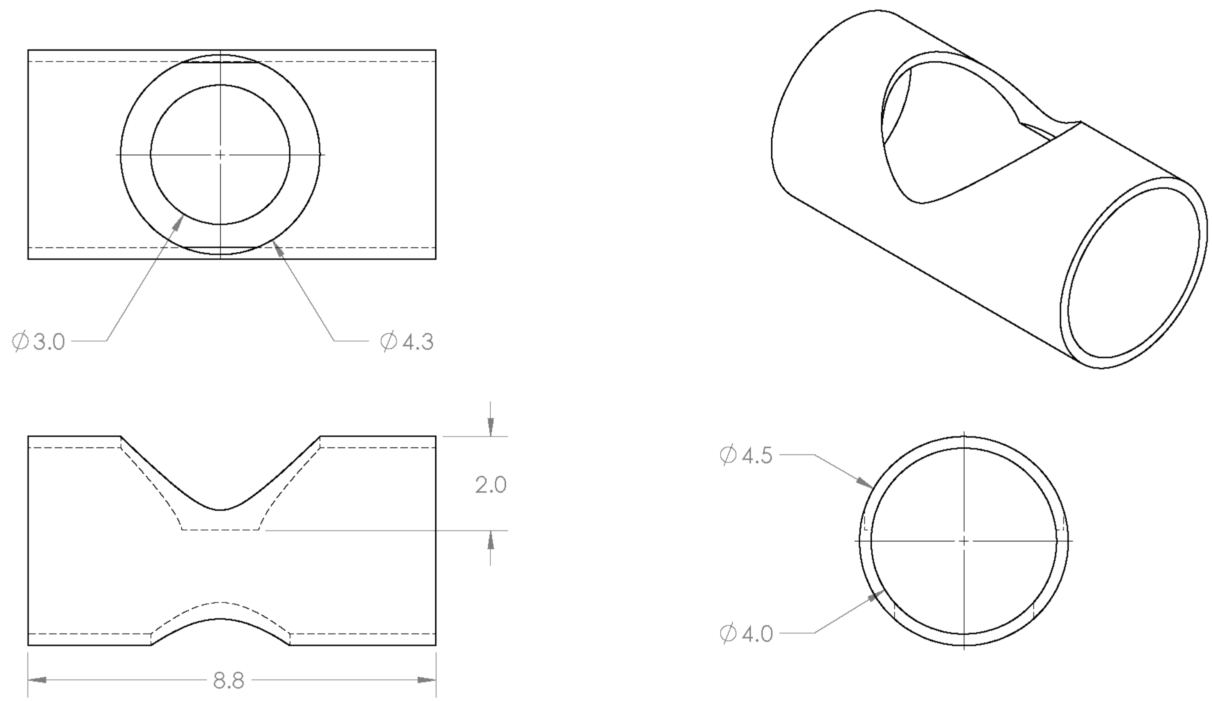
1.1
A
B
1
2



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NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
ONE PLACE DECIMAL ±0.01
TWO PLACE DECIMAL ±0.005
THREE PLACE DECIMAL ±0.0001

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL: ABS

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	M Peauroi	6/6/18
CHECKED	A Jackson	6/6/18
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

The VARUNA

TITLE:
Vertical Thruster Tube

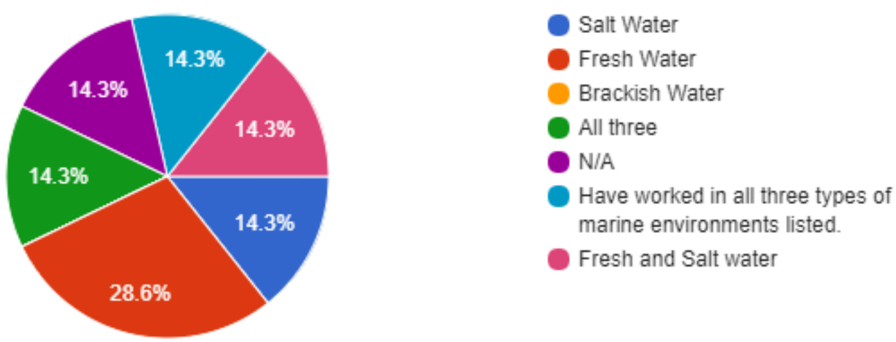
SIZE	DWG. NO.	REV
A	P006	1

SCALE: 1:3 WEIGHT: SHEET 1 OF 1

Appendix D - Customer Needs Report Survey

What type of marine environment do you work in?

7 responses



We will be equipping the AUV with a CTD sensor package. Are there other sensor packages that you think would be useful to be able to accommodate in the future?

7 responses

Water quality or oxygen level
acoustic mapping and cameras
Could be interesting to have a package for sensing ambient water current. In addition, having support for sensing the concentration of chemicals would be interesting.
multibeam sonar, other small water quality sensors (nitrogen, dis ox, turbidity, etc.)
pH, PAR, nutrient (EC)
Can it measure Dissolved Oxygen as well? Nitrates could also be useful.
Camera, imaging sonar, lasers

What battery life do you usually work with on your field work? What would you prefer to work with?

7 responses

I think 2-3 hours
depends on vehicle, 21" dia. usually 10 KW
Depends on the type of mission. I would assume that 2 to 3 hours would be sufficient.
I would expect the vehicle to be able to operate underwater for at least an hour - preferably 3-4 hrs
8+ hr
For non-tethered robots... 2 hours? Prefer as long as possible.
Tether, but would like 2-3hour battery life

What level of maneuverability would you look for in an area roughly the size of a football field?

7 responses

RC controlled
Football field is small, so very maneuverable
Accurate navigation within a few meters would likely be acceptable.
If the vehicle is for duration, very little, possibly not even being able to make a turn. If for workspace intervention, it should be able to turn almost on a dime
10m radius turns, position accuracy +/- ~5m
Turning radius of 5m?
holonomic, hover over a point and maintain position +/- 2 meters with current

What is an acceptable rate of data acquisition?

7 responses

20 Hz or 10 is also fine as Speed is not the concern for this application
not a simple question, depends on the missions requirements if a vehicle is doing .5 m/sec and I want .5 meter resolution it's an easy answer but I don't have a vehicle to work with here and I don't have a mission clearly stated.
Depends on what's being sensed. I would assume that 1 - 2 hz is probably acceptable.
sonar data should be taken every 5 meters of travel or so
1sample / 10m
Depends on how fast whatever you're measuring changes. Don't want to sample so slowly that you miss some feature.
Depends on the data and transmission lines. 5-10HZ

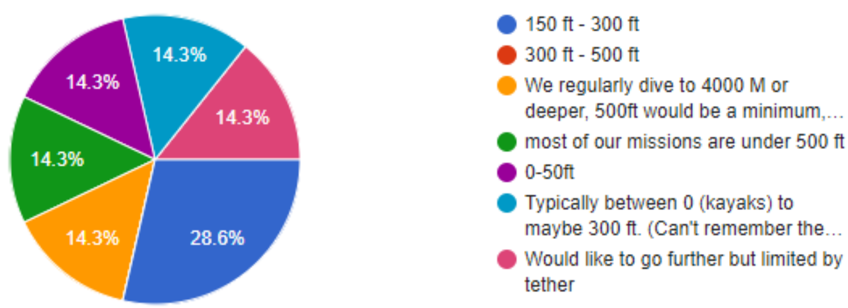
If you have any additional input or comments, please share them with us here.

7 responses

Looking forward to see great AUV.
You can look up some papers on physical oceanography to get some of these answers to form a mission, then designa vehicle around the mission(s)
Make sure you put handles on it so is easily liftable onto a boat.
if for work area intervention make sure there is a glass window for cameras, etc.; provide more than enough room for payload additions, cabling, etc.
N/A
Negative.
Make sure it doesn't leak, Rule #1!

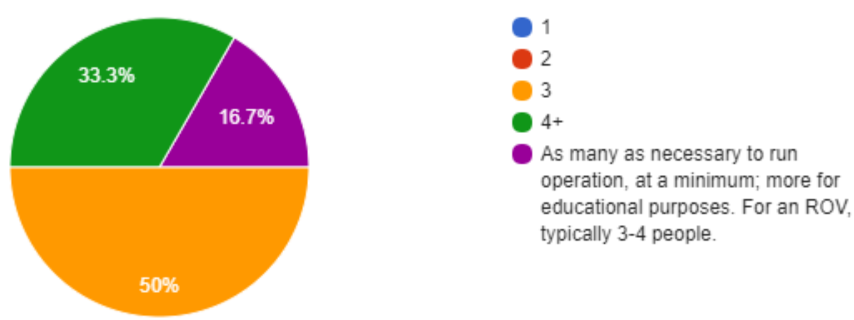
What depth do you usually work at when going on expeditions? If you do not see your preference listed below, let us know what depth you need.

7 responses



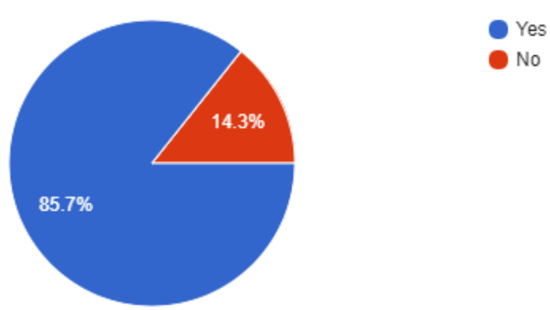
How many people do you bring on the average expedition?

6 responses



Would it be beneficial to be able to have a device operable by one to two people?

7 responses



Appendix E - Design Decision Matrices

E.1 - Preliminary Design Decision Matrix

(~) okay, (-) bad, (+) good

STOPLIGHT CHART

	Thrstr+ servos	2Thrstr+ Fixed wing	3Thrstr+ Fixed wing	2Thrstr+ servo	5Thrstr
Simplicity (MECH)	(+)	(+)	(+)	(-)	(+)
Simplicity (ELEC)	(-)	(+)	(+)	(-)	(+)
Simplicity (Controls)	(-)	(-)	(~)	(+)	(+)
Reliability	(-)	(+)	(~)	(-)	(~)
Battery/ Power	(~)	(+)	(~)	(+)	(-)
Cost	(+)	(~)	(~)	(+)	(-)
Hydrodynamics	(+)	(~)	(+)	(+)	(-)

Figure E-1: The “Stoplight Chart”

SIMPLICITY

Mechanical Simplicity:

Our idea of the simplicity came in the form of waterproofing of the connections. With the addition of the servo motors, the team would have to make our own waterproofing methods. This would be difficult to fabricate via the means we have available.

Electrical:

More components = more connections = more possible points of failure

Controls:

We wanted independent control of pitch and yaw

Rear thruster as correctional (PID) control for fixed wing direction

Control system for horizontal and forward movement

More thrusters → more control

RELIABILITY

More moving parts → More opportunity for failure

Off-the-shelf > DIY

Thrusters vs Servo

BATTERY

More thrusters→ More power needed

HYDRODYNAMICS

5 thruster design requires thin thrusters set into wings

Angled fixed wing to provide upward force, causing AUV to move down at high speeds

Torpedo design with minimal additions

E.2 - In-Depth Design Decision Matrix

The primary mechanical issues our team faced were providing thrust and roll, pitch, and yaw control in a way that does not undermine other criteria such as waterproof-ability, power efficiency, and maneuverability. In order to address these system level issues, our team considered the following system options:

- One thruster with actuators
- Two thrusters with fixed wings
- Two thrusters with actuators
- Three thrusters
- Five thrusters

The tradeoffs of each system option were considered with respect to the design criteria. When considering each option, the team examined the waterproof-ability, maneuverability, power efficiency, mass, thrust, hydrodynamics as well as the cost and time required of each design.

One thruster in conjunction with actuator-controlled fins is a baseline design commonly used by many AUVs. Through the typical use of a streamlined torpedo shape, this option provides the least underwater drag. The use of four actuator-controlled fins provides moderate power efficiency and maneuverability with respect to designs that utilize more thrusters. However, this lack of thrusters results in less thrust and moderate maneuverability. Additionally, the use of actuators presents far greater difficulty in waterproofing the vessel and its components.

The two-thruster design provides the most power efficiency but moderate maneuverability and mass as it relies on fixed wings to direct the vehicle downward and positive buoyancy to move up, rather than using thrusters or actuators to control pitch or depth. Additionally, the lack of thrusters and actuators results in the easiest and most reliable design with respect to waterproofing. This design makes use of a similar torpedo shape, but the use of two tail cone thrusters and wings results in greater underwater drag while increasing thrust.

The three thruster design features two tail cone thrusters to control yaw and an additional thruster positioned on top of the vessel for pitch control, providing good thrust and maneuverability. Using an additional thruster instead of actuators results in worse power efficiency and mass but greater waterproof-ability.

The two thruster and two actuator design features good thrust capabilities and maneuverability, but its power efficiency and mass are moderate. Additionally, the use of actuators results in poor waterproof-ability.

The five-thruster design features the best thrust and maneuverability at the expense of the least power efficiency. The bulkiness of the thrusters also results in a less streamlined shape, resulting in poor mass and drag functionality. Additionally, the number of thrusters results in a moderate level of waterproof-ability.

The team evaluated all the system options using the selection matrices in Figure E-2, and the two top designs based upon weighted criteria were the two thruster and three thruster designs. Our team decided to adopt the three-thruster design, but to keep the option of a hybrid approach between these two designs, using two tail cone thrusters with fixed wings with the addition of a third thruster on the top front portion of the vehicle, as a possible future design change. The third thruster in the front provides the potential for maneuverability without wings, while as a future design iteration, power efficiency could be increased by adding fixed wings that would allow for the third thruster to spend most of its time off. This design would still display the superior thrust and drag capabilities and waterproof-ability from both the two thruster and three thruster configurations.

	TARGET or									DESIGN IDEAS	
CRITERIA	FACTOR	1 = Baseline		two thursters		three thrusters		two thrusters, two		five thrusters	
Time – Design	40	40		35		30		40		30	
Time – Build	35	35		30		30		35		30	
Time – Test	30	30		35		30		30		30	
Time weighting	13		13		12.56		11.30		13.00		11.30
Cost – Prototype	$ 400.00	$ 400.00		$ 400.00		$ 600.00		$ 500.00		$ 1,000.00	
Cost – Production	$ 300.00	$ 300.00		$ 400.00		$ 600.00		$ 500.00		$ 1,000.00	
Cost weighting	8		8		9.33		14.00		11.67		23.33
mass	6	3	18	3	18	2	12	2	12	2	12
thrust	5	3	15	4	20	4	20	4	20	5	25
power draw	17	3	51	3	51	2	34	2	34	1	17
drag	12	3	36	2	24	3	36	3	36	1	12
maneuverability	8	3	24	2	16	4	32	4	32	5	40
waterproofability	18	3	54	5	90	4	72	3	54	5	90
controlability	13	3	39	2	26	4	52	4	52	4	52
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
	TOTAL		237.0		244.1		253.7		236.3		234.4
	RANK										
	% MAX		93.4%		96.2%		100.0%		93.2%		92.4%

Figure E-2: Design decision matrix spreadsheet

Appendix F - Analysis and Calculations

F.1 - Power Budget

Table F-1: Electrical Characteristics of On-board Components

	Input Voltage (V)		Current (A)		Power (W)	
Component	**Voltage Range**	**Op Voltage**	**Op Current**	**Max Current**	**Operating Power**	**Max Power**
T200 Thruster	6-20	16	5	25	80	350
Arduino Mega 2560	7-12	12	3.00E-02	5.00E-02	3.60E-01	1.75E-01
ESC	8.4-25.2	12	4.00E-02	30	4.80E-01	360
Pressure Sensor	2.5-5.5	5	6.00E-07	1.25E-03	3.00E-06	6.25E-03
Magnetometer/IMU	1.7-4.2	3.3	1.23E-02	2.00E-02	4.06E-02	8.40E-02
Conductivity/Temp	3.3-5	5	1.81E-02	5.00E-02	9.07E-02	2.50E-01
GPS	3.3	3.3	2.00E-02	6.80E-02	6.60E-02	2.24E-01
UBEC (DC to DC)	5.5-26	5	0.5	1	2.5	5
Data Logger	3.3-5	5	2.00E-03	6.00E-03	1.00E-02	3.00E-02

Table F-2: Expected Mission Profile

Op Mode	Time (hours)
idle	0.1666666667
max power	0.02
standard	0.5

Table F-3: Analysis of Power Needs in Idle Mode

Idle	Power (W)	Qty	Total Power (W)
Arduino Mega 2560	1.75E-01	2	0.35
Pressure Sensor	0	1	0.00
Compass	8.40E-02	1	0.08
GPS	2.24E-01	1	0.22
DCtoDC conv	2.5	2	5.00
Data Logger	3.00E-02	2	0.06
		total	5.72
		Watt-hours	0.95
*		Amp-hours	0.06

Table F-4: Analysis of Power Needs in Max Power Mode

Max Power	Power (W)	Qty	Total Power (W)
T200 Thruster	350	3	1,050.00
Arduino Mega 2560	1.75E-01	2	0.35
Pressure Sensor	0	1	0.00
Compass	8.40E-02	1	0.08
GPS	2.24E-01	1	0.22
DCtoDC conv	15	2	30.00
Data Logger	3.00E-02	2	0.06
ESC	0	3	
		total	**1,080.72**
		Watt-hours	**0.00**
		Amp-hours	**0.00**

Table F-5: Analysis of Power Needs in Standard Mode

Standard	Power (W)	Qty	Total Power (W)
T200 Thruster	80	3	240
Arduino Mega 2560	0.18	2	0.35
Pressure Sensor	0.00	1	0
Compass	0.08	1	0.084
GPS	0.22	1	0.224
DCtoDC conv	2.50	2	5
Data Logger	0.03	2	0.06
ESC	0	3	
		total	**245.72**
		Watt-hours	**122.86**
		Amp-hours	**7.68**

Table F-6: Battery Needs Analysis Results

Total Battery Capacity (Ah):	**7.74**	
mAh:	**7738.25**	
Battery Voltage (V)	**16**	
safety factor	**2**	
Battery Needed (mAh):	**15476.5**	**16V**

F.2 - Mass Budget

Item	Dry Mass (kg)	Weight (N)	Displ (m^3)	B (N)	Density (kg/m3)	B - W (N)	x_cg (m)
Nose cone	0.595	5.83695	0.00076	7.4556		1.61865	0.102
Tail cone	0.352	3.45312	0.000627	6.15087		2.69775	1.417
Battery bottle	1.44	14.1264	0.00235	23.0535		8.9271	0.9601
Controls bottle	1.821	17.86401	0.00235	23.0535		5.18949	0.8331
Payload bottle	1.45	14.2245	0.00235	23.0535		8.829	0.4775
Vertical thruster	0.33	3.2373		1.87		-1.3673	0.257
Vertical thruster brace	0.327	3.20787	0.00030560747	2.998009346	1070	-0.2098606542	0.256
Left thruster	0.33	3.2373		1.87		-1.3673	1.34
Right thruster	0.33	3.2373		1.87		-1.3673	1.34
Lateral thruster brace	0.021	0.20601	0.000192	1.88352		1.67751	1.347
Total weight and buoyancy							
Total x_cg and x_cb							

Item	x_cb (m)	Qty	W total	B total	B - W total	W x-mom	B x-mom
Nose cone	0.102	1	5.83695	7.4556	1.61865	0.5953689	0.7604712
Tail cone	1.417	1	3.45312	6.15087	2.69775	4.89307104	8.71578279
Battery bottle	0.9601	1	14.1264	23.0535	8.9271	13.56275664	22.13366535
Controls bottle	0.8331	1	17.86401	23.0535	5.18949	14.88250673	19.20587085
Payload bottle	0.4775	1	14.2245	23.0535	8.829	6.79219875	11.00804625
Vertical thruster	0.257	1	3.2373	1.87	-1.3673	0.8319861	0.48059
Vertical thruster brace	0.258	1	3.20787	2.998009346	-0.2098606542	0.82121472	0.7734864112
Left thruster	1.345	1	3.2373	1.87	-1.3673	4.337982	2.51515
Right thruster	1.345	1	3.2373	1.87	-1.3673	4.337982	2.51515
Lateral thruster brace	1.347	1	0.20601	1.88352	1.67751	0.27749547	2.53710144
Total weight and buoyancy			79.21575	97.17886601	17.96311601	60.82306439	74.16031504
Total x_cg and x_cb						0.7678152941	0.7631321303

Figure F-1: Mass budgeting spreadsheet

F.3 - Computational Fluid Dynamics Results

F.3.1 - The Calculation Method

Calculating the values of the parameters used in our analysis of the hydrodynamics of the VARUNA utilized the COMSOL Multiphysics variables along with user defined variables. To determine the values of the pressure and viscous drags and their respective drag coefficients, COMSOL calculates the pressure on the individual elements of the automated mesh. The program then generates global quantized values from the individual elements which can be used to calculate the desired physics. The Equations (1) through (4) below were used to find the drag forces and coefficients:

$$D = pn_x \tag{1}$$

$$D_{stress} = K_{stress}n_x \tag{2}$$

$$C_{D,pressure} = \frac{8D}{\pi \rho U_{in} d^2} \tag{3}$$

$$C_{D,viscous} = \frac{8D_{stress}}{\pi \rho U_{in} d^2} \tag{4}$$

where p and $K_{stresss}$ are the pressure and viscous stress calculated by the simulation program, n_x is the normalized x component of the vectorized values, ρ is the density of the fluid, U_{in} is the fluid speed at the "inlet", and d is the diameter of the hull of the model. Equation (1) gives the calculation for the pressure drag, D, Equation (2) gives the calculation for the viscous drag, D_{stress}, and (3) and (4) give the pressure and viscous drag coefficients, respectively.

F.3.2 - Validating the Model

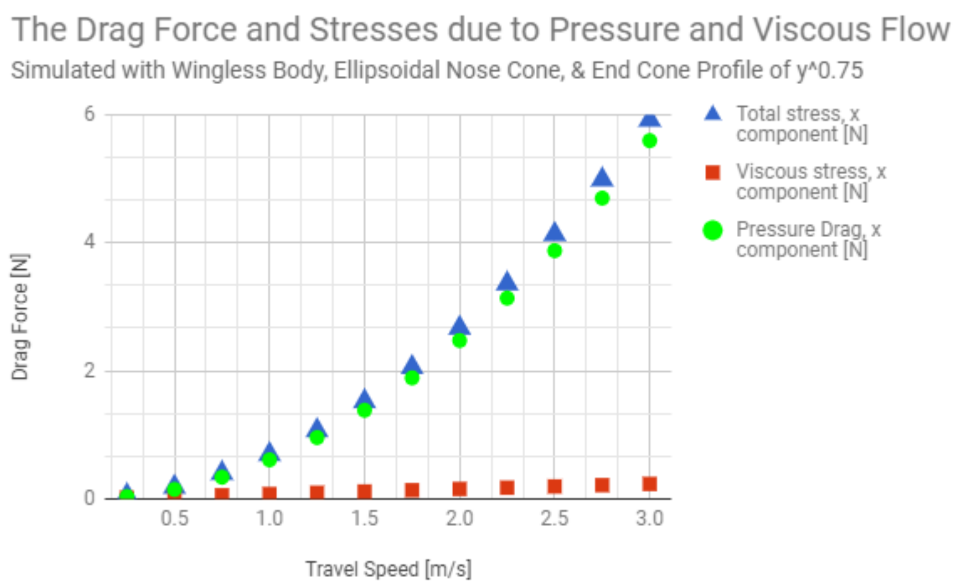


Figure F-2: Pressure and Viscous drag force distribution on the simulated VARUNA

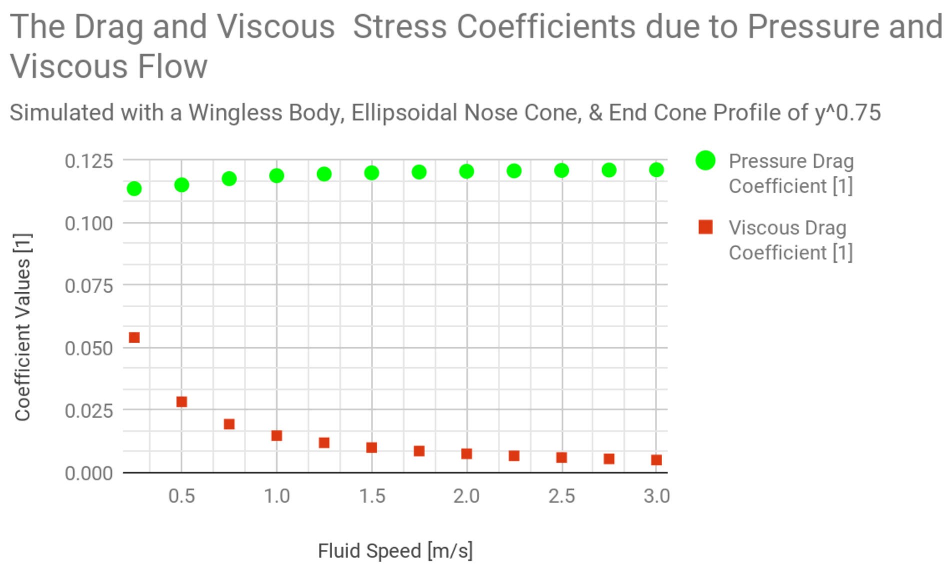


Figure F-3: Pressure and viscous drag coefficients

Any time a simulation is run, it is important to validate the model that the simulation is based off. As stated in Section 3.1.2.2, assumptions are a very important aspect of running a good CFD simulation. These assumptions, which arise from the boundary and initial conditions of the model, need to be validated - this is usually done by experimental data. The data that we compared our results to came from the *Fluid Mechanics* text written by Frank White, displayed in Figure F-4 below and in Section 3.1.2.2. The figure displays the experimental values of four different geometries cruising through a fluid. Using non-dimensional analysis, we observed the values for the experimental drag coefficients and our drag coefficients. Referring to Table F-7, one can see our values are in fact lower than the 0.15 value for the experimental coefficients from White's text. Averaging out the right column in Table F-7 yields a drag coefficient of 0.12, which corresponds to a lower drag force.

Also, referencing Figure F-5 validates and confirms the theory behind the pressure drag. Note the high pressure at the front stagnation point on the nose and the low pressure at the back-stagnation point at the tail.

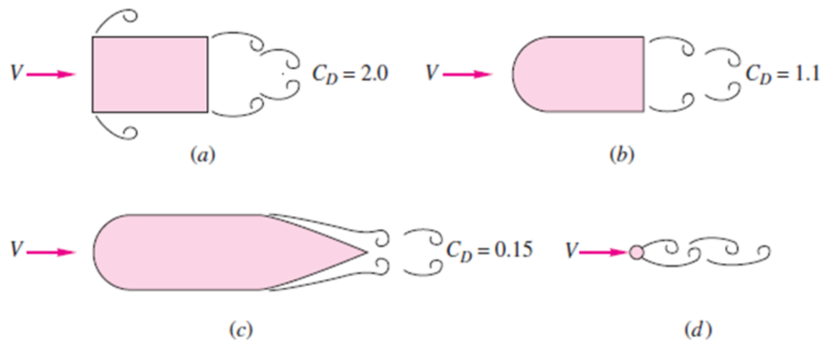


Figure F-4: Published experimental drag coefficient values for four different object geometries

Table F-7: The table displays the drag coefficients at various travel speeds from the CFD simulations.

Pressure Drag Coefficient vs. Speed	
U_in [m/s]	**Pressure Drag Coefficient [1]**
0.25	0.1137
0.50	0.1152
0.75	0.1177
1.00	0.1189
1.25	0.1195
1.50	0.1200
1.75	0.1203
2.00	0.1206
2.25	0.1208
2.50	0.1210
2.75	0.1211
3.00	0.1212

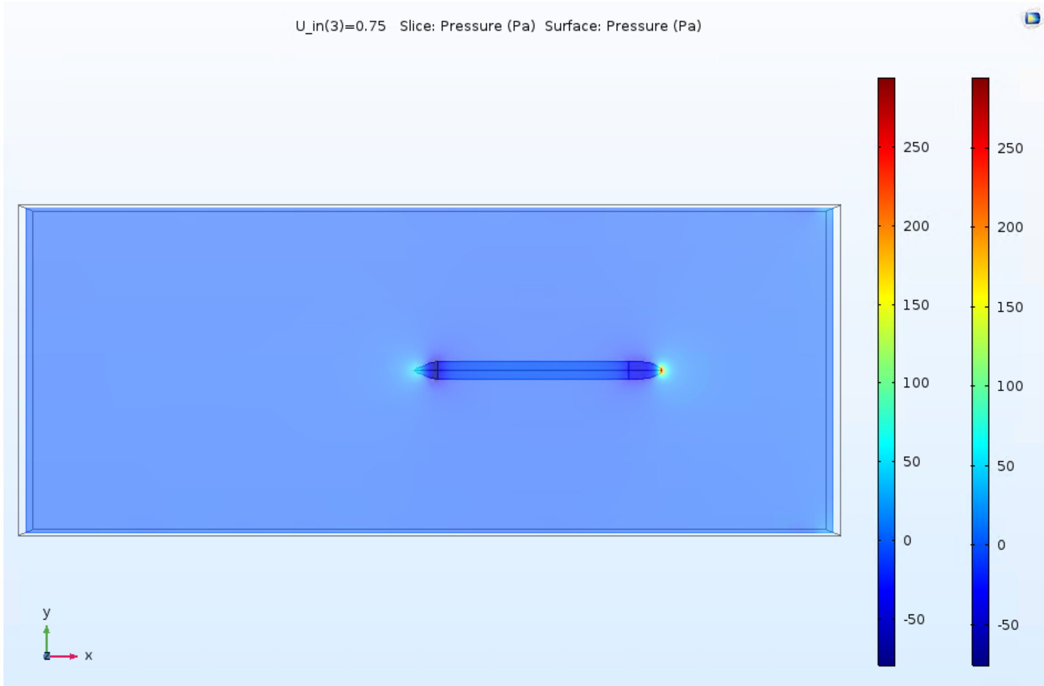


Figure F-5: Pressure distribution along the surface of the AUV model

Appendix G - Programming Documentation

G.1 How Things Work

The following codes can be used to test individual components or to be built upon in integrated coding blocks.

G.1.1 - ESC

The ESCs are programmed like servos. They use the "writeMicroseconds" function to send PWM data to the motors. They go from 1100ms to 1900ms, but it is highly suggested that the motors only go from a range of 1300 to 1700, as full power draws up to 25A and there are fuses in the system to prevent the motors from going over 10A. If more power is required, the fuses must be changed or removed.

```
#include <Servo.h> //esc/motors are considered Servos in Arduinos

byte ESCPin = 9; //choose a pmw pin
Servo ESC; //create Servo item

void setup() {
  servo.attach(servoPin); //'attach' is the function used to connect servos

  servo.writeMicroseconds(1500); //send "stop" signal to ESC.
  delay(7000); //delay to allow the ESC to recognize the stopped signals
}

void loop() {
  int signal = 1700; // Set signal value, which should be between 1100 and 1900
  // 1100 - 1500 backwards, 1500 - 1900 forwards

  servo.writeMicroseconds(signal); // Send signal to ESC.
                                   //'writeMicroseconds' used to run the motors
  delay(2000);

  signal = 1500;
  servo.writeMicroseconds(signal);
  delay(2000);

  signal = 1300; //Backwards
  servo.writeMicroseconds(signal);
  delay(2000);

  signal = 1500;
  servo.writeMicroseconds(signal);
  delay(2000);
}
```

G.1.2 - Magnetometer

```
//Libraries required to run magnetometer:
#include <Wire.h>
#include <Adafruit_Sensor.h>
#include <Adafruit_BNO055.h>

Adafruit_BNO055 bno = Adafruit_BNO055(); //magnetometer variable

int piezoPin = 11;

void setup() {
  // put your setup code here, to run once:
  Serial.begin(9600);
  Serial.println("Magnetometer Test");
  Serial.println("");

  if(!bno.begin())//turns on Magnetometer. REQUIRED!!
  {
    while(1);
  }
  uint8_t system, gyro, accel, mag = 0;//gyroscope, accelerometer, magnetometer variables
  int mag1 = mag*1;// change to an "int" variable
  while(mag1 != 3)//calibration finishes when it reads "3"
  {
    bno.getCalibration(&system, &gyro, &accel, &mag);
    mag1 = mag*1;
    Serial.println(mag1);//print out current calibration status
  }
}

void loop() {
  //get the magnetometer information
  imu::Vector<3> event = bno.getVector(Adafruit_BNO055::VECTOR_MAGNETOMETER);

  float Pi = 3.14159;

  //getting magnetometer and heading values:
  float heading = (atan2(event.y(), event.x()) * 180) / Pi; //convert to heading
  if (heading < 0)
  {
    heading = heading + 360; //get a 0-360 reading
  }
  Serial.println(heading);
  delay(100);
}
```

G.1.3 - DataLogger

The DataLogger will take Strings of data from the Arduino, making it easy to compile lots of data information. It is highly suggested that if multiple data sets are sent before a new line, that there be commas between each set.

```
//This code takes input from the Serial port and send it to the datalogger

void setup() {
  // put your setup code here, to run once:
  Serial.begin(9600);//Serial port on computer
  Serial1.begin(9600); //DataLogger serial port - make sure it is connected properly!
}

void loop() {
  // put your main code here, to run repeatedly:
  if(Serial.available()) //when data from serial port is there
  {
    String inByte = Serial.readStringUntil('\n'); //read it as a string
    Serial1.println(inByte); //print to Data Logger
  }

}
```

G.1.4 - Pressure Sensor

```
//get data from pressure sensor

double value;

void setup() {
  // put your setup code here, to run once:
  Serial.begin(9600);
}

void loop() {
  value = analogRead(A0)*5; //choose a analog pin - here we use A0
  value = value/1024; //turn into voltage. the Pressure sensor runs from 0.5V to 4.5V.

  value = 75*value - 37.5; //values from linear chart, converts voltage to PSI

  if (value < 0) //if less than 0 we set to 0
    value = 0;

  Serial.println(value*0.703); //0.703 turns PSI into depth
  delay(100);
}
```

G.1.5 - Temperature Sensor

```
//get data from temperature sensor

#include <Wire.h>
#include "TSYS01.h"

TSYS01 sensor;

void setup() {
  Serial.begin(9600);
  Serial.println("Starting");
  Wire.begin();
  sensor.init();
}

void loop() {

  sensor.read();

  Serial.print("Temperature: ");
  Serial.print(sensor.temperature());
  Serial.println(" deg C");

  Serial.println("---");

  delay(1000);
}
```

G.1.6 - Arduino Communication

The communication uses two Arduinos: a sender and a receiver. In use, these are generally the controls Arduino and payload Arduino.

```
//SENDER

int x = 194;//random characters/strings
void setup() {
  // put your setup code here, to run once:
  Serial1.begin(9600); //onboard Serial Port
}

void loop() {
  // put your main code here, to run repeatedly:
  Serial1.print("Hello?");
  delay(10);
  Serial1.print(", ");
  delay(10);
  Serial1.println(x);
  delay(1000);
}
```

```
//RECEIVER

void setup() {
  // put your setup code here, to run once:
  Serial1.begin(9600); //onboard Serial Port, will be receiving data
  Serial.begin(9600); //Computer Serial Port
}

void loop() {
  // put your main code here, to run repeatedly:
  if(Serial1.available())//when data is received from other arduino
  {
    String inByte = Serial1.readStringUntil('\n');//read until new line
    Serial.println(inByte);//print entire string
  }
  delay(10);
}
```

G.2 Library Information

G.2.1 - Non Downloaded

Two native libraries must be used in the programs. They are:

Wire.h

Servo.h

The thrusters are considered servos, so any program using them requires the Servo library included. Any sensor that uses the I2C port must use the Wire library. Currently, the two sensors that use the I2C are the IMU and the temperature sensor.

G.2.2 - Downloaded

There are multiple libraries that must be downloaded in order for the related sensors to work. They are:

Adafruit_BNO055

Adafruit_Sensor

BlueRobotics_TSYS01_Library_master

The Adafruit BNO055 and Sensor are required for any program that uses the IMU. The TSYS01 library is required for any program using the Blue Robotics temperature sensor. These libraries can be downloaded by typing the names into Google and finding their GitHub pages. They will also be included in the project USB stick given to Dr. Kitts. When downloading or adding libraries, make sure they are added to the Arduino's libraries folder, otherwise the programs using the libraries will not be able to find them.

G.3 - Important Programs

G.3.1 - Main Functions in the Code

G.3.1.1 - IMUCheck

Any program that uses the IMU must have this calibration set-up, otherwise the IMU will not function. "mag1 = mag*1" is seen multiple times in here because mag needs to be turned into an int for it to be used in a while loop. "Serial.println(mag1)" is used for checking and can be commented out. The "tone" function at the end lets the user know the calibration is done - this can be changed to something different if the user so desires.

```
void IMUCheck() //turns on magnetometer and calibrates
{
  if(!bno.begin())//turns on Magnetometer
  {
    while(1);
  }

  uint8_t system, gyro, accel, mag = 0;
  int mag1 = mag*1;
  while(mag1 != 3)
  {
    bno.getCalibration(&system, &gyro, &accel, &mag);
    mag1 = mag*1;
    Serial.println(mag1);
  }
  tone(piezoPin, 1000, 500);
}
```

G.3.1.2 - Magnetometer Readings

Use "MagnetReading()" in the program to get heading data. It runs from 0 to 360 but can be changed to -180 to 180 if that is preferred by commenting out the if statement.

```
void MagnetReading()
{
  imu::Vector<3> event = bno.getVector(Adafruit_BNO055::VECTOR_MAGNETOMETER);

  float Pi = 3.14159;

  heading = (atan2(event.y(), event.x()) * 180) / Pi;
  if (heading < 0)
  {
    heading = heading + 360;
  }
}
```

G.3.1.3 - Pressure Readings

WaterMod is either 0.686 or 0.703, for freshwater and saltwater respectively.

```
void PressureReading()
{
  Pressure = analogRead()*5;//*choose pin;
  Pressure = Pressure/1024; //turn into voltage. the Pressure sensor runs from 0.5 to 4.5.

  Pressure = 75*Pressure - 37.5; //values from linear chart, converts voltage to PSI

  if (Pressure < 0) //if less than 0 we set to 0
    Pressure = 0;

  //CONVERT TO DEPTH
  dDetected = WaterMod*Pressure;
}
```

G.3.1.4 - SerialCheck()

This is the function that is used with the GUI. It takes a String from the serial port and parses it into the required parameters.

```
void SerialCheck()
{
  //SERIAL CONNECTION
  boolean xbreak = 0;
  String param;
  int TypeOfWater;
  while(xbreak == 0)
  {
    //read serial port
    if (Serial1.available() > 0)
    {
      ParamInfo = Serial1.readString();

      param = getValue(ParamInfo, 'a', 0);
      xTotal = param.toInt();

      param = getValue(ParamInfo, 'a', 1);
      yTotal = param.toInt();

      param = getValue(ParamInfo, 'a', 2);
      dTotal = param.toInt();

      param = getValue(ParamInfo, 'a', 3);
      xIncrement = param.toInt();

      param = getValue(ParamInfo, 'a', 4);
      xIncrement = param.toInt();

      param = getValue(ParamInfo, 'a', 5);
      dIncrement = param.toInt();

      param = getValue(ParamInfo, 'a', 6);
      TypeOfWater = param.toInt();

      if (TypeOfWater == 0) //FreshWater
      WaterMod = 0.703;
      else //SaltWater
      WaterMod = 0.686;
```

```
      digitalWrite(ledTest1, HIGH);
      //check info; send confirmation to program if right/wrong
      //ok legit i messed with this for a bit and i have no idea how to
      //send info back, so we'll use an LED for now...
      xbreak = 1;
    }
    delay(10);
  }
}

String getValue(String data, char separator, int index)
{
    int found = 0;
    int strIndex[] = { 0, -1 };
    int maxIndex = data.length() - 1;

    for (int i = 0; i <= maxIndex && found <= index; i++) {
        if (data.charAt(i) == separator || i == maxIndex) {
            found++;
            strIndex[0] = strIndex[1] + 1;
            strIndex[1] = (i == maxIndex) ? i+1 : i;
        }
    }
    return found > index ? data.substring(strIndex[0], strIndex[1]) : "";
}
```

G.3.2 - Basic Test

This is a test used for making sure the motors and main controls sensors are all working properly. It moves all motors forwards and backwards one at a time, prints heading data, then prints pressure data.

```
#include <Servo.h>
#include <Wire.h>
#include <Adafruit_Sensor.h>
#include <Adafruit_BNO055.h>

byte servoPinRight = 6;//one
byte servoPinLeft = 7;//two
byte servoPinTop = 4;

Servo motorRight;
Servo motorLeft;
Servo motorTop;

int signal = 1550; //slow speed
int piezoPin = 11;
int x = 0; //random counter

//IMU Params
Adafruit_BNO055 bno = Adafruit_BNO055();
float heading;
```

```
double dDetected;
double Pressure;
int PressurePin = A0;

void setup() {
  // put your setup code here, to run once:
  Serial.begin(9600);
  IMUCheck();
  delay(1000);

  pinMode(PressurePin, OUTPUT);
  Serial.println("1");

  motorRight.attach(servoPinRight);
  motorRight.writeMicroseconds(1500);
  delay(7000);
  Serial.println("2");

  motorLeft.attach(servoPinLeft);
  motorLeft.writeMicroseconds(1500);
  delay(7000);
  Serial.println("2");

  motorLeft.attach(servoPinLeft);
  motorLeft.writeMicroseconds(1500);
  delay(7000);
  Serial.println("3");

  motorTop.attach(servoPinTop);
  motorTop.writeMicroseconds(1500);
  delay(6000);
  Serial.println("4");
}

void loop() {
  // put your main code here, to run repeatedly:

  motorLeft.writeMicroseconds(signal);
  delay(2000);
  motorLeft.writeMicroseconds(1500);
  delay(2000);
  motorLeft.writeMicroseconds(signal - 100);
  delay(2000);
  motorLeft.writeMicroseconds(1500);
  delay(2000);

  motorRight.writeMicroseconds(signal);
  delay(2000);
  motorRight.writeMicroseconds(1500);
  delay(2000);
  motorRight.writeMicroseconds(signal - 100);
  delay(2000);
  motorRight.writeMicroseconds(1500);
  delay(2000);
```

```
 motorTop.writeMicroseconds(signal);
 delay(2000);
 motorTop.writeMicroseconds(1500);
 delay(2000);
 motorTop.writeMicroseconds(signal - 100);
 delay(2000);
 motorTop.writeMicroseconds(1500);
delay(2000);

Serial.println("Heading");
while(x < 20)
{
   MagnetReading();
   Serial.println(heading);
   x++;
   delay(100);
}

Serial.println();
Serial.println("Depth");
while(x < 40)
 {
    PressureReading();
    Serial.println(CurrentDepth);
    x++;
    delay(100);
 }

 tone(piezoPin, 1000, 500);

 while(x > 0)
 {
   //go forever
 }

}
```

G.3.3 - Controls System

This showcases the two types of controllers. First is the full proportional controller, where both motors are being changed (Note: not full controls code):

```
void Controls()
{
  PressureReading();
  MagnetReading();

  if (Dir == 0)
  {
    if (heading > 10 && heading < 180)
    {
      if(heading > 60)
      {
        motorLeft.writeMicroseconds(1700);
        motorRight.writeMicroseconds(1300);
      }
      else
      {
        motorLeft.writeMicroseconds(signal + heading*1.5);
        motorRight.writeMicroseconds(signal - heading*1.5);
      }
    }
```

In the half proportional controller, it is modified such that the motors will never go backwards, and only one motor changes at a time. This has less of a chance of roll:

```
void Controls()
{
  MagnetReading();

  if (Dir == 0)
  {
    if (heading > 15 && heading < 180)
    {
      if(heading > 60)
      {
        motorLeft.writeMicroseconds(1500);
        motorRight.writeMicroseconds(1700);
      }
      else
      {
        motorLeft.writeMicroseconds(signal);
        motorRight.writeMicroseconds(signal + heading*1.5);
      }
    }
```

G.3.4 - Proposed Final Code

This contains the main loop for the proposed final code. As it is proposed, it has not been tested in a full system. Any of this is subject to change upon testing. It uses the "millis()" function as a timing parameter to run the two main control loops at once.

```
void loop() {
  millisCurrent = millis();
  mod = (millisCurrent - previousMillis)%100;//every 100ms it will check the controls
  if(mod == 0)
  {
    Controls();
  }

  if(millisCurrent - previousMillis >= timeCheck)//if AUV has passed an x-interval
  {
    Payload(); //Get Payload data
    Xcurrent = Xcurrent + xIncrement; //Increment Xcurrent

    if (xCurrent >= xTotal && yCurrent < yTotal) //if X stretch has completed
    {
      yCurrent = yCurrent + yIncrement; //Increment Ycurrent
      xCurrent = 0;
      Turning();
    }

    else if(xCurrent >= xTotal && yCurrent >= yTotal)//both X and Y are complete
    {

      dCurrent = dCurrent + dIncrement;
      yCurrent = 0;
      xCurrent = 0;
      IncreaseDepth();
    }

    else if (xCurrent >= xTotal && yCurrent >= yTotal && dCurrent >= dTotal) //Complete!
    {
      //float back up, begin recollection
    }
    previousMillis = millisCurrent;
  }
  delay(1);
}
```

Appendix H - Safety Review of the VARUNA and its Systems

Manufacturing

Risk	Mitigation
Cutting and shaping the aluminum body	High-powered machining tools can be very dangerous if not used correctly. Additionally, machined aluminum can be dangerous because of small shavings of aluminum, which can cut skin easily, and sharp corners on finished parts. Machine shop guidelines will be strictly followed to avoid the risks that machining aluminum can cause.
Vibration	Vibration from power-tools can cause health problems. Non-vibrating or low vibration tools should be used if possible. The use of gloves when operating power tools should be required, and extended use of vibrating tools should be avoided through breaks or job rotation.

Assembly

Risk	Mitigation
Wiring electrical parts	A 14.8 V battery will be connected to the on-board computers, three thrusters, several sensors, and other electronics. Wiring these electrical parts poses the risk of electrocution. To minimize this risk, electrical components will not be wired unless at least two members of the design team are present, and at least one of those members is one of the electrical engineers on the team.
Hinges and Pinch Points	Watch for any pinch points and hinges that add potential for catching loose clothing or body parts.

Test/operation

Risk	**Mitigation**
Propellers	The AUV has three propellers, two in the back and one in the front. The propellers move at high speeds and can catch onto loose clothing, hair, jewelry, or fingers. In order to mitigate this risk, warning stickers will be placed on each of the propellers, and operators will be instructed to wear short sleeves, no jewelry, and long hair pulled back. To keep hands away from the propellers as much as possible, the handles for carrying and hoisting the AUV will be located away from propellers.A warning label can also be attached to the hull.
Electrical parts running in water	The AUV has some high voltage components that must be made to ensure that no active leads are exposed when the craft is exposed in the water. To avoid any exposed leads and active wires, ensure that the pressurized vessel is sealed. A simple soap and water test to see any air leakage is recommended. ● Mix soap and water and cover possible leakage points in it. Pressurize vessel. If air bubbles form, the seal is not good.
Weight	The AUV will weigh approximately 20 pounds on land. To mitigate the risks of injury in carrying the AUV, two sets of handles will be placed on the AUV so that it can be carried easily by one person.
Loss Prevention and Identification	To prevent losing the craft to the depths, the AUV will be made to have a net upwards force, or a slightly positive buoyancy, so that when the craft is shut off and submersed it will resurface without the application of upwards thrust.
Collision Prevention and	To prevent collision between the boat of the user and the AUV or other crafts on the water, the AUV will be outfitted with a beaconing light and/or manufactured with a brightly colored outer shell.
Handling of the AUV	When handling the AUV, it is advised that the user wear thick gloves and handle the AUV solely by its handles. This prevents damage to the user and the craft.
System Heat	To prevent overheating, run the AUV only for the allotted time of the mission.

Display

Risk	Mitigation
Burning out of the thrusters	The T200 Thrusters should not be run for extended periods outside of the environment that they were made for. Any demonstration of the thruster speeds should be performed while the thruster is submerged in water. Running the T200 outside of water will damage the bearings, which are lubricated by water and running it dry increases noise and vibration.
Stability	Again, due to the shape and weight of the AUV, ensure that any display niche is relatively low to the ground - if the AUV falls, it can cause damage to the system and any onlookers.

Storage

Risk	Mitigation
Risk of corrosion of materials of the AUV - more of a long term issue.	Rinse off the outside of the AUV with fresh water before storing the unit. This will make ensure that the effects of saltwater-induced oxidation are prolonged. Note that servicing the AUV is still necessary.
Weight of the AUV and proper storage - ensure the product will not fall.	Store the AUV in a structured manner - ensure the stability of the AUV.

Disposal

<table>
<tr><th>Risk</th><th>Mitigation</th></tr>
<tr><td>Disposal of Lithium Polymer (LiPo) batteries [12]</td><td>Due to the possibility of the battery still holding a charge even after it has been damaged or has died, it is important to ensure that the battery is completely empty - i.e. when testing it the voltage reading should be at 0 V. To do this the following steps are taken:
Discharge method
Discharge battery using the XT90 discharge plug.
Cut the discharge lead and twist the voltage and ground wires together
Take the discharged battery to a local battery recycling facility
Saltwater method:
Get a plastic container which you can afford to throw away and fill it with cold water.
Mix it with salt and make sure it’s dissolved completely. Experiments have shown that using 30g per liter of water gives a good result.
Put the battery in the salty water and leave it somewhere fireproof for two weeks. Depending how much charge it had originally, you might want to leave it longer.
Finally, wrap the battery with paper and it’s ready to be thrown away.</td></tr>
<tr><td>Disposal of polyurethane foam [13] [14]</td><td>Safe disposal of this foam is imperative:
Any kind of thermal disposal can produce toxic nitrous compounds
All polyurethane products contain di-isocyanates, which can be harmful when machined particles make contact with the skin or eyes</td></tr>
<tr><td>Disposal of ballast [15]</td><td>The ballast used in this product will be made of lead - lead is a material that is known to cause many health hazards. Proper handling/disposal of it is recommended. Lead is volatile to human life and the environment -</td></tr>
</table>

	great care must be taken in its disposal.

The Risks of Boating and Boat Safety

Users running a mission and/or testing with The VARUNA may need to utilize a boat if it is necessary to deploy The VARUNA in deeper waters. Boating can be very dangerous even without the presence of an AUV. If the team deploying the craft must use a boat to perform their experiments, knowing the dangers of boating and how to prevent accidents is as essential as the experiment itself.

Any time that a person uses a boat, the individual should ensure that there are enough life vests for every member on the vessel. This provides an extra measure of safety in the case of an incident where the passengers must swim to shore. Life vests should not be worn within the cabin of the vessel to prevent the possibility of becoming trapped in the event that the boat capsizes or sinks. All boats should also be equipped with a flare gun that is still certified and operable. It is also important to have a working onboard radio with ship-to-shore and ship-to-ship capabilities.

The table on the following page was retrieved from the California's Division of Boating and Waterways. It includes a non-exhaustive list of precautions. This table does not contain all boating safety procedures, but all passengers and the captain of the vessel should be aware of these basic safety measures. It should also be noted that much of the boating regulations are dependent on the size of the boating vessel.

Battery Handling

The batteries used for The VARUNA are 22.2 [V], 20 [Ah] Lithium Polymer batteries. It is important to look at the safety data sheet that accompanies the battery. The following list contains the important information to keep in mind when operating the AUV and charging the battery afterwards.

Safety and Handling

- Always monitor the battery and charger during the entire charging process
- Always charge and discharge LiPo batteries in a fireproof location, which could be a container made of metal (such as an ammunition box), ceramic tile, or a bucket of sand
- Never charge or discharge a LiPo battery while it's inside the model. A hot pack could ignite wood, foam, plastic, etc.
- Never continue to charge LiPo batteries if the charger fails to recognize full charge. Overheating or swelling of the LiPo cells is an indication that a problem exists, and the batteries should be disconnected from the charger immediately and placed in a fireproof location
- Never leave the battery unattended while it charges

For a more exhaustive list of handling recommendations, see a Safety Data Sheet for Lithium Polymer batteries.

For Crafts between 16 and 26 feet [16]

Life Vests	All motorboats, regardless of length, must carry a U.S. Coast Guard-approved life jacket in serviceable condition and of a type and size appropriate for the intended wearer, the conditions and the boating activity. The life jackets must be within easy reach for each person on board. Under California state law, every child under 13 years of age must wear a U.S. Coast Guard-approved life jacket while the boat is underway unless the child under age 13 is in an enclosed cabin.
Fire Extinguisher	One Type B-I Coast Guard-approved fire extinguisher must be carried when no fixed fire extinguishing system is installed in machinery spaces.
BackFire Flame Arrestor	A Coast Guard-approved backfire flame arrestor is required for inboard gasoline motors that are not exposed to the atmosphere above the gunwale level.
Muffling System	An effective muffling system is required for the exhaust of each internal combustion engine. Unmodified outboards usually meet legal requirements (see page 37).
Ventilation	All motorboats or motor vessels, except open boats made after 1940 and using gasoline as a fuel must have at least two ventilator ducts fitted with cowls or their equivalent for the efficient removal of explosive or flammable gases from all engine and fuel tank compartment bilges Boats built after July 31, 1990, that have a gasoline engine for electrical generation, mechanical power or propulsion must be equipped with an operable ventilation system.
Sound Signaling Devices	A vessel of less than 39 feet 4 inches (12 meters) must be able to provide a means of making an efficient sound signal but is not required to carry a whistle or bell.
Visual Distress Signals	All boats 16 feet or more in length must carry devices aboard at all times. Boaters must carry at least one of the following devices that are suitable for day or night use: ● Hand red Flare, distress signals ● Floating orange smoke distress signals (day) ● Pistol projected parachute red flare distress signals

	• Hand-held rocket-propelled parachute red • Handheld orange smoke distress signals (day only) • Distress signal for boats, red aerial pyrotechnic flare • Orange flag (day) • Electric distress light for boat (night)
Navigation Lights	Navigation lights must be kept in serviceable condition and displayed between sunset and sunrise and at times of restricted visibility. If practicable, a sailing vessel may exhibit sidelights and a stern light or lighted lantern showing a white light, which must be exhibited in sufficient time to prevent collision.

Appendix I - Ethical Considerations

I.1 - Ethical Justification of our Project

Only 5% of the world's oceans have been explored by humans. Ocean health is a large signifier of the effects our environment is experiencing due to climate change. The collection of more volumetric data about unexplored areas of the ocean will only benefit our development as a society. For example, a discovery of previously untapped resources could potentially bring advancements to the medical field or an encounter with an unidentified organism could offer inspiration for new survival techniques. These possibilities are the principal motivations for our senior design project. We aim to contribute an AUV to the efforts of marine scientists in their quest to explore our oceans.

Our vehicle will be designed to accommodate various sensor payloads, making it able to meet the specific needs of each user. We aim to provide increased capabilities to scientists that may not otherwise have affordable, user-friendly options. The AUV will not be limited to ocean research applications, making it available for research of local inland bodies of water, such as Lake Tahoe. Our team has been in contact with geologists that are interested in using our project to explore the path of fault lines below the water's surface. We believe that developing a tool for scientific research of both local and far-away underwater environments will contribute to the common good of our society. We place value in responsibly exploring and managing earth's limited resources.

I.2 - Ethical Engineering Choices

A professional engineering team has many ethical responsibilities to consider when completing a project. The technical competence of the engineering decisions is crucial to the success of the project, both structurally and ethically. If a project is built upon invalid assumptions and incorrect calculations the product may behave unpredictably, increasing risk for the users and the surrounding environment. In the case of our project, the sound design of the physical vehicle is important for reducing the likelihood of electronic components interacting with the marine environment in which it will be submerged. The safety of the user is also a major aspect of the design. In this regard, our team must practice empathy, putting ourselves in the position of the user and anticipating their experience of our product. Providing features that will make the deployment and collection of our tool possible for a small team of non-engineers is critical.

An ethical engineer is also responsible for looking beyond the immediate implications of a product's development and use. Adopting a "big picture" view of the project's creation involves life cycle analysis and interrogation of possible social impacts. A life cycle analysis involves investigation of a product in every stage of its existence: seeking resources of ethically sound origins, efficient use of resources during its use, and environmentally and socially conscious disposal of its parts at the end of its life. Sustainable design choices mean more than responsible consumption of limited resources, it also strives to leave minimal negative impact once the product becomes unusable. Possible social impacts are also present in a life cycle analysis. It is important to consider where any potential waste may be directed and what implications it will have for that surrounding community. The most vulnerable populations must be protected at every stage of the product's life.

Our design will employ high efficiency brushless thrusters in an effort to maximize battery life and reduce our consumption of power. In order to safely dispose of the electronic components of our robot, it is important for us to design a vehicle that will be retrievable after every deployment. We want to minimize the introduction of harmful waste into the ocean or lake that is being studied, so the mechanical integrity of the structure is imperative. The current realities of electronic waste and recycling are troubling and tend to target vulnerable communities outside of the United States, so maximizing the life of our electronic components is also of interest from the social justice perspective.

I.3 - Ethical Pitfalls and Risks

As discussed previously, the failure of our project can result in the loss of our vehicle during an operation. The main points of weakness in our design are a catastrophic leak and a loss or surge of power. If our design isn't watertight, leaks could cause the electronics inside to be destroyed, meaning we would have to replace all the devices or build a new vehicle. Environmental risks such as kelp or native obstacles can clog and stop the thrusters, which would cause a spike in current that could damage the thruster and other components.

The consequences of most failures would most likely be the loss of our vehicle. If something smaller scale was to go wrong, such as programming or electrical issues, the vehicle is positively buoyant, so the vehicle will float up and be retrieved and fixed. This possibility isn't as catastrophic as a leak, as the problem can easily be fixed or replaced.

During development, we will be running the vehicle in a clear pool of water with no environmental obstacles, so the main risk involved with that would be water leakage and electrical and programming issues. Operators must also practice the utmost caution when entering the water at the same time as the vehicle, because placing powered electronics in the water can always pose potential danger. In order to mitigate any physical risk for the user, our team will provide a clear operation manual with guidelines for safe practices.

Another risk is the vehicle's effect on the environment. Ideally, we want to minimize our impact, but that isn't always possible. The vehicle could possibly disrupt animals and inhabitants of the area of study. In order to minimize this, the vehicle will be retrievable after every mission, meaning there is no physical waste that remains in the environment, and the missions will only run for a maximum of 10 hours, meaning that our impact on the area of study is minimized as much as possible.

Appendix J - Project Timeline

AUV Team!				Winter Break			
Week:				12/11-12/17	12/18-12/24	12/25-12/31	1/1-1/7
	to do						
	in progress						
	complete						
Tasks:			**Lead:**				
Fully Dimensioned CAD Model			Maddie				End of week
	External Shape						
	Internal Setup						
Fully Dimensioned CFD Model			Anthony				End of week
	3 Thrusters & Fixed Wing						
		Roll					
		Thrust					
Motor Control Program Outline			Erin				End of week
	Interpret Sensor Data						
	Horizontal Control						
	Vertical Control						
	Forward Control						
	Roll Control						
Complete Battery Selection			Shae				
	Figure out PWM vs Power		Shae				End of week
	Thruster test --> speed vs power		Shae				End of week
	CFD analysis --> power vs thruste		Anthony				End of week
Mass/Volume Layout			Maddie				End of week
Benchtop Electronic Setup			Shae				End of week
have	Battery	6 cell 22.2 C V LiPo for testing					
have	Arduino						
have	T200						
have	IMU/Magnetometer						
have	UBEC						
need	Fuse						
have	Pressure Sensor						
have	Zigbee						
have	GPS						

Electronic Board Layout		Shae				End of week
Physical Prototype Model		MECHs				
	Bottle & Endcap Calcs (Order End			Due by 12/18		
	Run buying from Blue Robotics pressure vessels by Dr. Kitts	Anthony				
	Waterproof connectors & penetrati	Tyler				End of week
	Chassis & Foam Research	Maddie				End of week
	Epoxy & Potting Research	Tyler				End of week
	Wing Connection	Tyler				End of week
	Ballasting	Maddie				End of week
	Connecting Thrusters	Maddie				End of week
	Machining & Tolerances	Anthony				End of week
		All				
Detailed, Fully dimensioned mechanical drawings		All				
Get necessary parts machined (@SCU)		All				
Get MBARI Machined parts		All				
	Build/Assemble	All				
Proof of Concept Testing		All				
	Turning Radius Test	All				
	Navigation Control Test	All				
	Depth Control Test	All				
	Testing for sensor data in Tahoe	All				
Optimization and Finalization						
SD Conference Registration Due (2/2/18)						
Senior Design Conference (5/10/18)		ALL				
Senior Design Thesis		ALL				

AUV Team!			Winter Quarter 2018						
Week:			Week 1 1/8-1/14	Week 2 1/15-1/21	Week 3 1/22-1/28	Week 4 1/29-2/4	Week 5 2/5-2/11	Week 6 2/12-2/18	Week 7 2/19-2/25
	Connecting Thrusters	Maddie							
	Machining & Tolerances	Anthony							
		All							
Detailed, Fully dimensioned mechanical drawings		All							
Get necessary parts machined (@SCU)		All							
Get MBARI Machined parts		All							
	Build/Assemble	All							
Proof of Concept Testing		All							
	Turning Radius Test	All							
	Navigation Control Test	All							
	Depth Control Test	All							
	Testing for sensor data in Tahoe	All							
Optimization and Finalization									
SD Conference Registration Due (2/2/18)									
Senior Design Conference (5/10/18)		ALL							
Senior Design Thesis		ALL							

AUV Team!			/inter Quarter 2018						Spring Break	
Week:			Week 6 2/12-2/18	Week 7 2/19-2/25	Week 8 2/26-3/4	Week 9 3/5-3/11	Week 10 3/12-3/18	Finals 3/19-3/25	Spring Break 3/26-4/1	Week 1 4/2-4/8
	Machining & Tolerances	Anthony								
		All								
Detailed, Fully dimensioned mechanical drawings		All								
Get necessary parts machined (@SCU)		All								
Get MBARI Machined parts		All								
	Build/Assemble	All								
Proof of Concept Testing		All								
	Turning Radius Test	All								
	Navigation Control Test	All								
	Depth Control Test	All								
	Testing for sensor data in Tahoe	All								
Optimization and Finalization										
SD Conference Registration Due (2/2/18)										
Senior Design Conference (5/10/18)		ALL								
Senior Design Thesis		ALL								

Week:				Winter Finals 3/19-3/24	Spring Break 3/25-3/30	Week 1 4/2-4/8	Week 2 4/9-4/15	Week 3 4/16-4/22	Week 4 4/23-4/29	W 4
	to do									
	in progress									
	complete									
Task:			Lead:							
VARUNA Water Test										
	EEs:									
	Fuses for thrusters		Shae							
	Temperature sensor		Erin							
	Controls Sheild		Shae							
		GPS pins								
		Piezzo pins								
		Pressure pins								
		change A <-> A pins								
		data logger pins								
	Male SC for Controls		Shae							
		6 male bullets								
		1 Molex crimp								
	Female SC for Sensor		Shae							
		3 female bullets								
		2 Molex crimps								
	Change thruster cable length		Shae							
	Switch to Arduino (servo -> molex)		Shae							
	Programming Port SCs									
		female SC -> 4pin molex								
		USB -> 4pin molex								
		male SC -> 4pin molex								
		USBA -> 4pin molex								

				Winter Finals	Spring	Week 1	Week 2 4/9-	Week 3	Week 4	Week 5	Week 6 5/7-	Week 7	W
	Controls wiring												
		switch -> battery											
		switch -> DC/DC & SC											
		Change common power/gnd to 16 AWG wire											
		shorten pressure sensor/move arduino?											
		shorter fuse holders?											
		cover all exposed metal											
	re-do programming port SCs												
	Bench test of whole set-up		All										
	MEs:												
	Control electronics shelf												
	Nuts for Male SC		Tyler										
	Machine exoskeleton		Tyler										
	Buoyancy and Weighting		Maddie										
	Potting		Maddie										
		All things											
		Test pressure sensor											
		new programming port SC											
		new vertical thruster cable											
	Lateral thruster brace		Tyler										
	Vertical thruster brace		Tyler										
	Nose cone machining decision		Anthony										
		drawings											

Week:				Winter Finals 3/19-3/24	Spring Break 3/25-3/30	Week 1 4/2-4/8	Week 2 4/9-4/15	Week 3 4/16-4/22	Week 4 4/23-4/29	Week 5 4/30-5/6	Week 6 5/7-5/13	Week 7 5/14-5/20	Week 8 5/21-5/27	Week 9 5/28-6/3
		drawings												
Fully functional VARUNA	EEs:													
	GPS sensor		Erin											
	Order conductivity sensor		Shae											
	Data logger		Erin											
	Arduino <-> Arduino comm		Erin											
	Control system		Erin											
	Payload Bottle electronics		Shae											
		SC -> DC/DC												
		SC -> Arduino TX/RX												
	Payload shield													
		Conductivity sensor												
		Data logger												
		Temp sensor												
		A <-> A												
	Electromagnetic kill switch													
	MEs:													
	IMU platform (?)		Maddie											
	Nose Cones		All											
	Powder coating		Tyler											
	Testing locations		Anthony											
Open Water Testing														
	Depth Control													
	Compass Control													
	Find Location													
	Handle													
	Tether													

Week:				Week 4 4/23-4/29	Week 5 4/30-5/6	Week 6 5/7-5/13	Week 7 5/14-5/20	Week 8 5/21-5/27	Week 9 5/28-6/3	Week 10 6/4-6/10	Spring Finals
Improvement and Optimization											
Senior Design Conference											
	Power Point Presentation										
		Matlab plots of temp & conductivity data									
		Full CAD assembly									
End of Quarter Demo											
Write the Thesis											

Appendix K - Budget Spreadsheet

Table K-1: Budget

Component	Link	Price ($)	Quantity	Total	Current Inventory
T200 Thrusters	Blue Robotics	$194.00	3	$582.00	3
4" Watertight Enclosures	Blue Robotics	$40.64	3	$121.92	-
O-Ring Flange	Blue Robotics	$29.00	6	$174.00	
End Caps	N/A	DONATED	6	DONATED	
Vents/Plugs	Blue Robotics	$8.00	3	$24.00	
Red Connectors	Blue Robotics	$4.00	5	$20.00	
Red Plugs	Blue Robotics	$4.00	2	$8.00	
Black Connectors	Blue Robotics	$5.00	1	$5.00	
Adjustable Connectors	MBARI	DONATED	3	DONATED	
SubConn Connectors	RSL	DONATED	3	DONATED	
Switch	Blue Robotics	$14.00	2	$28.00	
Arduino Mega	adafruit	$35.00	2	$70.00	3
Electronic Speed Controller (ESC)	Blue Robotics	$25.00	3	$75.00	2
Multistar High Capacity LiPo pack (14.8V, 10Ah)	HobbyKing	$40.87	3	$122.61	-
IMU/Magnetometer	adafruit	$30.49	1	$30.49	1
Pressure Sensor	Amazon	$17.98	2	$35.96	2
GPS Sensor	SparkFun	$39.96	1	$39.96	1
Data Logger	SparkFun	$14.95	2	$29.90	ordered 1/23 (2)
Conductivity Sensor	MBARI	DONATED	1	DONATED	-
Temperature Sensor	Blue Robotics	$56.00	1	$56.00	-
UBEC (12V DC/DC Conv)	HobbyKing	$8.63	2	$17.26	2
Sheet Metal Ribs	Home Depot	$54.36	1	$54.36	
Hose Clamps	Home Depot	$3.21	8	$25.68	

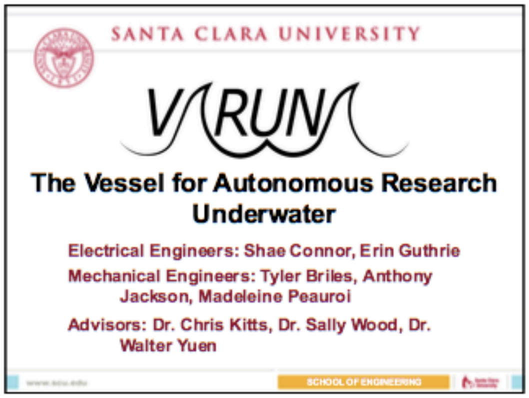
Nose Cone	MBARI	DONATED	1	DONATED	
Tail Cone	MBARI	DONATED	1	DONATED	
Handles	Home Depot	$1.77	2	$3.54	
TOTAL	**--**	**--**	**--**	**$1,523.68**	

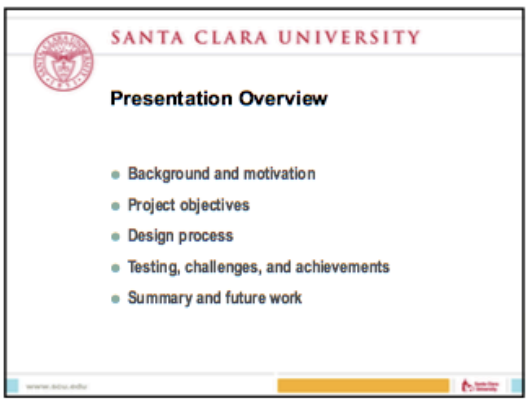
Appendix L - Product Design Specifications

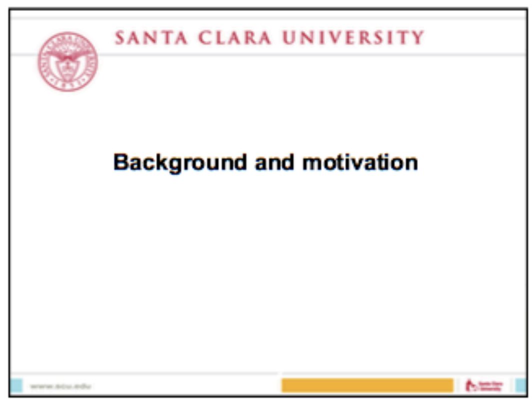
Table L-1: Product Design Specifications

Element/Requirements	Parameters		
	Units of Datum	Datum	Target/Range
Length	Feet	4.0	3 to 4
Diameter	Inches	12.0	7.5 to 9.5
Depth	Feet	300.0	100 to 300
Endurance	Hours	4	3 to 4
Velocity Range	ft/s (knots)	5(3.0)	8.5(5)
Navigation(GPS Sensor)	USD	49.95(x2)	99.90
Processor (Arduino)	USD	35.00	35.00
Data Exporting	bits(Hz) (Hz-frequency res)	12.0 at 1.0	12.0 at 1.0
Environment	--	Clean Water	Salt Water/Ocean

Appendix M – Senior Design Conference Slides







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Similar products

REMUS 100

MBARI Dorado class AUV

Bluefin Sandshark

Sparus II

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Similar products

Product Name	REMUS 100	MBARI Dorado	Bluefin Sandshark	Sparus II
Length and diameter	L = 1.7 m D = 0.19 m	L = 2.4 – 6.4 m D = 0.53 m	L = 1.1 – 2 m D = 0.124 m	L = 1.6 m D = 0.23 m
Mass	36 kg	475 kg	5 kg	50 kg
Depth rating	100 m	6000 m	200 m	200 m
Payloads	Configurable	Imaging, mapping, water sampling	Configurable	Configurable
Cost	$$$	$$$$	$$	$$$$

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Project objectives

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Mission

To build the foundation of an autonomous marine robot capable of scanning volumes of water not always accessible by ROVs, as the beginning of a multi-year project that will be carried on in the RSL

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Criteria

• Scans volumes up to 100 m deep	First AUV for the RSL to complete this kind of mission
• Less than 25 kg (~50 lbs)	Easily deployable by 2 people
• Modular and configurable	Can be carried on by future students in the RSL
• Less than $2500	Accessible to organizations with less funding

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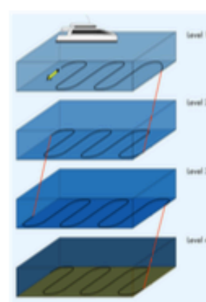
Mission profile

- User inputs:
  - Volume of water to be scanned (x, y, and z lengths)
  - Depth increments
  - Data resolution

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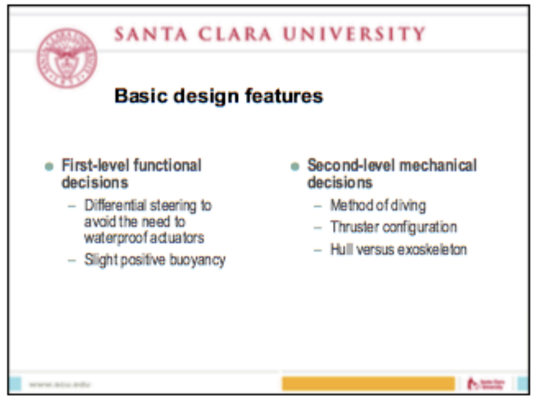
Design process
Overview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Basic design features
First-level functional decisions
– Differential steering to avoid the need to waterproof actuators
– Slight positive buoyancy
Second-level mechanical decisions
– Method of diving
– Thruster configuration
– Hull versus exoskeleton


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Design ideas
Body


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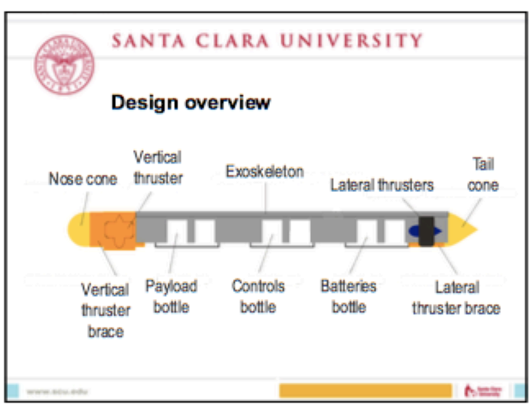
Design decisions
Diving
Thrusters
Body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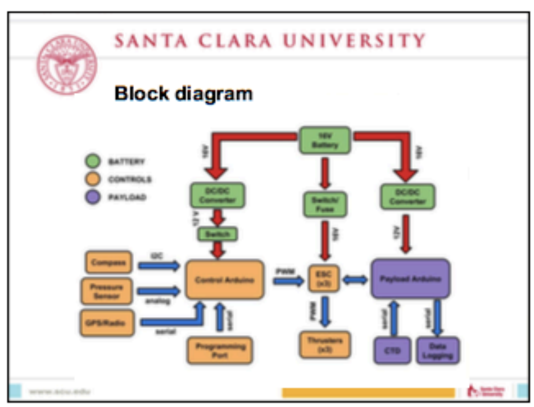
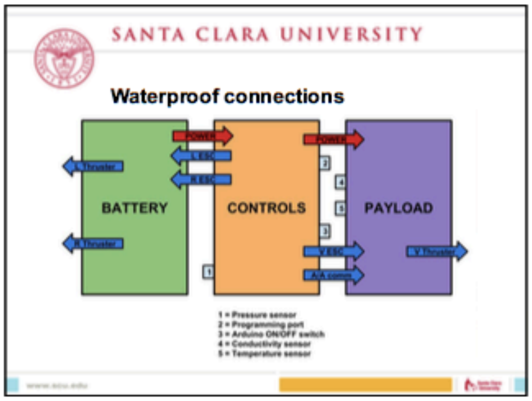
Design overview
Nose cone
Vertical thruster
Exoskeleton
Lateral thrusters
Tail cone
Vertical thruster brace
Payload bottle
Controls bottle
Batteries bottle
Lateral thruster brace


SANTA CLARA UNIVERSITY
Block diagram
BATTERY
CONTROLS
PAYLOAD
16V Battery
DC/DC Converter
Switch/ Fuse
DC/DC Converter
Switch
Compass
Pressure Sensor
GPS/Radio
Control Arduino
ESC (x3)
Payload Arduino
Programming Port
Thrusters (x3)
CTD
Data Logging
I2C
analog
serial
PWM
16V
12V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Waterproof connections
BATTERY
CONTROLS
PAYLOAD
POWER
1 = Pressure sensor
2 = Programming port
3 = Arduino ON/OFF switch
4 = Conductivity sensor
5 = Temperature sensor


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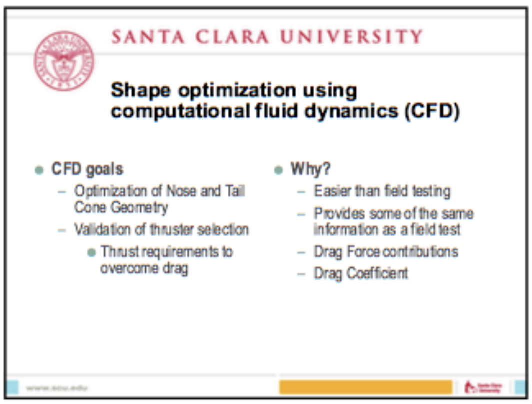
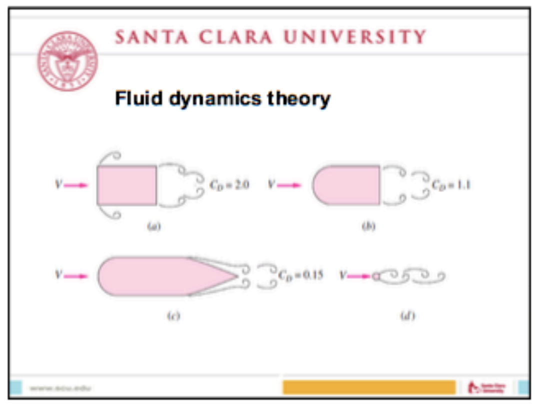
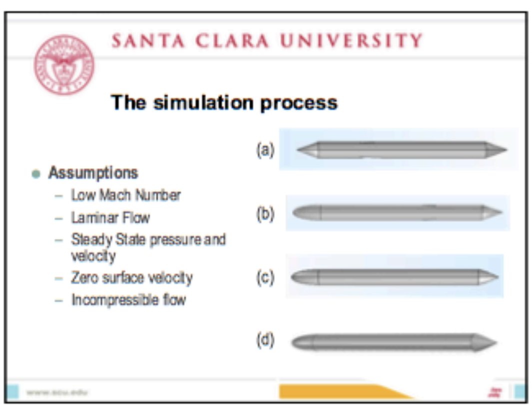
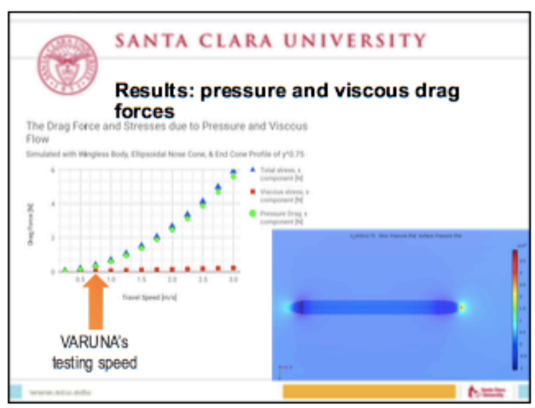
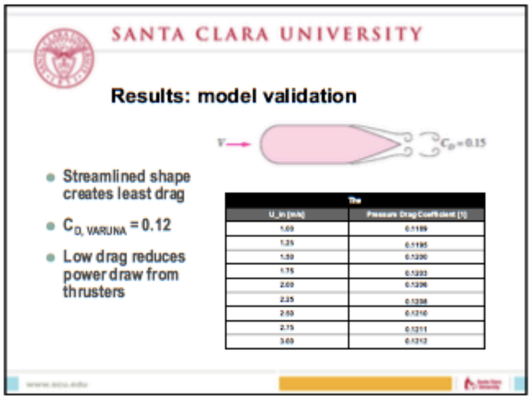
Design process
Structure


SANTA CLARA UNIVERSITY
Shape optimization using computational fluid dynamics (CFD)
CFD goals
– Optimization of Nose and Tail Cone Geometry
– Validation of thruster selection
Thrust requirements to overcome drag
Why?
– Easier than field testing
– Provides some of the same information as a field test
– Drag Force contributions
– Drag Coefficient


SANTA CLARA UNIVERSITY
Fluid dynamics theory
$C_D = 2.0$
$C_D = 1.1$
$C_D = 0.15$
(a)
(b)
(c)
(d)


SANTA CLARA UNIVERSITY
The simulation process
Assumptions
– Low Mach Number
– Laminar Flow
– Steady State pressure and velocity
– Zero surface velocity
– Incompressible flow
(a)
(b)
(c)
(d)


SANTA CLARA UNIVERSITY
Results: pressure and viscous drag forces
The Drag Force and Stresses due to Pressure and Viscous Flow
VARUNA's testing speed



The	
U_in [m/s]	Pressure Drag Coefficient [1]
1.00	0.1189
1.25	0.1195
1.50	0.1200
1.75	0.1203
2.00	0.1206
2.25	0.1208
2.50	0.1210
2.75	0.1211
3.00	0.1212

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Design process

Power

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Electrical characteristics

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Operation profile

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Battery selection

Standard	Power (W)	Qty	Total Power (W)
T200 Thruster	80	3	240
Arduino Uno	0.18	2	0.35
Pressure Sensor	0.00	1	0
Compass	0.08	1	0.084
GPS	0.22	1	0.224
DCtoDC conv	15.00	2	30
Data Logger	0.03	2	0.06
ESC	0	3	
		total	270.72
		Watt-hours	135.36
		Amp-hours	8.48

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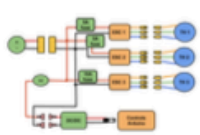
Battery selection and power connections



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Design process

Controls

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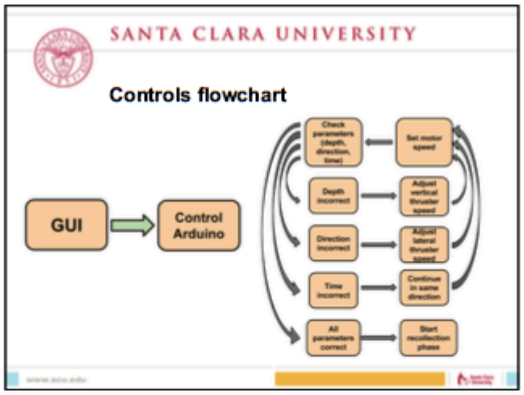
SANTA CLARA UNIVERSITY
Controls flowchart
GUI
Control Arduino
Check parameters (depth, direction, time)
Set motor speed
Depth incorrect
Adjust vertical thruster speed
Direction incorrect
Adjust lateral thruster speed
Time incorrect
Continue in same direction
All parameters correct
Start recollection phase


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GUI
Parameters For Volumetric Data
Communication Setup
Available Com Ports
Refresh Com Ports
Connect
Disconnect
Baud Rate: 9600
Data Bits: 8
Parity: NONE
Stop Bits: 1
Flow Control: NONE
Parameter Specification
X-Distance(m)
Y-Distance(m)
Total Depth(m)
X-Increments(m)
Y-Increments(m)
Depth Increments(m)
Saltwater
Freshwater
Send Data


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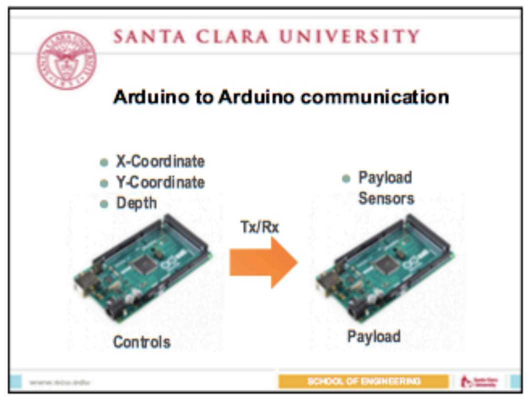
Design process
Payload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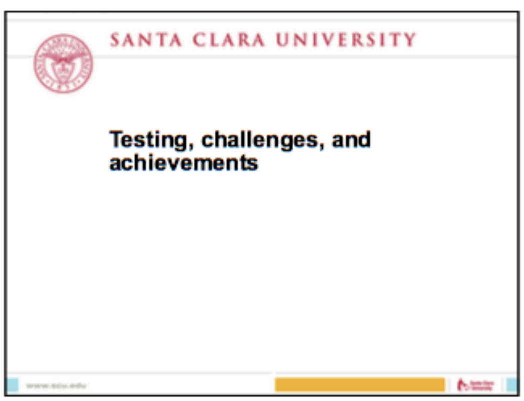
Arduino to Arduino communication
X-Coordinate
Y-Coordinate
Depth
Tx/Rx
Payload Sensors
Controls
Payload
SCHOOL OF ENGINEERING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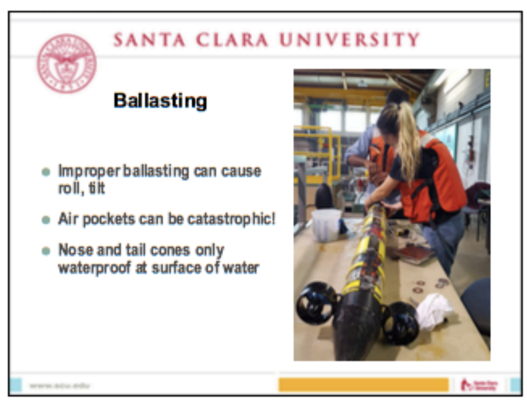
Testing, challenges, and achievements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Ballasting
Improper ballasting can cause roll, tilt
Air pockets can be catastrophic!
Nose and tail cones only waterproof at surface of water

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Heading test (with prototype)

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Heading data verification (with the VARUNA)

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Diving verification (with the VARUNA)

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Summary and future work

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What we've accomplished

- Scans volumes up to 100 m deep
- Less than 25 kg (~50 lbs)
- Modular and configurable
- Less than $2500

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Before we leave

- Reevaluate nose and tail cones
- Refine heading and depth control
- Test diving capabilities up to 100 m
- Install kill switch
- Isolate roll contributors
- Payload Arduino and temperature data

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For future groups

- Wings and/or keel
- More developed control system
- IMU stabilization
- Leak sensors
- GPS checks in long missions
- Return to drop-off location

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Acknowledgements

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Appendix

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Battery Selection Matrix

	Lithium Polymer	Lead Acid	Nickel Metal Hydride
Cost	🟢	🟢	🟠
Weight	🟢	🔴	🟠
Energy Density	🟢	🔴	🟠
Stability	🔴	🟠	🟠
Safety	🔴	🟠	🟢

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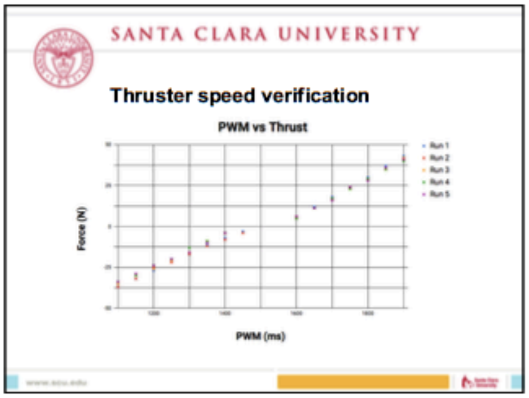
Mass spreadsheet

Item	Dry Mass (kg)	Weight (N)	Displ (m^3)	B (N)	Density (kg/m3)	B - W (N)
Nose cone	[illegible]	[illegible]	[illegible]	[illegible]		[illegible]
Tail cone	[illegible]	[illegible]	[illegible]	[illegible]		[illegible]
Battery bottle	[illegible]	[illegible]	[illegible]	[illegible]		[illegible]
Controls bottle	[illegible]	[illegible]	[illegible]	[illegible]		[illegible]
Payload bottle	[illegible]	[illegible]	[illegible]	[illegible]		[illegible]
Vertical thruster	[illegible]	[illegible]		[illegible]		[illegible]
Vertical thruster brace	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Left thruster	[illegible]	[illegible]		[illegible]		[illegible]
Right thruster	[illegible]	[illegible]		[illegible]		[illegible]
Lateral thruster brace	[illegible]	[illegible]	[illegible]	[illegible]		[illegible]
Total weight and buoyancy						
Total x_cg and x_cb						

Item	x_cg (m)	x_cb (m)	Qty	W total	B total	B - W total	W x-mom	B x-mom
Nose cone	[illegible]	[illegible]	1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Tail cone	[illegible]	[illegible]	1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Battery bottle	[illegible]	[illegible]	1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Controls bottle	[illegible]	[illegible]	1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Payload bottle	[illegible]	[illegible]	1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Vertical thruster	[illegible]	[illegible]	1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Vertical thruster brace	[illegible]	[illegible]	1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Left thruster	[illegible]	[illegible]	1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Right thruster	[illegible]	[illegible]	1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Lateral thruster brace	[illegible]	[illegible]	1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Total weight and buoyancy				[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Total x_cg and x_cb							[illegible]	[illegible]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Thruster speed verification
PWM vs Thrust
Run 1
Run 2
Run 3
Run 4
Run 5
Force (N)
PWM (ms)


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