University of Southern Queensland

Faculty of Health, Engineering and Sciences

miniROV

A dissertation submitted by

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In fulfilment of the requirements of

Bachelor of Engineering

Major in Mechatronics

October 2014

ABSTRACT

ROVs (Remotely Operable underwater Vehicle) are versatile vehicles used to get into hard-to-reach and/or dangerous marine environments. Current ROVs are expensive and require either a hardwire tether to the operator(s) or expensive acoustic communication methods, both limiting the distance an operator (usually more than one) is from the ROV. Given that underwater diving is a very dangerous profession, making up 27% of Australia’s ocean and harbour deaths prior 2012/2013, there is an obvious need for an affordable ROV which is wirelessly controllable by a single operator in a location remote from the ROV, and which is capable of verbal and visual communication with divers, in particular marine archaeologists.

In determining if such a ROV is possible, a comprehensive study of existing ROVs, communication techniques, components/elements available, and costings were examined.

From this a system model of a buoy buddy system was developed. There are three main elements to this model: a buoy, a ROV, and the operator. The buoy is hardwire tethered to the ROV. The operator is then able to wirelessly communicate with the buoy through traditional IP networks (i.e. GSM or WiFi networks).

It was concluded that the system model would be economically and physically feasible. Further work is required to ascertain if this system model derived will become a reality.

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CERTIFICATION OF DISSERTATION

I certify that the ideas, designs and experimental work, results, analyses and conclusions set out in this dissertation are entirely my own effort, except where otherwise indicated and acknowledged.

I further certify that the work is original and has not been previously submitted for assessment in any other course or institution, except where specifically stated.

M. Robe

0061004798

ACKNOWLEDGEMENTS

Firstly, I would like to thank my parents and brothers for their endless support and encouragement. They are the foundation of who I am today.

I would also like to thank my supervisor, Dr Andrew Maxwell, and my long-time friend Mr Andrew Bolous, for their guidance and contributions.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF APPENDICES

NOMENCLATURE AND ACRONYMS

The following abbreviations have been used throughout the text and bibliography: -

ROV	Remotely Operated/Operable underwater Vehicle
AUV	Autonomous Underwater Vehicle
SCUBA	Self-Contained Underwater Breathing Apparatus
CM	Centre of Mass
CB	Centre of Buoyancy
HD	High Definition
SD	Standard Definition
TMS	Tether Management System
AGE	Arterial Gas Embolism
DAN	Divers Alert Network
CFD	Computational Fluid Dynamics
ESC	Electronic Speed Controller
PVC	Polyvinyl Chloride
PMMA	Polymethyl Methacrylate
VBS	Variable Ballast System
LED	Light Emitting Diode
GPS	Global Positioning System
IP	Internet Protocol

LIST OF CONSTANTS & VARIABLES

$g = gravity = 9.81(ms^{-1})$

$F_D = Drag\ Force(Nm)$

$C_D = Drag\ Coefficient$

$\rho = density\ of\ liquid\ (kg/m^2)$

$v = velocity\ (ms^{-1})$

$A_p = Projected\ Area\ (m^2)$

$T = Thrust\ Force\ (Nm)$

$D_p = Diameter\ of\ Propeller\ (m)$

$\Delta v = Change\ in\ velocity\ (ms^{-1})$

$CSA = Cross\ Section\ Area\ (mm^2)$

$P = Pressure\ (MPa)$

$h_d = maximum\ depth\ of\ ROV\ (m)$

CHAPTER 1

INTRODUCTION

1.1 Outline of Study

The need for an affordable ROV (Remotely Operable underwater Vehicle) which is wirelessly controllable by a single operator in a location remote from the ROV, and which is capable of verbal and visual communication with divers, in particular marine archaeologists was identified from preliminary research detailed in Chapter 2.

Study in this area has never been undertaken by anyone at USQ.

The purpose and scope of this study is detailed in 1.4 Research Objectives.

1.2 Introduction

ROVs are versatile vehicles used to get into hard-to-reach or dangerous marine environments. There are many different versions of ROVs in the marketplace at the moment. They currently require either: a hardwired tether from the operator all the way to the ROV, or expensive acoustic communication methods to communicate between the operator (on a boat) and the ROV.

This study firstly looks at already implemented designs for industrial and hobbyist ROVs. An Autonomous Underwater Vehicle (AUV) system like the Bluefin-21 (by Bluefin Robotics) has cost tens of thousands of US dollars to produce and requires technology that small organisations cannot afford.

These designs are then assessed to see what can be improved upon to achieve wireless communication that is economically and physically viable so that an operator can manually control the ROV from remote locations.

This study will also address the need for effective verbal *and* visual communication between divers, more specifically marine archaeologists, and people above the surface of the water.

The system model will be of a ROV which is capable of giving these features to divers and operators at a reasonable cost (i.e. less than AUD $4 000).

1.3 The Problem(s)

As briefly outlined in Section 1.1, this study looks at two major problems relating to ROVs and marine archaeology;

The first problem – marine archaeologists have no method of live verbal *and* visual communication with people above the surface of the water.

The second problem – ROVs lack the ability to communicate wirelessly with an operator on land or in various other remote locations. They are also very expensive devices.

The specific effects of the second problem, and which will be addressed in Chapter 3 and Chapter 4, are;

- Complications related to wireless transmission in the air and water.
- Tether management options

1.4 Research Objectives

The research comprised of identifying the problems, trends and needs for marine archaeologists and ROVs. The main research objectives were derived from the project specification (Appendix A). They are:

- Research into previous designs of ROVs
    - Covered in Section 2.4 and 2.5
- Factors related to designing a ROV.
    - Covered in Chapter 3: METHODOLOGY and Section 4.2
- Critically evaluate the subsystems used in the previous designs of ROVs
    - Also covered in Chapter 3: METHODOLOGY. This is also critically evaluated through Chapter 4 where elements of the ROV were chosen and required critical evaluation.
- Selection of appropriate methods of navigating (controlling) ROVs
    - For this study, it is the research into a computer integrated system that is capable of controlling and receiving data from an operator and correctly conveying that data to the vehicle.

        - The innovative new wireless control system is covered in Section 4.3.
- Integration of electronic components with the mechanical.
    - This objective is referring to the integration of the components into the frame/compartments, essentially a system model.
        - This is covered in Chapter 4: SYSTEM DESIGN.

A research objective that was not previously covered in the project specifications was the investigation into marine archaeologists. The primary focus of the old specifications only involved the research into a ROV, on its own, the actual study encompasses more than that. It has extended objectives to:

- Include in the design a method of live communication with divers.
    - This is to incorporate both verbal *and* visual aids for divers.

As time permits a prototype was to be constructed and tested. A yearlong study into this field proved that manufacturing a prototype was not possible in such a short time-frame. However, a thorough investigation into a feasibility study involving a complete system design and model was done.

1.5 Conclusions

This dissertation aims to come up with an innovative system design for a wirelessly controlled ROV capable of voice and video capture.

The research is expected to result in a system model which will specify possible elements of design and components required to solve the problem outlined in 1.3.

A review of literature for this research will identify what the minimum components required for the design to be beneficial to marine archaeology.

The outcomes of this study will be used for the design and development of a ROV capable of video *and* audio capture over wireless transmission.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Chapter 2 covers the preliminary research into the areas of recreational SCUBA diving, marine archaeology, and of currently manufactured ROVs. The benefits of a ROV for marine archaeology will also be covered.

2.2 SCUBA Diving & Marine Archaeology

SCUBA diving is the act of submersing oneself completely underwater where the diver uses a self-contained underwater breathing apparatus (SCUBA). This is different from two other methods of diving, breath-hold and air pumping from the surface, as SCUBA diving allows divers to have an extended diving time over breath-hold and are not limited to the length of the tube supplied for air pumping. SCUBA divers require an air tank (for breathing), buoyancy compensators (for making the diver neutrally buoyant at any depth), a dive computer (for changing buoyancy depending on depth & air pressure in tank), dive boots & fins (for propulsion), a mask & a snorkel, double regulators (for on demand breathing), pressure and temperature gauges, and an emergency air regulator (safety in case of primary regulator failure). Optionally, pairs of divers can take ultrasound communicators which attach to their full-face masks for verbal communication.

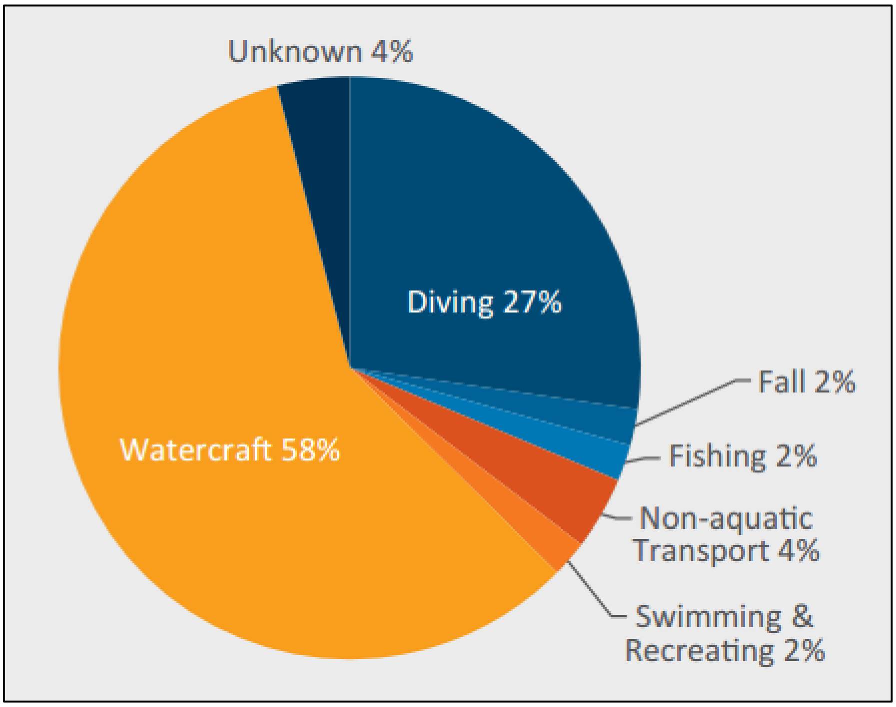


Figure 2-1: Ocean / Harbour Drowning Deaths by Activity Immediately Prior, 2012/13 (Source: Denoble, et al., 2008)

Diving, inclusive of SCUBA, snorkel and free diving, account for 27% of Australia's Ocean/Harbour deaths prior to 2012/2013 (Figure 2-1). The most common cause of death for divers is drowning. This isn't due to one singular item failing, it is better reflected as a chain of actions done by the diver that cause the death. For example, the regulator may start failing which causes the diver to panic and do an emergency ascent, leading to death. Ascending too fast, or ascending while holding breath, can cause lung expansion due to the extreme change in ratio of outside body pressure to lung pressure. The gas in the lungs has to go somewhere, including: air between the lungs (mediastinal emphysema), air underneath the skin (subcutaneous emphysema) and collapsed lung (pneumothorax). This is referred to as an arterial gas embolism (AGE) (Denoble & Douglas, 2009). AGE is the most common cause of death as it can lead to other causes, for example drowning.

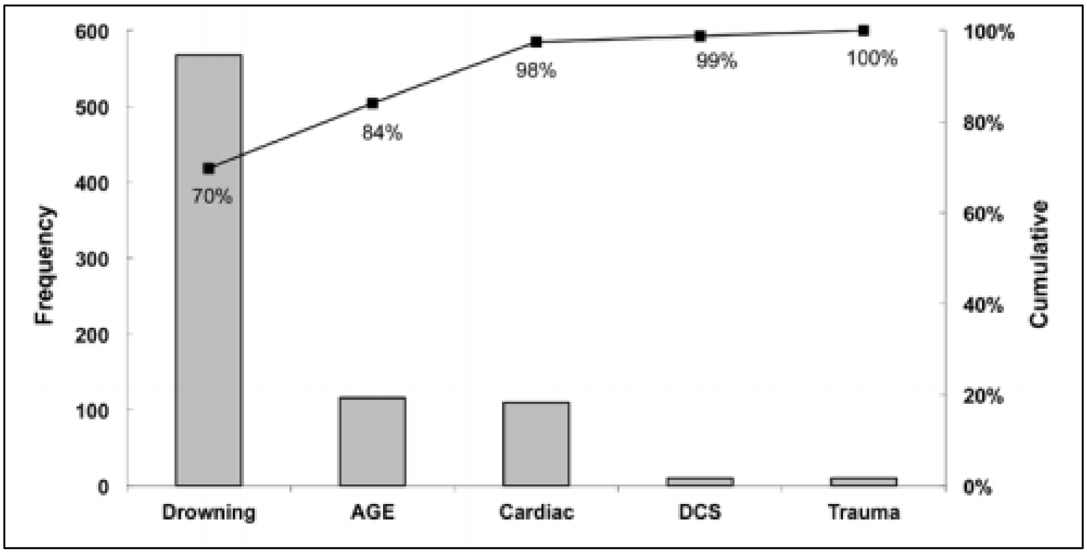


Figure 2-2: Cause of death in 814 DAN America scuba fatalities (not previously published) (Source: Denoble, et al., 2008)

The current known causes of death (triggers) pre 2008 are gas-supply problems (41%), entrapment/entanglement (19%) and equipment issues (16%). These make up 76% of the triggers. Emergency ascent (60%), insufficient breathing gas (20%) and buoyancy problems (14%) made up 94% of all causes of death (Denoble, et al., 2008). The gas-supply & equipment issues can be interrelated as triggers which cause panic, creating previously mentioned causes of death. The addition of emergency air helps remove this panic.

Marine archaeology is the application of archaeology underwater. Archaeology is the investigation of the physical remains of material cultures found through artefacts, structures, human remains or animal and plant remains. For marine archaeologists, this is often in shallow depths (no more than 100m) where they investigate ship wreaks and the oceans floor for evidence of historical events. The divers’ equipment is very similar to that of recreational SCUBA divers, however they do require delicate excavation tools and cameras.

The application of a ROV underwater with the divers would add another dimension for non-divers. A ROV could transport small payloads including diver finds and safety equipment for the divers. The ROV would also be able to stream live footage and chat with the divers.

2.3 What is a ROV?

A ROV is a Remotely Operable Underwater Vehicle. They are abbreviated to ROV to avoid confusion with remote control vehicles. Typically ROVs are operated through the use of an umbilical cord which is tethered from the controller to the vehicle. Umbilical cords are made of multiple collections of cables to send signals to and from the vehicle as well as power. This includes receiving the video feed of what the vehicle is seeing to the operator. On a large scale, umbilical cords are used to send power from the operators' location to the vehicle. The operator controls the vehicle with the use of a computer or a joystick controller from a boat (industrial) or the land (hobby).

ROVs have many different uses since they are capable of navigating into hard to reach locations. They are not restricted (like divers are) to any shallow depth, and do not have dive duration limitations that affect safety.

2.4 Types of ROVs

2.4.1 Glider

Gliders have very little mechanical movements, so they use less electricity. This allows them to travel large distances sampling water content over several days, to weeks at a time. They move by changing depth; once at the apex of the dive they sample water, then return to the surface. At the surface they transmit their data onshore, then receive orders for their next sample location. On board, gliders can be equipped with:

- sensors for sampling the water for scientific purposes
- gyroscopic compasses & accelerometers for stability & direction
- batteries for running components
- a pump for evacuating a floodable chamber

To change depth, the glider either fills a bladder with water or shifts a battery package to the tip of the vehicle. Figure 2-3 shows a glider using a small hydraulic to shift the battery pack to change the pitch. Obviously this glider wouldn't be able to rise to the surface without some assistance. To do this it empties the flooded chamber at the rear. This gives it positive buoyancy and will cause it to rise.

To change direction, it can either rotate a battery pack to change side balance, or it can use ailerons. Both actions roll the vehicle to change direction.

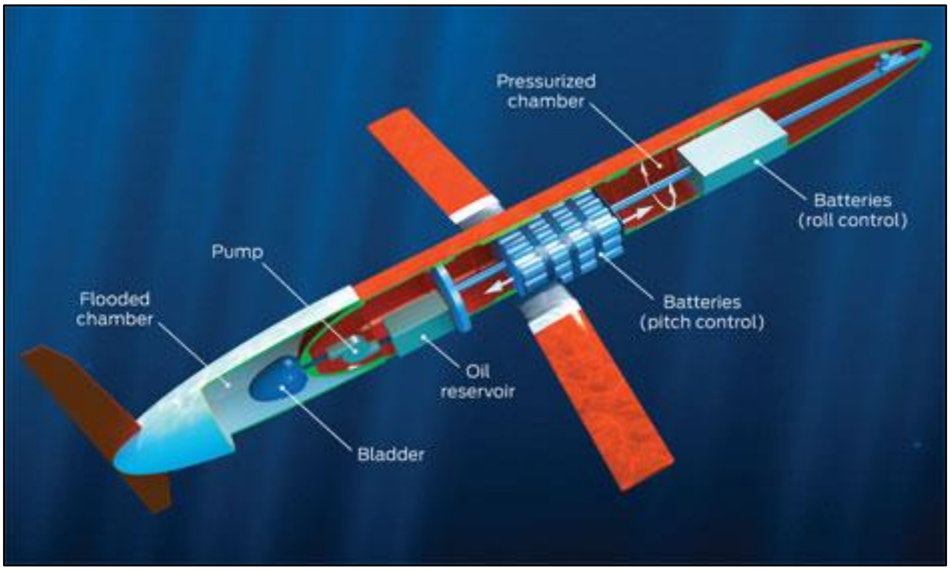


Figure 2-3: Spectrum AUV glider (Source: MacNeill, 2008)

These gliders are able to control their pitch and roll on the fly, but they are completely unable to change their yaw.

2.4.2 Robotic

In the hobbyist market, the robotic ROVs are solely used for observing underwater. When it comes to the industrial applications of these ROVs, they are designed to test and manipulate objects underwater. Robotic ROVs are the most versatile of all the underwater vehicles. This version of vehicle typically uses an organised set of 3 or 8 thrusters to control the horizontal thrust and elevation. On board, they can have different tools for manipulation, these include; grappling, welding, cutting, etc. These tools typically attach to the manipulator arm(s).

Figure 2-4: ROV Operators (Source: Kempin, 2010)

The number of operators required to control the vehicle can number 6; where 2 control the cameras, 2 control the ROVs direction and the final 2 are there to do the delicate jobs such as operating manipulator arms.

2.5 Previous Designs

2.5.1 Bluefin-21

The Bluefin-21 is an autonomous underwater vehicle (AUV) capable of carrying different payloads due to its modular design. It is outfitted with multiple sensors making it capable of highly accurate autonomous activities.

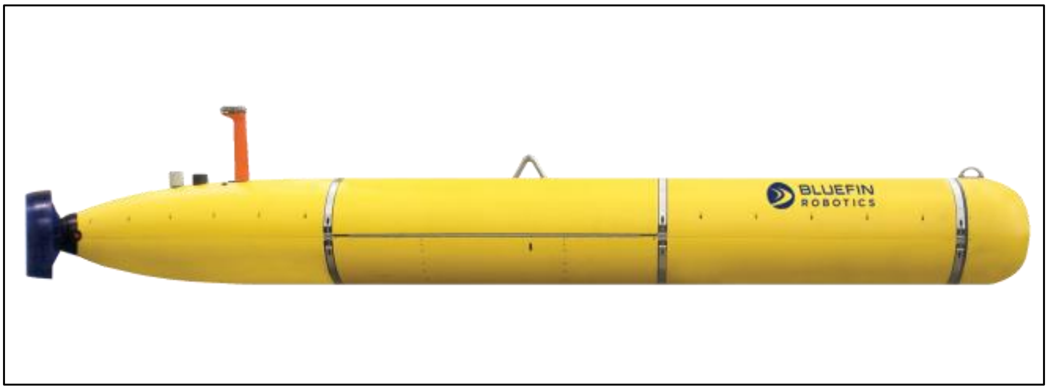


Figure 2-5: Bluefin-21 AUV (Source: BlueFin Robotics, 2014)

Even though the Bluefin-21 boasts lots of features, it comes with a large cost. It was estimated that a simple mission off the coast of Western Australia in 2014 cost over USD $1 000 000.

Table 2-1: Bluefin Specifications (BlueFin Robotics, 2014)

Depth limitation	4.5km
Weight	750kg
Cost	Over $1million USD for a mission
Maximum Speed	4.5 knots
Runtime with standard Payload	25 hours @ 3knots
Payloads	1. EdgeTech 2200-M 120/410 kHz side scan sonar (option: EdgeTech 230/850 kHz dynamically focused) 2. EdgeTech DW-216 sub-bottom profiler 3. Reson 7125 400 kHz multibeam echosounder

2.5.2 Dive Works Work Class ROV

The Work Class ROV by Dive Works is an extremely heavy ROV, deployable from large sea vessels for underwater exploration. Its design for inspection, repair and maintenance of vessels, petroleum asset inspections & subsea surveys makes this a very versatile vehicle. It features a Tether Management System (TMS) which drops down with the ROV inside of it, then once the ROV is out of it, it helps keep the tether out of the ROV's way. It is capable of operating at depths of 2km with a radius from the TMS of 200m.

Figure 2-6: DIVEworks Seaeye Leopard ROV (Source: DIVEworks, 2014)

Table 2-2: DIVEworks Seaeye Leopard Specifications (Source: DIVEworks, 2014)

Depth limitation	2.2km
Weight	3300kg
Payloads	1. Adjustable height garage to accommodate ROV tool skids 2. up to 400kg extra for tooling/skid

2.5.3 Hercules

Built for the Institute for Exploration (IFE), Hercules is capable of performing delicate tasks at a depth of 4km. Designed for study and recovering of artefacts from ancient shipwrecks, this ROV has a High Definition (HD) camera for the intricate processes. To reach the depths of 4km, Hercules goes down with its own TMS called Argus.

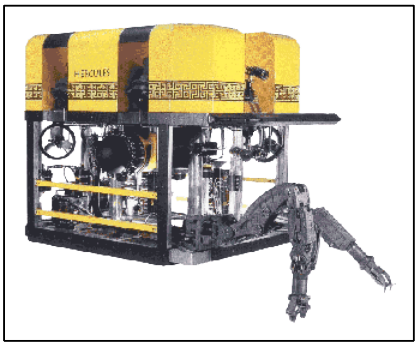


Figure 2-7: Hercules ROV by IFE (Source: NOAA, 2014)

2.5.4 Global Explorer

The Global Explorer is a portable ROV weighing approximately 13600kg able to be transported in 40ft shipping containers or it can be side loaded onto a Boeing 737. The ROV can be launched from a vessel with an A-Frame or an articulated crane. It features the ability for 3D & HD video streaming through a fibre optic. Its most significant feature is its large payload bay and manipulator arm. The manipulator arm is an Orion 7-function spatially correspondent hydraulic manipulator. This manipulator arm is capable of picking up objects, and is also outfitted with the capability to cut wire rope.

Table 2-3: Global Explorer ROV Specifications (DEEP SEA SYSTEMS International, 2014)

Depth limitation	3000m
Weight	14ton (30,000lb)
Payloads	Up to 200lb (90kg) on the bay reduced to 80lb (36kg) with the suction sampler.

2.5.5 Sea Explorer

The Sea Explorer is the most advanced glider on the market. It dives by changing its buoyancy and is capable of reaching speeds of 1 knot. It does not having moving wings or any external moving objects. This reduces the risk of entanglement on debris and makes it easier to launch. As it is an automated system, when it surfaces, it sends the GPS location the pilot then dives again with the new GPS location specified.

Figure 2-8: Sea Explorer AUV (Source: ACSA Alcen, 2014)

Table 2-4: Sea Explorer AUV Specifications (Source: ACSA Alcen, 2014)

Depth limitation	700m
Weight	59kg
Maximum Speed	1 knot
Turn radius	20m
Runtime	Up to 2 months
Payloads	Two 9L wet/dry bays

Optional Sensors	CTD (SeaBird) DO (SeaBird) Turbidity (WetLabs) Chlorophyll, CDOM, Phycobilins (WetLabs) CDOM (WetLabs) Hydrocarbon MiniFluo (ACSA) Acoustic recorder (ACSA) Acoustic positioning (ACSA) Altimeter

2.5.6 OpenROV

OpenROV is a hobby specific underwater vehicle. It is designed to be open source, meaning the coding and hardware are up to the user to change and adapt to their preference. It is not a product you simply buy and use immediately. The current system uses very little sensory input and allows for users to view what is going on through a web user interface. It operates with a BeagleBone Black (BBB) and a customised Arduino sending telemetry and power through Power over Ethernet (POE). The assembled model is only capable of video imagery to a depth of 100m.

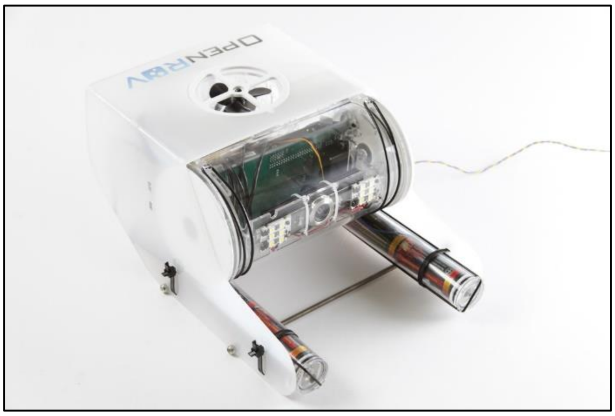


Figure 2-9: OpenROV image (Source: OPENROV, 2014)

Table 2-5: OpenROV Specifications

Cost	$849USD (KIT), $1450USD (Assembled)
Depth limitation	100m
Weight	N/A but is easy for a single person to carry
Payloads	Lithium batteries

2.6 *Conclusions*

A ROV that is able to provide live verbal *and* visual communication with the divers and operators above the surface of the water would be extremely beneficial. Currently, these vehicles are extremely expensive. A more affordable alternative would be ideal, especially if the system can be initiated and operated wirelessly from remote locations by single operator. The details to designing a ROV is covered in Chapter 3.

CHAPTER 3

METHODOLOGY

3.1 Introduction

The specifics to the major design aspects of ROVs is covered in Chapter 3. They are:

- current methods of communication (between operators and vehicle)
- buoyancy & stability of the ROV underwater
- hydrodynamic drag and how to calculate the thrust produced from a combination of motors and propellers
- hardware required for functional purposes, including:
    - video streaming
    - depth limitations
    - methods of controlling the vehicle through motors and computers.

3.2 Methods of Communication

The most common system that is currently implemented in most industrial ROVs is the hardwired tether. Using this system ROVs are capable of reaching depths of 3000 metres below the surface. This system is acceptable, but has the annoying possibility of the tether coiling up and tangling with debris or with the vehicle itself.

To achieve these great depths, the use of a tether management system (TMS) is used. Figure 3-1 is an example of such a system. The TMS drops a cage holding the vehicle in it into the ocean. The cage continues to descend into the depths until it is at the desired operational depth. Once the required depth is achieved, the vehicle leaves the cage. The total distance travelable away from the cage equates to the total length of the rolled up umbilical cord inside the cage.

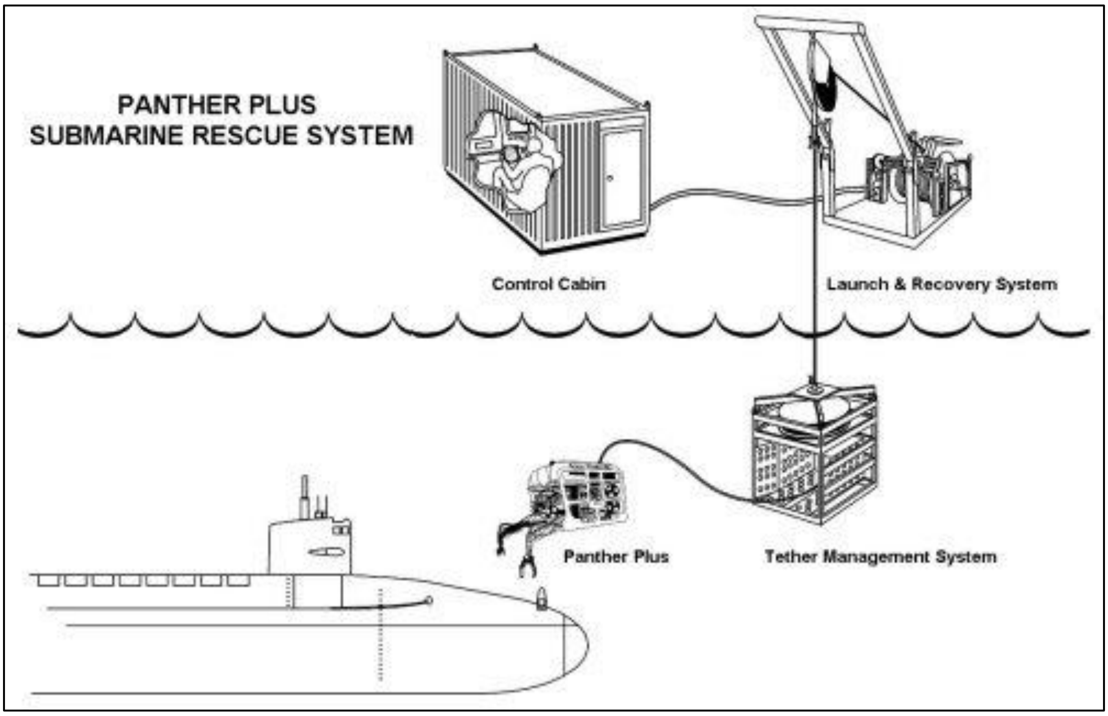


Figure 3-1: TMS, System Design (Source: Tarmey, 2006)

A TMS is only used with highly expensive ROV applications. The cheapest alternative at the moment for small scale applications is a tether directly connected to the operator's controls. This is not very flexible in terms of operational location.

A less common method of communicating with a ROV from a boat is by the use of acoustic wavelengths underwater. The operators' boat has a node which transmits/receives control and visual information to and from the boat to the ROV. These vehicles are not designed to have a long runtime, typically taking a few hours to perform a singular task.

3.3 Buoyancy & Stability

Buoyancy is an important part of the design of a ROV. If the vehicle has positive buoyancy, it will constantly want to float, making the vertical thrusters work constantly. If the vehicle has negative buoyancy it will sink, making the vertical thrusters work constantly with possibility of picking up dirt causing cloudy video. It is important to note, for stability reasons, a neutral buoyancy will cause a torque-like effect and the ROV will slowly tip over. Since the ROV will tip at completely neutral buoyancy, the vehicle will have a slight positive buoyancy to counter this action. Buoyancy was first discovered by Archimedes of Syracuse in 212B.C. His law states that any object, wholly or partially immersed in a fluid, is buoyed up be a force equal to the weight of the fluid displaced by the object. This law can be used to derive a relationship between density and weight of an object in a liquid.

$$\frac{density\ of\ object}{density\ of\ fluid} = \frac{weight}{weight - apparent\ immersed\ weight} \tag{3.1}$$

For each element in the design, the buoyancy will be determined. This involves calculating the volume of each solid and liquid to be submersed, multiplying it by the density which will give a weight. Materials which are of higher density than sea water will sink, the opposite will give buoyancy. The formulae for typical volumes of simple shaped objects relating to this study can be seen in Table 3-1.

Table 3-1: Formulae for simple geometric objects

Type of 3D Shape	Formulae for Volume
Cube	$V = 3l$
Rectangular Prism	$V = W * D * l$
Cylinder (Solid)	$V = \pi r^2 . l$

The weight of a solid is subtracted from the liquid to give the buoyancy as shown in equation 3.2.

$$Buoyancy\ of\ element = W_{submersed\ solid} - W_{submersed\ fluid} \tag{3.2}$$

If the value from equation 3.2 is negative, the vessel will sink, the opposite will happen if this value is positive.

It will be necessary for the elements of the ROV to be buoyancy tested in order to determine the required ballast. Since there are many elements to the vehicle, these calculations will be done through PTC MathCAD®. The results for final design using MathCAD® are in 0.

Underwater, a ROV acts like a damped pendulum. Thus, for best stability, the centre of buoyancy (CB) and centre of mass/gravity (CM) have to be located apart with the CB above the CM (See Figure 3-2). This will mean the ROV will be more stable the further the distance between the CM and CB.

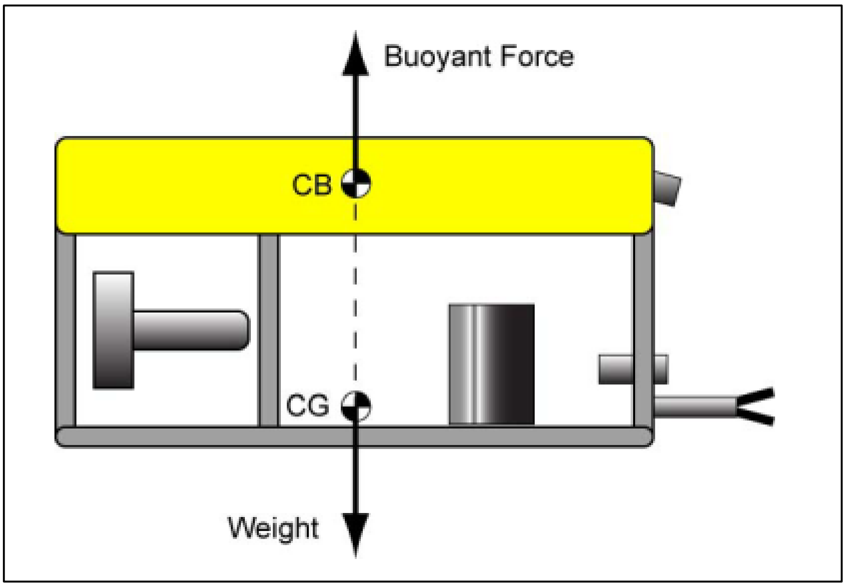


Figure 3-2: Centre of Buoyancy (CB) & Centre of Gravity (CM/CG) relationship (Source: Cornerstone Robotics, 2014)

Although it is important to know this relationship between the CM and CB, the distance apart from each other is not as important as the buoyancy of the vehicle. As long as the vehicle has a slight positive buoyancy, it will be very stable underwater.

3.4 Peer-to-peer underwater communication

Typically, divers use hand communication to relay to other divers what the situation is underwater. The creation of full face masks introduced the possibility of voice communication underwater. These voice communication tools are not common in recreational SCUBA diving, however they have a big impact to the ease of training new divers. The devices are not designed for extreme depths, typically being restricted to 60m max. The system would only be usable when other divers are able to utilise the underwater variant safely. They work as a two-way underwater radio where the sound is transmitted via ultrasonic waves to other units where the second diver can hear what is being said.

There are many different methods of communicating. Some use a specialised microphone which filters out background noise. Recently Casio released a Modulated Ultrasound version which works off bone vibrations in the skull (Coxworth, 2012).

3.5 Hydrodynamic Drag

The natural force on an object which resists its motion through a fluid (air or water) is called drag. As the ROV is an underwater object, this drag is called hydrodynamic drag. The portion of drag which is of importance is the pressure drag. Pressure drag is the inertia of the fluid causing resistance which is required to be pushed aside.

Bernoulli's equation for the pressure in a fluid is…

$$P_1 + \rho g y_1 + \frac{1}{2}\rho {v_1}^2 = P_2 + \rho g y_2 + \frac{1}{2}\rho {v_2}^2$$

The part of this equation relevant to the drag of an object is the kinematic contribution of the pressure of the fluid.

As pressure is a unit of the force applied over an area, we can solve the equation for pressure to find the drag force.

$$P = FA$$

$$F_D = PA = \frac{1}{2}\rho v^2 A_p$$

As drag is influenced by many other factors; shape, texture, viscosity, lift, etc. These factors can be neatened to one simple term called the drag coefficient (C_D).

This leaves us with the equation for the drag force (F_D N) (NASA, 2014):

$$F_D = C_D \frac{1}{2}\rho v^2 A_p \tag{3.3}$$

Where C_D is the coefficient of drag on the object (no units)

ρ is the density of the fluid in kilograms per cubic metre $(kg.m^{-3})$

v is the flow of the water in metres per second $(m.s^{-1})$

A_P is the projected area of the objects in (m^2)

The drag coefficient for simple objects is easily accessible through textbooks. This is a different situation for odd shaped objects. ANSYS CFD (Computational Fluid Dynamics) is a program that removes the problematic method of solving for the drag force of an object. ANSYS will be used for the design to inspect the fluid dynamics of the model, to help improve the design for optimised sizing. The value for the Drag Force can be used in conjunction with the thrust calculations in section 0 which will be used to solve for an estimated diameter for the propellers to achieve the required thrust.

The projected area A_p for the calculation is the two-dimensional area under the effect of the drag force. For simple shapes used in this study, refer to Table 3-2.

Table 3-2: Projected Area of common, simple shapes (Source: Robe, 2014)

Name of Shape	Formula for Projected Area (A_P)
Sphere	$A_P = \pi . r^2$
Cube	$A_P = l^2$
Rectangular Prism	$A_P = l.w$
Cylinder End	$A_P = \pi . r^2$
Cylinder Wall	$A_P = l.D$
NOTE: These formulae are for the shapes at a normal perpendicular angle (90^o) with the plane of impact of the drag force(F_D).	

Where l is the length of the object in metres (m)

r is the radius of the object in metres (m)

w is the width of the object in metres (m)

D is the diameter of the object in metres (m)

3.6 Thrust

Thrust is the amount of force produced by a propeller relative to the flow & density of the liquid. Often, the possible thrust capable for a propeller is given by the manufacturers with relevance to the revolutions of the motor it is attached to. Unfortunately, the supplier of the propellers available for the scale vehicle this study is going to model do not supply relevant data. The best option for the thrust to be found would be purchasing of multiple propellers & motors, then run the motor at 12V to find the optimal setup. This procedure tests the motor’s current draw at a specific speed and the thrust produced by the propeller. This test can be done in the future when the design is ready for prototyping.

The thrust output (T [N]) from the combination of the motors and propeller can be identified in the equation below.

$$T = \frac{\pi}{4} {D_p}^2 \left(v + \frac{\Delta v}{2}\right) \rho \Delta v \tag{3.4}$$

Where T is the thrust in Newtons (N)

D_P is the diameter of the propeller in metre/s (m)

v is the velocity of incoming flow in metres per second ($m.s^{-1}$)

Δv is the additional velocity/acceleration by propeller in metres per sec ($m.s^{-1}$)

ρ is the density of the liquid in kilograms per cubic metre (kg/m^3)

3.7 Hardware

3.7.1 Camera & Lighting

For manual control, a live visual feed of where the ROV is going is essential for proper navigation. Video cameras take multiple images and layer them to create a moving image. The number of images/frame per second is referred to as the frame rate. The higher the frames per second (FPS), the smoother the image will be. As the video is produced by multiple images, there is often a fairly high bandwidth related to high definition (HD) video.

There are currently three common resolutions for video capture: standard definition (SD) has a pixel density of 720 x 480 pixels, and high definition (HD) has 1280 x 720 and 1920 x 1080 pixel options.

The bandwidth for these cameras varies, ranging from as low as 1Mbps to over 10Mbps running with full 30FPS (perfect stream, low quality).

Ultra bright lighting will be required for the system model. Lumens is the measurement for the total amount of visible (to the human eye) light from a light source (integral LED, 2014). The general ratings for a household lighting is shown in Table 3-3. For lighting underwater (a task set objective) a luminosity of 800 lumens will be required. The most energy efficient light producing product is an LED (Light Emitting Diode). A LED with a power rating of 12W is capable of 806Lm of light, the equivalent of a 60W incandescent bulb (rated at 850Lm). They are frequently available for an inexpensive cost and are also available pre-made as singular high powered LEDs or as an array of multiple LEDs. It is necessary to keep to the voltage within the manufacturer product requirements.

Table 3-3: integral LED household lumen ratings (Source: integral LED, 2014)

Area	Lumens/Sq M
Kitchen	300-400
Kitchen (Task)	700-800
Living Room	400-500
Hallway	300
Bedroom	300-400
Bedroom (Task)	700-800
Bathroom	500-600
Bathroom (Task)	700-800
Reading Area	400

3.7.2 Inverters

Inverters are used as a device to change DC to AC voltage, and vice versa. Fortunately these are very easy to acquire for the common Australian voltages of 12V and 240V. If the battery bank on the buoy is set to 12VDC, high amperage, it can be scaled up to 240VAC by the inverter to be sent down the power supply lines to the ROV. Like on the surface, this process can occur again on the ROV, transforming the power from 240VAC to 12VDC to operate all the required components on the ROV. Prices of inverters vary from AUD ~$30 to over AUD $600 through Jaycar Electronics. The cost of these will be dependent on the amperage draw of the ROV components and the total length of the tether investigated in Section 3.7.3.

3.7.3 Umbilical Cord (Tether)

The umbilical cord, also referred to as the tether, is the item that transmits data and power from the surface of the water to the ROV. It is crucial that communication between the buoy, on the surface, and the ROV, underwater, be consistent and capable of transmitting all the data from the ROV to the buoy 24/7. There are two options for this are: to use Power over Ethernet (POE) or a high speed Ethernet cable (CAT5E) with separate power supply. The one major benefit of using POE is that data is transmitted through only two cables. This benefits the design by making the tether lighter and more buoyant, keeping it away from the ROV naturally. It also reduces the cost of increasing the buoyancy of the tether and is easier than going with the other option (CAT5E).

Deducing when the use of AC over DC power transmission is an important factor for the tether. The loss of any power over a distance is reliant on the impedance (R) of the chosen cable over the required distance. Ohm's law is the basis for calculating the power loss over the specified distance.

$$P_{loss} = I^2.R \tag{3.5}$$

Where P is the power at the lost in watts (W)

I is the current transmitted down the line in amperes (A)

R is the impedance of the line over the required distance in ohms (Ω)

The impedance (R) varies depending on the gauge of wire chosen. This has been investigated in Section 0.

3.7.4 Telemetry

Telemetry is the automated transmission of measured data sent from a remote location (ROV) to a receiver (Operator) for monitoring and storage. The word telemetry comes from the Greek “Tele” meaning remote and “Metron” meaning measure. Telemetry is a wireless data transfer between transmitter and receiver, the most common being through GSM Networks (Global System for Mobile Communication) by using SMS (Short Message Service) to send and receive data. Telemetry can also be referred to in computer networking & telecommunications.

This section covers all relevant telemetry data/sensors available for ROVs.

GPS

Global Position System (GPS) consists of a network of multiple satellites (24 to 32 solar-powered satellites) orbiting Earth at an altitude of approximately 20,000km, with control stations on Earth located at Hawaii, Kawajale, Diego Garcia & Ascension Islands, and a receiver (MiTAC International, 2014). The GPS receivers are commonly mobile phones, GPS trackers, and GPS Navigation devices.

The control stations are used to monitor the satellites’ conditions. They initialise a sequence to triangulate the position of the receiver from three of those satellites, then they proceed to check the result against a fourth satellite. If the check procedure does not give conclusive results, the process is repeated again until a precise location is found. The measurement is done by timing the duration it takes for the microwave signals to travel from the satellites to the receiver.

A GPS would be a worthwhile addition to a ROV if it is to be autonomous. This would allow the possibility of adding waypoints for the ROV, like currently done with drones.

Depth

The best method to measure the depth a ROV will be located under the water’s surface is with the use of a pressure gauge. This can be measured using four different collector types: a Piezoresistive strain gauge (most common), Capacitive, electromagnetic, Piezoelectric, Optical and Potentiometric. All methods excluding the Potentiometric & Optical collectors detect the strain applied to a diaphragm. The last method is less common and observes a change in wiper location (Potentiometric) or observes the physical change in an optical fibre to detect strain (Optical). Essentially all collectors are strain gauges that determine the actual pressure applied to a surface. This pressure can be used to solve for the depth relative to atmospheric pressure.

Another option for depth measurement is by measuring the altitude above the sea floor. Sonar Altimeters are one such measuring device. They use sonar wave frequencies and their rebound time to calculate the distance off the ocean floor. There are many options of Sonar Altimeters available but are all of high cost ~ USD $1000 (Kongsberg, 2014).

Accelerometer vs Gyroscope

A Gyroscope is capable of measuring the poll, roll and yaw of a vehicle, irrespective of compass orientation (Goodrich, 2013). The device is used to maintain orientation based on the principles of angular momentum. An Accelerometer measures the instantaneous changes in velocity in any direction in proper acceleration called g-force (Dimension Engineering LLC, 2014).

Since a ROV has very slow movements and is designed to be very stable, the use of a gyroscope and accelerometer is somewhat unnecessary for the ROV in this system design. The application of a 6DOF (Six Degrees of Freedom) is relatively cheap when using electromechanical versions of these with prices ranging from AUD $2 to AUD $15.

Sensors

CTD (Conductivity, Temperature & Depth) sensors can be used to measure the salinity, temperature and depth by means of conductivity in sea water. The pressure on the gauge can give depth. The temperature and the salinity is measured by changes in the current produced by the device due to the salinity in the water.

3.7.5 Emergency Air Tank

As this ROV will be used to communicate and navigate near other divers, a viable payload could be the addition of emergency air (Kendig, 2007). This extra air availability would help save lives in emergencies where a diver may panic or their regulator may start to malfunction.

Spare Air is one such solution to this problem. Invented in 1986, Spare Air now has three different options for tank sizes (Spare Air, 2014). With a capacity range from 48L (Model 170) to 85L (Model 300), Spare Air allows divers to get in 30 to 57 emergency breaths (based on 1.6L per breath). This allows divers to safely make it to the surface of the water.

3.7.6 Manipulator Arm

Manipulator arms are relatively common amongst robotic ROVs. Typically being a 2 or 3 axis device, they are used by the larger ROVs to sample materials or remove/repair material to gain access to new areas. Some optional functions of these arms are:

- Gripping objects
- Wire/Rope cutting
- Wire brush
- Welding

For the purposes of this project, the addition of a manipulator arm would not be included unless specified by a client.

3.7.7 Motors

Primarily there are DC motors, Asynchronous and Synchronous AC motors. The major differences between the DC and AC versions of motors is that DC motors require brushes to make contact for them to work. These wear over time and cause DC motors to be less efficient than AC motors.

There are a couple advantages of using AC motors over DC motors; no brushes required & no commutator. Quite simply, AC motors are essentially a magnet inside which spins instead of a coil (DC) (Wolfe, n.d.). These are generally more expensive than standard DC motors, but the benefits significantly outweigh the minor increase in cost. This is evident over time as they do not require any maintenance (except maybe the bearings).

Electronic Speed Controllers (ESC) are a basic requirement for brushless motors, as they convert DC power to AC, allowing them to run. ESCs come in a variety of options ranging from 5A to 200A. The cheaper ESCs do not have the capability of forward and reverse control – they only have one direction. As the motors on a ROV are required to have bidirectional control, these cheap ESCs do not meet the required specifications.

3.8 Control System

3.8.1 Depth control

Adjusting the depth of the vehicle can be done in two different ways: changing buoyancy or using thrust produced by vertically aimed thrusters. As discussed in Section 3.3, the buoyancy of a system is very important for the stability of the system underwater. A negative buoyancy (required to sink the vehicle) will result in instability, which isn't desired. Mechanical adjustment of the ROV with vertically displaced thrust is the best method of changing the depth when under live operation.

The ROV will need to withstand the pressure that results from the depth at which it is required to operate in sea water. This can be expressed in the following formula…

$$P = \rho g h_d \tag{3.6}$$

Where P is the pressure in Pascals (Pa)

ρ is the density of the fluid in kilograms per cubic metre (kg/m^3)

g is the acceleration due to gravity which is 9.81 metres per second ($9.81 m/s$)

h_d is the maximum depth in metres (m)

Assuming the maximum length of the tether is 100m (without loss), and the density of sea water is 1025 kg/m^3, the maximum pressure the ROV will need to withstand is:

$$P = 1025 * 9.81 * 100 = 1005525 Pa \ or \ 1.01 MPa$$

3.8.2 Navigation

Navigation of the ROV will primarily be manual (controlled by an operator). For the operator to understand the ROV’s orientation and location, the computer system requires a gyroscope, compass and depth gauge. There are multiple devices that can accept these tools. These devices are Linux based computers, Arduino boards and BeagleBone Blacks. The data processed by these computers can be sent over a hardwired network device (Ethernet) or wirelessly (acoustic or traditional IP networks).

3.9 Conclusions

An affordable version of a ROV is possible if only the absolutely necessary components for full functionality are used. The motor and propeller combination is outside the scope of this project. Tests done in laboratory conditions will need to be completed to decide on these components.

Since the ROV will be around a diver most of the time, a payload of emergency air and ultrasonic communication services will be required in the system design.

CHAPTER 4

SYSTEM DESIGN

4.1 Introduction

Chapter 4 encompasses the design process (Section 4.2) required to achieve the specifications detailed in Section 1.4.

The requirements and components of the ROV are chosen in Section 4.6, which dictates the final design, depicted in Section 4.7.

The same process is covered for the buoy where the requirements and components are selected in Section 4.8. The final design of the buoy is not required for this study, but an example is given in Section 4.10.

4.2 System Model

A system model that encompasses the design requirements of the ROV has been addressed. This model (Figure 4-1) has nine major areas that need addressing in the design process. They are addressed in sections 4.2.1 to 4.2.9. Another major factor to take into consideration is cost. The whole system should not exceed AUD ~$4000 for it to be feasible; the complete system cost is in Chapter 5.

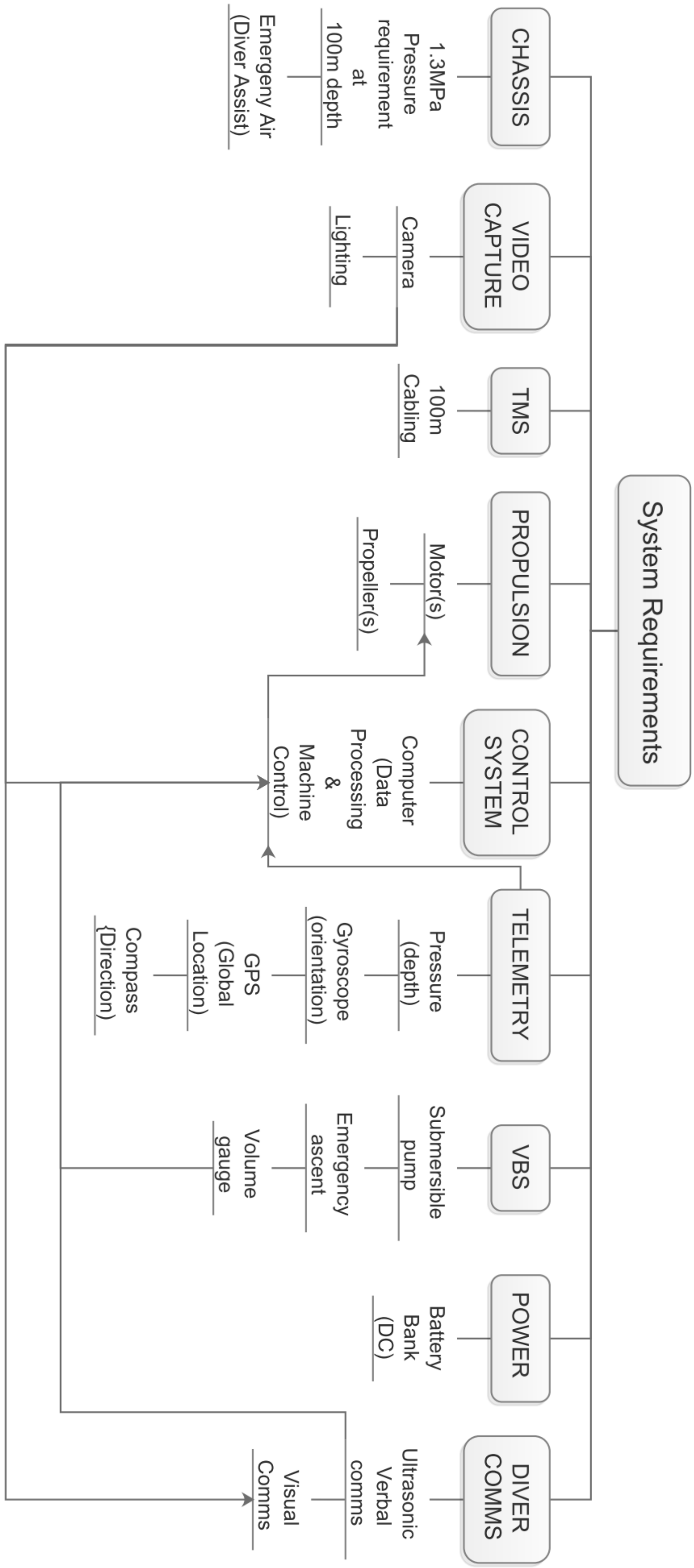


Figure 4-1: System Model Specifications (Source: Robe, 2014)

4.2.1 Chassis

The chassis of the ROV will be required to withstand all pressures up to and including a depth of 100 metres below the surface of the water. This minimum pressure requirement has been calculated in Section 4.6.1 to be 1.3MPa. This is a different situation for the buoy, where there is no pressure exerted on its body. Both chassis requirements are discussed in Sections 4.5.1 and 4.8.1 for the ROV and buoy, respectively.

The ROV will have an extra payload for the emergency air, previously discussed in Section 3.7.5.

4.2.2 Video Capture

Video capture will only occur on the ROV and this will have to be of a high clarity, allowing for clearer live footage. The choices made for the video feed have been discussed in Section 4.6.4

4.2.3 Tether Management System

The TMS, from this point on in the report, will be referring to the method of tethering the devices together for means of communication. The two feasible options for this are discussed in Section 4.3 and the tether is discussed in Section 4.6.4.

4.2.4 Propulsion

Propulsion is the design subcategory that includes the motor and propeller combination. This combination is required to provide two times thrust necessary to overcome the drag coefficient of the ROV. As discussed in Section 3.6, this combination will be optimised by using laboratory testing. For the pricing and drawings, a standard high torque motor has been chosen in Section 4.6.2.

4.2.5 Control System

The control system is the most complicated element of the design. The methods of communication between the ROV and the operator wirelessly are discussed in Section 4.3.

The ROV will have its own computer system consisting of a BeagleBone Black and a customized Arduino MEGA board. The ROV computer system will communicate with an Android phone on the buoy via power over Ethernet. The ROV computer is discussed in Section 4.6.5 and the buoy computer is discussed in Section 4.9.2.

4.2.6 Telemetry

The telemetry sensors have already been discussed in previous section 3.7.4, where all possible telemetry options were considered.

The only devices to send telemetry throughout the system will be:

On the ROV – Gyroscope/Accelerometer/compass combo, two pressure gauges and a volume gauge (VBS) which are discussed in greater depth in Section 4.6.4.

On the buoy – there will be the android phone which is capable of GPS and compass data acquisition, which are discussed in section 4.9.2.

4.2.7 Variable Ballast System

The ROV VBS consists of two volume gauges – required to give full capacity, a submersible pump, and an emergency compressed air canister. These features are discussed in detail in Section 4.6.3.

4.2.8 Power

The power requirements are considered solely by assumption for this system model. The laboratory testing for the motor and propeller combination will give the main drain on a battery bank. The batteries will be stored on the buoy, which allows constant daytime charging by a semi-flexible solar panel. These aspects are discussed in Section 4.9.1.

4.2.9 Diver Communications

The diver communications have already been discussed in detail in Section 3.4. The decision for the visual device (camera) and the verbal device (ultrasonic coms) are discussed in Sections 4.6.4 and 4.9.2, respectively.

4.3 Methods of Communication

This section covers ideas for a method of communication between the operator and the ROV through means of wireless transmission.

4.3.1 Completely Wireless

Wireless communication is not possible from an underwater object to an above the surface object/operator. An issue occurs when investigating possible methods of communication from above the water to below the water, and vice versa. It is possible to send data 1.5km/s underwater using acoustic methods (low frequency waves), however it is severely affected by multipath propagation (Goh, et al., 2009). Multipath propagation occurs due to reflection and refraction of the signal. Multipath propagation causes the signal to take multiple pathways. This can cause data to arrive at irregular intervals. This is not ideal. This is the first problem with are completely wireless solution. To fix this problem, it is possible to use electromagnetic (EM) wave propagation. EM wave propagation happens at a higher frequency than acoustic wavelengths, traveling at $3\text{x}10^8$m/s. The increase in frequency means more signals will be sent and received, this makes it more accurate than the acoustic solution.

The second problem occurs with the application of acoustic signals out of water. Acoustic & EM communication is not very good in the air as it does not act as well as it does in water. To fix this, a buoy of some sort would have to be in place to change the communication method between the air and the water. This buoy converter has already been constructed by the University of Buffalo. The buoy is designed to convert air-based radio waves to water-based acoustic waves, creating an *Underwater Network Architecture*.

4.3.2 Operator to buoy tether

In this section, the method of tethering a buoy to the operator and using acoustic waves for communicating with the ROV to the buoy is considered. This method of communication has one major flaw - it requires a tether running on the surface of the water from the operator to the buoy. The buoy would also need another anchor to stop it floating back to the operator’s location.

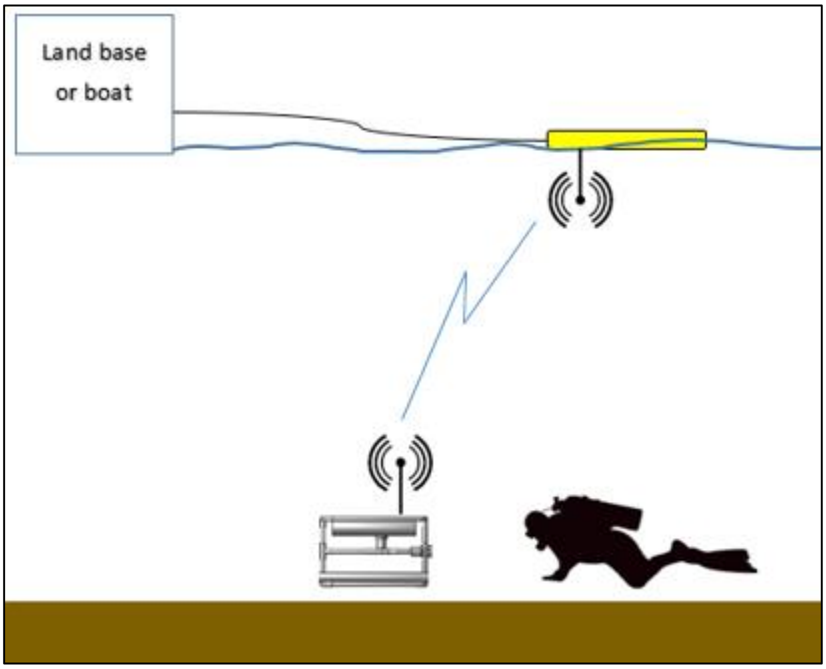


Figure 4-2: Buoy-Operator tether (Source: Robe, 2014)

This sort of system would be better done by having a wired acoustic transmitter on a boat to talk with the ROV underneath the boat. As the idea is currently, there are some major points to consider:

- ROV would need to surface to send its location to the operator
- ROV is restricted to the buoys location
- Increased interference underwater, however negligible, when using acoustics

However, this communication idea still has some positives to consider:

- Long-distance control is possible due to acoustic communication
- Fast response time for control
- ROV could dock with the buoy to recharge its batteries

4.3.3 ROV to buoy tether

In this section, the method of communicating with a tether from a buoy to the ROV, then wirelessly from the buoy to the operator is considered. This method proves best since wireless communication through air is incredibly common across the globe.

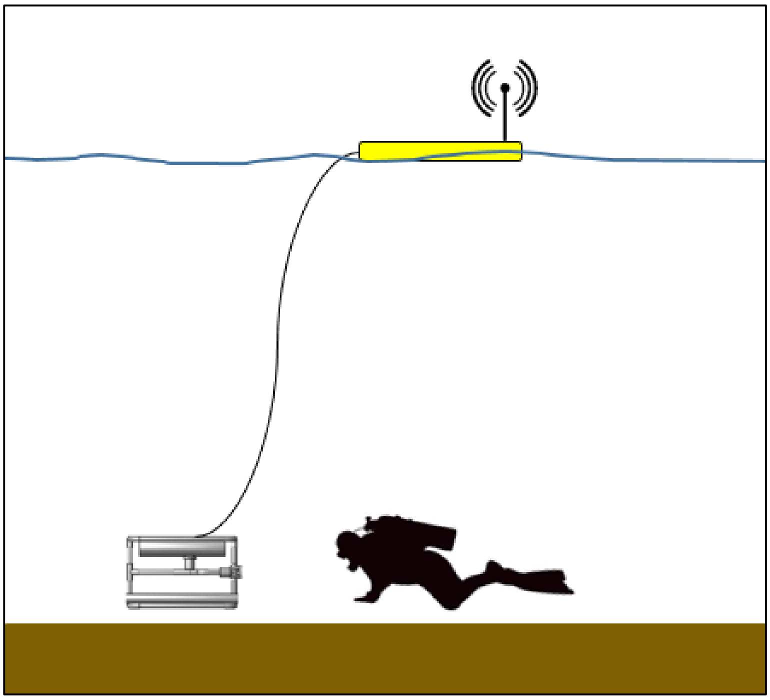


Figure 4-3: Buoy-ROV tether (Source: Robe, 2014)

This method allows the vehicle to have no batteries on board if needed. This is because the buoy can have a solar panel attached to generate electricity to charge a bank of batteries on the buoy. The ROV could also dock with the buoy if required, keeping the benefits of this docking noted in 4.3.2.

This method would be accessible through the traditional IP network infrastructure with the possibility of communication through a device as small as a phone. The limitation of this communication method is the transmitter/receiver chosen to be on the buoy. The maximum signal range possible of this device will determine the maximum distance from which an operator is able to control the ROV. The buoy's transmitter/receiver could be changed to cater for different communication methods in the future.

This method of tethering the ROV to the buoy would bring many benefits, solving issues previously outlined in Section 4.3.2:

- Operator does not need to be nearby

- The buoy gets towed along by the ROV (no longer limited to buoy location)
- The buoy can charge an array of batteries through solar panel(s)
    - Charging is continuous and can occur while the ROV is operating
- It utilises current technology which is readily available in today's IP network infrastructure.

However, this communication method does have its limitations:

- ROV is limited to the length of the tether
    - This length can be pre-set for different tasks making it quite versatile
- ROV still has the issue of tether entanglement with the motors

An important addition to this design would be a method of calculating, like with GPS, the location of the ROV relative to the buoy. A method of locating the ROV relative to the buoy has not been undertaken in this project.

4.4 *Full System Overview*

The communication method discussed in section 4.3.3 has been chosen for its benefits of powering the vehicle and communicating with the operator. The system of components and their connections has been made into a schematic (Figure 4-4) to help decide on components required for the overall system.

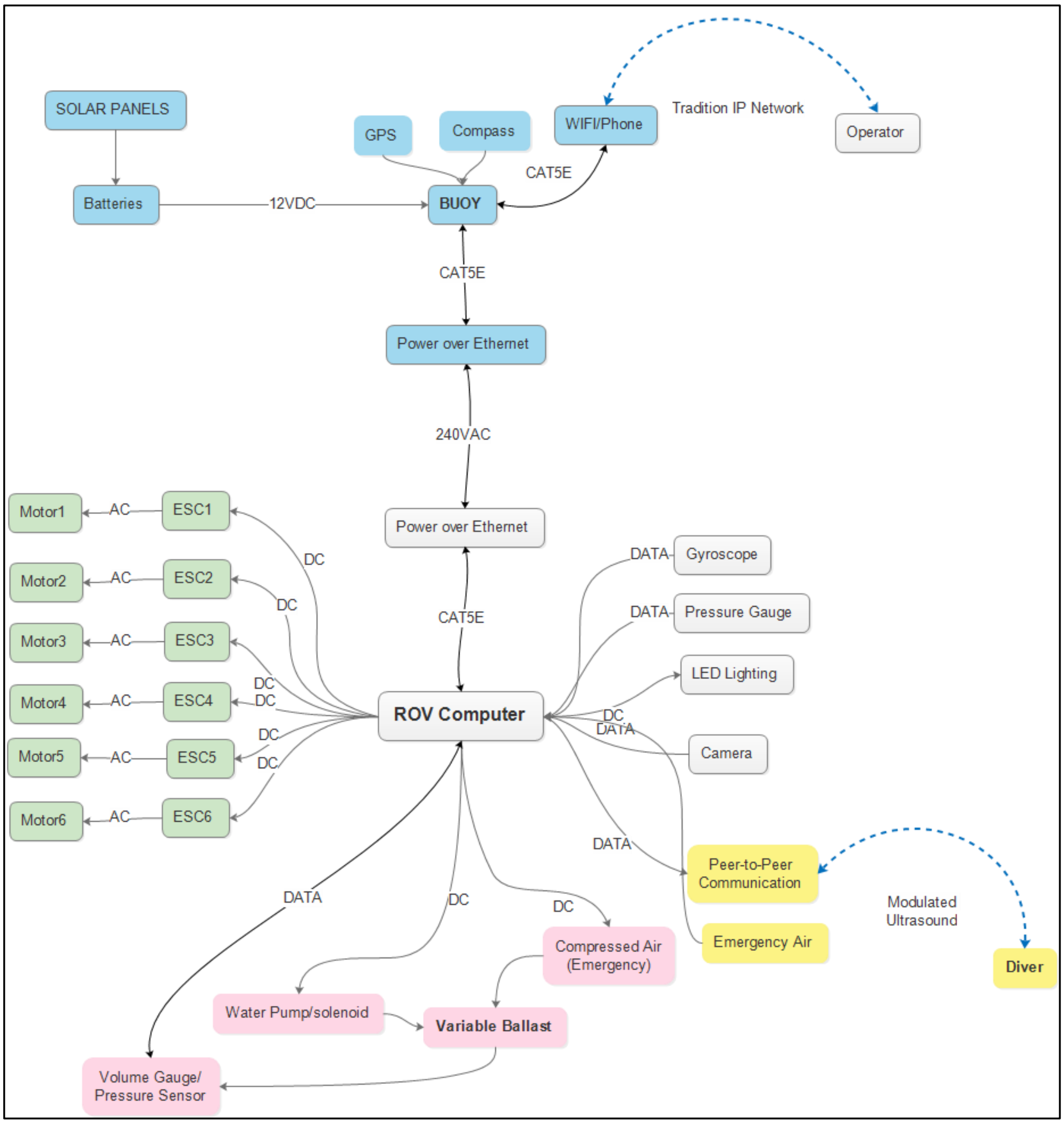


Figure 4-4: Overall System component schematic (Source: Robe, 2014)

To improve the system’s portability, it will be required to fit in a standard sedan. This will ensure ease of transport for the ROV and buoy system, making it easy to load and unload at different locations using everyday vehicles such as a four-wheel drive car, utility vehicle or ordinary sedan. Use of an everyday vehicle could result in a loss of rear seat space.

4.5 ROV Requirements

4.5.1 Structural Requirements

Structural integrity of the ROV will be verified to be able to withstand the pressure of salt water at a depth of 100m below sea level. A Factor of Safety of 1.3 shall be applied to all structural elements of the ROV. The material yield strengths are to be used as the maximum allowable stresses for the elements, ensuring the safety of all equipment and continued functionality of the components.

The complete design is required to withstand an external pressure of 1.01MPa, with a FOS of 1.3, this makes the minimum permissible pressure 1.313MPa.

4.5.2 Electrical Requirements

The electrical requirements for the ROV, at a minimum, need to run all sensory equipment, the Variable Ballast System and all motors simultaneously. This may not necessarily happen at any stage during operation, but will ensure that the power requirements will be satisfactory in the worst case situation. Commonly the use of the low power draw sensors will be operational, however the major drain will be in the motors' draw (typically 4 motors in operation simultaneously). Therefore it is important for the tether to also accept a standard voltage of 240V with a small amperage draw which will be inverted to a lower voltage 12V and higher amperage.

If the computer fails to operate while it should be in operation, there needs to be a failsafe to return the ROV to the surface and send out a beacon notifying the operators of the failure. The failure protocol will notify the operators which component has failed. The exact reason why, will not be included in the error, but an error message stating the failed component will help narrow down as to why it may have failed.

4.5.3 Functional Requirements

The ROV is required to be 3DOF (3-Degrees of Freedom): rotation around the Z-axis of the vehicle (Turning), horizontal displacement on the XY-Plane (Forward/Reverse), and vertical displacement in the Z-axis (up/down). It will also be required to have the ability to transport an extra payload, up to 2kg, of any small items the archaeologists may wish to send to the surface easily. To allow for this payload, the vehicle will need variable ballast. It will also be important, as this ROV will be operational near divers, for there to be Emergency Air on board.

It is not required to carry batteries for power, but will need to convert the received AC power to DC through an inverter, which will happen through Power over Ethernet. The cable transmitting the power in 240VAC, will also be transmitting the telemetry data between the ROV and the buoy.

There will be a small high definition camera showing what is happening to the operator. Overlayed on this image will be the pressure and GPS location of the buoy (location of ROV relative to the buoy is not covered in this study). The pressure sensor will give an idea of depth which will be stored and graphed for operators to see onscreen, along with the GPS location.

4.6 ROV Equipment

4.6.1 Frame Materials

The frame will need to be constructed of materials with structural properties that will not yield and fail with 1.3MPa of external pressure on the elements.

The choice of PVC tubing was chosen for the framework as it is a very easy material to work with and is very strong. It is also readily available in different sizes and shapes, and is hollow, making it possible to store important components while keeping the compartment watertight. It also has the benefit of being high in tensile yield strength ranging from 35 to 65MPa with a density of 1350 to 1450 kg/m^3 (MatWeb, LLC, 2014). The typical strength for household PVC tubing for water drainage is near the middle at 53.5MPa (Holland Plastics, 2014). The strength for the PVC elements will be done assuming the worst case of 53.5MPa.

For the camera and electronics bay, a transparent acrylic PMMA tube will be used. These have a yield strength ranging from 48 to 76MPa with it typically being 60MPa with a density of 1170 – 1180kg/m^3 (Holland Plastics, 2014).

The maximum permissible stress these tubes can withstand is called the hoop stress. Hoop stress (σ_h $[MPa]$) is solved by the following formula for thin-walled pressure vessels:

$$\sigma_h = \frac{pr}{t}$$

This is rearranged to give the maximum pressure (p)…

$$p = \frac{\sigma_h t}{r} \tag{4.1}$$

Where t is the wall-thickness of the pressure vessel in metres (m)

r is the radius of the pressure vessel in metres (m)

σ_h is the hoop stress on the pressure vessel in mega pascals (MPa)

The available PVC and PMMA materials are listed in Appendix B. The maximum pressure capabilities for each material were calculated by Equation 4.1. These results are graphed in Figure 4-5.

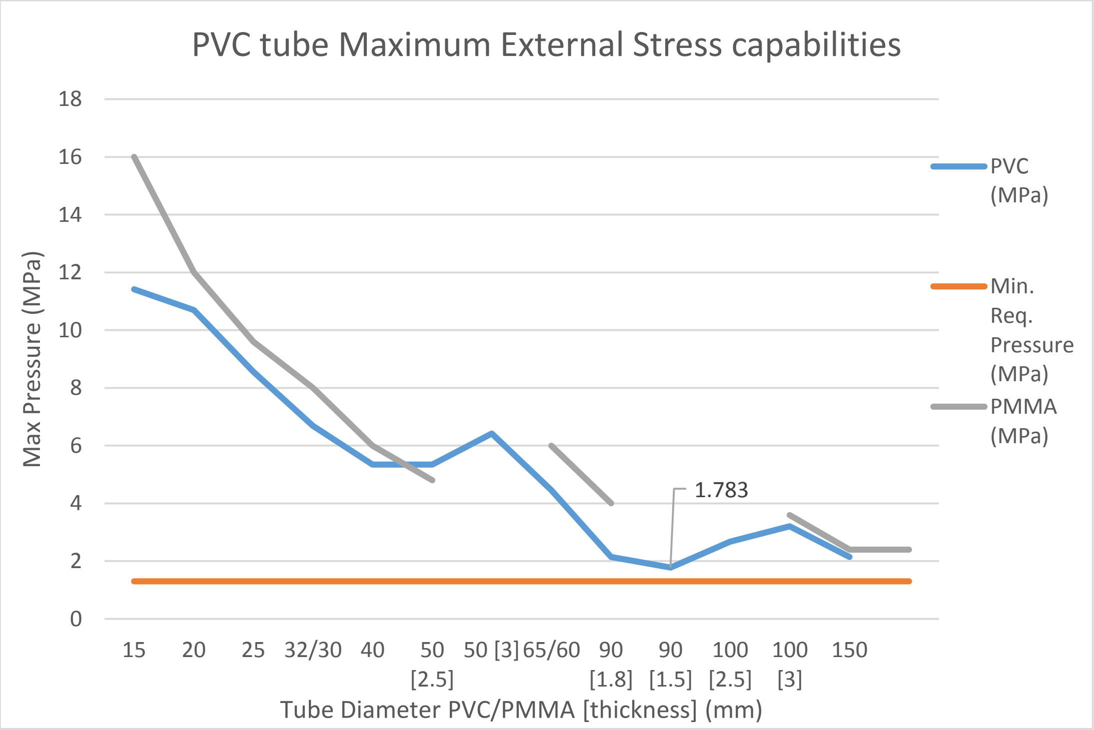


Figure 4-5: PVC & PMMA Max. Stress (Source: Robe, 2014)

As the vessel is required to withstand a pressure of 1.3MPa (4.5.1), all sizes of PVC and PMMA tubing will be suitable. Both PVC and PMMA far outdo this requirement, the smallest for the PMMA tubing being 2.4MPa and PVC being 1.783MPa. With a 1.3 FOS, the tubing would be able to dive to a depth of 136.4m with no yielding issues.

4.6.2 Thrust & Motor Layout

Thrust was covered in Section 3.6, highlighting the main equation for forward thrust. Initially, the layout for the motors was chosen to be very simple, as per Figure 4-6.

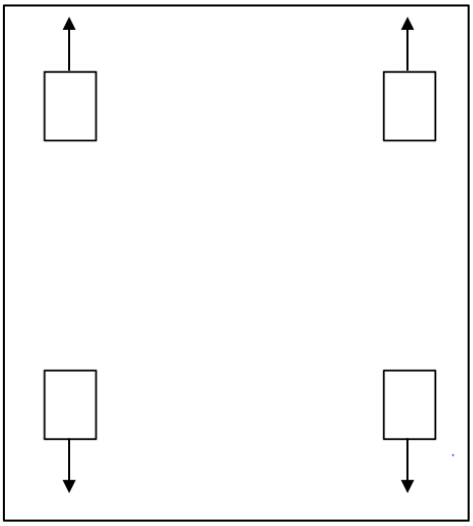


Figure 4-6: Preliminary motor layout (Source: Robe, 2014)

It was noted, however that if an acute angle between the motor thrust direction and the actual thrust direction was introduced it would help the ROV pivot better on the z-axis (Figure 4-7). This reduces the previous forward and reverse thrust for the vessel but can increase its rotation to be very nimble.

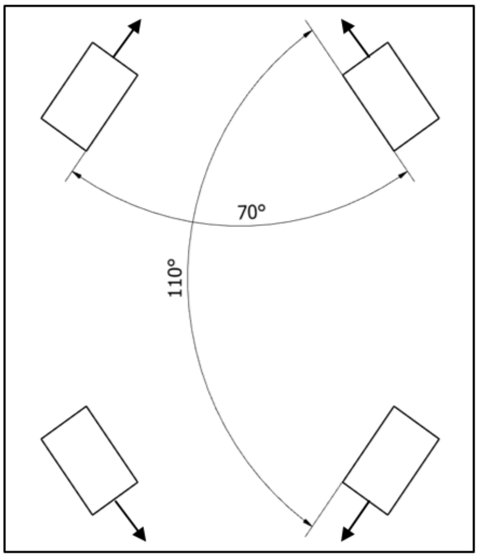


Figure 4-7: Final motor layout (Source: Robe, 2014)

The forward thrust for the vessel can now be calculated by taking the cosine of this new angle to give a relative thrust.

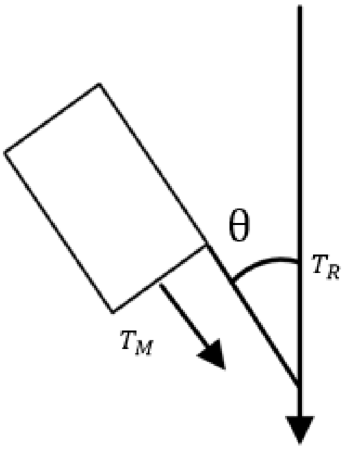


Figure 4-8: Relative-to-motor thrust visual (Source: Robe, 2014)

For the introduced angle in Figure 4-7, θ would be 35°. T_M denotes the motors thrust and T_R is the relative thrust we want to find for the forward thrust for the vessel. The adjusted thrust equation for T_R can be calculated as:

$$T_R = \cos\theta \cdot (T_M)$$

$$T_R = \cos\theta \cdot \left[\frac{\pi}{4} {D_p}^2 \left(v + \frac{\Delta v}{2}\right) \rho \Delta v\right] \tag{4.2}$$

Where θ is the introduced angle between 0° and 90°

D_P is the diameter of the propeller in metre/s (m)

v is the velocity of incoming flow in metres per second $(m.s^{-1})$

Δv is the additional velocity/acceleration by propeller in metres per sec $(m.s^{-1})$

ρ is the density of the liquid in kilograms per cubic metre (kg/m^3)

An increase in theta will reduce the forward thrust by a set percentage relative to the change in the angle. As theta increases, the amount percentage of actual motor thrust (T_M) used for the forward thrust (T_R) can be seen in Figure 4-9. At 35^0 the motor outputs 81.9% of its actual thrust in the forward direction.

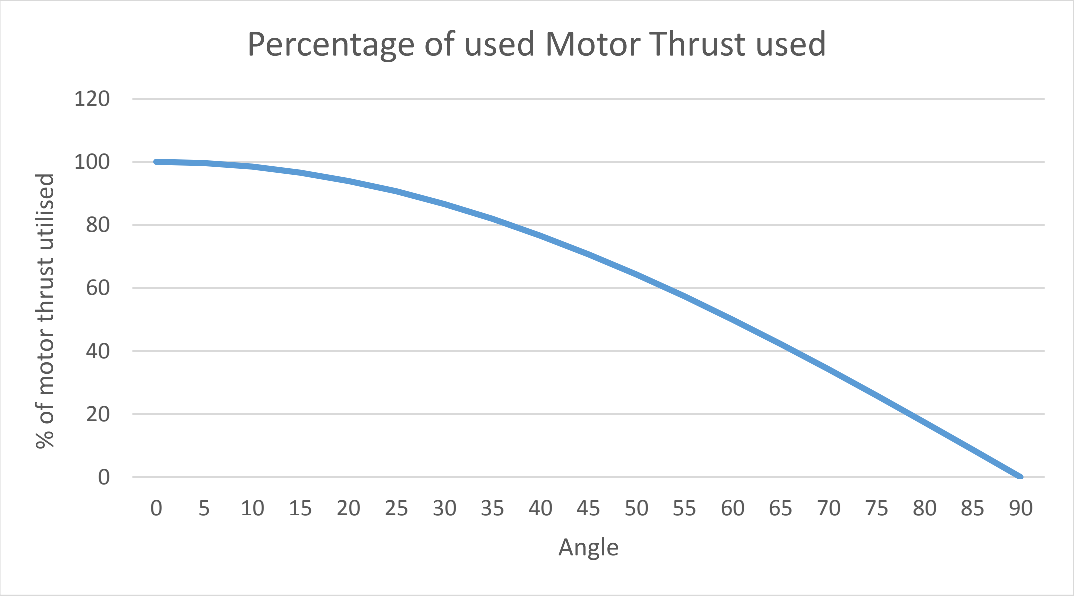


Figure 4-9: Percentage of utilised motor (Source: Robe, 2014)

The motors are 1700kV motors from Hobby King. These are high torque motors and have been chosen for example costing purposes only as tests would need to be done to find the optimal setup for the motor and propeller choices.

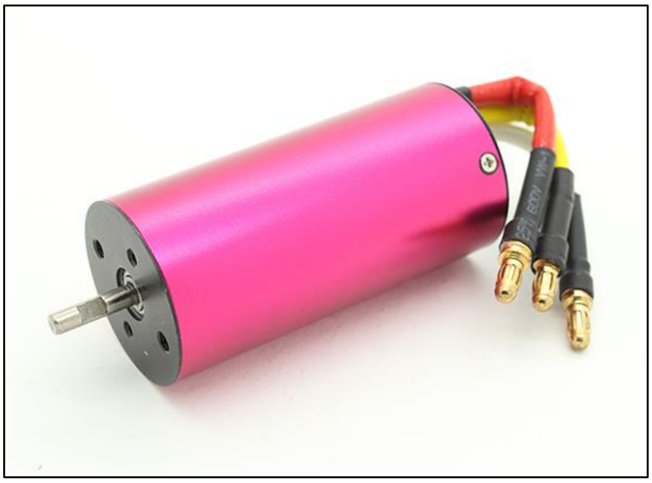


Figure 4-10: Hobby King 1700kV Brushless motor (Source: Hobby King, 2014)

4.6.3 Variable Ballast System

The Variable Ballast System (VBS) is a tank that has variable water/air levels. Variations in the water level will be accomplished using a custom made submersible water pump which will be activated with a solenoid valve to add and disperse water from the tank. Salt water will be the only liquid in this system for changing buoyancy, so a filter will be put over the inlet to reduce cavitation and improve the pump rate. This pumping action will be utilised for changing buoyancy of the ROV for payloads and a negative buoyancy can also be used to make the ROV an anchor for the buoy.

There will be two inlets for the tank, one with the previously described pump subsystem, the other will have a high pressure air canister connected to it. This high pressure air canister will be a one use item for emergency resurfacing of the ROV if anything fails.

The pump’s impellor will be supplied by Hobby King and the impellor cage, with inlet and outlet, will be 3D printed. The level of the tank will be measured using two 80mm high sensitivity water sensors valued at USD$8.98. These sensors work by conductance, outputting a current between 5 and 20mA for the level reading. As the diameter of the tank will be greater than 40mm, they will be used in series, as the first one is overfilled (reading 0 – 40mm, the second sensor starts recording the level over 40mm (40 – 80mm).

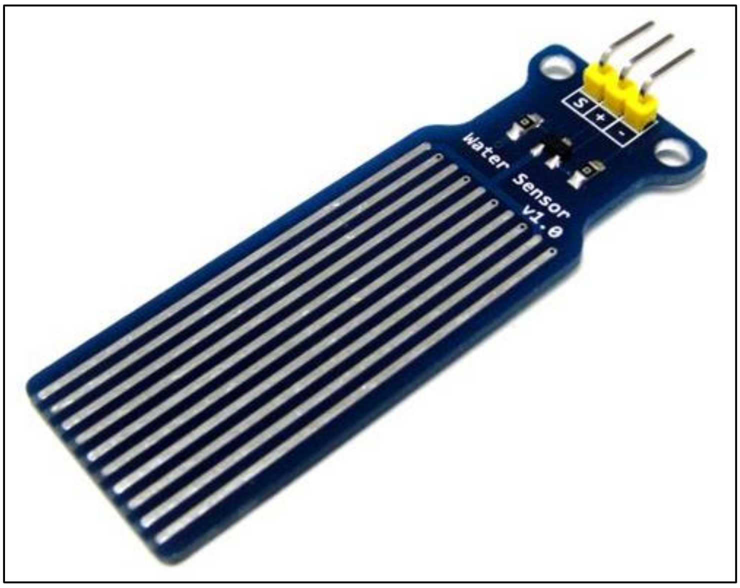


Figure 4-11: High Sensitivity water level (Source: Emart, 2014)

The solenoids for the system will be supplied from Irrigation Store Australia. Their MV75 12VDC Micro Solenoid is has operating specifications of 20kPa to 1.25MPa, which is appropriate for the application. This does not include operation in sea water at a pressure of 1.01MPa; a trial pressure test will need to occur to ensure its plastic case will be structurally sound for underwater use. Figure 4-12 shows the solenoid with the two male ends for the inlet/outlet which is capable of a 5 to 50 Litres per minute flow rate.

Figure 4-12: MV75 Micro 12V Solenoid (Source: Irrigation Australia, 2014)

4.6.4 Camera, Telemetry and tether

The camera chosen for the ROV will be a standard 1080p web camera running at 30FPS. Web cameras are already designed for low data rates, making them ideal for this application. 3D imagery will not be used as it requires a large bandwidth and is above the requirements for the design. The web camera will be in a separate sealed unit than the other computer components. A Logitech HD Pro c920 has been chosen as the brand is reputable and known for its reliability.

Figure 4-13: Logitech HD Pro Webcam C920 (Source: Logitech, 2014)

To increase the clarity of the camera's footage, the addition of two individual High powered LEDs will be used. The chosen LEDs are a 12W adjustable current LED by Luminus. The SST-90 has adjustable drive currents from 1A to 9A, allowing adjustable brightness for the LED, which will be required when looking directly at divers.

Figure 4-14: Luminus SST-90 LED (Source: lck-led, 2014)

All data produced by the pressure sensors, camera, gyroscope and tank level for the variable ballast system will be passed through the computer system and transmitted through a tether by means of Power over Ethernet.

Assuming that the current drain by the ROV is 3A, the tether can be chosen. Data for American Wire Gauge (AWG) dimensions from 1 to 24 gauge were considered and the power loss over a 100m tether can be formulated using the method from Section 3.7.3. This relationship between the gauge of the wire and the power loss with a 12VDC input are shown in Figure 4-15.

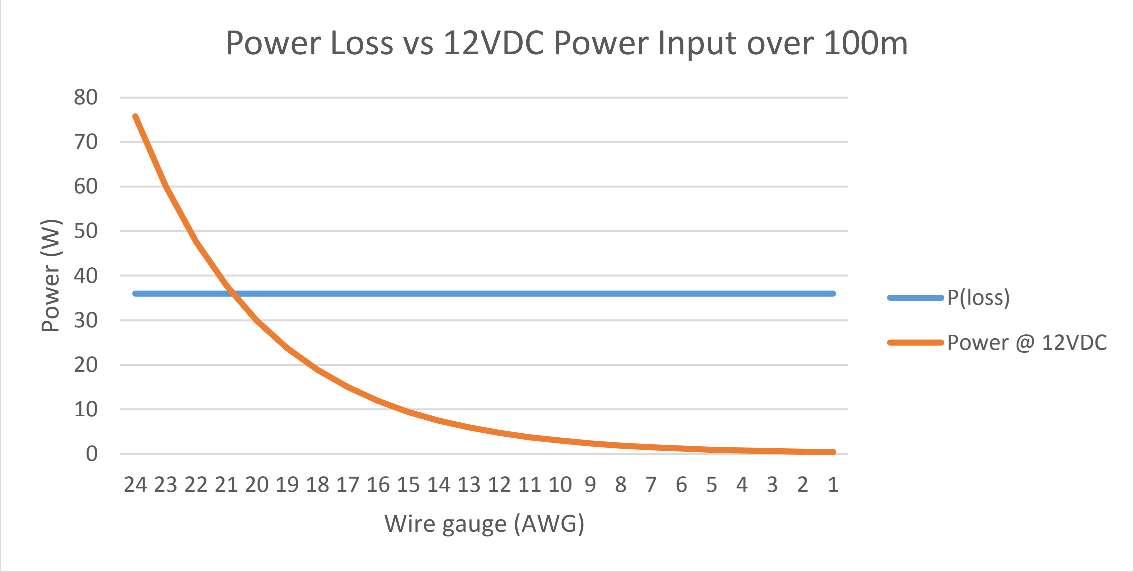


Figure 4-15: 12VDC Power loss analysis (Source: Robe, 2013)

Due to the size of the loss with DC, AC transmission will be utilised. The percentage of power loss can be seen in Figure 4-16 where Australian standard 240VAC was considered compared with the 12VDC power loss.

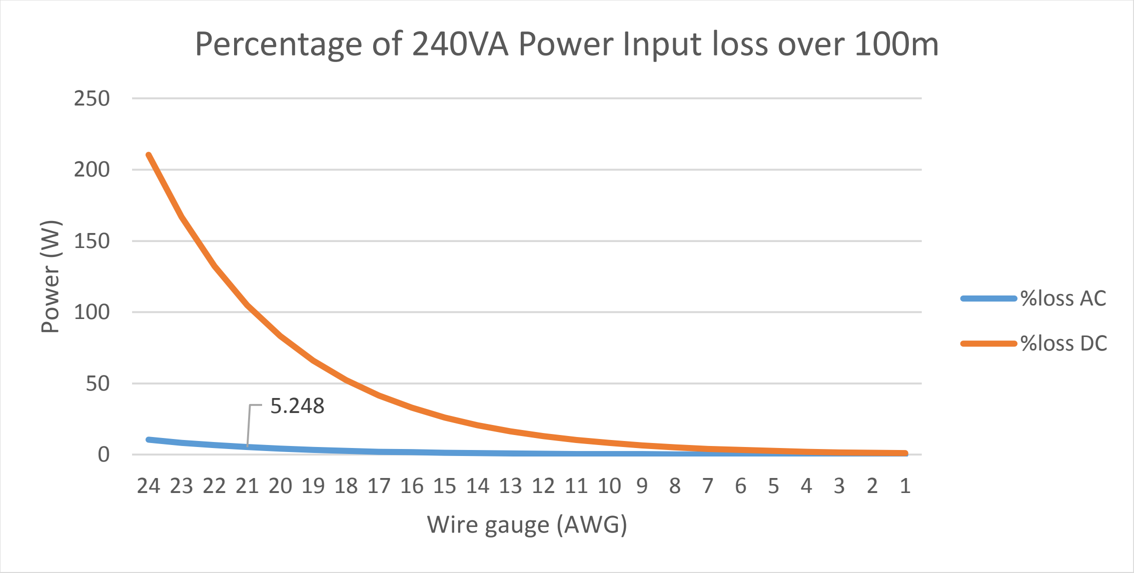


Figure 4-16: 12VDC vs. 240VAC Power loss over 100m (Source: Robe, 2014)

As AWG21 only has a loss of ~5% it has been chosen. This loss will leave an input power of ~227.4VAC at the ROV which is sufficient for an AC to DC converter.

4.6.5 Computer & Electronic Equipment

A Beaglebone Black with three Arduino boards will be used to control the ROV and record all data produced by the other components of the ROV. The Beaglebone Black will be the main processing unit, capable with interfacing with the Ethernet network.

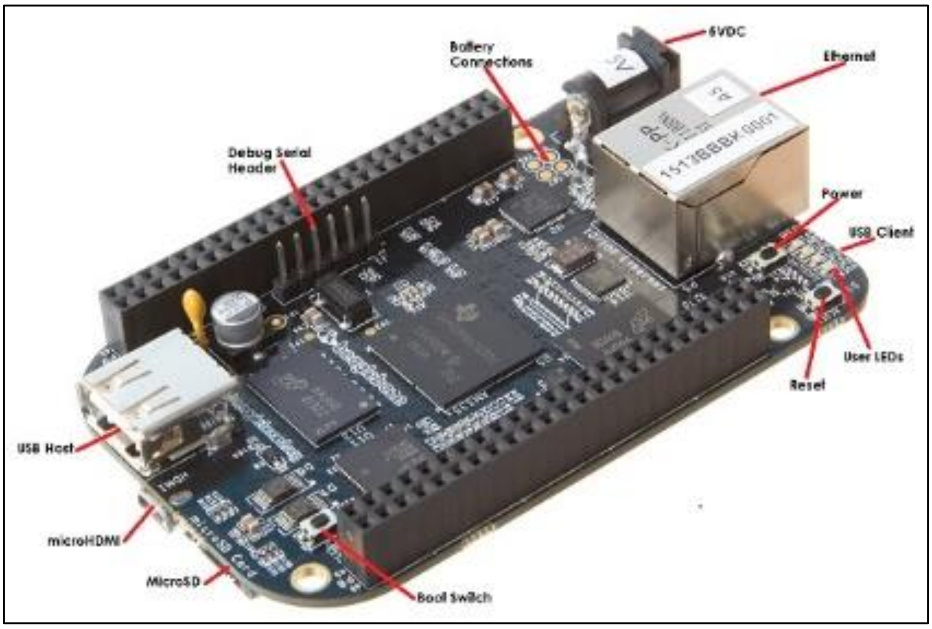


Figure 4-17: Beaglebone Black (Source: elinux, 2014)

There will be one Arduino MEGA board which will compute the Tank Level of the VBS and can feed the telemetry from the sensors back to the BeagleBone Black. The Arduino MEGA v3 has been chosen as it has 16 Analog input pins; where it is required to use only 5(2 – pressure, 1 – VBS level, 2 - Solenoids) this will leave 11 spare analog ports for other sensors in the future. This board has enough computing power to be the driver for the motors as well. The 54 digital I/O ports will be capable of outputting to the motor and the orientation sensor (gyroscope and accelerometer). Initially, a bread board will be utilised to test the second board’s operation with an Arduino MEGA board before construction a custom board.

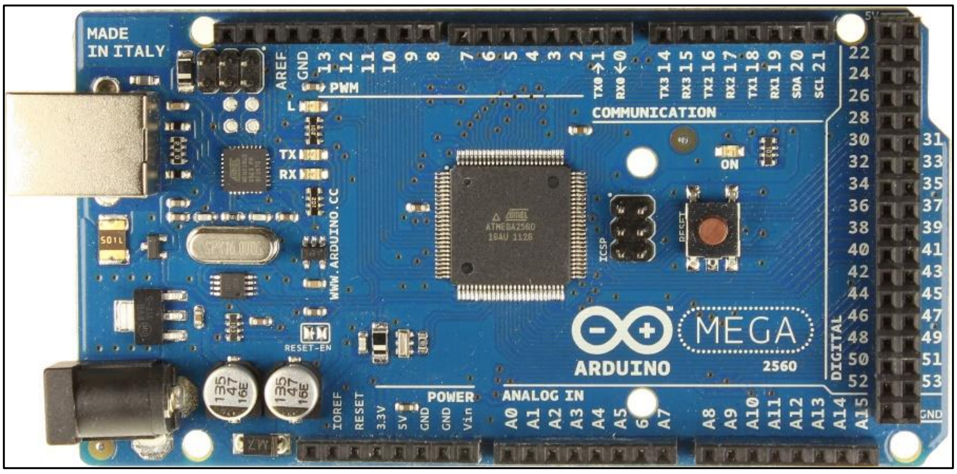


Figure 4-18: Arduino MEGA (Source: Marian, 2014)

The two solenoids only require outputs, but these will be fed back into the analog inputs to show when they are on and off. The pressure sensors will be set at two different locations on the ROV to allow for averaging to occur; this will be a feasible solution to a usually expensive use of depth perception measurement.

This computing equipment was chosen as it is light weight and compact.

The analog absolute pressure sensor is a P51-3000psi cylindrical device valued at USD $96.20. Using piezoresistive technology the sensor outputs an analog signal between 4 to 20mA when pressure between 0 and 3000psi (20.684MPa) is applied to it. The maximum measureable pressure by this sensor far exceeds the system models required depth.

Figure 4-19: Piezoresistive pressure sensor (Source: digi-key, 2014)

There is a 9DOF (nine degrees of freedom) gyroscope/accelerometer/magnetometer will be included. The chosen model is a Pololu MiniMU-9 valued at USD$14.95. The device measures the change in angle per second with the gyroscope, the g-forces by the accelerometer and the gauss (magnetic field) by the magnetometer. Table 4-1 shows the IMU's measurements step-sizes.

Table 4-1: MinIMU-9 9DOF measuring capabilities (Source: Pololu, 2014)

Measurement	Measurement Units	Sensor
$\pm 250, \pm 500, \pm 2000$	°/s (change in angle per second)	Gyroscope
$\pm 2, \pm 4, \pm 8, \pm 16$	g (g-force)	Accelerometer
$\pm 1.3, \pm 1.9, \pm 2.5, \pm 4, \pm 4.7, \pm 5.6, \pm 8.1$	Gauss (magnetic field)	Magnetometer

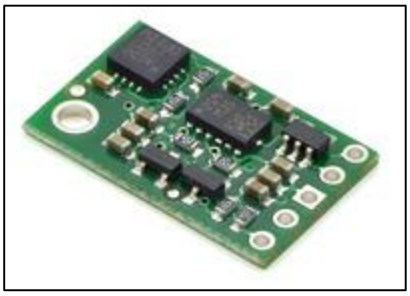


Figure 4-20: MinIMU-9 9DOF Gyro, Compass, Accelerometer (Source: Pololu, 2014)

For voice communication with the divers, a modulated ultrasound device will need to be altered to work with the Beaglebone Black. The ROV will be inclusive of an Ultrasonic voice communicator.

The ultrasonic voice communicator chosen is an Ocean Reef GSM G-Power Communicator. It has a range of 500m and has a runtime of 25hrs. The device will require alteration to work with the computer/phone.

Figure 4-21: Ocean Reef GSM G-Power communicator (Source: Ocean Reef, 2014)

Unfortunately, this device has a maximum permissible depth of ~40 metres. The reason behind this is not specified by Ocean Reef. The product would need to be examined and reinforced to allow for a depth possibility of 100m.

4.7 Final ROV Design

4.7.1 Structural Analysis

NOTE: The detailed drawings for this section can be found in Appendix C.5. Also, the hard 90^{o} corners have been drawn for a higher probability of successful fluid analysis to occur.

Three preliminary designs were created after the preliminary research. Two of which were very similar and are not included in this study. The two designs included function in completely different ways and can be seen in Appendix C.1. The second design would be the least expensive option of the two, but it is not as easy to adjust for different payloads. For this single reason design 1, the cubic shaped one, has be slightly altered for the final design.

The final model has a large compartment for housing the major computing components (4.6.5) shown in green and a small transparent tube for holding the camera and two LEDs. The model also features two large 2.776L buoyancy chambers and two narrow 0.954L weights for concentrating the centre of mass in a lower position. All of these chambers are designed to be attached using ordinary electronics zip ties.

The model has a wet weight of 5.101kg (Appendix C.4) and measures 639.4mm long by 449.03mm wide by 450mm high. These dimensions make for a relatively small ROV, which would be very easy to transport.

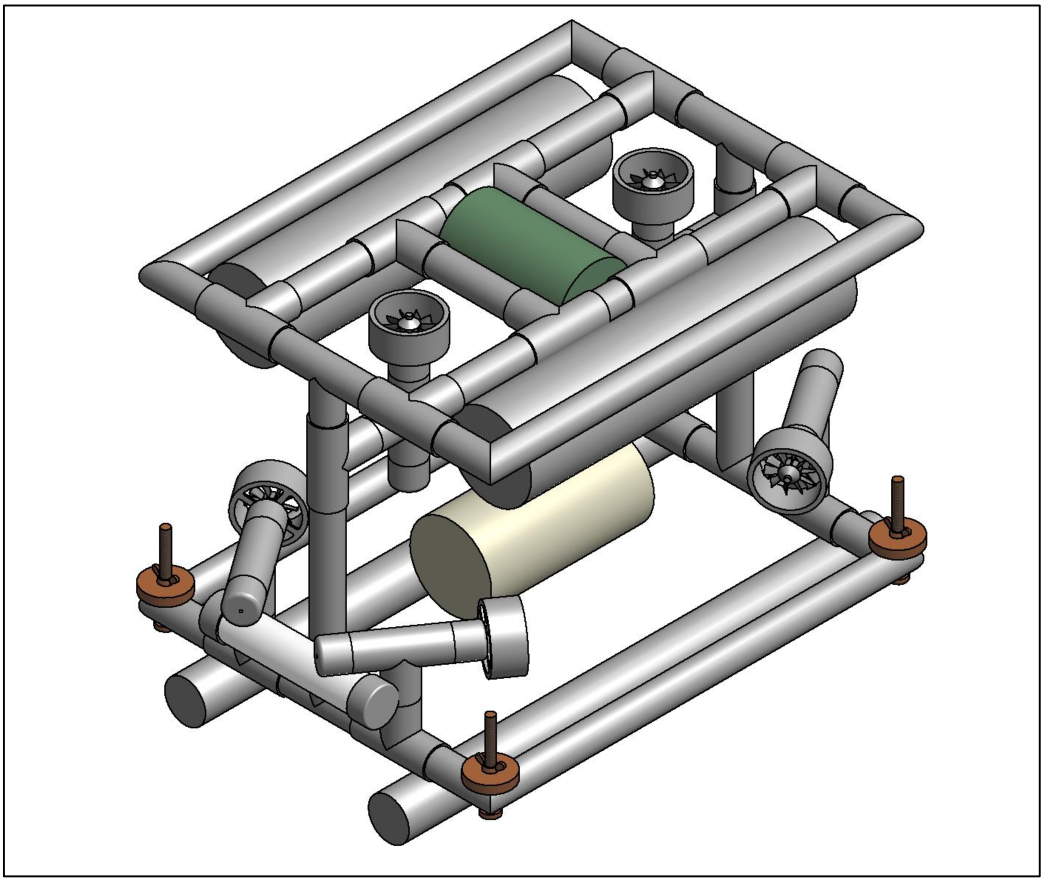


Figure 4-22: Final ROV Design (Source: Robe, 2014)

NOTE: Figure 4-22 shows the ROV without a mesh on the bottom. The mesh runs from corner to corner, fixed between the balance weights and the structure. This mesh will be required for the prototype to carry a payload(s) up to 2kg.

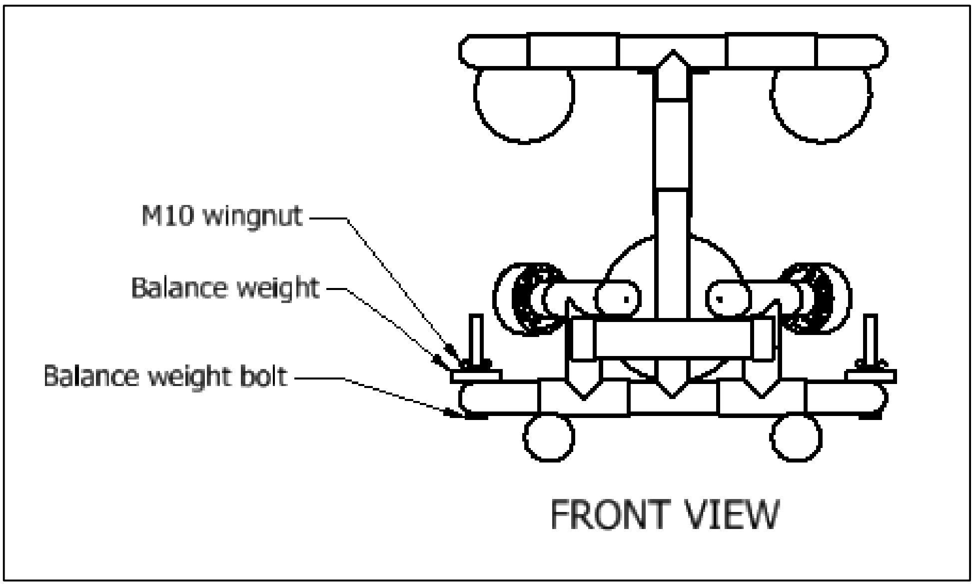


Figure 4-23: ROV design highlighting balancing weight adjuster (Source: Robe, 2014)

The bottom four corners of the vehicle have primary balancing rods (Figure 4-23). These rods are used to adjust the balance of the ROV each time it is launched. This allows for the Centre of Mass to be equally distributed. The balancing weights can be constructed of any material of high density that has an internal diameter of 10mm.

The motor assembly is set in wax. This method has been used by Massachusetts Institute of Technology (MIT) in their SeaPerch ROV project (Appendix C.3). This will seal in the motor and keep it watertight. There is no need for sealing the motors with tape since brushless motors do not need to breathe. Although my design has a tighter seal around the motor, a tolerance of 2mm before the 32m end cap will be used to create the wax seal.

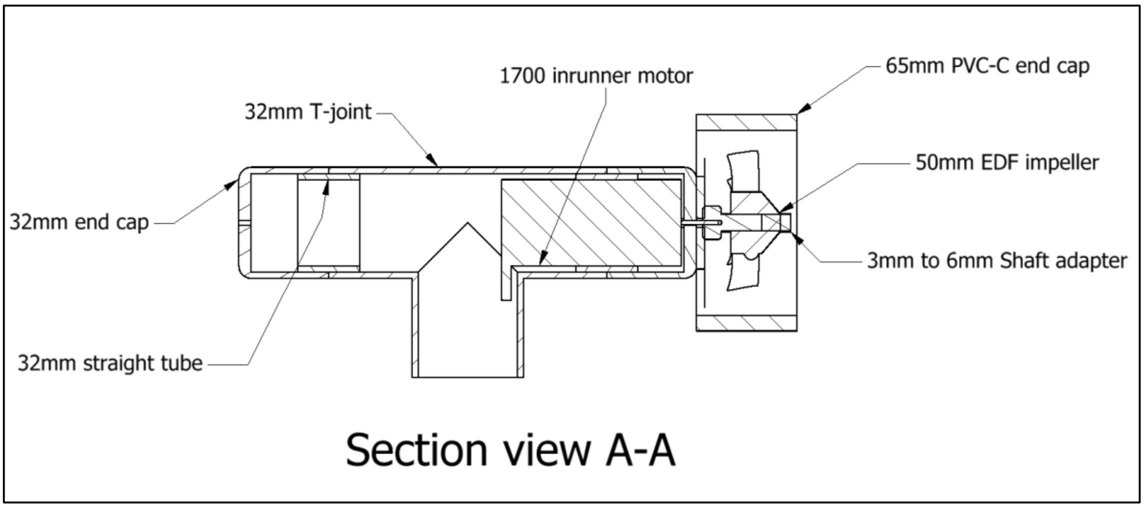


Figure 4-24: Sectional view of the motor assembly (Source: Robe, 2014)

As this design simply slips onto another 32mm PVC tube on the frame, the motor assemblies can be adjusted to their own angles relative to the x-direction for thrust, discussed in Section 4.6.2.

4.7.2 Components

All of the elements to construct the ROV mechanically, and electronically is in Table 4-2.

Table 4-2: ROV component/element costs (Source: Robe, 2014)

QTY	Component	Cost
	Frame Components	
1	100mm Straight 1m PVC	AUD $9.80
6	100mm End Caps PVC	AUD $9.90

1	50mm Straight 1m PVC	AUD $5.50
4	50mm End Caps PVC	AUD $4.00
1	32mm Straight 3m PVC	AUD $11.77
8	32mm Corner PVC	AUD $15.60
18	32mm T-Joint PVC	AUD $46.80
14	32mm End cap PVC	AUD $23.10
1	100mm PMMA tubing	AUD ~$30.00
1	3D printed Components	AUD ~$50.00
N/A	Assorted high pressure connections	AUD ~$20.00
	FRAME TOTAL	AUD $226.40
	All sourced locally in Australia through Hollands Plastics, Bunnings & Master home Improvement.	
	Computer Components	
1	Pololu MinIMU-9[#]	USD $14.95
2	P51-3000psi M20 pressure sensor[#]	USD $192.40
1	BeagleBone Black[#]	USD $54.95
1	Customised Arduino MEGA[#]	AUD ~$100.00
2	High sensitivity water gauges[#]	USD $17.96
	Other Components	
2	MV80 Micro Solenoids[#]	AUD $33.12
1	Logitech HD Pro C920 Webcamera[#]	AUD $159.95
2	Luminus LED[#]	USD $70.00
7	1700kV Brushless Motors	AUD $139.93
7	Dr Mad Thrusters 50mm Impeller	AUD $13.51
7	45A X-Car [#]	AUD $134.05
1	Air Canister[#]	AUD ~$20.00
1	Wax ring[#]	USD $5.00
1	Spare Air[#]	USD $310.00
1	Ocean Reef GSM G-Power communicator[#]	USD $621.95
	NON-FRAME TOTAL	AUD $2415.53*
	GRAND TOTAL	AUD $2641.93*

[*] denotes approximations, not including postage under the assumption of 1.41 multiplier for converting USD to AUD.

[#] denotes items not drawn up for the simulation. The model does have enough space to hold all of the payloads

4.7.3 Fluid Analysis

As discussed in Section 3.5, ANSYS is used to model the fluid dynamics of a 3-dimensional model. ANSYS Fluent is capable of solving the force in the three different directions (X-Y-Z). The force on the elements in a given direction will give a drag force, which can be manually substituted into equations 3.3 (Section 3.5) and 4.2 (Section 4.6.2) to compute the drag coefficient for the design and an estimated propeller diameter.

It is essential that the fluid properties for sea water be used in the simulations, not the default settings for air.

Table 4-3: sea water properties at 10oC (Source: ITTC, Appendix C.5)

Fluid Property at 10°C	Value	Units
Density	1027	$kg.m^3$
Viscosity	0.001397	$kg.m.s$

Initially, ANSYS CFX was unable to compute any results. The model was constrained as shown in Figure 4-25.

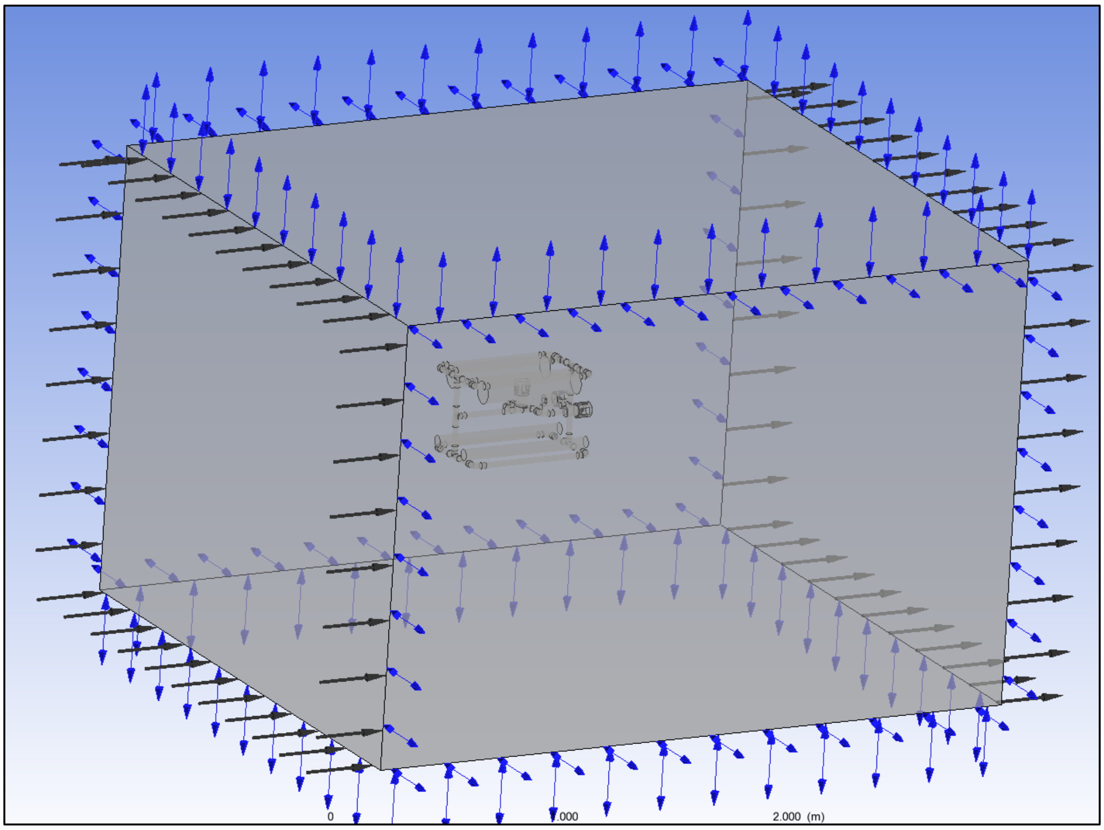


Figure 4-25: ANSYS CFX fully constrained ROV model (Source: Robe, 2014)

The Blue arrows in the simulation window show an open boundary (allow water to flow out, but not directly) the two black arrows are the inlet and outlet.

Since CFX was giving errors, another one of ANSYS' other fluid modelling programs, Fluent was used. ANSYS Fluent is not a very user friendly program when used for such a short period. However, results for a *partially* complete model were attainable.

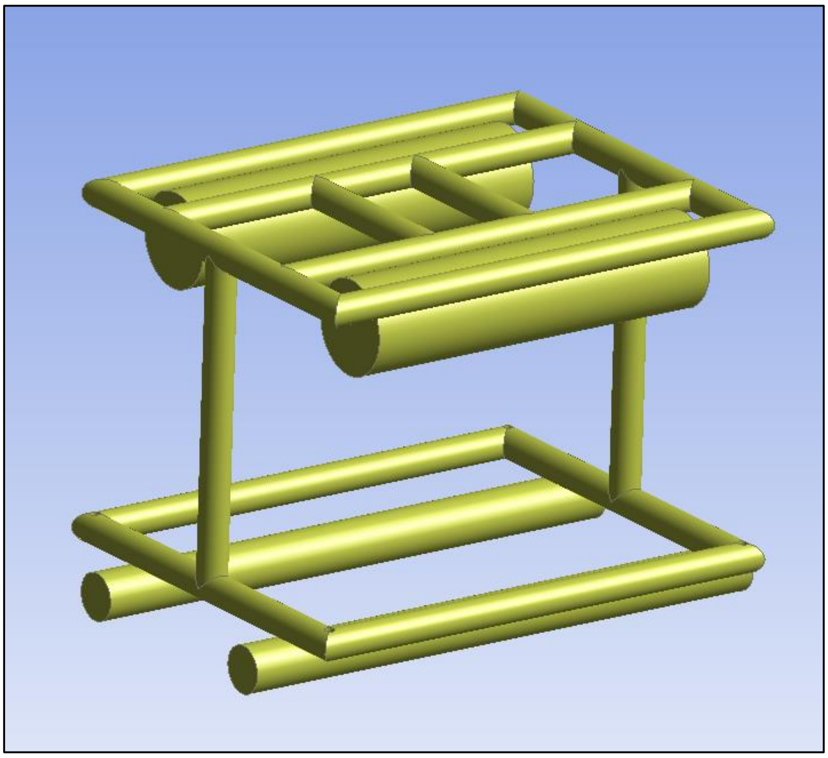


Figure 4-26: Incredibly simplified version on the inventor model for ANSYS (Source: Robe, 2014)

It is unknown whether this was due to lack of computing power or the program that was causing these issues. Results produced by Fluent can be viewed in three different methods. They are: graphics and animations, plots/graphs, and reports. If a simulation in Fluent is setup to compute forces in each plane, it is possible to find the drag or lift forces produced from an object in any fluid. Figure 4-27 shows an outputted result for the static pressure on and around a simplified version of the final. This result was used to compute the approximate drag force of the final design. It is interesting how much turbulence is caused by the two buoyancy capsules. This will not be of concern for the design as the ROV will never operate at this speed in real operating conditions. The simulations done use inputs for the fluid velocity, specified by initial boundary conditions.

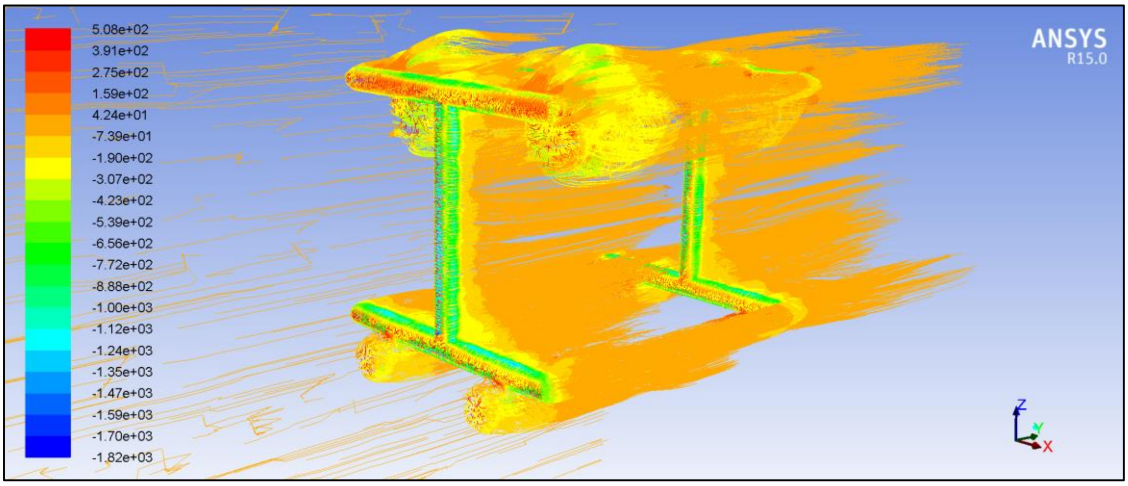
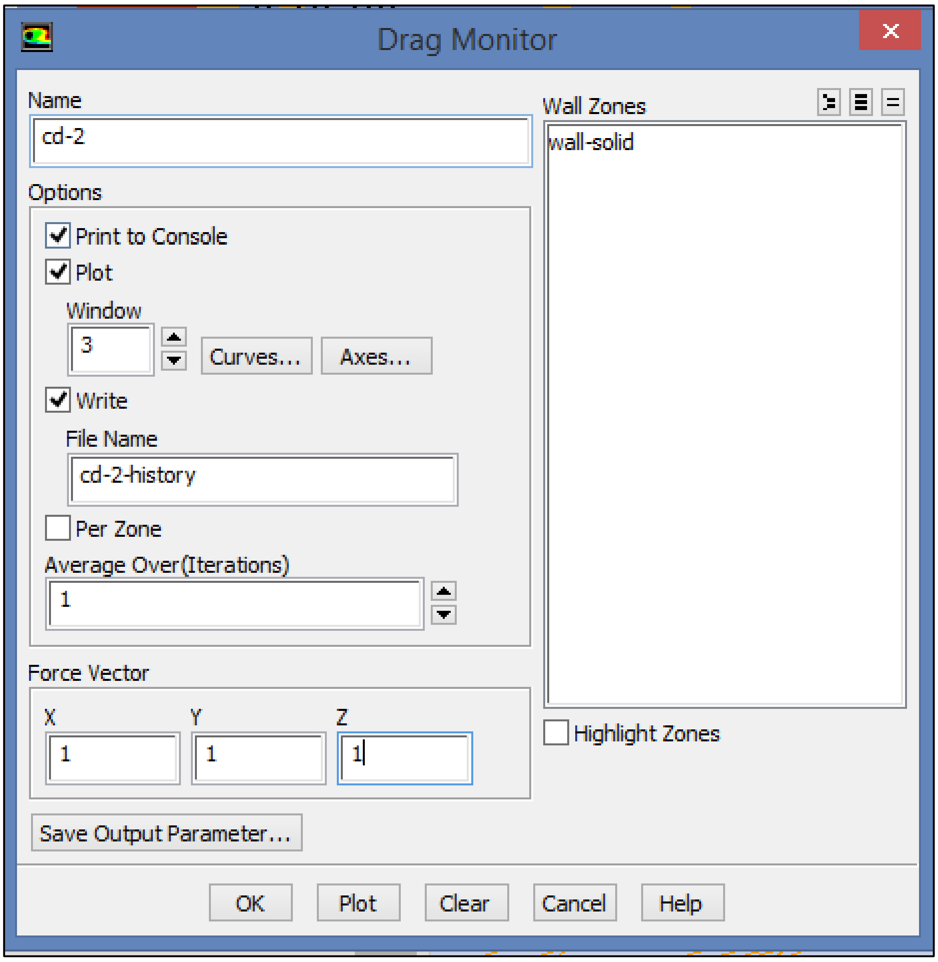


Figure 4-27: ANSYS Fluent simulation result with pathlines representing static pressure (Pa) (Source: Robe, 2014)

The dialogue window underneath this image can print out the previously mentioned reports. For the simulations in this study, drag force is considered. So a monitor is required for the program to compute the results. To do this, create a Drag Monitor in the monitor subsection. After selecting the monitor, designate which force vector(s) required for the program to watch. In Figure 4-28 the drag force on the wall-solid object (naming for the ROV) in the X-Y-Z vectors is considered. This is not the magnitude of all three vectors, it can be chosen later to only investigate one of the three.



Drag Monitor

Name: cd-2

Options

☑ Print to Console

☑ Plot

Window: 3

☑ Write

File Name: cd-2-history

☐ Per Zone

Average Over(Iterations): 1

Force Vector

X: 1

Y: 1

Z: 1

Wall Zones: wall-solid

☐ Highlight Zones

Figure 4-28: Drag monitor inputted for drag force in the X-Y-Z vectors (Source: Robe, 2014)

The results for a drag force (F_D) on the revised model for ANSYS (Figure 4-26) showed 27.415815 N. ANSYS is also capable of deriving the projected area in a specified vector, for the y-direction of the model (direction of fluid on ROV). The results for the same model were 0.488991m^2.

Substituting these values into the equation for drag force and thrust can give the drag coefficient and required propeller diameter needed for this vehicle. The drag coefficient for the model is 0.109 and the recommended propeller diameter is 62.83mm. This is lightly larger than the previously chosen propeller, but as stated in Section

The method taken to get from a 3-dimensional model to a working simulation through ANSYS Fluent can be read through, step-by-step in Appendix C.6.

4.8 Buoy

4.8.1 Structural Requirements

The structural integrity of this model uses the same basic modelling as with the ROV, but the buoy is required to be easily visible on the surface of the water. The design will be assumed to take no impact from any normal water vessels.

The structure will be completely sealed with a Photovoltaic (PV) panel on the surface. With the added weight of the PV panel(s) and the battery bank, the buoy shall continue to be buoyant. To achieve this a buoyancy of +20% of the weight of the buoy will be required to keep it completely buoyant 24/7.

4.8.2 Electronic Requirements

The electronics on board of the buoy take higher priority than that of the ROVs. It will have a cut-off setting so the buoy will always be capable of continuous data transfer so the ROV and buoys' location will never be lost. This cut-off will be applied once the total energy drain is computed for the components on the buoy (GPS, compass and wireless communication link).

The battery capacity is required to be sufficient for a continuous runtime for the ROV of 3 hours (optimal will be found). This is a long period of time for a ROV to be functioning, but will give operators of the ROV ample time to move it before conversing the divers. The cost of this high capacity setup will cause the buoy to be extremely heavy. There will be an optimal weight to ROV runtime to be found; this will only be solvable once a prototype will be built.

4.8.3 Functional Requirements

The minimum functional requirements of the buoy are:

- Compass, to give a heading for the buoy (not the ROV, this is outside of the scope of this system model),
- GPS (Global Positioning System), to give a location (of the buoy, not the ROV)
- Batteries, for powering the whole system
- PV Panels, to charge the batteries continuously in 12hours
- Wireless communication with Traditional IP Network (achievable through a mobile phone device or long-distance WIFI)
- Wireless communication with the Divers
- A spoolable 100m roll of 2-core 16AWG wire

4.9 Buoy Equipment

4.9.1 Photovoltaic Panel(s) & battery bank

Assuming that the current requirements for the ROV are approximately 10Ah total storage for 1hour operation, for a 3hr operating duration approximately 35Ah will be required. This will leave an extra 5Ah for the buoy to continue operation when the rest of the power is drained by the ROV. There are many different types of low capacity batteries available: NiCd(Nickle Cadium), NiMH(Nickle-Methal Hydride), LiIon(Lithium Ion), LiPo(Lithium Polymer). Higher capacity batteries are typically lead-acid and are used in cars. These lead acid batteries are designed with a high burst current (for starting engines) – they are not designed to be completely discharged and recharged frequently.

Batteries which allow for complete discharging and recharging are Deep Cycle batteries. These are high capacity and are constructed from tougher lead components and different conductor types. The two best conductor options for a constantly shifting buoy are the Gel and AGM versions as there is no chance of spillage.

AGM batteries are a battery utilising Absorbed Glass Mat (AGM) technology as a sponge-like material. This sponge-like material suspends the electrolyte within high porous glass fibre mat separators. These differ from the more expensive option of gel batteries, which use a gel to hold the battery plates securely in place. Both versions of these batteries offer no chance of spillage and are incredibly sustainable as long as they do not get over charged.

Battery Barn in Toowoomba offer the FullRiver AGM version battery at 40Ah for AUD $244. This battery is not orientation specific and it has a slim profile due to its low amperage rating. These features allow for multiple batteries to be installed in a low profile area.

Requiring a 35Ah, 420Wh drain from the components a 56.875Ah minimum battery capacity will be required. Assuming a 30% safety net for discharge and a power consumption of 80% (for a sustainable battery life) of the battery’s capacity…

The chosen batteries will be capable of a total discharge time of ~6.4hrs until the 80% battery limitation is met.

Figure 4-29: Century Deep Cycle Gel battery (Source: Century Batteries, 2014)

Photovoltaic Panels convert solar radiation to DC electricity. The PV panel chosen is a USD $209.95 semi-flexible 62W solar panel that would take ~18.5hrs to charge the battery bank (assuming 30% extra to charge). The standard variant PV panels are very heavy, weighing about 7.5kg whereas the Kulkyne panel is only 1.3kg. This weight difference is extremely important to stop the buoy from tipping over.

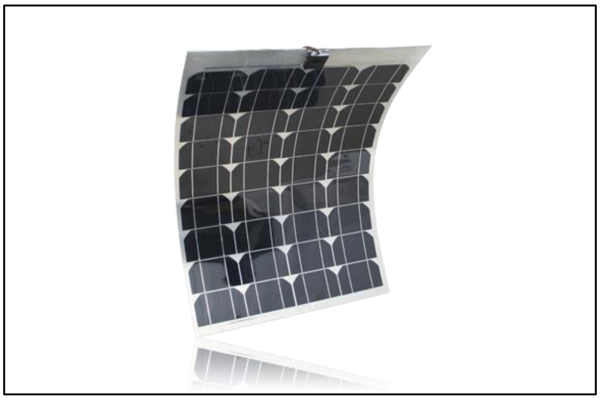


Figure 4-30: 62W Semi-flexible PV Panel (Source: Kulkyne Kampers, 2014)

To avoid any damage occurring to the batteries, a current regulator will be included.

4.9.2 Electronic Components (GPS, Compass & Wireless transmission)

Different types of electronic components were considered, however the decision to purchase an affordable Android phone would be the best solution. Android phones come standard with GPS, WiFi, GSM networking and compass capabilities. A Samsung Galaxy Neo has been chosen as it is the most affordable (AUD$125) Android device available with full functionality with Australia’s 3G Network.

Figure 4-31: Samsung Galaxy Neo (Source: JB Hifi, 2014)

The second option was to use a WiFi network adapter, typically used in laptops, for the communication with the operator. This can be adapted with a high power, long distance antenna. This comes at a higher cost than the Android alternative but would be more secure and easier to test with another computer. Using a long distance WiFi antenna option, the GPS and compass would need to be integrated into another computer. If this method was used, a TP-Link Hi Power long distance signal booster could be used (Figure

4-32). This booster is capable of a 50km range, which would be more than sufficient for the system model.

Figure 4-32: TP-Link TL- WA5110G Hi Power Long Distance WiFi (Source: Stardot, 2014)

Other components (GPS and compass) for the second buoy communication method has not been covered in this study. This would need to be considered as it has a higher chance of lower power consumption than the Android alternative.

4.10 Final Buoy Design

3-dimensional models for the buoy concept have not been investigated in detail for this study. The design will essentially consist of a large electronics box measuring a minimum of 800 x 540mm to house the Kulkyne PV panel. This box will have a depth slightly larger than the smallest width of the batteries; for the chosen batteries this is 174mm. One of the smaller faces will have a plastic spool for the 100m long tether to coil onto. The method of keeping the tension for the tether has not been covered. The other small face will have high buoyancy tubing mounted to it.

The battery packs will be mounted relatively close to the absolute middle of the structure. As they weigh 13.4kg each, the batteries are the main weight component on the buoy. The buoyancy of the device will need to exceed the sum total weight of the components by 20% to reduce the chances of submersion and, if submersed, the duration of submersion.

4.10.1 Components

All of the elements to construct the ROV mechanically, and electronically are in Table 4-4. Most of these values are estimated from prior experience constructing projects.

Table 4-4: Buoy component cost list (Source: Robe, 2014)

QTY	Component	Cost
	Frame Components	
1	Sealable Electronics Box	AUD ~$100.00
1	Waterproof Phone Box	AUD ~$10.00
	FRAME TOTAL	AUD $110.00*
	Computer Components	
1	Android Phone	AUD $125.00
1	Power over Ethernet	AUD ~$60.00
	Other Components	
1	Fittings	AUD ~$50.00
2	Deep Cycle AGM battery	AUD $488.00
1	Semi-Flexible Solar Panel	AUD $209.95
1	Current regulator	AUD ~$20.00
1	22AWG wire at 308m a reel (ferret.com.au)s	AUD $109.29
	NON-FRAME TOTAL	AUD $1062.24*
	GRAND TOTAL	AUD $1172.24*

[*] denotes approximations, not including postage under the assumption of 1.41 multiplier for converting USD to AUD.

CHAPTER 5

CONCLUSIONS

This study investigated the problems, trends and needs of marine archaeologists and ROVs and was successful in designing a system model which would be capable of:

- Long-distance, wireless operator control
    - Possible with a tether between the ROV and buoy
- Live verbal and visual communication with marine archaeologists

In this study these aspects have been researched to be economically and physically feasible. The ROV communicates with a buoy through a tether. The buoy is capable of two-way communication with an operator in a remote location.

The ROV's frame is constructed with PVC tubing. The capsule for video capture is made from PMMA tubing which is a transparent material. The frame costs a total of AUD $226.40. The components of the complete system with buoy comes to AUD $3814.17 which is below the AUD $4000 budget. This valuation does not include GST and postage for items from the United States of America. These extra costings could easily inflate the cost to over AUD $4000. This would still be a very affordable design as it features two innovative ideas in its system model listed at the start of this chapter.

If the objective of the research was to have an innovative, sustainable design capable of only wireless control (i.e. ignoring anything related to divers), the cost immediately drops to AUD $2500.11. This is achieved by not including the verbal communicator (Ocean Reef GSM G-Power communicator) and the emergency air for the divers.

The overall design would be relatively easy to transport as the ROV has small dimensions of 639.4 x 449.03 x 450mm and the buoy can be minimised to being approximately 800 x 540 x 180mm. The package would be quite easy to pack for transport between locations.

5.1 Future Work

The testing procedure outlined in Section 3.6 for the propellers, ESCs and motors will need to be done. Currently, these tests have never been done for the non-standard hobby market components.

Before building the main structure, the testing of the theoretical electronic system will need to be dry tested. This will ensure that the system will be sufficient for continuous work without load. A beneficial addition would be a method of ascertaining the location of the ROV relative to the buoy.

Another subsection which requires more work is a variable ballast system. The submersible pump has to withstand a pressure of 1.01MPa while pumping water into a tank. The design of the impeller, choice of motors and choice of valves is very important here.

Building and testing of a prototype of the elements of the system model, primarily the ROV, is necessary to evaluate if the computed values are accurate before doing field work.

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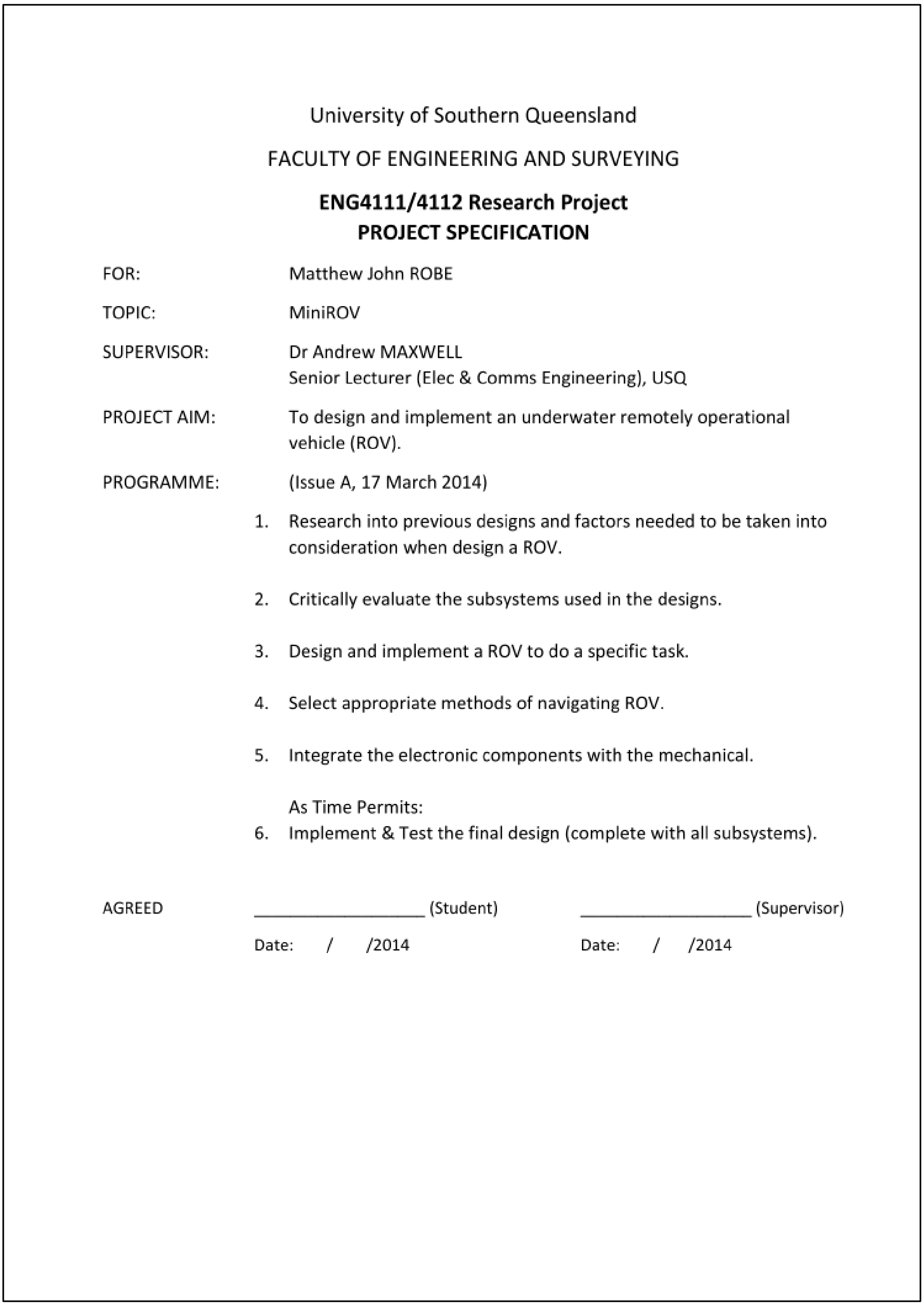
APPENDICES

Appendix A Project Specification



University of Southern Queensland

FACULTY OF ENGINEERING AND SURVEYING

ENG4111/4112 Research Project
PROJECT SPECIFICATION

FOR: Matthew John ROBE

TOPIC: MiniROV

SUPERVISOR: Dr Andrew MAXWELL
Senior Lecturer (Elec & Comms Engineering), USQ

PROJECT AIM: To design and implement an underwater remotely operational vehicle (ROV).

PROGRAMME: (Issue A, 17 March 2014)

1. Research into previous designs and factors needed to be taken into consideration when design a ROV.
2. Critically evaluate the subsystems used in the designs.
3. Design and implement a ROV to do a specific task.
4. Select appropriate methods of navigating ROV.
5. Integrate the electronic components with the mechanical.

As Time Permits:

6. Implement & Test the final design (complete with all subsystems).

AGREED ___________________ (Student) ___________________ (Supervisor)

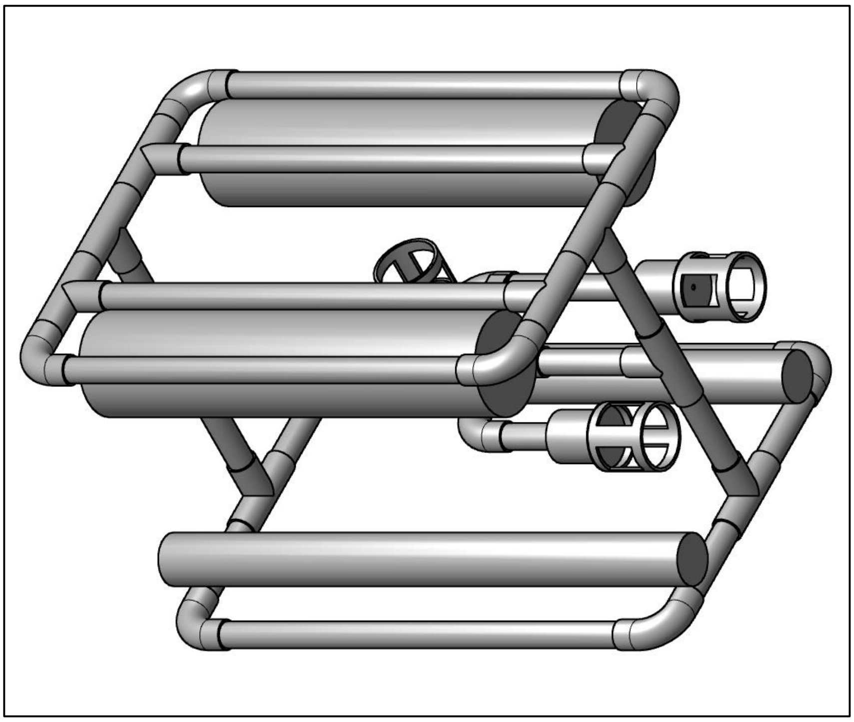
Date: / /2014 Date: / /2014

Appendix B Table of Materials

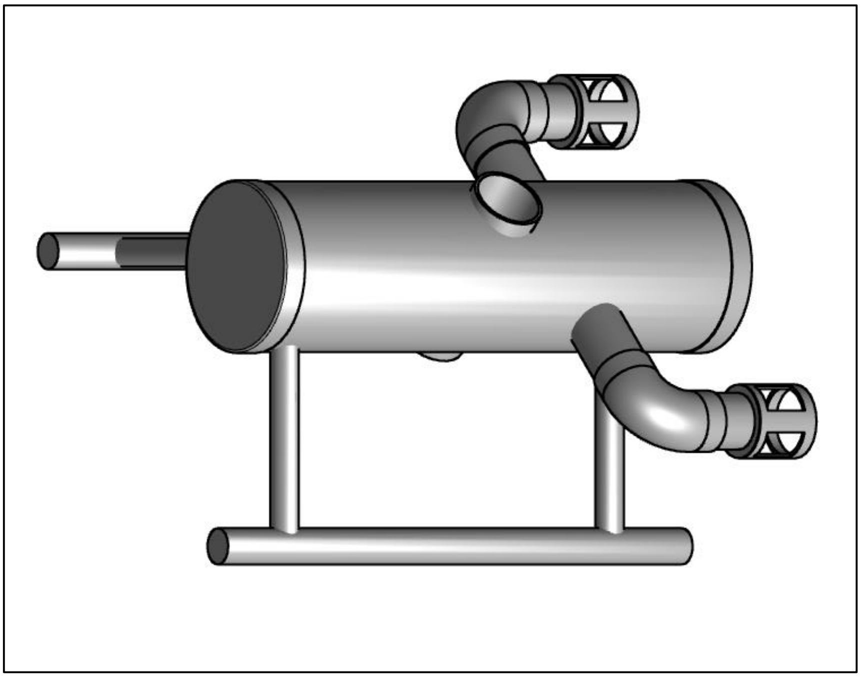
PVC				
Outside Diameter (mm)	Thickness (mm)	Description	Length (mm)	Max pressure (MPa)
15	1.6	Full Length – Straight	1000	11.413
20	2	Full length - Straight	1000	10.7
25	2	Full length – Straight	1000	8.56
32	2	Full length – Straight	1000	6.688
40	2	Full length – Straight	1000	5.35
50	2.5	Full length – Straight	1000	5.35
50	3	Full length – Straight	5000	6.42
65	2.5	Full length – Straight	1000	4.458
90	1.8	Full length – Straight	1000	2.14
90	1.5	Full length – Straight	5000	1.783
100	2.5	Full length – Straight	1000	2.675
100	3	Full length – Straight	5000	3.21
150	3	Full length – Straight	1000	2.14
Holland Plastics PMMA clear Tubing				
15	2	Full Length – Straight	N/A	16
20	2	Full Length – Straight	N/A	12
25	2	Full Length – Straight	N/A	9.6
30	2	Full Length – Straight	N/A	8
40	2	Full Length – Straight	N/A	6
50	2	Full Length – Straight	N/A	4.8
60	3	Full Length – Straight	N/A	6
90	3	Full Length – Straight	N/A	4
100	3	Full Length – Straight	N/A	3.6
150	3	Full Length – Straight	N/A	2.4
200	4	Full Length – Straight	N/A	2.4

Appendix C ROV Design

Appendix C.1 ROV preliminary designs



Design #1: A small, simple 3 motor ROV.

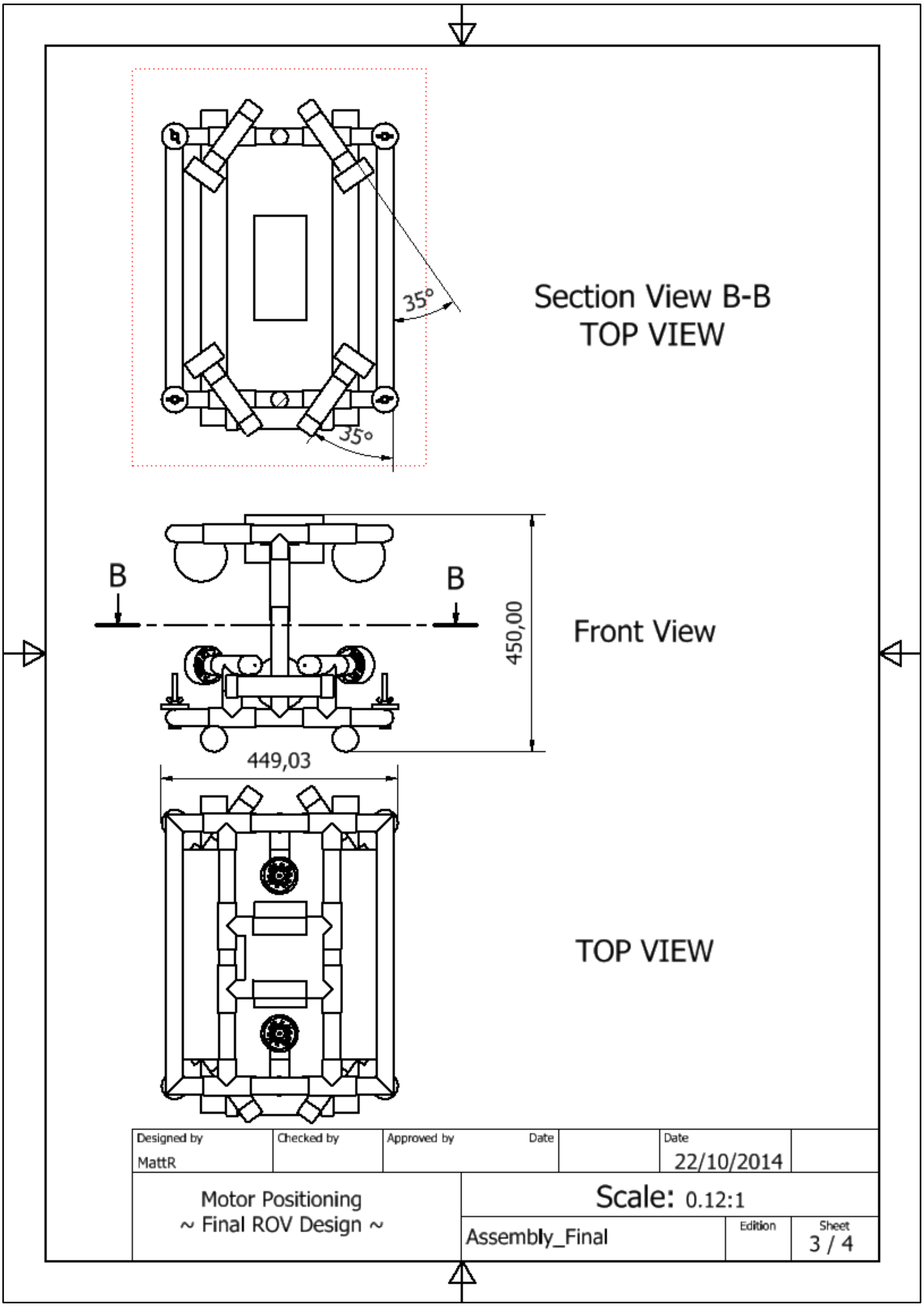


(should have a clear cap on the left most face of the major 150mm element)

Design #2: A small, complex to build, cheap to manufacture ROV.

Appendix C.2 ROV Detailed Drawings

NOTE: All final drawings do not include the corner 90^0 PVC-C. This was done for the simulations, as they have a higher chance of success when using a smaller number of parts.

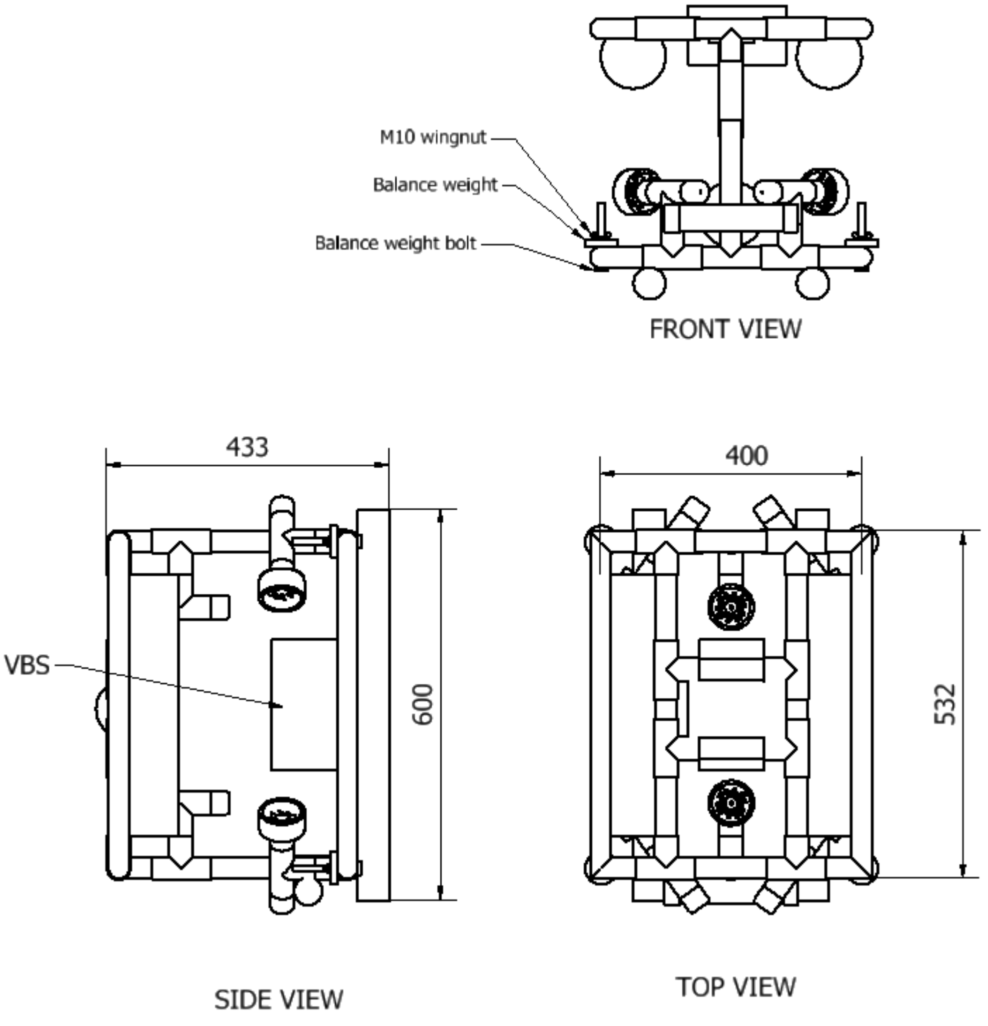


Designed by	Checked by	Approved by	Date	Date
MattR				22/10/2014

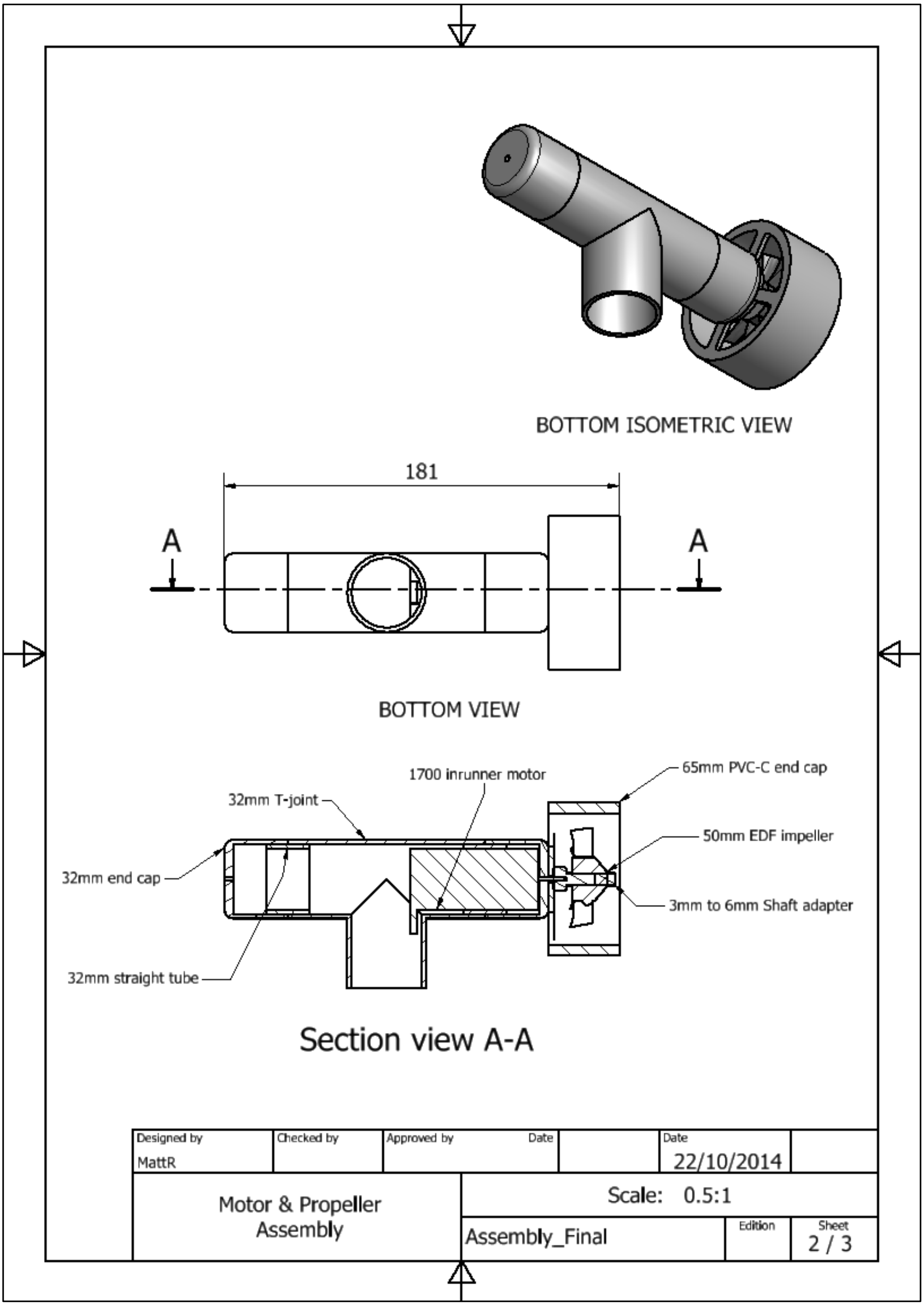
Motor Positioning
~ Final ROV Design ~

Scale: 0.12:1

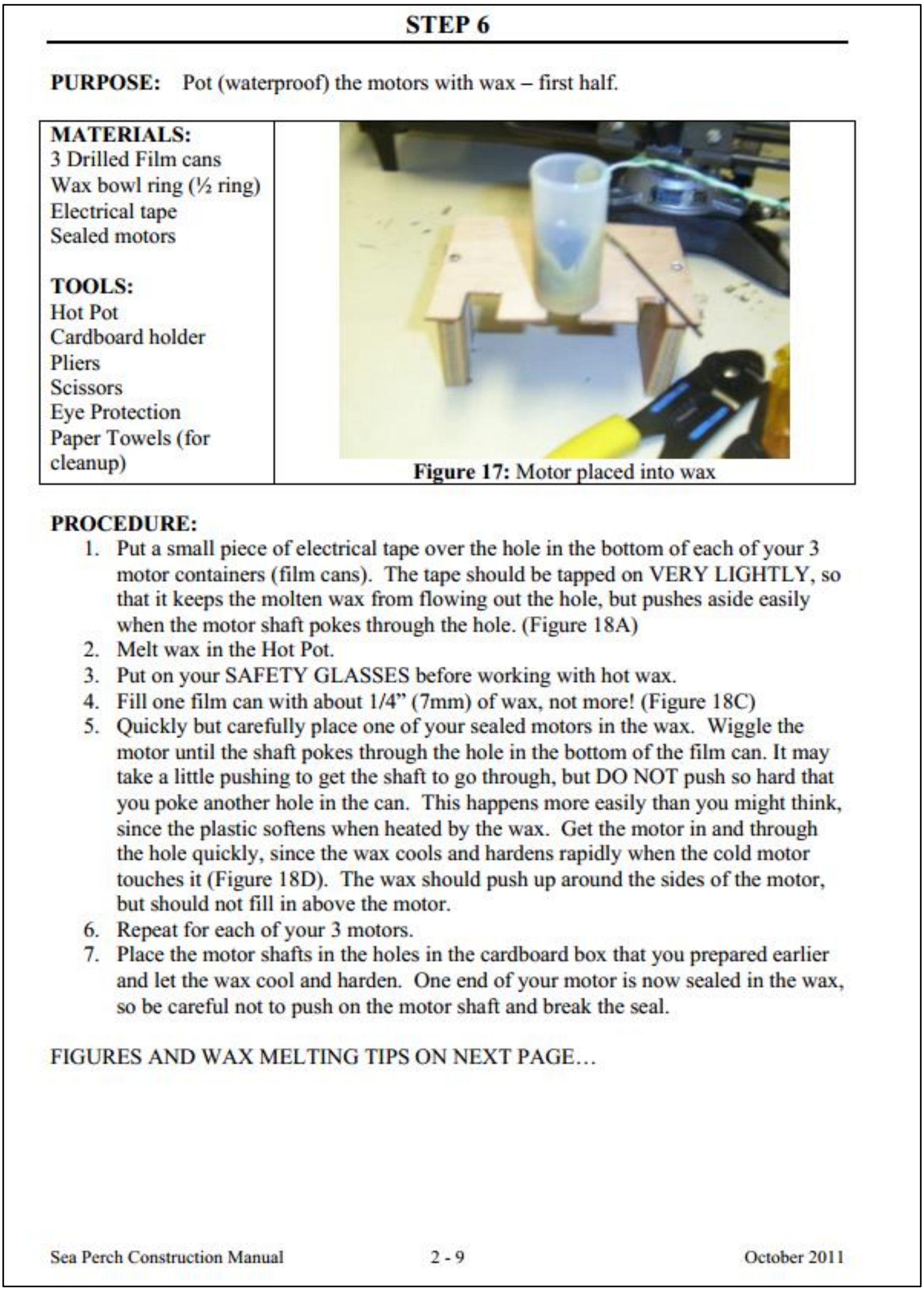
Assembly_Final	Edition	Sheet
		3 / 4



Designed by MattR	Checked by	Approved by	Date		Date 22/10/2014	
Final Design, complete with no full VBS drawn	Scale: 0.12:1					
	Assembly_Final				Edition	Sheet 1 / 4


BOTTOM ISOMETRIC VIEW
181
A
A
BOTTOM VIEW
1700 inrunner motor
65mm PVC-C end cap
32mm T-joint
50mm EDF impeller
32mm end cap
3mm to 6mm Shaft adapter
32mm straight tube
Section view A-A
Designed by
MattR
Checked by
Approved by
Date
Date
22/10/2014
Motor & Propeller Assembly
Scale: 0.5:1
Assembly_Final
Edition
Sheet
2 / 3

Appendix C.3 MIT Wax for waterproofing (pages 9-11)



STEP 6

PURPOSE: Pot (waterproof) the motors with wax – first half.

MATERIALS:
3 Drilled Film cans
Wax bowl ring (½ ring)
Electrical tape
Sealed motors

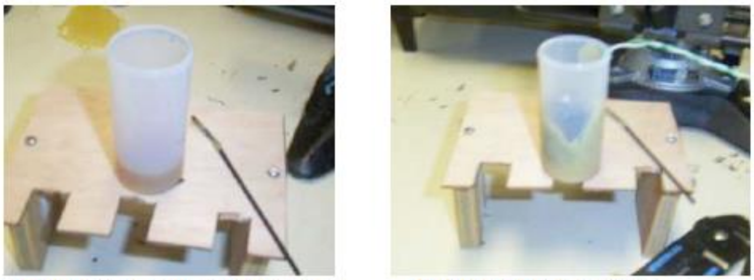
TOOLS:
Hot Pot
Cardboard holder
Pliers
Scissors
Eye Protection
Paper Towels (for cleanup)

Figure 17: Motor placed into wax

PROCEDURE:

1. Put a small piece of electrical tape over the hole in the bottom of each of your 3 motor containers (film cans). The tape should be tapped on VERY LIGHTLY, so that it keeps the molten wax from flowing out the hole, but pushes aside easily when the motor shaft pokes through the hole. (Figure 18A)
2. Melt wax in the Hot Pot.
3. Put on your SAFETY GLASSES before working with hot wax.
4. Fill one film can with about 1/4" (7mm) of wax, not more! (Figure 18C)
5. Quickly but carefully place one of your sealed motors in the wax. Wiggle the motor until the shaft pokes through the hole in the bottom of the film can. It may take a little pushing to get the shaft to go through, but DO NOT push so hard that you poke another hole in the can. This happens more easily than you might think, since the plastic softens when heated by the wax. Get the motor in and through the hole quickly, since the wax cools and hardens rapidly when the cold motor touches it (Figure 18D). The wax should push up around the sides of the motor, but should not fill in above the motor.
6. Repeat for each of your 3 motors.
7. Place the motor shafts in the holes in the cardboard box that you prepared earlier and let the wax cool and harden. One end of your motor is now sealed in the wax, so be careful not to push on the motor shaft and break the seal.

FIGURES AND WAX MELTING TIPS ON NEXT PAGE…



A: Film can partially filled with wax **B:** Motor placed into wax

Figure 18A and B: Potting the motors

Wax Melting Tips:
Always wear SAFETY GLASSES when working with hot wax. The soft wax used in this project can get very sticky. An apron and gloves (latex, nitrile, etc.) are highly recommended. To facilitate cleanup, put a drop cloth on the work bench, on the ground below it, and on the wall behind it. Avoid getting wax on your clothes. To get wax off your skin, wash with warm water and dish soap.

1. The molten wax is hot, but should not be hot enough to burn the thick skin on your the palms of your hands. More sensitive skin or large quantities of hot wax may cause burns. In case of a burn, quickly rinse the area with LOTS of cold water.
2. One wax ring will usually pot about 6 motors (enough for 2 SeaPerch ROVs).

    1. Once all three of your containers have a motor in them, we will fill them the rest of the way with wax, in 2 steps.
    2. Fill the container with wax up to 1/2 inch below the top (Figure 19A & B). (We fill them up only partway, since the wax shrinks as it cools, and we want to make sure everything is filled with wax, not air pockets.) Pour the wax so that it fills in all the air spaces around the motor.
    3. Lift your container and look at it from the side to see if you have any air bubbles. Get out any air bubbles while the wax is still liquid by squeezing the container.
    4. Set the container up on your stand to cool, and repeat for the other two.
    5. While you are waiting for your wax to cool, make sure your SAFETY GLASSES are on, and put on an apron and gloves since the wax often squirts out during the next steps!
    6. Once the wax has cooled, push the caps up to the knots in the wires and coil the wires into the cans. Make sure the caps go on well, and then remove them again.
    7. Carefully fill one container to the top with wax, creating a positive meniscus (Figure 19C).
    8. Quickly but carefully roll the cap onto the container, leaving as little air inside as possible (Figure 19D). Watch for wax squirting out the hole in the cap!

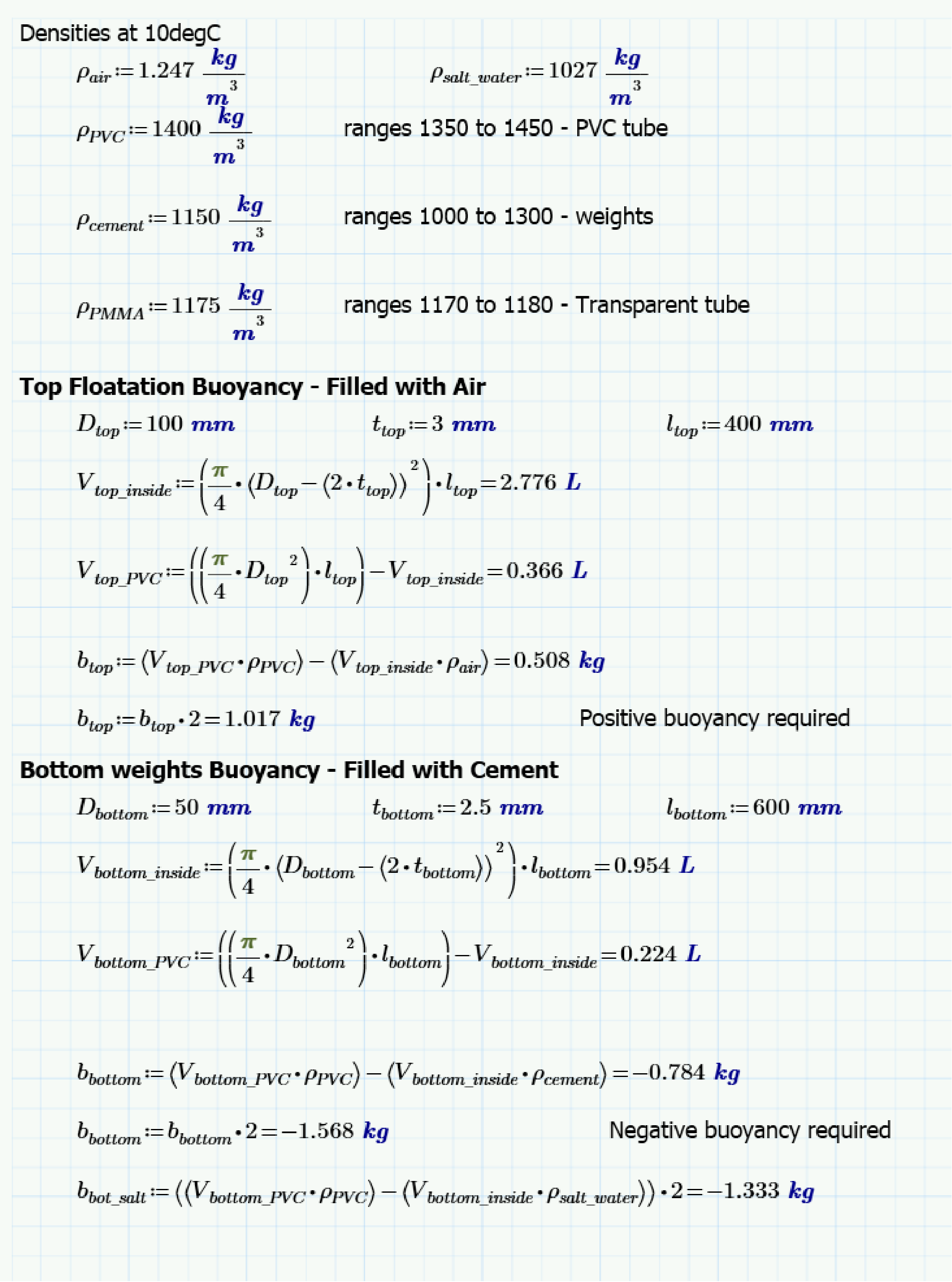
9. Repeat these steps for the other 2 motors, and let the wax cool and harden. ***TIP- Once wax is hardened, recheck motors with test wire to make sure connections are still good, and wax did not seize the motor.**

A: Second wax layer **B:** Filled part way

C: Positive meniscus **D:** Filled all the way

Figure 19 A-D: Potting the motors – Final two wax steps

Appendix C.4 ROV Buoyancy calculations using PTC MathCAD®.



Densities at 10degC

$\rho_{air} := 1.247\ \frac{kg}{m^3}$ $\rho_{salt\_water} := 1027\ \frac{kg}{m^3}$

$\rho_{PVC} := 1400\ \frac{kg}{m^3}$ ranges 1350 to 1450 - PVC tube

$\rho_{cement} := 1150\ \frac{kg}{m^3}$ ranges 1000 to 1300 - weights

$\rho_{PMMA} := 1175\ \frac{kg}{m^3}$ ranges 1170 to 1180 - Transparent tube

Top Floatation Buoyancy - Filled with Air

$D_{top} := 100\ mm$ $t_{top} := 3\ mm$ $l_{top} := 400\ mm$

$$V_{top\_inside} := \left(\frac{\pi}{4}\cdot\left(D_{top}-\left(2\cdot t_{top}\right)\right)^2\right)\cdot l_{top} = 2.776\ L$$

$$V_{top\_PVC} := \left(\left(\frac{\pi}{4}\cdot D_{top}^{\ 2}\right)\cdot l_{top}\right) - V_{top\_inside} = 0.366\ L$$

$$b_{top} := \left(V_{top\_PVC}\cdot\rho_{PVC}\right) - \left(V_{top\_inside}\cdot\rho_{air}\right) = 0.508\ kg$$

$b_{top} := b_{top}\cdot 2 = 1.017\ kg$ Positive buoyancy required

Bottom weights Buoyancy - Filled with Cement

$D_{bottom} := 50\ mm$ $t_{bottom} := 2.5\ mm$ $l_{bottom} := 600\ mm$

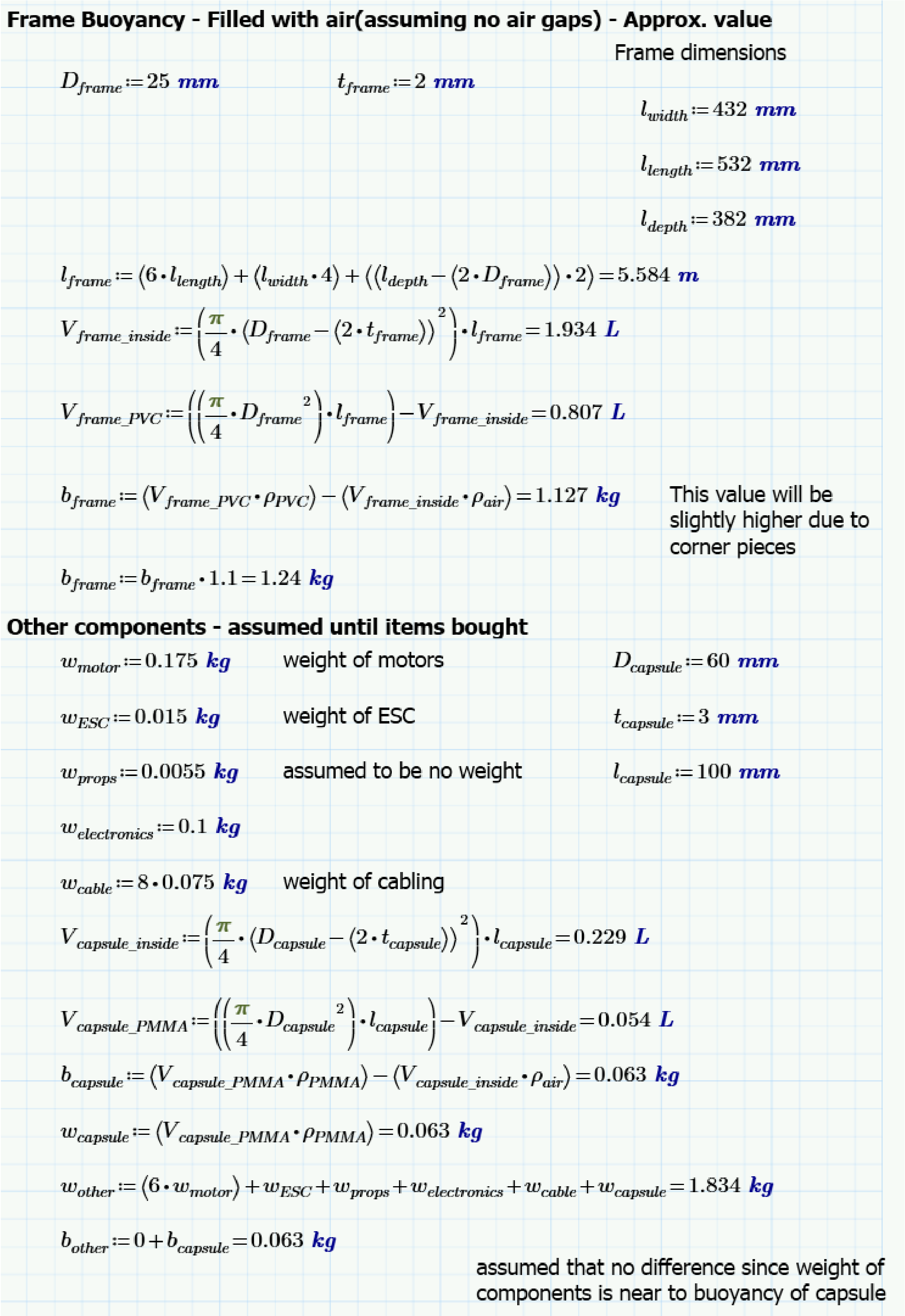
$$V_{bottom\_inside} := \left(\frac{\pi}{4}\cdot\left(D_{bottom}-\left(2\cdot t_{bottom}\right)\right)^2\right)\cdot l_{bottom} = 0.954\ L$$

$$V_{bottom\_PVC} := \left(\left(\frac{\pi}{4}\cdot D_{bottom}^{\ 2}\right)\cdot l_{bottom}\right) - V_{bottom\_inside} = 0.224\ L$$

$$b_{bottom} := \left(V_{bottom\_PVC}\cdot\rho_{PVC}\right) - \left(V_{bottom\_inside}\cdot\rho_{cement}\right) = -0.784\ kg$$

$b_{bottom} := b_{bottom}\cdot 2 = -1.568\ kg$ Negative buoyancy required

$$b_{bot\_salt} := \left(\left(V_{bottom\_PVC}\cdot\rho_{PVC}\right) - \left(V_{bottom\_inside}\cdot\rho_{salt\_water}\right)\right)\cdot 2 = -1.333\ kg$$



Frame Buoyancy - Filled with air(assuming no air gaps) - Approx. value

$D_{frame} := 25\ mm$

$t_{frame} := 2\ mm$

Frame dimensions

$l_{width} := 432\ mm$

$l_{length} := 532\ mm$

$l_{depth} := 382\ mm$

$$l_{frame} := \left(6 \cdot l_{length}\right) + \left(l_{width} \cdot 4\right) + \left(\left(l_{depth} - \left(2 \cdot D_{frame}\right)\right) \cdot 2\right) = 5.584\ m$$

$$V_{frame\_inside} := \left(\frac{\pi}{4} \cdot \left(D_{frame} - \left(2 \cdot t_{frame}\right)\right)^2\right) \cdot l_{frame} = 1.934\ L$$

$$V_{frame\_PVC} := \left(\left(\frac{\pi}{4} \cdot D_{frame}^{\ 2}\right) \cdot l_{frame}\right) - V_{frame\_inside} = 0.807\ L$$

$$b_{frame} := \left(V_{frame\_PVC} \cdot \rho_{PVC}\right) - \left(V_{frame\_inside} \cdot \rho_{air}\right) = 1.127\ kg$$

This value will be slightly higher due to corner pieces

$$b_{frame} := b_{frame} \cdot 1.1 = 1.24\ kg$$

Other components - assumed until items bought

$w_{motor} := 0.175\ kg$ weight of motors

$w_{ESC} := 0.015\ kg$ weight of ESC

$w_{props} := 0.0055\ kg$ assumed to be no weight

$w_{electronics} := 0.1\ kg$

$w_{cable} := 8 \cdot 0.075\ kg$ weight of cabling

$D_{capsule} := 60\ mm$

$t_{capsule} := 3\ mm$

$l_{capsule} := 100\ mm$

$$V_{capsule\_inside} := \left(\frac{\pi}{4} \cdot \left(D_{capsule} - \left(2 \cdot t_{capsule}\right)\right)^2\right) \cdot l_{capsule} = 0.229\ L$$

$$V_{capsule\_PMMA} := \left(\left(\frac{\pi}{4} \cdot D_{capsule}^{\ 2}\right) \cdot l_{capsule}\right) - V_{capsule\_inside} = 0.054\ L$$

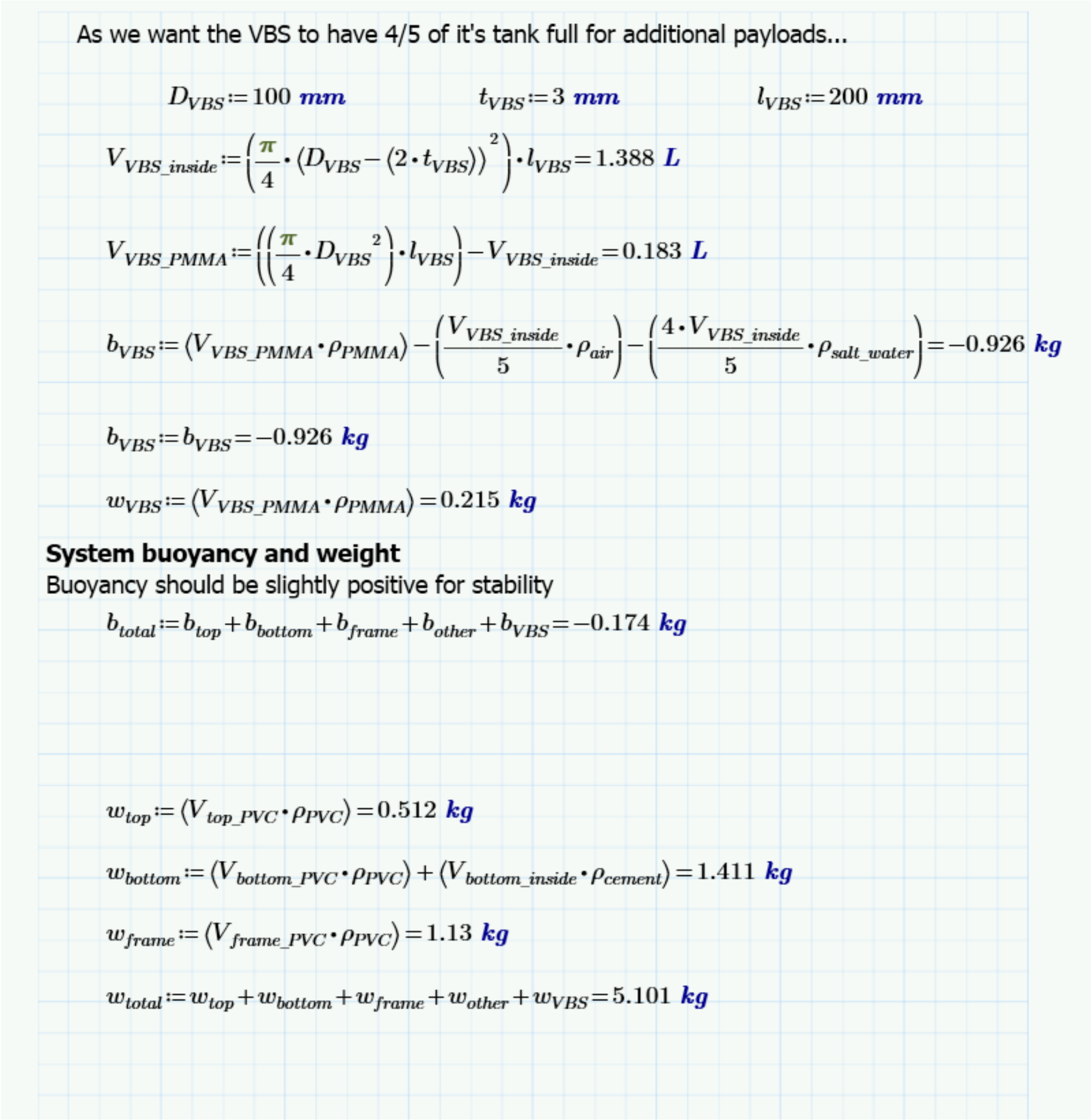
$$b_{capsule} := \left(V_{capsule\_PMMA} \cdot \rho_{PMMA}\right) - \left(V_{capsule\_inside} \cdot \rho_{air}\right) = 0.063\ kg$$

$$w_{capsule} := \left(V_{capsule\_PMMA} \cdot \rho_{PMMA}\right) = 0.063\ kg$$

$$w_{other} := \left(6 \cdot w_{motor}\right) + w_{ESC} + w_{props} + w_{electronics} + w_{cable} + w_{capsule} = 1.834\ kg$$

$$b_{other} := 0 + b_{capsule} = 0.063\ kg$$

assumed that no difference since weight of components is near to buoyancy of capsule



As we want the VBS to have 4/5 of it's tank full for additional payloads...

$D_{VBS} := 100\ \mathbf{mm}$ $t_{VBS} := 3\ \mathbf{mm}$ $l_{VBS} := 200\ \mathbf{mm}$

$$V_{VBS\_inside} := \left(\frac{\pi}{4} \cdot \left(D_{VBS} - \left(2 \cdot t_{VBS}\right)\right)^2\right) \cdot l_{VBS} = 1.388\ \mathbf{L}$$

$$V_{VBS\_PMMA} := \left(\left(\frac{\pi}{4} \cdot D_{VBS}{}^2\right) \cdot l_{VBS}\right) - V_{VBS\_inside} = 0.183\ \mathbf{L}$$

$$b_{VBS} := \left(V_{VBS\_PMMA} \cdot \rho_{PMMA}\right) - \left(\frac{V_{VBS\_inside}}{5} \cdot \rho_{air}\right) - \left(\frac{4 \cdot V_{VBS\_inside}}{5} \cdot \rho_{salt\_water}\right) = -0.926\ \mathbf{kg}$$

$$b_{VBS} := b_{VBS} = -0.926\ \mathbf{kg}$$

$$w_{VBS} := \left(V_{VBS\_PMMA} \cdot \rho_{PMMA}\right) = 0.215\ \mathbf{kg}$$

System buoyancy and weight

Buoyancy should be slightly positive for stability

$$b_{total} := b_{top} + b_{bottom} + b_{frame} + b_{other} + b_{VBS} = -0.174\ \mathbf{kg}$$

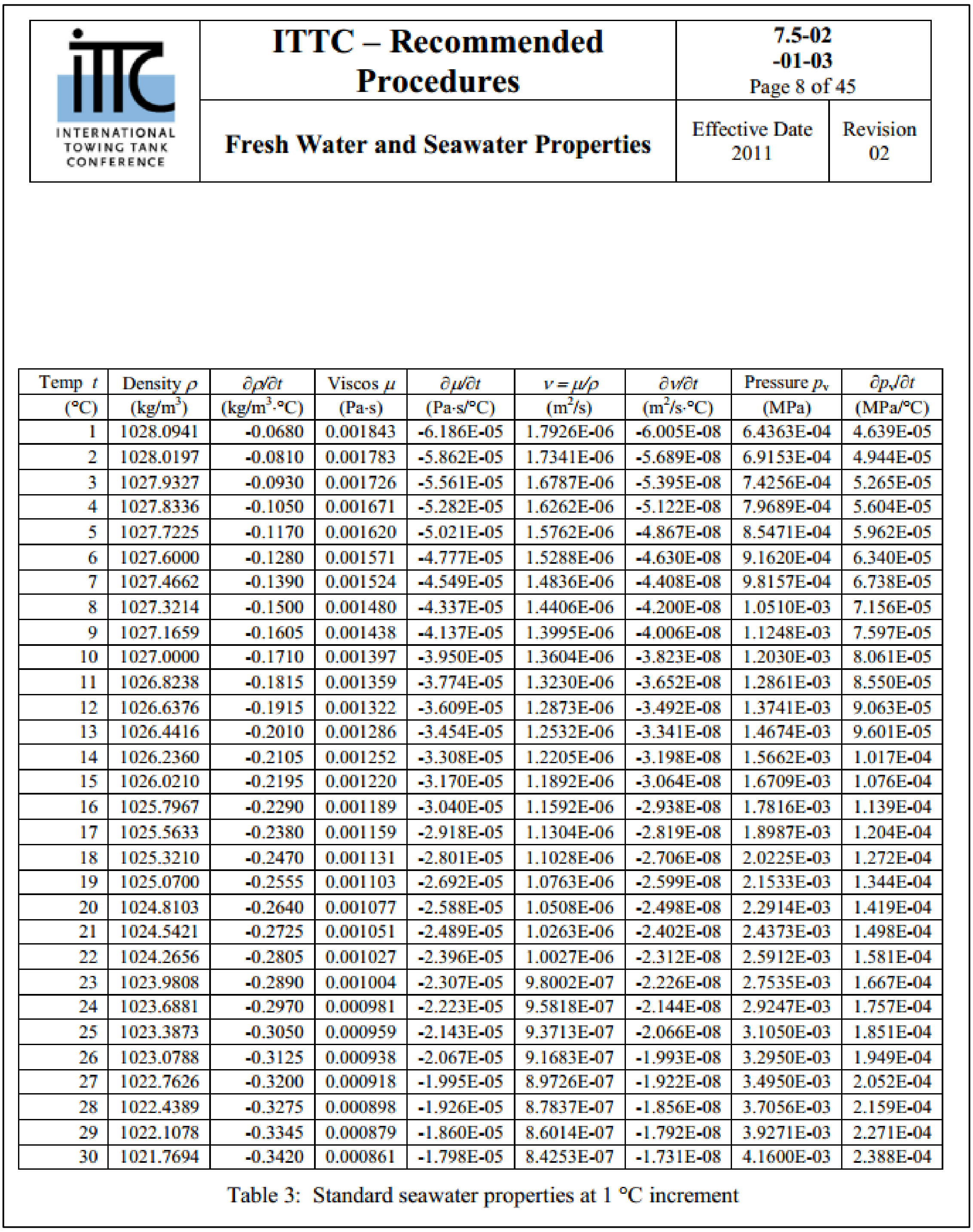
$$w_{top} := \left(V_{top\_PVC} \cdot \rho_{PVC}\right) = 0.512\ \mathbf{kg}$$

$$w_{bottom} := \left(V_{bottom\_PVC} \cdot \rho_{PVC}\right) + \left(V_{bottom\_inside} \cdot \rho_{cement}\right) = 1.411\ \mathbf{kg}$$

$$w_{frame} := \left(V_{frame\_PVC} \cdot \rho_{PVC}\right) = 1.13\ \mathbf{kg}$$

$$w_{total} := w_{top} + w_{bottom} + w_{frame} + w_{other} + w_{VBS} = 5.101\ \mathbf{kg}$$

Appendix C.5 Sea Water Properties



INTERNATIONAL
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CONFERENCE

ITTC – Recommended Procedures

7.5-02 -01-03
Page 8 of 45

Fresh Water and Seawater Properties

Effective Date 2011

Revision 02

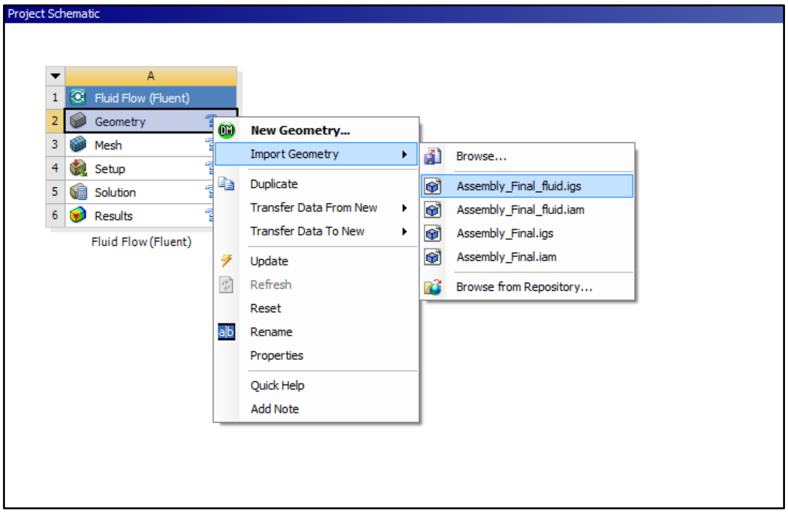
Temp t (°C)	Density ρ (kg/m^3)	$\partial\rho/\partial t$ (kg/m^3·°C)	Viscos μ (Pa·s)	$\partial\mu/\partial t$ (Pa·s/°C)	$\nu = \mu/\rho$ (m^2/s)	$\partial\nu/\partial t$ (m^2/s·°C)	Pressure p_v (MPa)	$\partial p_v/\partial t$ (MPa/°C)
1	1028.0941	-0.0680	0.001843	-6.186E-05	1.7926E-06	-6.005E-08	6.4363E-04	4.639E-05
2	1028.0197	-0.0810	0.001783	-5.862E-05	1.7341E-06	-5.689E-08	6.9153E-04	4.944E-05
3	1027.9327	-0.0930	0.001726	-5.561E-05	1.6787E-06	-5.395E-08	7.4256E-04	5.265E-05
4	1027.8336	-0.1050	0.001671	-5.282E-05	1.6262E-06	-5.122E-08	7.9689E-04	5.604E-05
5	1027.7225	-0.1170	0.001620	-5.021E-05	1.5762E-06	-4.867E-08	8.5471E-04	5.962E-05
6	1027.6000	-0.1280	0.001571	-4.777E-05	1.5288E-06	-4.630E-08	9.1620E-04	6.340E-05
7	1027.4662	-0.1390	0.001524	-4.549E-05	1.4836E-06	-4.408E-08	9.8157E-04	6.738E-05
8	1027.3214	-0.1500	0.001480	-4.337E-05	1.4406E-06	-4.200E-08	1.0510E-03	7.156E-05
9	1027.1659	-0.1605	0.001438	-4.137E-05	1.3995E-06	-4.006E-08	1.1248E-03	7.597E-05
10	1027.0000	-0.1710	0.001397	-3.950E-05	1.3604E-06	-3.823E-08	1.2030E-03	8.061E-05
11	1026.8238	-0.1815	0.001359	-3.774E-05	1.3230E-06	-3.652E-08	1.2861E-03	8.550E-05
12	1026.6376	-0.1915	0.001322	-3.609E-05	1.2873E-06	-3.492E-08	1.3741E-03	9.063E-05
13	1026.4416	-0.2010	0.001286	-3.454E-05	1.2532E-06	-3.341E-08	1.4674E-03	9.601E-05
14	1026.2360	-0.2105	0.001252	-3.308E-05	1.2205E-06	-3.198E-08	1.5662E-03	1.017E-04
15	1026.0210	-0.2195	0.001220	-3.170E-05	1.1892E-06	-3.064E-08	1.6709E-03	1.076E-04
16	1025.7967	-0.2290	0.001189	-3.040E-05	1.1592E-06	-2.938E-08	1.7816E-03	1.139E-04
17	1025.5633	-0.2380	0.001159	-2.918E-05	1.1304E-06	-2.819E-08	1.8987E-03	1.204E-04
18	1025.3210	-0.2470	0.001131	-2.801E-05	1.1028E-06	-2.706E-08	2.0225E-03	1.272E-04
19	1025.0700	-0.2555	0.001103	-2.692E-05	1.0763E-06	-2.599E-08	2.1533E-03	1.344E-04
20	1024.8103	-0.2640	0.001077	-2.588E-05	1.0508E-06	-2.498E-08	2.2914E-03	1.419E-04
21	1024.5421	-0.2725	0.001051	-2.489E-05	1.0263E-06	-2.402E-08	2.4373E-03	1.498E-04
22	1024.2656	-0.2805	0.001027	-2.396E-05	1.0027E-06	-2.312E-08	2.5912E-03	1.581E-04
23	1023.9808	-0.2890	0.001004	-2.307E-05	9.8002E-07	-2.226E-08	2.7535E-03	1.667E-04
24	1023.6881	-0.2970	0.000981	-2.223E-05	9.5818E-07	-2.144E-08	2.9247E-03	1.757E-04
25	1023.3873	-0.3050	0.000959	-2.143E-05	9.3713E-07	-2.066E-08	3.1050E-03	1.851E-04
26	1023.0788	-0.3125	0.000938	-2.067E-05	9.1683E-07	-1.993E-08	3.2950E-03	1.949E-04
27	1022.7626	-0.3200	0.000918	-1.995E-05	8.9726E-07	-1.922E-08	3.4950E-03	2.052E-04
28	1022.4389	-0.3275	0.000898	-1.926E-05	8.7837E-07	-1.856E-08	3.7056E-03	2.159E-04
29	1022.1078	-0.3345	0.000879	-1.860E-05	8.6014E-07	-1.792E-08	3.9271E-03	2.271E-04
30	1021.7694	-0.3420	0.000861	-1.798E-05	8.4253E-07	-1.731E-08	4.1600E-03	2.388E-04

Table 3: Standard seawater properties at 1 °C increment

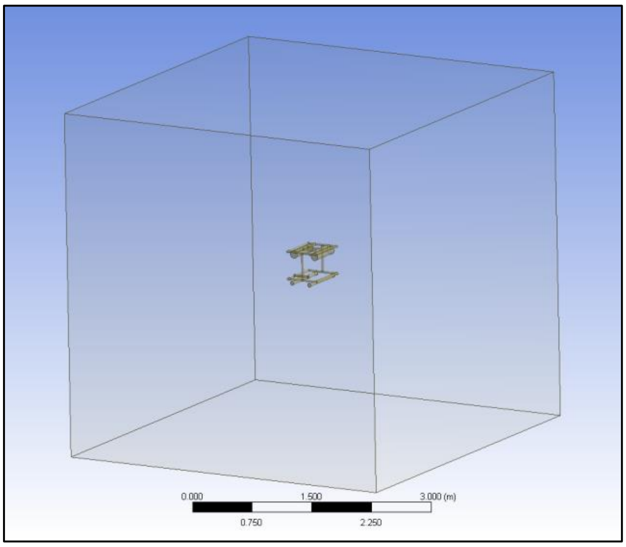
Appendix C.6 3D *.iges models to working simulations

No captions for images here since they are all my work for the walkthrough.

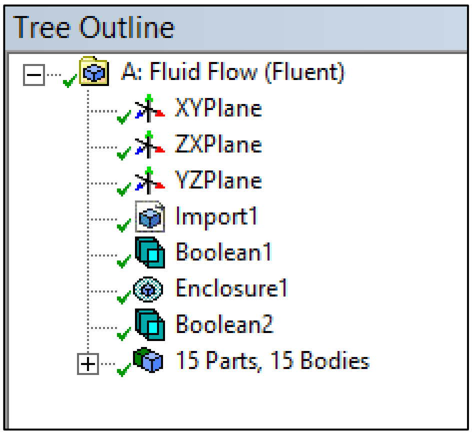
The inventor based *.iam or *.ipt file was saved as a *.iges file for easier manipulation through ANSYS. ANSYS Workbench is started up, and “Fluid Flow (Fluent) is dragged to the project schematic to make a standalone fluid analysis. The *.iges file is imported into the geometry by going to the standalone analysis and importing the 3D file into the geometry, shown below.



This is "edited" so that all parts of the geometry form into one, using the Boolean tool 'unite'. An enclosure is them produced to encompass the ROV with a 2m buffer, shown below.



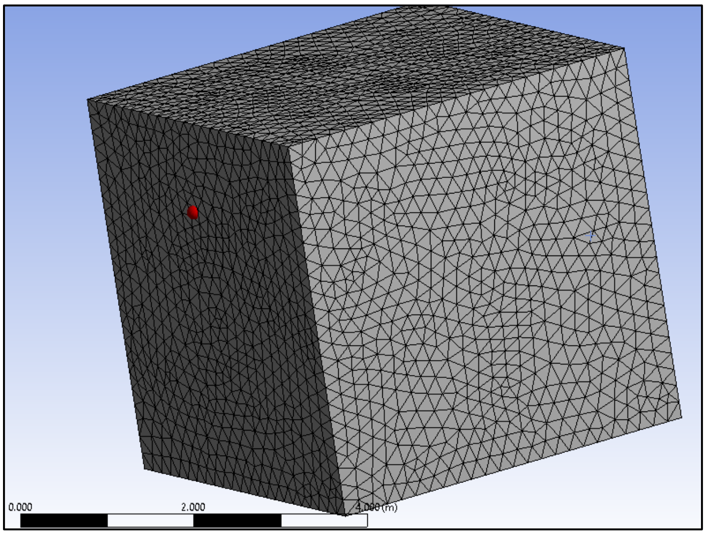
The solid that is the ROV is then subtracted from the enclosure to create an interior "wall". This leaves an outline of the ROV inside the cube. The tree in the DesignModeler will look like the below image.



Tree Outline

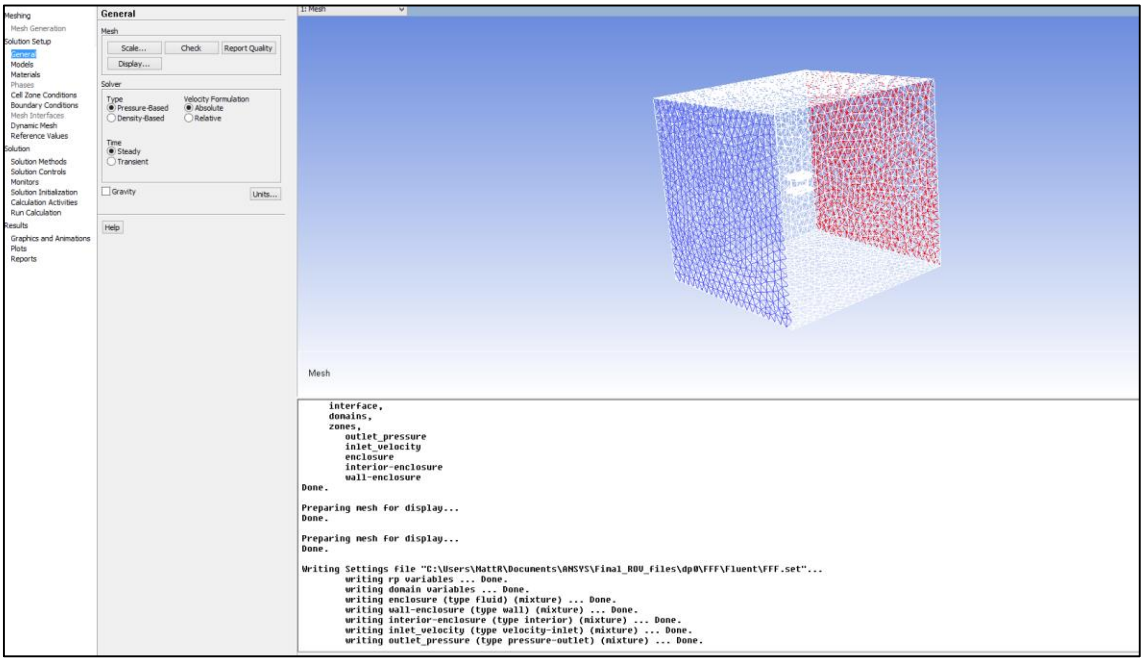
- A: Fluid Flow (Fluent)
  - XYPlane
  - ZXPlane
  - YZPlane
  - Import1
  - Boolean1
  - Enclosure1
  - Boolean2
  - 15 Parts, 15 Bodies

Now it’s time to create a mesh of the interior and exterior of the ROV, using the meshing program (second option down in the standalone analysis tool). The mesh is of medium grade, which takes a tolerable amount of time to calculate and draw, without taking an hour or so just to build a mesh. In this section, named selections are done… One called “INLET VELOCITY” the other “OUTLET PRESSURE”. Now the mesh is generated, this can take a while…



This is what it looks like with the external mesh and internal mesh done. You can only see the internal mesh if you activate “Wire Frame” mode. Updating of this mesh is required back on the Workbench area. Now to set up the simulation…

Enter the “setup” area of the standalone analysis on the Workbench. A window showing the below will appear.



Type
● Pressure-Based
○ Density-Based

Velocity Formulation
● Absolute
○ Relative

Time
● Steady
○ Transient

☐ Gravity

```
     interface,
     domains,
     zones,
        outlet_pressure
        inlet_velocity
        enclosure
        interior-enclosure
        wall-enclosure
Done.

Preparing mesh for display...
Done.

Preparing mesh for display...
Done.

Writing Settings file "C:\Users\MattR\Documents\ANSYS\Final_ROV_files\dp0\FFF\Fluent\FFF.set"...
        writing rp variables ... Done.
        writing domain variables ... Done.
        writing enclosure (type fluid) (mixture) ... Done.
        writing wall-enclosure (type wall) (mixture) ... Done.
        writing interior-enclosure (type interior) (mixture) ... Done.
        writing inlet_velocity (type velocity-inlet) (mixture) ... Done.
        writing outlet_pressure (type pressure-outlet) (mixture) ... Done.
```

Where the red face is the OUTLET_PRESSURE and the blue face is the INLET_VELOCITY. “Check” is required in the General area, this checks the mesh so that there are DEFINITELY no errors. In the “materials” tab, a new fluid is created for sea_water. Choose a new name, enter it’s density and viscosity, then click on “change/create”, select no in the “Question” window.

Next the cell zone conditions need to be made. It defaults to air for the enclosure, edit it to being sea_water. Continue to “Boundary Conditions”, here the inlet velocity is set to 1m/s. Jumping down to “monitors” create whatever monitors are required for the simulation. I chose to make a drag in the X-Y_Z vectors.

Selection of “Standard Initialization” for the Solution Initialisation is required. Compute it from the INPUT_PRESSURE. And initialize…

At the bottom of the Solution tree, Select “Run Calculator”. Input desired iterations (I found 100 to be accurate enough). Check the case… Then run the calculation. This is the most time consuming part of the simulation. As the software steps through the iterations until it finds the constants.

Viewing of the results can occur in the “Results” tree, in the form of the plots, print outs (Reports) and visual aids.