UoSS Orca

University of Southampton Human Powered Submarine team

Abstract

This report describes the design of the University of Southampton's entry the UoSS Orca, which will be entered into the International Submarine Race 2015. This report provides an overview of the design and manufacturing processes which has been fervently carried out by our team.

Acknowledgements

The members of the Southampton University Human Powered Submarine Team (SUHPS) would like to thank QinetiQ for the financial support provided for our entry. As our major sponsor we would not have made it to the competition without their generosity.

We would also like to thank our other sponsors Tindale Systems and Zest Racing who helped in the manufacturing, Andark Diving and Watersports Centre who helped train our diver team and provided testing facilities, and the Education Enhancement Fund of the University of Southampton who contributed to the logistics of the competition.

Finally, the team would like to thank the ISR race organisers for putting on this unique and challenging event. This has been an exciting project and has provided educational and outreach opportunities as well as aiding the continued professional development of the team. It has also allowed non-engineers to get involved in an engineering project they would not usually have access to.

Table of Contents

Table of Figures

Table of Tables

1 Introduction

1.1 The University of Southampton

The 13th International Submarine Races represent the University of Southampton's debut into the competition, with a multidisciplinary team of male and female engineers, ship scientists, biologists, chemists, environmental scientists, psychologists, and computer scientists.

The aim of SUHPS is to excel in the competition and provide a return on investment for our financial supporters, ultimately through positive media exposure in a successful race. Further, the team will embrace and champion the competition's set goals of inspiring and advancing educational experience by translating theoretical knowledge to reality, fostering advances in subsea vehicle dynamics, propulsion and life support systems, and to increase public awareness to subsea challenges.

1.2 Background

The University of Southampton is listed within the top 15 UK research universities, ranking 11th on the research fortnight rankings for Research Excellence Framework 2014. A Russell Group institution, Southampton has internationally known research centres working in the maritime area such as the Institute of Sound and Vibration Research, and has more than one department deemed a 'centre of excellence' one of which is the Maritime Centre of Excellence which houses the Global Technology Centre.

The University of Southampton prides itself on the close relationships it has developed with talented people and likeminded organisations across the world. One of the main aims of the university is to place a high value on excellence and creativity, supporting independence of thought, and the freedom to challenge existing knowledge and beliefs through critical research and scholarship, with the moto to change the world for the better.

The University has teams competing in other human powered competitions such as human powered flight, but we are the first team to compete with a human powered submarine.

1.3 Aims

Given that this year's event represents our first attempt at the competition, we have set a number of aims we consider to be realistic:

- Lay the foundations for future submarine race entries;
- Create a first iteration submarine based on firm principles on which future years can build;
- Enter a working submarine and complete a race.

1.4 Objectives

- Students will have the unique opportunity to build a submarine themselves by turning their collective theoretical knowledge into a reality, producing a working submarine which can enter international races;

- Students will benefit from graduate opportunities that arise from organised networking events both through the competition (there are centrally-held careers fairs and networking lunches during the week of the competition in Maryland) and potential corporate collaborators (and vice versa for corporate collaborators that have the benefit of access to world-leading undergraduates);
- Students will have the chance to hone their mentoring and teaching skills by engaging in personally-rewarding STEM Outreach events;
- Participating in an international competition will raise the profile of the University, its Engineers and associated sponsors on a global stage;
- Forging and reinforcing links with local and multinational businesses and Further Education providers will lay the foundations for future academic and graduate connections;
- Nurture enthusiasm amongst other students within the university to become involved in the project to ensure an ongoing legacy in the form of future submarine entries to the competition.

1.5 Team Personnel

The team itself, which is overseen by a four-strong undergraduate and postgraduate committee, is organised into five smaller sub-teams, each of whom specialise in one area of design/manufacture. These are: Hull, Life Support & Ergonomics; Transmission; Propulsion; Control Surfaces; Marketing & Finance. Each sub-team contains 8 – 10 members, with the core manufacturing and race team consisting of 11 members. This is still the first year since the formation of SUHPS and so we hope to expand our core team in future years.

2 Design Principles

The submarine is designed to be operated by a single pilot whilst using SCUBA equipment to provide life support during submersion. A simple design was chosen in order to reduce the risk of failure during operation in the wet tests and the competition, increasing the chance of improved reliability and reducing the need for difficult repairs. The CAD programmes SolidWorks and Rhino were used in order to design the submarine.

2.1 Hull design

To produce a suitable design for the submarine the size of the pilot and the transmission system were the main constraints. These factors determined the minimum size of the submarine.

In order to be able to check the pilot size a rough model of a pilot was created in SolidWorks as shown in the Figure 1.

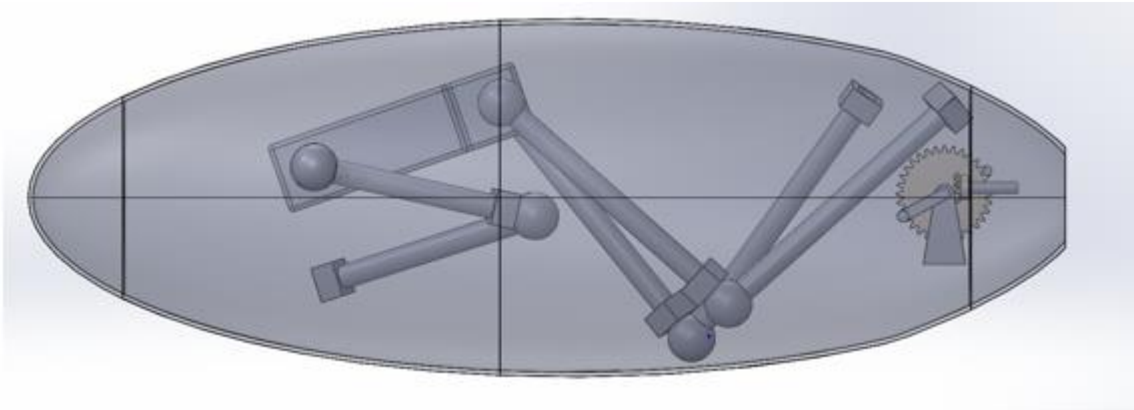

Figure 1. Mock mannequin of Submarine pilot

The main dimensions were the width of the pilot's shoulders, his height, and the height of his legs when bent. This model was combined with the restrictions imposed by the transmission to produce the dimension constraints in the table.

Item	Dimension (m)
Height of Pilot	1.83
Shoulder width	0.48
Height of Transmission	0.30
Transmission Shaft Length	0.62

Table 1. Dimension constraints

2.1.1 Methodology

The ideal hydrodynamic shape was found from a literature search to be an elliptic front with a parabolic tail from various literature. Equations for those shapes were used to create side and plan view curves, which were used as the basis of the hull model.

As we were a new team there were several iterations of the hull design as issues that we had not foreseen began to arise. From a modelling standpoint, the hull model in Figure 2 can be seen as unsuccessful as the shape included rather tricky geometry. This geometry proved too difficult to translate into a working mould. Due to these practical considerations, the initial design was edited.

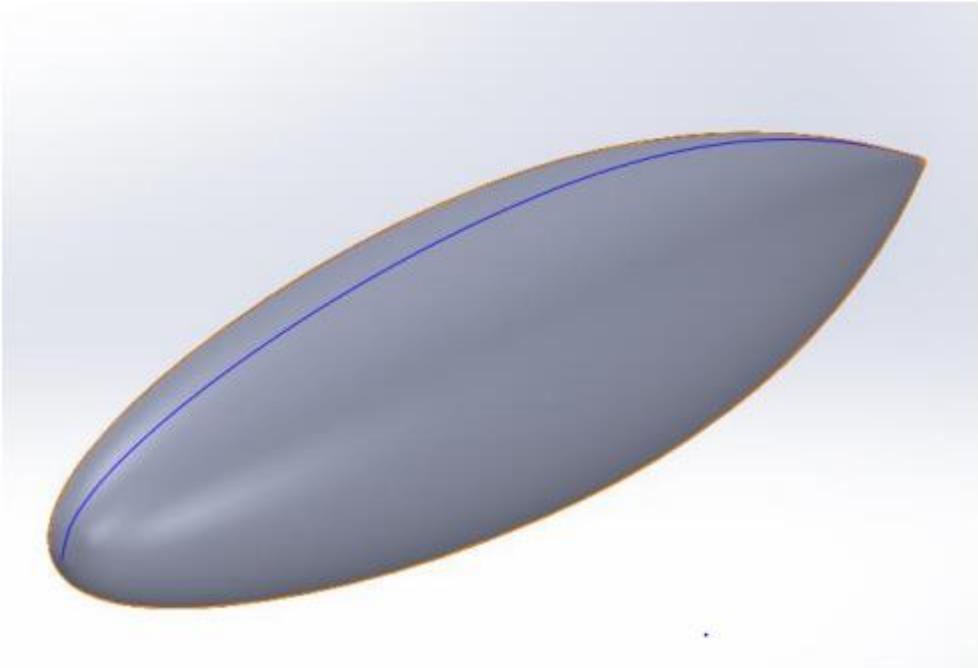

Figure 2. NACA 16015 Revolved

The final design can be seen in Figure 6. This design carries forward the equations that were based on the ideal hydrodynamic shape, but the cross-section of this model was modified to suit manufacturing requirements. A comparison between the cross-sections of the initial and revised models can be seen in Figure 5. The modified cross-section is less than ideal due to the parallel sides of the hull.

This was the original design but the pilot was too large to fit inside and the transmission system was taller than first anticipated.

The second iteration was produced to fit the first transmission system (Figure 3). However, from a hydrodynamic prospective, this hull would create too much drag so the transmission system needed to be modified.

Figure 3. Whale Hull

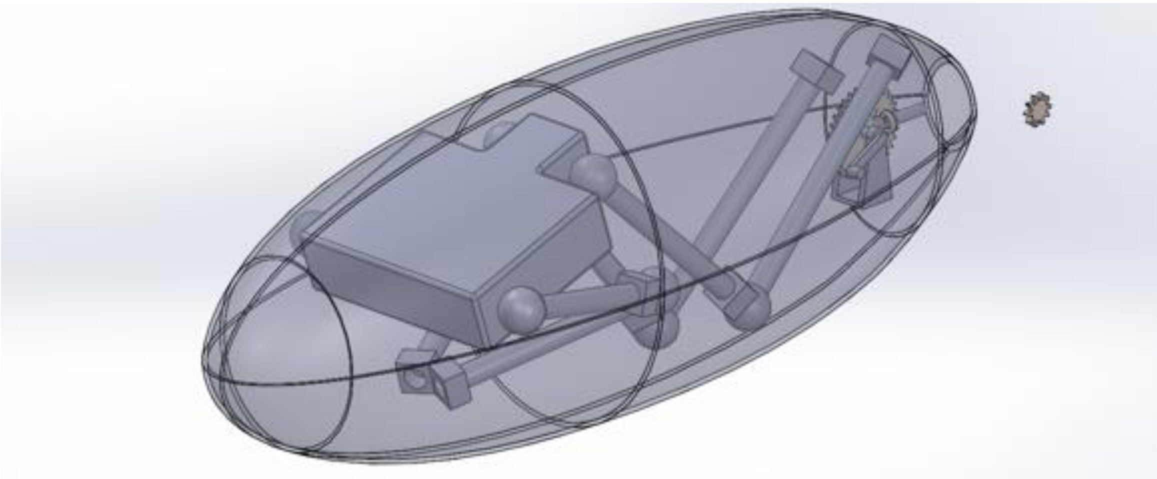

Figure 4. 3rd iteration of the hull

The 3rd iteration hull design was created once the transmission dimensions were known and the size of the pilot taken into account (Figure 4). This design proved too complicated be built during the manufacturing of the plug. The design was then edited as shown in Figure 6.

Figure 5. Comparison of cross-sections

The 4th iteration became the final hull design (figure 6).

Figure 6. Final hull design

2.1.2 Hydrodynamic Testing

Once the final hull design had been determined a CFD was run on the supercomputer at Southampton University using CCM+. This produced the figure below and allowed the propulsion team to assess the propeller needed for the submarine (figure 7).

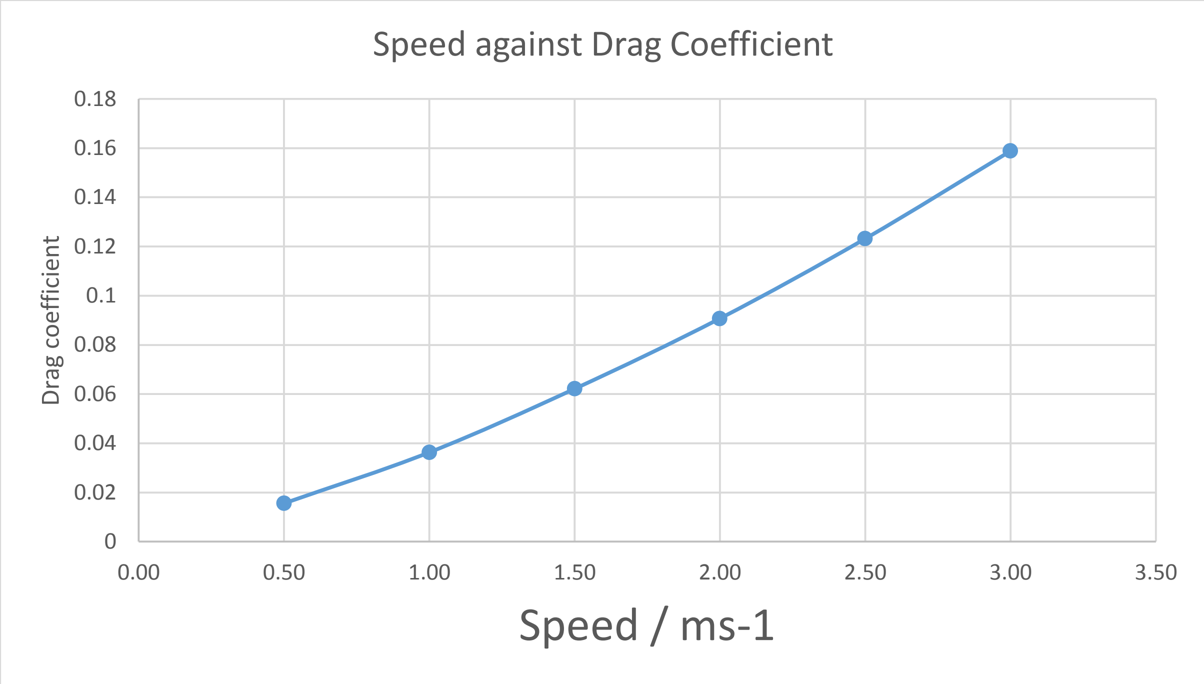

Figure 7. Speed against drag

The first iteration of the hull had a drag coefficient of 0.00391 at 2 ms-1. In comparison, the drag of the final has increased significantly with the extra volume that has been added into the shape. This will be taken into account in the design work the 2016 entry where the towing tank at Southampton University will be used to test several models of the submarine.

2.1.3 Manufacturing

At the start of the year we aimed to build the submarine ourselves using renewable fibre glass. However, we found that being a new team it took us a long time to produce our hull design so we enlisted the help of Zest Racing through sponsorship to help build the submarine from a plug that we made. Next year we will aim to build the submarine by ourselves. Working with Zest Racing meant that the hull would be an accurate shape as many teams in past have mentioned not being able to create the desired shape which will in turn affect the drag.

The plug was made out of foam and then covered in Jesmonite (Figure 8a). This was then used this to produce one half of the submarine. The second half was then made from the first half and the two were bonded together. The plug was made by cutting accurate angles along the length of the foam using a wooden frame to support it (Figure 8b). This frame also acted as a guide so that two people standing either side of it could cut whole strips of foam away along its length using a 'hot wire method' – as the name suggests this method involves supplying a length of fine wire with a charge so that it becomes hot enough to cut materials when kept taught (Figure 8c). In this way, the team were able to strip incremental sections of foam away, leaving us with an elliptical cylinder of foam (Figure 8d).

The foam was then dry sanded to remove any lumps (Figure 8e). This smoother mould was painted with three layers of different coloured Jesmonite – a gypsum-based composite – with 'wet sanding' taking place between each application (Figure 8f). The different colour Jesmonite acted as a measure of the depth of the sanding. The smooth plug was then sent to the manufacturer who used Matrix 300g 2x2 Twill Glass, Glass Bi-ax, and Multi-purpose Epoxy Resin to build the hull. The hull is 3mm thick and 6mm at the join of the two halves.

Figure 8. Hull manufacturing process

2.1.4 Life Support & Dead Man’s Switch

The dead man’s switch will consist of a bicycle brake which has to be compressed at all times. The buoy will be held in place by a string latch and a pin. If the driver lets go of the bike switch this will cause the spring-loaded pin to retract, a regular bike brake cable will connect the two. The buoy will be attached to a reel of fluorescent load bearing string, which can be rewound to retrieve the buoy. The string will be fed to the top of hole from which the buoy is released by a metal ring attached to the inside of the hull (to avoid entanglement within the hull).

The buoy will be painted a bright colour and will have a fibreglass top to ensure the foam does not create friction during use. The buoy will be of cylindrical shape of 15 cm diameter and 15 cm depth, the circular face will face the surface. The buoy will be situated next to the pilot door to the sub, and the cable will be fed to the buoy through metal rungs installed in the inside hull of the sub. The door will be held shut by one door hatch, the handles will be removed and cables rapped round and attached to them such that when pulled the latches will release. The door will buoyant so once release the door will open.

The pilot will have one air tank situated under the support bench and a backup pony in case of emergency. Testing is being performed at Southampton Hospital to mimic some of the conditions in a controlled environment and conduct power testing versus oxygen consumption to calculate the size of the air tanks required.

2.1.5 Submarine Hatch

The main issue with the hatch design was the dead man’s switch. We wanted to keep it as simple as possible and decided early on to have only one door on the submarine. The door measures 1.4 meters in length and is held down at the rear end by a single hinge. Creating a double hinge would have been too time consuming, and this also kept the design simple. At the front, we decided to put the dead man’s switch mechanism on the port side of the submarine, as putting it in the middle would have gotten in the way of the pilot’s head. We used a bike’s brake for the switch itself, and it is connected to a simple pivoting system. On the other end is a door lock held back by a spring. This causes the resting position of the lock to be open. Consequently, when the pilot releases the switch, the lock retracts and the door opens. Foam was put onto the door, making it positively buoyant. This ensures that the door opens when the lock is retracted, allowing the pilot to easily exit the submarine. Five draining holes were drilled into the hatch to allow for air to escape when it is submerged. A picture of the hatch during the construction process is shown below (figure 9).

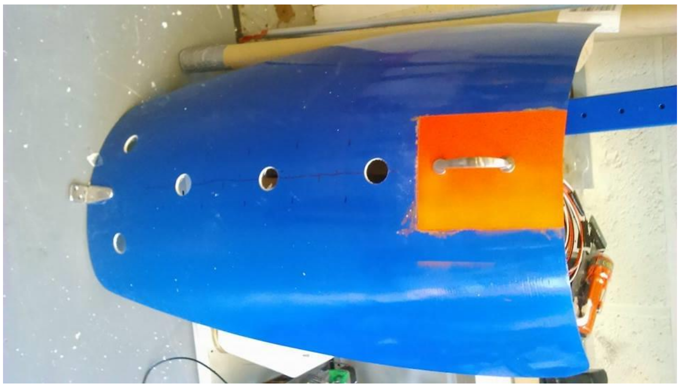

Figure 9. Hatch during construction

2.1.6 Braking/Reverse thrust

Due to friction, it is believed that the vessel will stop sufficiently quickly enough when pedalling by the pilot ceases. If the pilot requires to stop quicker, then they are able to pedal backwards to provide reverse thrust from the propeller.

2.1.7 Evaluation

In the future we will aim to build the submarine all by ourselves using renewable composites. We will look at decreasing the drag coefficient by testing models in the towing tank. We will also aim to test the pilot in a decompression chamber to look into the breathing of the pilot.

2.2 Transmission

The Transmissions sub-team decided to use a traditional bicycle crank system to transfer the energy from the pilot to the propellers. This was decided on as it is a simple easy system to acquire and install, it is also cheaper than the original system we had designed. The original system called for an innovative step- system which would enable easy access into the submarine. The step system was based on a cross trainer and the pedals are linked to a rotary wheel. The rotary wheel will then be connected to a bevel gear to transfer the power onto the drive train.

However after serious consideration in regards to space, the transmission sub-team decided to change the system into a more compact system. The current transmission system employs a bicycle crank. 1.5:1 Bevel gears then connects the cranks to the drive train. One of the bevel gears is welded on the crank pin directly, thus cutting down on as much moving parts as possible, to prevent as much loss as possible. Moreover, to add to the simplicity of the system, the transmission team decided against the use of a gear box due to complexity and timing restrictions.

Academic studies have found that a comfortable cadence for human powered submarine pilots is between 30-40rpm. This suggest the transmission system should have a ratio of approximately 1:5 or more. However, due to the final size of the hull a ratio of 1:2 was used.

Single speed and direct drive was used in order to improve reliability so the input from the pilot translates the energy from the rotation of the pedals to the rotation of the driveshaft and in-turn, the propeller.

At the beginning of the design phase, the hull was 2.8 meters long and the transmission system was located at 2.4 meters from datum front. Once the hull was redesigned to be shorter, the transmission system had to be moved to a new location at 1.6 meters. This ensures that the system is unobstructed while the pilot is pedalling. The transmission design models are shown below (Figure 10).

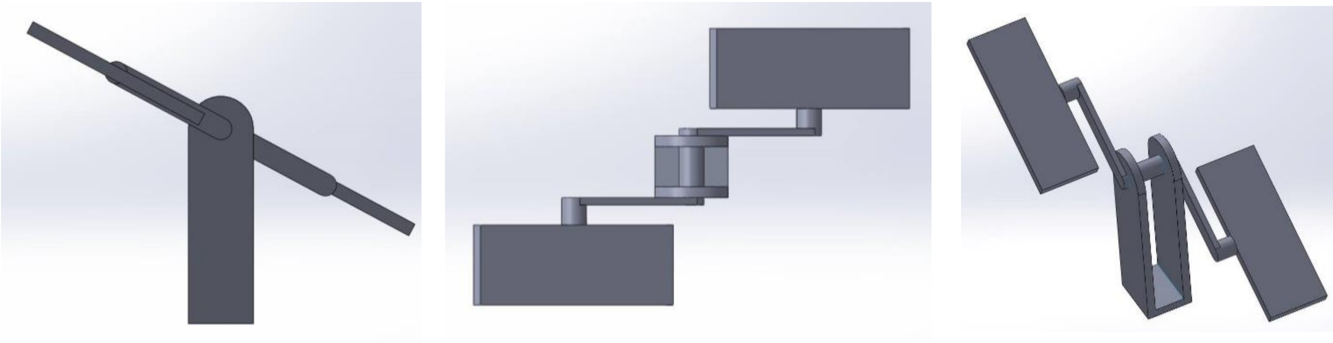

Figure 10. Side, top and isometric view of transmission system

2.2.1 Evaluation

Our experience this year has taught us we can use thinner metal plates next year which would reduce the weight of the system. We would also use a key and circlips method to assemble the system instead of glue which is the method we used this year to provide stronger support. A bigger gear ratio would make the system more efficient and so this would be considered next time.

2.3 Control

The Control subsystem consists of the design and manufacture of control surfaces (fins) as well as the buoyancy system and mechanisms for moving surfaces. It was established that the primary requirements for this race is that the submarine follows a strictly straight path as quickly as possible. Hence the final design composed of four rear fins and an electronic control system with buoyancy created with expanded polystyrene foam through a trial and error process (Figure 10).

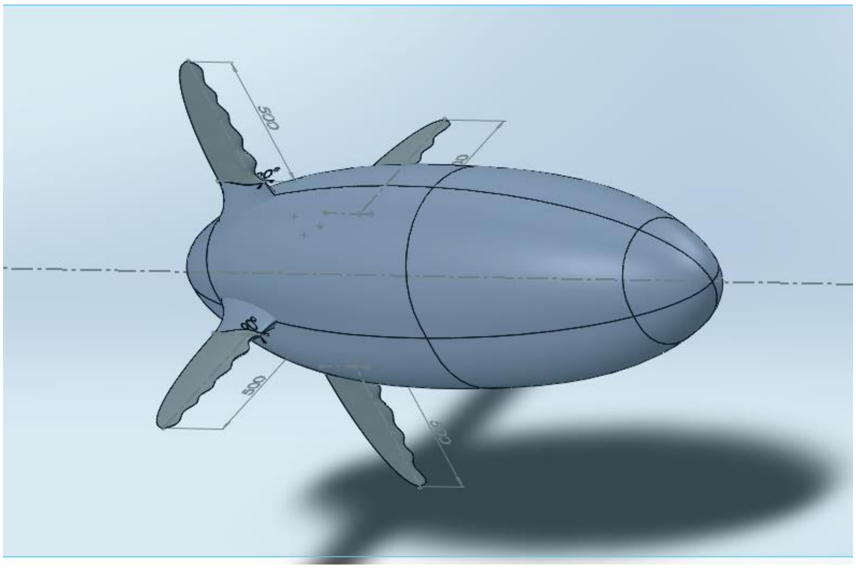

Figure 11. Placement of control surfaces

2.3.1 Control Surfaces

In early discussions it was noted that the propeller was to be a single prop and hence both the torque and precession of the rotating system would affect the movement of the craft significantly. An additional requirement is that the fins provide some form of stability, analogous to the vertical stabilizers on planes, but four fins reducing the effects of both pitching and yawing. Stability is essential for the craft to continue in a straight line. The Diagram below describes the effects of the hull and fins on this stability (Figure 12).

If the craft yaws to the side by a set angle then the vertical stabilizer counters this and returns the submarine to the correct angle. The body would create a lift too, which counters the vertical stabilizer. For this reason the fins must be placed as far backwards as possible to increase the moment arm.

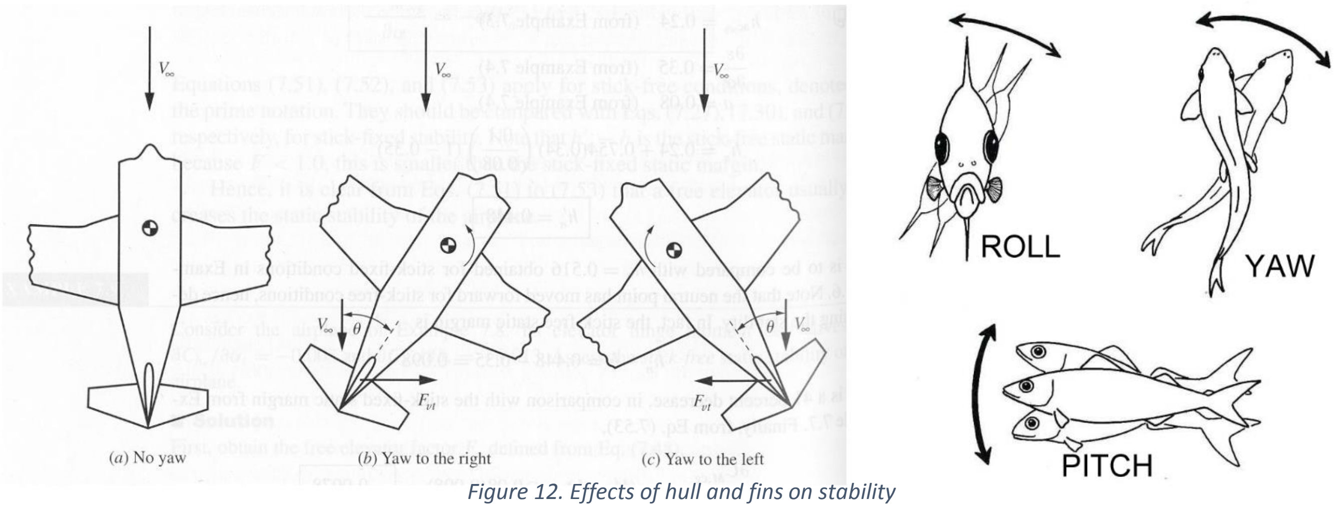

Figure 12. Effects of hull and fins on stability

It was noted that due to the continuous changes in hull designs and difficulties in determining the effect of the hull on stability that, for the first race without significant testing and redesigns, that the fins may not be effective enough to stabilize the craft. However the use of electronics to vary the angle of attack of the vertical fins will ensure yaw stability. Pitch stability is improved by buoyancy neutrality at a certain depth. If pitching occurs and the craft rises then due to the buoyancy of the craft it will sink to the correct depth once the angle of attack of the submarine is restored, which is done by the horizontal fins. It should be noted that the design of the fins have included a large safety margin to ensure this passive stability occurs.

Initially two small fins placed at the front of the submarine were considered however these would be detrimental to the stability of the craft if placed ahead of the centre of gravity as well as further manufacturing and use of precious internal space.

The NACA0012 foil was used, a symmetrical fin was moved due to it theoretically having no pitching moment, and hence lowering the load on the servos if made to move, if they are placed at the quarter chord point. The servos were chosen so that they could withstand the lift produced by the fin close to the fin stalling with an added safety factor of two. NACA0012 also had a low drag coefficient and small proportionality to the lift produced by the fin as opposed to other shapes.

Another requirement of the fins is to be as hydrodynamic as possible, the use of fin-tips were considered however due to structural problems and increased root bending of the fins these were discarded although they improved stability slightly. An elliptical fin shape was adopted to reduce the induced drag particularly with the two vertical fins which in theory should always be producing lift to counter the rotations of the propeller (Figure 13). This however incurred manufacturing difficulties, particularly with foam.

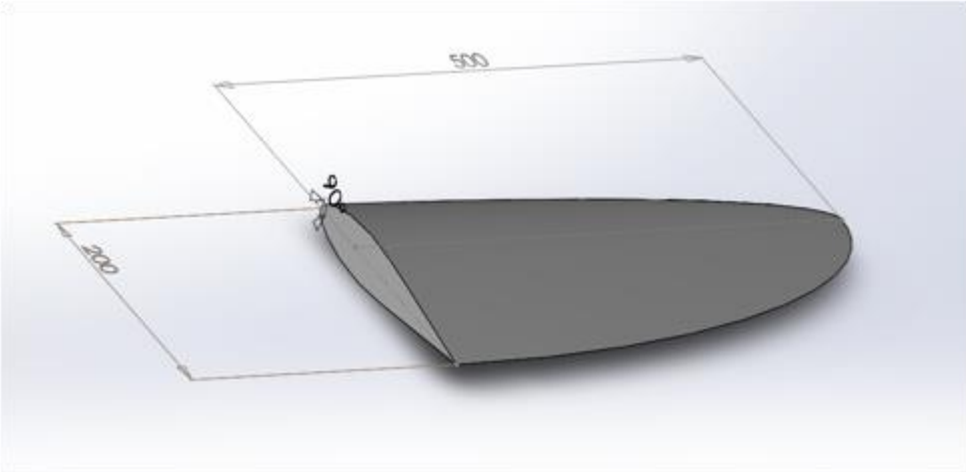

Figure 13. Fin shape

Foam provided the simplest, cheapest and quickest method of manufacturing fins. Other options included timber and aluminium. The two latter would require Computer Numerical Control (CNC) machining which proved costly. Hence foam was adopted with the addition of a fiberglass layer to improve strength significantly. Fibreglass added both safety issues and surface finishes that would not be to a hugely great standard. However costs were approximately ten times less. An additional advantage to foam is the shift of buoyancy parts from inside to outside of the hull to save space, while the thickening of the aerofoil would induce only a slightly greater drag.

Both vertical fins were designed to operate at the optimum lift to drag conditions providing a moment to counteract the approximate torque of the propeller of 20Nm. Due to the variable nature of this torque and dependence of the pilots pedalling speed the two vertical fins were designed to move, which will also prevent the craft from veering off course. Although challenging to make move, there were an abundance of electronic engineers within the team.

It was decided to move the whole fin, due to simplicity and to ensure the fins remained symmetrical. Using flaps would effectively vary the chamber of the fins and hence induce a small moment. Although this can be negligible, it was still found to be less effective in moving the sub.

The transmission rod that would rotate the fins or hold them in place was to be cylindrical in order for ease of rotation. Cylinders are bluff body objects and hence produce a huge amount of drag. An attempt to produce a cover proved ineffective and time consuming. Initially thin Acrylonitrile butadiene styrene (ABS) was tested and it was hoped to be flexible enough to twist with the fin, however the prototypes were ineffective and too rotationally rigid while easy to locally buckle and bend under small loads. The attempt to cover the rod were left due to time constraints.

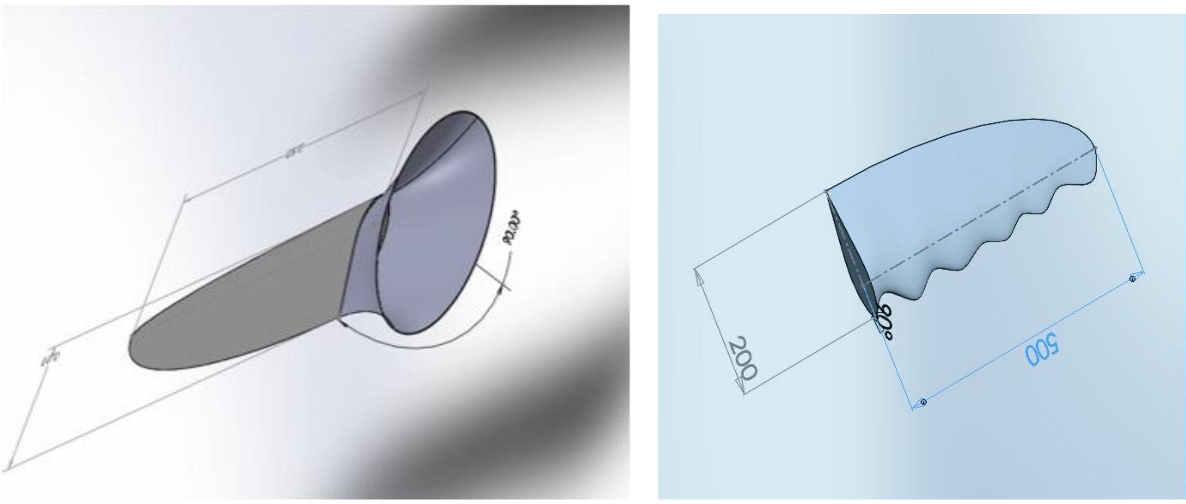

Figure 14. Fin designs

Another design innovation that could be successfully implemented was the use of wavy leading edge fins (Figure 14). Inspired by whales this late change of design based on research journals would reduce the effects of stall if occurred due to the failure of the surfaces while improving the lift capabilities. On the other hand slight difficulties in manufacture were produced with fibreglass layup, while foam shaping simple (Figure 15). [1]

Figure 15. Foam fin ready for fibreglass

2.3.2 Buoyancy

Due to the complexity in hull design and the constant changing of designs the buoyancy system has varied considerably. The weights of all components, disregarding their buoyancy, was taken as the maximum buoyancy force required in the early stages of the design process. This demanded a 18m^3 box of foam at worst to be placed inside the hull.

Initially the design was a row of airtight canisters than can be moved to allow changes in other designs to be accounted for. However the complexity of constructing such a system, the time involved as well as costs lead to a simpler design; whereby foam would be bespoke cut once all other components completed. The design of a hot wire cutter and the purchase of excess foam ensured that quick manufacturing in complex shapes can be performed (Figure 16). The foam design would also allow for foam to be formed into ergonomic shapes if required.

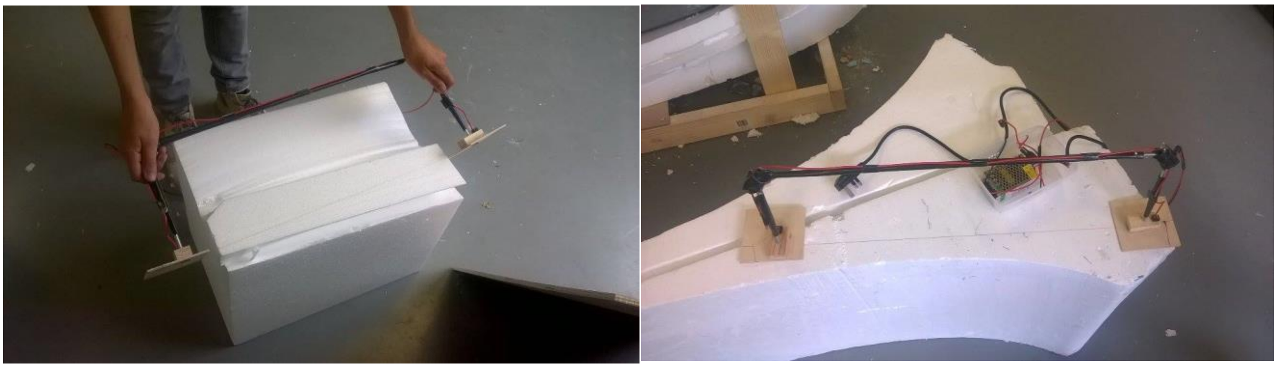

Figure 16. Hot wire cutter designed and used by the team

2.3.3 Electronics

An electronic control system was designed based on the strong team interests and that it relieves the pilot of the responsibility when racing. It also provides the much needed experience to produce a far better system for future races which involve curved tracks.

A major issue with electronics in the design is the waterproofing, in particular the moving parts, coupling a servo to the fins through a watertight system. A waterproof servo at a depth of 2m, where it was found typical submarines float, where far too expensive. While the alternative, an o-ring and circlip coupler made ourselves would keep costs minimal, although adding to manufacturing time. It was decided than an arduino coupled with sensors would be used, since they were readily available and are appropriately accurate. Another idea discussed was the use of plastic sheets, one side clamped to the transmission rod, while the other to the box, forming a flexible rotatable airtight seal, however it was found that this was unreliable.

Water-tightening the design was a simple, however the structure on which the servo would sit was far more challenging. A proposed welded aluminium square section bar frame was a concept discarded as it increased manufacturing time considerably and proved complicated. A thick bent plate (3mm) would instead be used, and bent into the correct shape (Figure 17). Each plate would be bent individually according to the curvature of the hull at that position. The plate would be bolted down onto the hull surface.

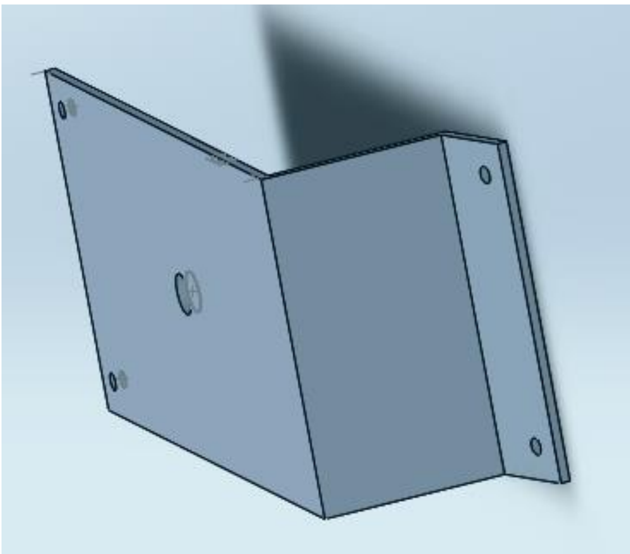

Figure 17. Servo housing

The servos purchased are waterproof at depths of 1m, and hence provided some safety in case of leakages above normal servos, while their cost was not extortionate. The servos were mounted to the plates using small aluminium blocks.

To cover the electronics designed boxes made of laser cut materials such as MDF or acrylic were considered, however there were an abundance of potential failure points in such designs, especially with the large number of joints. Hence ABS was chosen to be vacuum formed over left over foam. Using a single ABS sheet provided less holes for water leakages as well as structural rigidity. ABS manufacture was also extremely simple.

A separate large ABS box was formed to contain the arduino and battery systems. Rubber was used between each ABS box through which screws clamped the design to the aluminium plate to ensure water-tightness especially around wires which must pass out of the box.

Below is the final servo assembly, included our outlines of the o-rings and circlip. Grub Screws were used to attach the coupler to the servo (Figure 18).

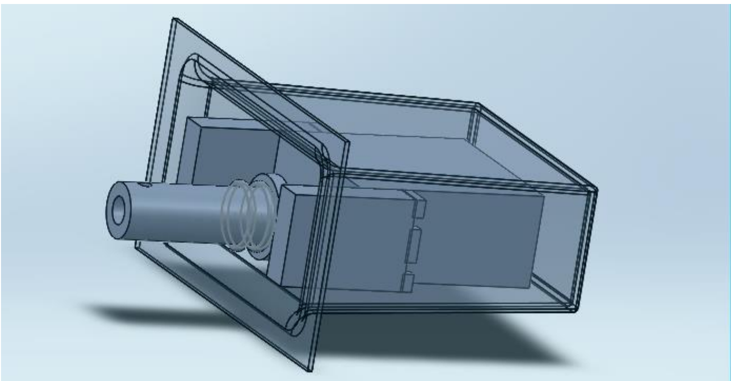

Figure 18. Final servo assembly

2.3.4 Evaluation

After a year of designs, it was found that improvements can be made to the fin designs. The fins are manufactured to a much higher strength and thickness than required, this was due to the unknown strengthening properties of a fibreglass layer upon the fin. For future competitions fins would be designed much thinner to reduce viscous drag components, while perhaps another layer of fibreglass will maintain their strength. Using machinery to sand the fins to a high smoothness would also improve the hydrodynamics of the design. Additional manufacturing, perhaps using a small CNC machine to create fins flush to the hull of the submarine or produce parts that lower the drag effects of cylindrical rods.

Further analysis can be performed upon the internal structural parts to reduce the amount of materials used, both improving costs and reducing wastage. Plate thicknesses may be able to be reduced as well as the rod diameters which controls the size of the fins.

With the construction of a small CNC in preparation for the next competition, blended parts to the hull can also be formed, moving the servo outside of the hull allowing the overall hull to reduce in size. However the hydrodynamic consequences of adding shapes externally against reducing the size of the hull must be quantified.

2.4 Propeller

2.4.1 Initial Thoughts

When looking at marine propellers there are three main designs: Fixed Pitch (FP), Variable Pitch (VP), and Contra Rotating (CR).

Each has certain advantages and for FP that is that they are the easiest to make and that there is very little that can go wrong. This is mainly due to the fact that other than the propeller itself there are no other moving parts. It is also quite easy to drive as only one blade needs to spin in one direction. VP has some advantages that are especially relevant for the human powered element in that the pilot can maintain a constant cadence at their maximum efficiency. This is due the properties of the propeller changing over time, and is equivalent to having gears. CR propellers are some of the most efficient and also remove a lot of the torque produced due to the two directions of rotation. They are however the most complicated to implement due to the transmission system having to spin in two directions.

We initially toyed with all three however the transmission team requested the use of only one propeller. This left us with either FP or VP and while VP would have been better in terms of providing power, we felt that for our first year it would be quite risky and it made more sense to ensure that we had a working propeller to ensure that we could actually compete.

2.4.2 Materials

The choices of materials were metal, wood, or fibreglass. Metal would have been ideal, however with our experience it wasn't really possible. Wood and fibreglass were about on a par with each other and so we went for fibre glass as it was easy to manufacture in house. For this a 3D printed mould was used as a base to cover in the fibreglass.

2.4.3 Design process

The design started with looking at designs that existed already and from that it seemed like going for fewer blades that are long and thin was the most efficient option for a propeller that rotates relatively slowly. The other thing we had to work out was how to attach the propeller to the drive shaft. In the end it was decided that we would weld a metal plate onto the drive shaft and then place the body of the propeller between that and another with pins through to ensure that the propeller would keep spinning at the proper rate.

The next stage was numerical analysis and a program called JavaProp (created by Martin Hepperle in 2009) was used. While this program is primarily designed for aircraft propellers the fluid properties can be changed in order to use water as the medium. Another interesting point on the program is that there is an option to calculate with a shroud around the propeller, and with the speeds involved this always added to the efficiency and so we decided to produce one for the sub. After running the calculations we eventually settled on a prop with a diameter of 0.5m and a shroud which produced the following table (Table 2).

Propeller			
v/(nD)	1.837	v/(ΩR)	0.585
Efficiency η	91.921 %	loading	low
Thrust T	122.56 N	Ct	0.1919
Power P	400 W	Cp	0.3835
Torque Q	19.1 Nm	Cs	2.2248
β at 75%R	45.9°	Pitch H	1.19 m

Table 2. Results of propeller calculations

For the duct we ended up going with an accelerating design following the Kort Nozzle design as this was well documented and so the next stage was to start with CAD. For the duct a NACA profile (4415 was imported) and revolved to make the model shown below (Figure 19).

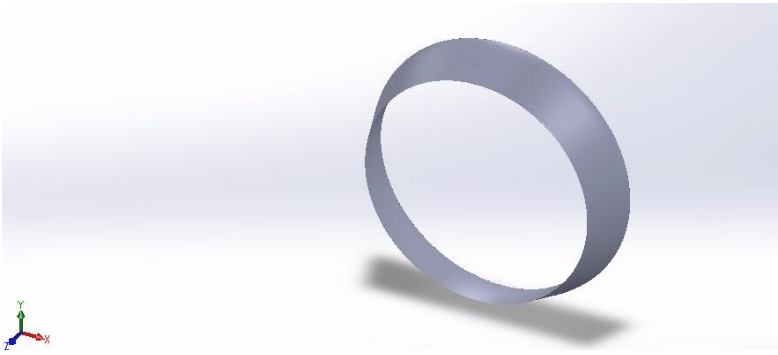

Figure 19. Duct profile

Next the prop was designed following a similar process, an aerofoil was imported into the program and then extruded according to a 3D curve that was designed to ensure the at the intended 200RPM the aerofoil would be at the optimal angle of attack along its length. The end was left square as that was the most efficient when combined with the duct (Figure 20).

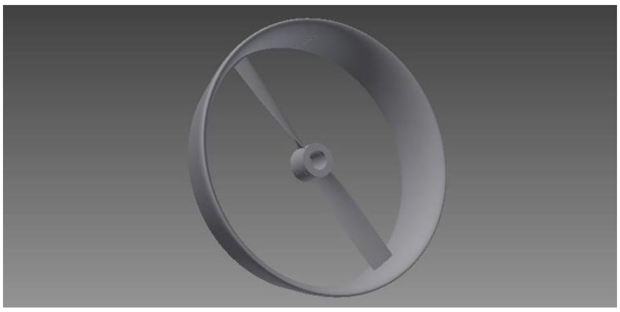

Figure 20. Final propeller design

2.4.4 Manufacture

All of the parts needed were 3D printed in house using some printers that were available to students (Figure 21). The only issue with this was that the parts to be printed were quite large and so the printers didn't have the build volume to print the complete parts. This meant that they had to be broken down, printed separately, and then glued together afterwards. These were then coated in fibreglass using a home kit. Initially there was some difficulty as none of us had ever laid any fibreglass before but we were able to learn quickly and eventually coat the complex structures properly.

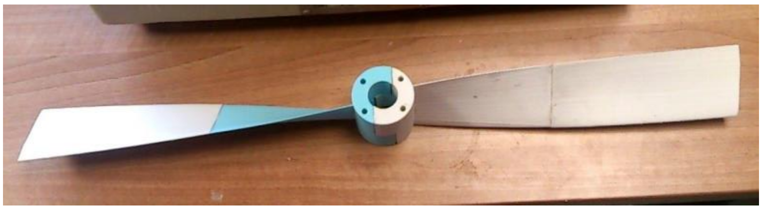

Figure 21. 3D printed propeller

2.4.5 Evaluation

For next year's propeller the ideal would be a variable pitch propeller. This would still keep things relatively easy from the transmission side of things, but also provide extra efficiency allowing the pilot to remain peddling at the optimal rate. We may also look at using metal for this as that will make it a lot easier to integrate with the motors needed to change to rotation of the propeller blades. For a non-propeller design, initial ideas are focussed around a single fin, such as that used by free divers and spear fishers. This would involve a fully integrated design with a flexible hull, with the fin constructed with layered composites to allow maximum strength and flexibility.

3 Diving and Safety

3.1 The team

Our dive team consists of three pilots (1 main, 1 backup, 1 female) and three other divers. There will always be 1 pilot and 4 safety divers in the water, with another diver on land as support. The safety divers will help the pilot in and out of the submarine and lower and submerge the submarine. For the safety of the pilot, there has been a rigorous training programme to ensure they are physically able and comfortable to power and control the submarine during the competition. This has consisted of gym and cycling training sessions, and a number of open water dives to build confidence underwater.

3.2 Pilot air consumption

For diver safety, the air consumption during each race has been calculated (See below). We will follow the general rule that states there must be a minimum of 50 bar left in each tank at the end of the race, and a secondary source will be available for the pilot's safety.

An estimation of the consumption rate of air by the pilot is made on a number of assumptions:

- A breathing rate of 50 L/min during heavy exercise for our pilot who has very good physical fitness.
- Each stage of the race will take a maximum of 10 minutes to complete.
- Minimum air required: *10 mins * 1.3 bar * 50 L/min = 650 L*

A Standard 12 L SCUBA tank at 220 bar will have *220*12 = 2640 L*. This tank will provide plenty of air, much more than required for the competition and will require more space within the submarine. Therefore a smaller tank can be considered: 7 L tank at 220 bar will provide *220*7 = 1540L.* This size will provide sufficient air supply whilst retaining the 50 bar minimum required by the rules after the race. However, the size tank we will use will likely depend on space available once the hull interior has been completed.

For safety, a 3 l pony cylinder filled to 220 bar will be used as the secondary source, this will have (*220*3 =*) *660 L.*

In summary, the team have opted for an aluminium tank with an additional 3-litre pony for safety. An aluminium tank is preferred over a steel tank to reduce the weight within the submarine and comply with competition rules.

4 Finance

As this is the first time our team have competed and we were a newly formed team in October 2014 we had to find funding to support our submarine. The members of our team who wanted to be involved but had no engineering background formed the marketing sub-group and were in charge of finding funding and advertising the team's existence through media and outreach. Finances for our entry were raised from two main sources, and a selection of smaller sponsors were used to fulfil various team requirements.

The first major sponsor was QinetiQ – who sponsored us for over £10,000 to cover the main build, pilot training and some of the logistics costs including some flights and submarine transport to the USA.

Our second major sponsor was the University of Southampton Education Enhancement Fund, who provided around £5000 to cover further logistics costs including the rest of the team member flights.

Smaller sponsors included Andark Diving and Watersports, a local diving school, who provided discounted training for many of our divers, as well as a suitable man-made lake for testing purposes. A University alumna was also interested in sponsoring the team through his company Tindale Systems.

Finances were managed by one finance director, who liaised with other committee members throughout the year. A system, based on google drive, was designed in order to manage the team's finances, whereby sub-team members could 'order' parts via an online form. The requests could then be approved by the finance director, or forwarded to other committee members in areas of uncertainty.

The entire system was integrated so that each sub team's current budget and usage could at a glance be compared with their remaining budget, and the team's budget as a whole. The benefit of such a system was that it was easily updateable, and funds could easily be redirected following under and overspends by a given sub team.

Thanks to this system, finance management was successful for our team.

References

[1] http://www.appliedfluids.com/UUST01.pdf