Design and Development of UUV

Brenden Matthews

University of New South Wales
Australian Defence Force Academy
School of Engineering and Information Technology
Canberra, ACT 2600, Australia

In an age of globalization, the Unmanned Underwater Vehicle (UUV) concept, model and purpose has become increasingly popular in various marine industries such as: mine reconnaissance by naval authorities, research aids for scientists and by oceanographers as an effective mechanism for monitoring the coastal environment. This rapid expansion has created a greater demand for access to lower-cost UUVs with a refined reliance on technology to enable routine survey and sounding missions as opposed to crewed workboats and expensive on-site labor; two detrimental factors in a scarce capital world. This paper seeks to examine, the vital components of what constitutes and powers a UUV by segmenting and critically analyzing each phase of the construction process. The report begins by discussing relevant literature which has been published in the industry. By critically analysing this literature, it has provided a benchmark for the current conceptual design to meet which is also discussed in the report. This design process is capable of generating initial sizing of a nose cone, tail cone and main body along with, performance and stability analysis. Centre of gravity (COG) analysis, along with the fluid dynamic aspects will also be examined. On completion of the design stage the UUV will be evaluated then built, for further testing.
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I. Introduction

Approximately seventy percent of the Earth’s surface is covered by water, whether this be in the form of dams, lakes, rivers, seas or oceans (Ross 2006); to date there is actually very little scientists know about the marine environment in comparison to land. Presently, large areas of the world’s sea beds and oceans remain undiscovered and untouched (Ross 2006); which has created an appealing demand for the exploration of this environment. This growing demand has instigated a niche to develop a superior UUV which would not only allow scientists but other personnel to accurately map the underwater world at a much faster rate whilst ensuring the safety of themselves and their mechanical equipment. The development of the UUV, not only assists scientists in mapping the submerged world, it also has optimistic benefits in other applications such as mine field surveillance and clearance testing for submarines (Madan, Desa, Prabhudesia, Sebastio, Pascoal, Desa, Mascarenhas, Maurya, Navelkar, Afuzulpurkar, Khalap 2007).

For over a decade now, the UUV has been promoted as a prominent option and tool in gathering numerical data by organisations such as the ocean research community, commercial seafloor survey, subsea mineral exploration companies and defence communities (Madan et al 2007). The UUV has become an accepted tool within these communities as it is becoming more popular tool for data collection and more organizations are beginning to recognize the UUV’s potential and future potential. For example, the first recognised UUV to be engaged in the military was for live mine countermeasure operations. The US Navy used the UUV in Operation ‘Iraq Freedom’ which occurred in 2003 located in the waters of the Northern Arabian Gulf. The UUV, Hydroid REMUS 100, used its side-scan sonar to systematically map approaches into the port of Umm Qasr (Unknown Author 2009).

The purpose of this thesis is to develop and construct a UUV which will be used for housing optical devices for underwater surveying. The purpose of the UUV is to offer a more cost effective and time efficient device for surveying underwater, whether it be for oceanography or mine reconnaissance as opposed to using a small submarine. This cost effective, time efficient outcome will be achieved by utilising the model already built by the Australian Defence Force Academy (ADFA) and will focus on improving features such as: the nose...
cone, tail cone and developing thrust via a shaft and propeller. The design requirements which must be adhered to are:

- Speed is 2m/s
- Be able to house a 150mm cube payload
- Payload weight is 5-10kg
- No longer than 1.3m in length
- Total weight including payload be less than or equal to 25 kilograms.
- Cost Effective

These design requirements have been nominated by the customer (thesis supervisor) and have been established from previous studies from students at ADFA.

B. Limitations

The timeframe for this project is limited to a two-semester period, along with continuing on with current studies. In this time period, a conceptual model of the UUV has be developed and analysed with programs such as CATIA and ANSYS to fulfill the required operational requirements for the UUV. This time constraint shall be controlled by following the dates and timings set out in the Gantt Chart. The Gantt Chart for this thesis is attached at Appendix A. A second limitation of this thesis encounters a strict budget; on completion the UUV it must be of a reasonable price to a consumer. There has been no set budget, as it is the first professional platform built by the school; however the estimated completion figure is approximately $1500. A further limitation of this thesis will contend with the lack of workshop support; all required products and parts of the UUV will need to be manufactured by myself within the ADFA student workshop.

II. Literature Review

The literature review and analysis has been segmented into six sections: current industry designs, hull optimisation, propulsions and steering, ballast and depth control, current industry design sustains and finally current industry design improvements.

Before starting the literature review, a basic understanding of Buoyancy Force must be understood and it is best described by Archimedes' principle (law of buoyancy and flotation) which is:

- a body immersed in a fluid is buoyed up by a force equal to the weight of fluid displaced
- a floating body displaces its own weight of the liquid in which it floats

Using these laws, you can drive the final buoyancy force as seen in the below equation (1).

\[ F_B = \gamma \times (\text{volume of submerged object}) \]  

From equation (1) it is calculated that for static equilibrium of an object (UUV), its weight must be equal to this buoyant force, therefore the object must displace its own weight of the liquid in which it floats (Street 1996). Therefore if the UUV weighs less than the buoyancy force then it will float, and on the other hand, if it is heavier than the buoyancy force, it will sink. This is a basic concept but one that is important with any system that operates within a fluid.

A. Current Industry Designs

As illustrated in figure 1, there is a diverse range of UUV’s that have been constructed overtime and after thorough research it is evident that it is not as simple as one UUV fits all projects. The need for the wide variety of designs is dependent on each UUV purpose as they have their own individual characteristics. For example, the design of the hull can vary immensely depending upon the nature of the vehicle and what it is designed to achieve.

The purpose of an UUV can fall into one of two main categories:

1. Observation
2. Work classes

An observation UUV is a small vehicle class that includes the majority of "low-cost" vehicles, most of which are typically all electric and operate above 300 meters water depth. These vehicles are used primarily for inspection and observation tasks. There has been a recent surge in the development of small vehicles, due

Figure 1. Seaeye Falcon and Cougar vehicles
primarily to the improvement in technology for electrically powered systems. These improvements have resulted in an increase in capability, performance and depth not previously achieved. A work class UUV is further broken down into two sub categories a light work class and heavy work class. A light work class UUV refers to electro-hydraulic vehicles ranging from 50-100 horsepower typically, which can only carry moderate payloads and have limited through-frame lift capability. These UUVs range in weight from 1,000-2,200 kg with typical payload capacities in the 220-600 lb (100-272 kg) range. A heavy work class UUV represents the class of UUVs being used for current deepwater operations to 3,000 meters ranging from 100-250 horsepower and having through-frame lift capabilities to 5,000 kg. With new requirements to perform subsea tie-in operations on deepwater installations and to carry very large driverless intervention systems, this class of ROV is becoming increasingly large, powerful and capable of carrying and lifting large loads- thus the term "heavy work class vehicle" has been adopted by the industry. However for the purpose of this project, this thesis paper will only be focusing on observational UUV as illustrated in figure 1. The main use of all UUVs regardless of what type it is, whether being observation or work class, is that they are primarily used for operations either in environments hazardous to humans or depths that pressurised vehicles carrying humans become impractical or uneconomical.

The U.S. Navy has numerous underwater vehicle projects underway. During the early development of UUVs the U.S. Navy received major support for research and development. The Office of Naval Research (ONR) created a master plan for the forward development of UUV's (Wernli 1999). This master plan identified four basic signature capabilities which include:

- **Maritime Reconnaissance (MR)**- centers of Intelligence, Surveillance, Reconnaissance (ISR) and the launch and coordination of UUV's for battle damage assessments and intelligence collection
- **Undersea Search and Survey (USS)** - provides the ability to rapidly survey selected areas through the use of a network of small UUVs, performing tasks such as; mine hunting/neutralisation, underwater object location and recovery and surveys.
- **Communication/Navigation Aid (C/NA)** - provides a communication/navigation relay for other underwater vehicles operating within the immediate area.
- **Submarine Track and Trail (ST&T)** - provides a mobile cueing function, but has the ability to grow into fully autonomous system.

The ONR are offering contracts for UUV's that are able to demonstrate capabilities within the four signature capabilities listed above. This is one reason why development in this area is becoming increasingly popular.

**B. Hull Optimization**

There are two types of hulls: either constructed in one single body or in compartments (Walker 2006). Both of these designs have one common factor between them, and that is drag. All devices that operate within a fluid, in particular water, must cope with hydrodynamic drag. Hydrodynamic drag sometimes called air resistance or fluid resistance refers to forces that oppose the relative motion of an object through a fluid (a liquid or gas). Drag forces act in a direction opposite to the oncoming flow velocity. Small improvements in drag can result in quite a substantial saving in either economical or thrust requirements. Very streamline objects such as fish or well-designed UUVs have very small values of $C_D$ compared to poor streamline object such as a cube.

The drag force is calculated by the equation:

$$FD = 0.5 \cdot \rho \cdot A \cdot V^2 \cdot CD$$  \hspace{1cm} (2)

From equation (2) it is evident that if you want to increase the velocity than you will be required to generate more thrust to overcome the extra drag that is created. This sort of parabolic relationship is a real constraint on aquatic motion (Hoerner 1965). The benefit that sea animals such as fish have over UUVs are that they are able to change their shape to reduce $C_D$ and able to reduce their surface area contact with the water through change in size or shape, where UUVs are unable to change their shape, well not at this stage (Deshpande, Sangekar, Kalyan, Chitre, Shahabudeen, Pallays, Teong Beng).

Current designs have used optimisation by the method of parameterisation of the hull to help the reduction in drag. From equation two, if we are able to reduce the size of the UUV either by the length or by the diameter then this will have a significant impact on reducing the drag on a UUV. This method involves axisymmetric bodies with parameterised lengths of $L_a$, $L_f$ and $R$, and two exponents $n_a$ and $n_f$ (Alvarez, Bertram and Gualdesi 2009), which can be seen in figure 2.

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Using the derivat equations set out in (Bertram, 2000), we can calculate the optimal radius's for the UUV, which is shown in equation (3).

\[ r_a = R \left( 1 - \left( \frac{L_a - x}{L_a} \right)^{n_a} \right) \quad r_f = R \left( 1 - \left( \frac{x - L_a - L_c}{L_f} \right)^{n_f} \right)^{1/n_c} \]

(3)

From these equations, an iterative procedure is employed to solve the nonlinear problem (Bertram, 2000). For full solution please refer to Alvarez et al 2009. Adopting this procedure we can reduce the drag force imposed on the UUV by limiting the size and shape of the design. Not only the length but also the nose and tail cone have an impact on the total drag force of the UUV. In fact it is the tail section which is the most important in terms of minimizing the hydrodynamic drag and therefore has a longer taper than the nose cone (Deshpande et al).

The majority of UUV’s which exist in the industry today all share similar characteristics and design traits as the one used for this thesis. Ignoring whether or not it is one solid body or segmented, the basic shape is the same. There is an optimised nose cone shape to help reduce the frontal drag created, followed by a cylindrical body generally made from PVC piping or fibreglass, followed by a tail cone that tappers down to the propellers. One such example can be seen in figure 3.

C. Propulsion and Steering

Many of the designs, currently being operated, use a combination of thrusters. One such design incorporates two horizontal thrusters mounted on both sides of the UUV which provides both movement forward and rearwards, along with pitch and yaw (Wang, Chen, Marburg, Chase, Hann date unknown). This design uses 12V dive scooters which have an operating depth of 20m. The Serafina MKII illustrated in figure 4, also uses a similar propulsion and steering mechanism. The Serafina use five thrusters in total, and utilises two of these thrusters for forward propulsion and turning, while the other three thrusters are used for depth control (Schill 2007). This UUV uses the three thrusters to submerge the UUV, once the

Figure 3. Starfish UUV

Figure 4. Serafina MkII
thrusters are turned off the UUV floats to the surface due to being positively buoyant.

To steer of the UUV, there are two methods which can be implemented: firstly, insert bow thrusters at the front of the UUV. These bow thrusters are built into the UUV and usually do not extrude the shell. The benefits of these bow thrusters are that they do not increase the drag of the UUV, due to no extruding elements (Anderson, Crowell 2005). The down side is they are only efficient at turning the UUV at zero forward velocity and don't have the force required to create a large enough moment to turn the UUV sufficiently whilst it is in motion. The second way of steering the UUV is whilst the UUV is moving; this is usually done by have thrusters mounted on the side of the UUV like the previous examples just discussed. The benefit of this is that you are able to efficiently turn whilst the UUV is moving. The downfall is that you require more thrust for propulsion to overcome the drag produced by these thrusters extruding from the main body envelope (Wang et al date unknown). A second downside is that it is nearly impossible to turn on the spot, due to the thrusters being side mounted. If the UUV is required to turn when it is stationery, the thrusters will still induce some forward velocity. Therefore very tight turns in a stationery position are near impossible.

There are numerous variations on the propeller system which can alter the thrust performance. Some of these systems include:

- Fixed pitch propellers
- Ducted propellers
- Potted and azimuthing propulsors
- Contra-rotating propellers
- Overlapping propellers

This thesis will not go any further in analysing these types of propellers other than just mentioning a few types which are available due to the time restriction as previously outlined. For more information regarding propellers Carlton 2007 is a recommended starting point.

D. Ballast and Depth Control

In designing an UUV, ballast and depth control are highly critical aspects. It is not optimal for a UUV to sink to the bottom just as much as it is not optimal to float along the top of the water. There are two main types of diving principles (Wang et al date unknown) namely:

- Static Diving Principles
- Dynamic Diving Principles

Static diving principles refers to diving through decreasing a vehicle’s buoyancy – typically by allowing water into the ballast tanks, as opposed to using power/thrusters to dive. Whereas dynamic diving principles refer to a UUV using its control fins to guide itself downward while under power. Based on these principles there are five main concepts which are used in the industry today to control a UUV’s depth:

1. Piston ballast tank is the most common concept by far; it uses a cylinder with a movable piston. The cylinder has one end in the free water, and the piston is able to push water out or draw water in. As the piston draws water in, the internal chambers fills with water thus achieving negative buoyancy, therefore allowing the UUV to sink/dive. As the piston pushes water out the compartments, this reduces the UUV overall weight therefore being able to achieve either neutrally buoyancy or positive buoyancy, depending on which one it wants to achieve (Wang et al).

2. Hydraulic pumping system is similar to the piston ballast tank. Instead of having a piston, it has a hydraulic pump which is linked to the internal reservoirs. This is the same concept as above, except it is pumping water in to the ballast tanks to descend and pumping water out to ascend (Wang et al).

3. Air compressor systems use cylinders of compressed air. If the UUV wants to descend then a valve is opened, allowing water to enter into a ballast tank. If the UUV requires ascending, then the blow off valve is opened and the compressed air blows/expels the water out of the ballast tank through the blow off valve. Figure 5 shows how the UUV descends with flooding of the ballast tank and figure 6 demonstrates how the high pressure air blows/pushes out the fluid from the ballast tanks.

![Figure 5. Flooding of the main ballast tanks](image1)

![Figure 6. Blowing of the main ballast tanks](image2)
4. Thrusters are becoming more popular, in particular with small or miniature UUVs. Thrusters can be a dynamic diving method as mention above. The thruster’s concept requires that, the UUV always be slightly positive buoyant, which then uses the thrusters, commonly mounted vertically to force the UUV downwards. To return the UUV to the surface the thrusters are turned off and the positively buoyancy floats the UUV back to the surface. This concept is power intensive; especially to keep the UUV submerged the thrusters require to be going the whole time. It is also difficult to remain at a particular depth as fluctuations in depth are a common problem with the thruster depth control concept.

5. Finally, by controlling the COG, depth control is achievable. The DRIP UUV uses a weight that is moved along the inside of the vehicle by a motor and ball screw arrangement (Miller 2006). The DRIP UUV has slight positive buoyancy, so when it wants to dive the weight i.e. COG moves forward and turns on the rear thrusters. The opposite occurs if it needs to climb, the weight is shifted rearwards, and for a faster and steeper ascent the weight is moved further to the rear. Once again an issue with this design is being able to hover at a certain depth, this may be required if the operator requires to take a photo or closely examine an object at a certain depth.

E. Current Industry Design Sustains

The most prominent sustain, which are demonstrated in today’s industry designs is the use of thrusters (Anderson & Crowell 2005). The majority of current UUV designs use propellers which are attached to either electrical or hydraulics motors (Wang et al). This is mainly due to the efficiency difference between propellers and water jets at low speeds. Thrust is determined by mass and velocity, the amount of fluid and the speed of fluid as it exists in the thrust nozzle. Propellers are used at low velocities because they operate by moving a large amount of water more slowly whereas water jets work by moving a small amount of water quickly. It is not until approximately 40knots that water jets start to become favourable (Carlton 2007).

A second sustain worth mentioning is the use of bow thrusters at the front of the UUV for steering. Although they do not provide large forces for turning, the amount of drag that is reduced by having them housed within the UUV itself is well worth the loss of power in turning.

F. Current Industry Design Improvements

Many of the current UUV’s which have been developed, use the concept of a flooding hull. This concept is used to counteract for the buoyancy force imposed on the UUV. This concept works by having compartments on the lower side of the UUV which can be flooded by opening or closing a valve (Wang et al). The filling of certain compartments enables the user to adjust the COG, thus making the UUV efficient to climb, descend or remain horizontal when stationary. This may be very beneficial for large UUV especially used in the heavy work class, however for small UUV there is a lack of room for ballast compartments not to mention, being able to accommodate all the extra equipment such as solenoids and values to operate the ballast system.

In the case of Serafin MKII (illustrated in figure 4) two problems were fairly evident with the design which resulted to be the thrusters. The use of conventional DC motors, driving the propeller through a sealed shaft coupling, has hydrodynamic disadvantages in the five thruster configuration. The vertical mounted thrusters added significant drag and the seals of the drive shafts were prone to leakage (Schill 2009 pg: 29-41).

III. Conceptual Design

Concept design is the first activity in what is known as the ‘Acquisition Phase’. The acquisition phase has four main processors these being: conceptual design, preliminary design, detailed design and production phase. The conceptual design is the engineering effort to articulate the system design in functional terms as defined by Faulconbridge (2005). The conceptual design will be broken into the following main categories of the current design proto-type: waterproofing, COG, nose cone and means of propulsion.

A. SEIT Current Proto-Type

ADFA has currently constructed a proto-type UUV from the conceptual design, which can be seen in figure 7. It was manufactured to achieve the same goals and outcomes as the UUV constructed in this thesis. It has a Styrofoam nose cone, which has had shape optimisation conducted to reduce the drag profile and
therefore increasing thrust. The main body has been constructed out of 255mm PVC pipe. Inside, it has four bilge pumps in the front, which are used for directional control of the UUV. The front bilge pumps are located within the body so there are no extruding parts to increase the drag. These pumps are within the front wet section which is separated by a dry wall to the dry compartment. Within the dry compartment of the main body, the electronics and batteries are located. There is a second drywall which separates the dry compartment from the pumps at the rear. It is propelled by three 750GPH pumps which are attached via a collar in which they are housed. The details of the UUV can be seen in the CATIA model in figure 8. Note that there are only 3 bilge pumps visible; one pump was removed for clarity of the figure.

The UUV has adopted the use of thrusters to submerge to the required depth, however at this stage, the thrusters are unable to fully submerge the UUV due to the amount of force required to overcome the buoyancy force.

The dimensions for the UUV can be seen in figure 9. The technical data for the current UUV is as follows:

- Total weight including ballast is 25kg
- Total length is 1075mm
- 3 x 750GPH bilge pumps for forward propulsion
- 2 x 750GPH bilge pumps for ascending and descending
- 2 x 500GPH bilge pumps for lateral movement
- Total of 7 x bilge pumps
- Max speed of 0.2m/s
- 2 x 12Volt lead acid batteries
- Approx 2hr running time

There are numerous improvements which can be made to this design, which are discussed below.

B. Waterproofing

A problem which the proto-type UUV encountered was sealing of the dry section. Due to the amount of water pressure produced on the UUV when it was submerged, there was continual leakage through the top hatch. Three possible design methods which were evaluated to solve this leakage occurring were to: have no top hatch at all, however it would restrict the accessibility to the components within the UUV, secondly to create a flat top section of the sub which can be seen in figure 10; this would enable top plate to be screwed down securely to the body. The disadvantages of this approach would be the manufacturing of this flat plate, and sealing it to the existing body especially with limited workshop support, making this option not desirable. The third and preferable option was to manufacture a rolled piece of aluminum 3mm in thickness to the inside diameter and have nuts tack welded to this plate. The plate would then be adhered to the inside of the body around the hatch opening and then a manufactured top piece rolled to the outside diameter of the body. This top

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piece would then screw down onto a piece of 3mm polystyrene foam and clamp it to the body, thus ensuring waterproofing. This concept can be seen viewed in figure 11.

Unfortunately a suitable access panel was unable to be manufactured within the projects time restraints so in lieu the first option of having no top plate at all resulting in no access panel was chosen to eliminate leakage. This design change imposes that all elements within the dry section must enter through the rear of the UUV.

C. COG

A second issue that the proto-type UUV design faced was the balance of the COG. There were many factors that influenced the COG. One such factor was the nose cone being made of Styrofoam which had a large buoyancy force which required 5.2kg to neutrally buoyant it. This was a large amount of weight that was required to be added, just to submerge the nose cone. A well trimmed UUV in stable equilibrium assumes a horizontal attitude along the length of the UUV, with zero pitch $\theta = 0$ and zero roll angle. To ensure this, the vertical separation between the CG and CB in the YZ plane needs to be as large as possible to counteract hydrostatic pitch movement. An optimal value of the distance between CG and CB will be sought through simulation, and by proper part placement, to obtain a large enough hydrostatic pitch moment that will suppress the moment generated by the propeller rotation (Madan et al 2007). Placement of CG and CB can be seen in figure 12. By using simple COG calculations to calculate moments of inertia of the vehicle, it will then be able to derive the vertical and horizontal plane hydrodynamic derivatives (Barros et al 2004). The proper part placement mentioned above will become apparent in the next couple of sections.

D. Nose Cone

Another improvement that is being assessed is a flooded nose cone to replace the existing solid styrofoam nose cone. As previously mentioned the nose cone was made from styrofoam which had a large buoyancy force that moved the COG close to the front of the UUV. Figure 13 displays the nose cone made out of styrofoam. The nose cone required 5.2kg of weight added to it, to achieve neutral buoyancy. This extra weight moves the COG closer to the front of the UUV. With the COG closer to the front of the UUV, it means that the efficiency of the steering pumps is reduced. After numerous testing it was discovered that with the extra weight in the front of the UUV it moved the COG to far forward which made the UUV unable to be turned or steered efficiently. To overcome this turning issue, the UUV required the COG to be moved as far to the rear of the UUV as possible, thus increasing the moment arm for the front pumps. If the COG is at the rear of the UUV, then the efficiency of the front pumps to turn the UUV will be at its maximum due to the increased moment arm. To achieve this, the nose cone will be replaced with a wet section, i.e. flood the cone with water. To achieve this,
manufactured a nose cone mould, and then wrap it with fiberglass. Greater detail of the construction is detailed later in the paper. Figure 14 shows the hollowed cone with a reduced weight of approx 5kg.

Having the nose cone flooded will help move the COG to the rear of the UUV. Another way of moving the COG rearwards is through the addition of a prop to the rear of the UUV. The propeller system is a lot heavier than the three bilge pumps in the rear. This extra weight in the rear will also help move the COG.

E. Propulsion

One major design problem encountered with the proto-type design was the use of pumps as propulsion. This design with three pumps in the rear was not able to achieve the required speed of 2m/s. With the three 750GPH bilge pumps in the rear, the UUV could only achieve a maximum speed of 0.2m/s. After analysing the literature available on the topic, most UUVs now use propellers as a form of propulsion. Based on this information, a new tail cone was designed to allow a propeller to drive the UUV. This new design will minimise the drag that the tail cone produces, allow maximum flow to the propeller and increase the amount of thrust generated by the propeller. The current prop being utilised is a 12V electric outboard motor, commonly used by small river craft. The motor and shaft will remain incased in the manufactured cast iron casing, due to its proven water security. This will eliminate the problem of leaking drive shafts, mentioned in the previous research. A CATIA model of the motor can be seen in figure 14. This model has had both the head and shaft removed. The propeller will be fully contained within the tail cone, with only the propellers extruding. The tail cone is also flooded to reduce the buoyancy. After completion of the optimisation of the tail cone later detailed the final tail cone will look similar to figure 16. The main goal for the tail cone is to be interchangeable with the pump tail cone; therefore ensuring that the mounting/attaching of this tail segment can be integrated with the current three bilge pump design is imperative.

F. Flow Meters

Another issue that is currently being assessed is the equipment that will be required to test the propeller’s propulsion and whether depth has an effect on the overall thrust on the UUV. Research into impeller base flow meters, also known as turbine meters, has been conducted to measure the amount of thrust that the propeller produces. One such impeller can be seen in figure 17. With the use of these flow meters, validating the relations between the theoretical ANSYS models and real life scenario will be conducted. The flow meter requires measuring the flow rate between 35-170litres/min. Unfortunately the research has not been able to locate a reasonable priced device thus far; however as an alternative research into venturi meters and other flow measuring devices has been conducted, however they are not suitable to the test the UUV due to size, shape and location of mounting points on the UUV. Therefore the use of an electronic spring gauge to calculate the amount of thrust produced via the propellers was used.
IV. Detailed Design of UUV

A. Tail Cone and Nose Cone

As previously mentioned the proto-type UUV is driven by 3 bilge pumps and another colleague is endeavoring to optimise the inner shape of the tail cone to produce the most thrust to propel the UUV forward. This paper will explore the options for an optimised tail cone for the outer surface. This optimal shape can be used for the current propulsion system of the bilge pumps, but has also been designed to house a shaft driven propeller.

The basic set up of the tail cone is to find an optimised shape to reduce drag and to allow un-obstructed flow to the propellers. The restrictions imposed on the design are as follows:

1. The leading edge must have an outside diameter of 255mm
2. The leading edge must be tangent to the UUV body
3. The trailing edge must have an outside diameter between 80-90mm
4. The trailing edge must have a zero slope to ensure uniform flow to the propeller
5. The total length of the tail cone must be 350mm
6. The shape can never go below 80mm diameter

The problem can be illustrated by 2D sketch, see figure 18. The sketch to the right is half of the tail cone; hence the vertical height is half of the outside diameter. This sketch would then be rotated around the horizontal axis to produce the 3D tail cone shape. The lines numbered from 1-4 indicate possible curved lines of which the tail cone could look like.

\[
\text{Drag} = 0.5 \times \text{density of fluid} \times \text{velocity}^2 \times \text{drag coefficient} \times \text{surface area} \ (4)
\]

However after examining the total drag formula in equation (4), this indicates that a curved line between 1 and 2 would be the most optimal; due to the having minimal surface area. Therefore, the lower the surface area the lower the drag, which in turn would produce more thrust or require less thrust for propulsion.

The first step in solving this problem is to have a starting curve, or a way to alter the curve. This means, to be able to optimise the tail cone a parameterised line needs to be determined between the start and end point. First step to understanding this is to look at the work of K.C. Giannakoglou who explained the concept of parameterization for the airfoil of a plane using what is known as the PARSEC method. After numerous simultaneous equations the following equation 5 was produced:

\[
y = a_1x(1)^{(1/2)} + a_2x(1)^{(3/2)} + a_3x(1)^{(5/2)} + a_4x(1)^{(7/2)} + a_5 \tag{5}
\]

Where:

\[
a_1 = -4.501277542; \\
a_2 = -4.232150639 \times 10^{-3}; \\
a_3 = 2.30839065 \times 10^{-5}; \\
a_4 = (a_1 \times L^{(1/2)} + a_2 \times L^{(3/2)} + a_3 \times L^{(5/2)} - R_2) / (L^{(7/2)});
\]

After numerous attempts to run this through the NSGA optimisation code, it was found that the equation for calculating the surface area was incorrect or the parameterised line equation was incorrect. After careful trial and error, it was evident that the line equation was not completely correct; it confirmed to all the constraints except the one where the tail diameter must be 80mm, instead it was producing negative numbers.

The next step was to produce a second line equation and after extensive research the best way to model the behavior was via a
polynomial, seen in equation (6).

\[ y = a(1)x^3 + a(2)x^2 + a(3)x + a(4) \]  

(6)

From this equation, the constants \( a(1)-a(4) \) will be optimised with the NSGA code.

Initially the equation was run through the optimisation code to see what kind of tail shape it would produce. At first it was unable to calculate a shape due to having the probability range as positive and not allowing negative numbers. After adjusting the range from \([0 : 100]\) to \([-100 : 100]\) the optimiser was able to converge. The shape generated via the code can be seen to the in figure 19. This is very surprising how it increases the diameter of the tail cone at the start before it decreases. This is also a very unreasonable solution due to the dimensions on the vertical axis being negative. This is physically imposable to have a negative value for the diameter of the tail cone.

Next was to introduce all of the boundary conditions listed in the problem set up. With these boundaries in place, the code was unable to find a result. This was due to having so many restrictions imposed, the code found it difficult to find a solution. Figure 20, depicts a red cross when one or all of the constraints are not being met. A blue cross depicts that all of the constraints imposed are being met.

To solve this problem, a minimisation of the probability range was conducted, closer to the expected values and then recalculated the NSGA code. Figure 21 depicts the new values; it resembles a lot of UUV tail cones currently being produced. It also abided by all the constraints imposed on it.

Continuing on, the next step was to refine the curve to be as close as possible to my two main constraints which are leading edge diameter being as close as possible to 255mm and the trailing edge diameter to be as close to 80mm as possible. Firsty tried to restrict the height to be between 0.225-0.2251mm for the leading edge, the NSGA was unable to find a solution. Two of the constraints that were imposed were unable to be met. It was run for 1000 generations with a population of 100. The code produced the following data:

```
Generation 1000
Objectives: [ 46.0113 (-0.103411) ]
Constraints: [ 0.00868586 -0.0990958 0.00631489 0.00854431 0.0414557 -1.73285e-008 0.05 ]
Feasible: 0
Function Evals: 100000
Design:   4.12756000  -2.17917519   0.05854431   0.15580421
```

From this data, if we look at the constraints row, the constraints not being met are indicated by a negative number. So with this data printed, it is visible that constraints 2, 4 and 9 were unable to be met. The altering of these three constraints was conducted until a converged response was achieved. The code required to have both the generations and the population size increased up to 1000 and 300 respectively. After refining the constraint of the starting diameter between 254-255.5mm and rear diameter between 80-85mm the code converge around the 800 iterations. Figures 22 and 23 below, display the code when it started to achieve the constraints imposed. In addition the figures also depict the tail cone shape with the constants produced via the code. The constants can be seen in the design row from the printed data above.
Following these results, the code was run numerous times, altering the constraint boundaries for the start and exit of the tail cone. The smallest boundary that was able to be achieved was 254.5-255.5mm for the start diameter and between 80-85mm for the exit. Figure 24 below depicts that it converged around the 220 iteration mark. The reason it found a solution quicker was due to an increase in the population size to 500, which enable the code to find an answer quicker. The code was then run for 2000 iterations to see whether the constants would keep changing. From the graph, it is clear that there was little change between the coefficient values. The second figure 25 depicts the shape of the tail cone it produced. When comparing the tail cones, this cone in figure 25 looks to be more defined especially closer to the rear of the tail cone.

After numerous trial and error methods adjusting the NSGA code to refine the shape to the boundary conditions the final product is produced in figure 26 below. The final matlab code used to run the NSGA2 code can be viewed in Appendix B.
The nose cone for the UUV was conducted in a very similar way using boundary conditions and NSGA code to derive a most optimal outcome given the specific requirements. However this report did not produce the shape for the nose cone, it was produced by Dr Tapabrata Ray a PhD post graduate student.

B. Propeller mount

One of the main contributions to the UUV that this thesis provided was the thrust propulsion via a shaft and propeller. Therefore a propeller mount which would withstand the torque of the initial start up of the propeller, and also be able to incorporate the tail cone design as a whole must be created. To ensure the stability of the mount, it was manufactured out of pieces of aluminum which are 3x20mm in dimension. These were then bent into shape to conform with the angles of the tail cone, which are then fastened by nuts and bolts to the PVC collar for strength. The original intention was to brace each arm with a lateral brace, however after testing it was found that the bracings would be redundant and add extra weight which was not required. The aluminum strips then held the motor via pump clamp rings. It was unfeasible to fasten the aluminum strips to the pump via nuts and bolts, as to ensure the water tightness of the motor. Therefore the use of clamp rings was used, which provided sufficient force to hold the brackets in place. The propeller mount can be seen in figures 27 and 28.

V. Theoretical calculation setup

To accurately model the thrust requirements for the UUV, a UUV model was developed in Catia and then critically analysed using ANSYS. ANSYS allowed the calculation of the thrust required to produce vehicle speeds from 0.5 to 2.5m/s, in 0.5m/s increments. To calculate the required thrust, the conceptual model will be encompassed in a fluid which has been simulated to flow over the body (UUV) at the desired velocity. The engine will be modelled as a flat disc with an inlet and outlet to simulate the water propulsion from the propellers. Due to time constraints this report has not investigated into the vortices and eddies what the propellers would produce and only used manufactures thrust details. The flow velocity through the engine (mass flow rate multiplied by engine flow velocity) is then varied until the thrust produced from the UUV meets or exceeds the drag produced by the vehicle moving at the desired flow velocity. These results will then be compared to the calculated drag with the engine turned off.

A. Catia Model

Before any calculations could be carried out, a conceptual UUV model needed to be developed in CATIA as shown in figure 29. This model has been modified to be one solid shape, to ensure that the flow simulations would be able to converge.

After exporting other models into ANSYS it was discovered that because of the high detail of wet sections, front pumps and brackets, ANSYS was unable to apply a suitable mesh due to mesh interference. After several
attempts to build the model without the associated detail, it was decided to simplify the model to the figure above, which is basically one solid shape without the integrate details of wet sections, front pumps and brackets.

B. Application of Mesh
In CFD modeling, the software performs computations at a range of discrete locations within the domain. The purpose of applying a mesh is to decompose the solution domain into an appropriate number of locations for a more accurate result.

It is obvious, that to get the most accurate result, then the most refined mesh must be used. However, this is impractical on most cases. In using a mesh, there are several considerations that have to be taken into account. The amount of geometric detail relevant to the simulation physics must be set, including unnecessary detail will increase effort required for simulation and thus slows down computation time. A more reasonable approach would be refinement within the domain where the most complex flow gradients are suspected to be. These areas will require higher densities of mesh elements. The quality of results must not be compromised in choosing the level of detail. Poor quality elements can lead to poor quality results or, in some cases, no results at all. The detail and refinement for good quality must be balanced with efficiency as well. Greater and more complex elements will require more resources (memory and processing time). Small sacrifices in quality often outweigh the vast increase in computational time.

The basic building-blocks for a 3D mesh are tetrahedrons (unstructured), hexahedrons (usually structured), prisms (formed when a tetrahedral mesh is extruded) and pyramids (where tetrahedral and hexahedral cells meet). A tetrahedral mesh can be generated quickly, automatically, and can be used for complicated geometry. Isotropic refinement allows mesh refinement in all three directions and increases cell counts rapidly whereas inflation helps with refinement normal to the wall, but still isotropic in 2-D. Inflation is accomplished by extruding faces normal to a boundary to increase the boundary mesh resolution. In CFD, the transition from the inflated layer to the outer mesh is smooth, with collisions easily avoided.

A quick comparison between coarse mesh and the refined mesh with the addition of inflation is shown in figures 30 and 31.

\[
\frac{\partial (\rho k)}{\partial t} + \frac{\partial (\rho k U)}{\partial x} = \frac{\partial}{\partial x} \left[ \mu_t \frac{\partial k}{\partial x} \right] + 2 \mu_t S_{ij} S_{ij} - \rho \varepsilon \tag{7}
\]

\[
\frac{\partial (\rho \varepsilon)}{\partial t} + \frac{\partial (\rho \varepsilon U)}{\partial x} = \frac{\partial}{\partial x} \left[ \mu_t \frac{\partial \varepsilon}{\partial x} \right] + 1.44 \frac{\varepsilon}{k} 2 \mu_t S_{ij} S_{ij} - 1.92 \rho \frac{\varepsilon^2}{k} \tag{8}
\]

It can be seen that inflation has greatly increased the number of cells near the walls of the UUV, allowing more calculations to take place in these critical areas. Also with the more refined grid which has decrease the size of each tetrahedral by half, will also help increase the accuracy of this computer generated model. However; as mentioned above, the computational time of this refined model increased by a factor of 10.

C. Calculation of Drag and Require Thrust
To be able to gather data from the UUV, the \( k-\varepsilon \) model was chosen. The \( k-\varepsilon \) model is the simplest turbulence model to use and decreases computational time. Only the initial and boundary conditions are required, is the reason this model was used to compute the drag on the UUV. Also the difference in the more accurate models such as Reynolds stress was minimal compared to the \( k-\varepsilon \) model, thus the simple and less computational time method was used.

The \( k-\varepsilon \) model is a two transport equation method of solving turbulence problems. The two equation used are for the turbulent kinetic energy \( k \) and the rate of dissipation of turbulent kinetic energy \( \varepsilon \). This model is quite robust, economical and reasonably accurate for a wide range of turbulent flows.

The standard \( k-\varepsilon \) model has the governing equations outlined in Eq. 7 for the turbulent kinetic energy and Eq.8 for the rate of dissipation.
The values for $\sigma_k$ and $\sigma_\varepsilon$ are 1 and 1.30 respectively, these two values as well as 1.44 and 1.92 were found through comprehensive data fitting for a wide range of turbulent flows (Malalasekera 2007). In words both equations represent:

$$\text{Rate of change of } k \text{ or } \varepsilon + \text{Transport of } k \text{ or } \varepsilon \text{ by convection} = \text{Transport of } k \text{ or } \varepsilon \text{ by diffusion} + \text{Rate of production of } k \text{ or } \varepsilon - \text{Rate of destruction of } k \text{ or } \varepsilon$$

After importing the geometry with a tetrahedral mesh of the UUV into Fluent, there is an option in the Mesh menu that converts the current mesh to a polyhedral mesh. The conversion process involves decomposing the original mesh into multiple sub volumes, referred to as duals. These duals are associated with the original nodes of the cell and are agglomerated into polyhedral cells around the original nodes. The polyhedral cell now consists of duals of the original node, and thus the node can be removed (ANSYS Help).

Comparing the meshes shown in figures 32 and 33, the polyhedral mesh now has fewer cells than the original tetrahedral mesh, which makes it a coarser mesh. Having a lower cell count is the biggest advantage of the polyhedral mesh, as it results in the calculations converging quicker and lessens the computational time. The user also has full control over the conversion process, however the mesh cannot be modified with tools such as smooth or extrude.

Since converting the geometry of the UUV to quite simple shape, the option to convert the mesh into polyhedral to significantly reduce calculation time was pursued. The coarser mesh does give a less accurate result than using the original mesh, but the difference is so small that is negligible especially considering the dramatic decrease in time taken for the computations to converge.

VI. Theoretical Results

A. Grid Refinement effect on Drag

To investigate the grid refinement and effect on drag, three different levels of mesh were used to calculate the drag profile of the UUV under a set of conditions. With intervals of 0.5 m/s, the drag profile of the UUV from 0.5 m/s to 2.5 m/s was calculated. These results required numerous iterations to be able to calculate the thrust required from the propeller to overcome the drag at a given speed. All tests at the given speeds were started at zero velocity for the propeller; this gave the total drag when the motor is turned off. It was then an iterative process, running the simulation, calculating the total drag, recalculating the simulation with the required thrust to ensure the values are correct. These steps where repeated until and accuracy to 2 decimal places was achieved. The results from these experiments are shown in figure 34. One point of interest on the graph is around the 1.5-2 m/s range. This indicates that the propeller must produce between 8-10 N of thrust to overcome the total drag. With manufacturing data stating it produces 30LB of thrust and measured force via the electronic spring gauge of 30-35 N of thrust. It is evident that the propeller will be able to achieve the required 2 m/s.

![Figure 32. Tetrahedral Mesh](image1)

![Figure 33. Polyhedral Mesh](image2)

![Figure 34. Grid Refinement effect on Total Drag calculated](image3)
It can be seen from figure 34 that the coarse mesh and the coarse mesh with inflation have basically the same drag to speed ratio. Since there was no significant change in calculations, a finer grid had to be applied to see whether this coarse meshing is accurate enough. After running the same calculations with the refined mesh it can be seen that the total drag of the system actually reduces. This would indicate that the refined mesh along with the inflation around the body, gives a more detailed analysis of the boundary layer, which in turn actually decreases the drag on the UUV’s body. This is due to the coarse grid over shooting the CD value resulting in a higher calculated drag, whereas the more refined grid does not tend to overshoot the CD therefore resulting in a reduced total drag. This is demonstrated above by the fact that the refined mesh returns a value of a lower total drag. This graph also depicts that this grid refinement has a large impact on the total drag that is induced on the UUV at increasing speeds. This is illustrated by how the lines are diverging as the speed of the UUV is increased. Running this model at higher velocities would clearly identify a large discrepancy between the coarse mesh and the finer mesh, however, due to time restriction and computational time these interest were not conducted.

The results presented above, are also in line with the results produced in table 1, which was an experiment conducted by Muhammad Husaini. From Muhammad’s experiment it is clear that when the UUV velocity is increased, so does the total drag induced on the system. Muhammad does not have the same drag calculations due to his UUV being of a different shape and dimension. However the general trend is obtained from his results which are the total drag formula, in particular the velocity squared term, which increases the drag since all other terms remain constant.

<table>
<thead>
<tr>
<th>Velocity (m/s)</th>
<th>Resistance force (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>0.0643</td>
</tr>
<tr>
<td>0.5</td>
<td>0.3973</td>
</tr>
<tr>
<td>1.0</td>
<td>0.9315</td>
</tr>
<tr>
<td>1.5</td>
<td>1.5302</td>
</tr>
<tr>
<td>2.0</td>
<td>2.0595</td>
</tr>
</tbody>
</table>

The model created was a basic shape to highlight and identify possible trends between the total drag of the system and the thrust required to propel the system at a given velocity. It was also used to identify the relationship between the propeller being on or off.

VII. Production/Construction Phase

The construction phase was by far the most time consuming on the UUV thesis. The time and resources required to manufacture a UUV was highly underestimated. These implications were induced by a number of factors, and the most prominent factor was the lack of workshop support from ADFA. To explain the process of manufacturing, the process will be broken up into its respective parts, nose/tail cone, body, control system and fittings.

A. Nose Cone/Tail Cone

The first point to note is that the UUV is a platform for the school, therefore there are usually multiple students working on the project at the one time. However this project consisted of only two students: Trevor Blake and myself constructing the UUV, so we had to ensure that the integration of respective parts were sound. This becomes increasingly important when it comes to the fittings. The second point to note is that the nose cone and tail cone were manufactured in the same way, so this report will only be discussing how the tail cone was produced, and it was exactly the same for the nose cone. Finally, the investigation was done, for getting the nose and tail cone manufactured however; they were unable to be manufactured via the ADFA workshop. Investigation into outsourcing the components to a civilian company was also
conducted; however the quotes that were received stated that the material itself to manufacture the parts would be in excess of $1000 per piece, not including labor. The outcome from this was to manufacture the pieces myself, with the assistance of Trevor Blake.

The tail cone’s first step was to take the above mentioned design shape and create a mould for the fiberglass to be layered upon. To create this mould a jig was manufactured out of MDF (a type of manufactured wood) to the desired shape that the tail cone had to follow. The jig was then used to guide the hot wire (wire with current passed through to create heat) along to cut the foam. Once the foam was cut, it was covered with a non responsive coating to ensure that the fiberglass and resin did not have a bad reaction with the styrofoam. After numerous research, the most appropriate material to cover the styrofoam was aluminum foil, which was purchased from the supermarket. Once covered in aluminum foil, the layering of the fiberglass along with the resin was done. It was a wet layup and with no workshop support it was a trial and error experience. Figure 35 shows the dried fiberglass on both the nose and tail cones.

After the fiber glass and resin had set, both the nose and tail cone were coated with a special type of car putty. This was to ensure a smooth finish as well as ensure its strength and waterproof integrity. Once the putty dried, the excess was sanded off; figure 36 shows the putty setting prior to sanding.

Once set, it was then coated with a car primer paint which requires 30 degree heat to set and then finished with a top coat of paint. The completed tail cone can be seen in figure 37.

As previously mentioned, the nose cone was produced in the same manner and the final product can be seen in figure 38. To remove all the internal styrofoam, petrol was used to dissolve the foam away leaving behind the aluminum foil and fiberglass.

B. Body

The construction of the body was very simple, and was intentional for a couple of reasons. First reason being, that the nose and tail cone was very time consuming and secondly, the project was limited with the materials it had available. At first the SEIT was going to purchase a filament winding machine which would have enable the construction of a streamlined body from the nose to the tail, which would have reduced drag significantly. However when the quote came back for the filament winding machine to be a couple of thousand dollars, it was decided that the school would not be purchasing this machine. Instead keeping in line with the restriction of the minimal costs, it was decided to manufacture the body out of the same 255mm PVC pipe that the proto-type was constructed. This material has the properties to withstand the required water pressures induced at 10m depth for a safety factor which can be seen in table 2, and it is very durable and quite
inexpensive. The table depicts a smaller size PVC piping which is able to withstand the pressure, so therefore the larger diameter pipe would be able to withstand the water pressure keeping an appropriate safety factor.

| Table 2. Water Pressure at 10 Meters and PVC pipe Tabulated data |
|-------------------|-----------------|---------------|
| PRESSURE AT 10 METERS | PVC |
| GRAVITY | 9.81 m/s^2 | 28cm Internal Dia |
| DEPTH | 10 m | 30cm Outside Dia |
| PRESSURE | 100062 N/M^2 | 1cm Wall thickness |
| ABSOLUTE PRESSURE | 2 atm | MAX WP psi = 130psi |
| PRESSURE | 29.392 PSI | |

After confirming that the PVC pipe would be more than suitable, it was then just a matter of calculating the size of the body that was required to house the 2 batteries, payload and the control box. Extra length was also added to fit the two 20mm dry walls and have 30mm length of PVC pipe clear for the fittings to attach the nose and tail cones. The aim for the main body was to keep it as short as possible to reduce the total size and also reduce the drag imposed on the UUV. After computing the length, the final body can be viewed in figure 39 and how the dry walls are glued in can be seen in figure 40. The blue glue is PVC piping glue which plastic welds the collars and the pipe together to ensure a water tight seal. A multipurpose co-polymer sealant was also used on either side of the collars to ensure water security.

C. Control System

This was by far one of the most challenging areas in which the project undertook. This thesis was not to design, develop or manufacture a control system for the UUV. However one was required to be produced to operate the UUV. From the proto-type the lesson learnt was that the tether was unpractical and unsuitable for the UUV, so a remote control system had to be developed. After doing some research and guidance from other sources, the remote control system was based around Laser 4 radio control system which can be seen in figure 41.
First concern was the depth of penetration of the radio signal through the water. Dr Tapabrata Ray purchased a small remote control submarine which operated at 49 MHz, which was tested in the SEIT water chamber. The small remote controlled submarine appeared to work sufficiently at the depths of 3-4 metres. Modelling this small scale submarine, produced confidence that the Laser 4 will work since it operated at 36 MHz.

The next step was to integrate the Laser 4, which is an aircraft control, used for remote control planes as a remote for the UUV. This required help from the electrical area of SEIT. The way it works is by sending out an electrical signal at a certain bandwidth. We then had to capture the certain bandwidth via the receiver which then trips a specific switch created on our circuit board. Which switch is trip, at which bandwidth is determined via PICAX controller. The remote control can be seen in figure 42, which also indicates the steering and propulsion controls.

The PICAX controller allows us to manipulate which switch is on and off, thus in turn allowing us to control which pump turns on and when the propeller turns on, via the remote control. The way the control is set up can be seen in figure 43.

After a testing the control by itself, the system worked fine. Once the control system was housed and contained within the UUV, it was very unreliable. The control would suffer a lot of noise inference, which would cause pumps to turn on when they were not supposed to and at other times the propeller would not turn on at all. Another serious problem with the control system is that there is no speed control. With the remote that was purchased, there is the possibility to enable speed control; however this project did not undertake this task at this stage. The problem with no speed control is that the propeller is either on or off, which will be explained later in the paper. These problems have not been rectified as yet due to the time constraints on the thesis, and as mention the control system not being a major part of this project. This project has also used up all of its allocated time with the electrical staff, so a more sound control system will be develop after the submission of this paper.
D. Fittings/Connections

As mentioned previously, this is an important part of the UUV since it is a platform for a number of different projects, thus the components/parts must all align. Not only must they align but also be practical and functional. This means that the tail and nose cone must have the ability to be attached and removed quickly and easily, this is specially the case for the tail, since it is the only access to the internal dry section of the UUV. To best achieve this, a special kind of nut and bolt was used; these were called hollow wall anchors. How they work is the casket is place in one side of the collars, then the outer part is slid over the top of the casket and the small bolt goes into the casket and tightens it up. As the bolt is tightened the casket is compressed and expands out locking it in place. These bolts can be seen in numerous figures throughout the report. Using these bolts ensures the security of the parts, yet also a fast and efficient way of removing the components.

The front pumps are attached to the nose cone in a similar fashion. The anchor attached to them and once slid into the nose cone, a simple bolt is screwed in and fastens the pumps to the side of the wall. How the pumps are mounted can be viewed in figure 44.

Mentioned previously was how the propeller bracket is mounted. Figure 45 shows once the pumps, propeller and all internal components are housed the UUV is then fitted together. The UUV is in three main parts the nose cone, main body and the tail cone. These are simply connected again via the hollow wall anchors which can be seen at either collars.

Using these fittings and connections, allows the tail cone to be quickly and easily removed. This allows the swapping of the two types of propulsion systems for this UUV being the propellers and the bilge pumps effectively. Once again this project has ensured the integrated design is sound and effective.

VIII. Final Design

After implementing all the above designs and components, the assembled UUV can be seen in figure 46.
From the above picture it is clearly visible that the rectangular cut outs are for fluid inlets. These fluid inlets are to flood the front and rear compartments, and also to allow enough water to the front bilge pumps to reduce the chance of cavitations' of the impeller inside the bilge pump. The rear fluid inlets are for the other students design with the 3 bilge pumps at the rear for propulsion.

The UUV has numerous components which can be seen in figure 47.

Figure 47. UUV component layout

The total weight of the UUV is approx 23kilos which is detailed in table 3. The total length of the UUV is 1.3m. Directional control via the four 750GPH bilge pumps at the front. Forward propulsion via a 30LB thrust via the propeller at the rear. Inside the dry section contains two LB acid batteries, control box, sliding rail board and sufficient room to mount the payload, which is visible in figure 47.

Table 3. Weight by Component of the UUV

<table>
<thead>
<tr>
<th>Part</th>
<th>No. Of Parts</th>
<th>Weight of Part kg</th>
<th>Total Weight of Parts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nose Cone</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Bilge Pump</td>
<td>4</td>
<td>0.15</td>
<td>0.6</td>
</tr>
<tr>
<td>Main Body</td>
<td>1</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Rail Board</td>
<td>1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Large Battery</td>
<td>1</td>
<td>1.2</td>
<td>1.2</td>
</tr>
<tr>
<td>Small Battery</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Bulk Head + Rubber</td>
<td>1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Tail Cone</td>
<td>1</td>
<td>1.15</td>
<td>1.15</td>
</tr>
<tr>
<td>Motor + bracket</td>
<td>1</td>
<td>2.4</td>
<td>2.4</td>
</tr>
<tr>
<td>Ballast - Nose Cone</td>
<td>1</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>Payload</td>
<td>1</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td><strong>Total Weight of UUV</strong></td>
<td></td>
<td></td>
<td><strong>23.05</strong></td>
</tr>
</tbody>
</table>
IX. Testing

A. Waterproof

The first test that was conducted was to determine whether or not the UUV was waterproof. The test was successful for the front bulk head, which included the plugs for the pumps to attach into. However for the rear bulk head and collar the test was not so successful. The main reason for the test failing was due to a part not being manufactured in time. The request of an aluminum collar to be manufactured which included threaded holes tapped into it, to be able to fix the bulk head to it, would have stop the leaking. Unfortunately this collar did not arrive in time; therefore the contingency plan was to create a collar out of PVC plating. Although the collar was plastic welded into place, the problem was screwing on the bulk head tight enough to ensure a waterproof seal. Unfortunately PVC collar was unable to achieve enough force to ensure the water tightness. The project is still awaiting the aluminum collar, and when the collar arrives the PVC collar will be replaced with the aluminum one. The engineering drawing sent to the manufacture can be seen in figure 48.

B. Center of Gravity

Another test that was conducted was to find where the center of gravity of the UUV is, when all components are installed. This test was conducted hanging the UUV up via a thick strap until it would hang without assistance. The COG was found to be 120mm in front of the center of the dry section. Just to make sure the same test was repeated underwater, however this time 7 kilos of weight was applied to the strap to apply enough force to make the UUV nearly neutrally buoyant. This test confirmed the previous test results.

From this the conclusion of these tests, it was determined that ballast was required to be added to the front end of the UUV. This was achieved by adding 1.5 kilograms in the nose cone, and adding 5 kilograms to the front of the dry section underneath the rail board. The batteries were also position at the front end of the rail board with the light control box at the rear of the rail board, leaving room in the middle for the payload. Once all components were attached again, the UUV was submerged which resulted in a slightly positive buoyant UUV. The weight distribution achieved the slightly positive buoyancy that was specified in the report.

C. Underwater Control/Speed Test

Conducting the underwater control/speed test, introduced new implications and challenges. The first of these challenges was the speed at which the UUV travels. As mentioned above, the user has no control on how fast the propellers spin. During the testing phase, the UUV did reach its required speed of 2m/s however, the user was unable to stop and control the UUV. This lack of control resulted in the UUV colliding with the side of the pool. The link below is one of the test runs conducted of the UUV. Unfortunately the link is unable to run in PDF format. If you wish to view this video, please contact Dr Tapabrata Ray PhD.

After conducting a couple of tests, it was concluded that the UUV does work, however not in a safe manner. One test resulted in the side thrusters to turn on automatically, assuming due to noise, and the UUV collided with the side of the pool again. Due to the unresponsive nature of the control system, all further testing has been postponed until a more reliable control system is developed. The deferred testing was to ensure the safety and integrity of both the UUV and the swimming pool. It was however concluded that the UUV does travel and the required speed of 2m/s and that the bow thrusters are able to steer the UUV in all directions, once a more robust control system is developed.
X. Data Comparison

Unfortunately there was insufficient data recorded for the testing phase to conduct an elaborate report for data comparison. The testing was able to conclude that the UUV will achieve and extended beyond the required 2m/s velocity. It was also able to determine that the direction pumps at the front are able to turn and steer the UUV. The most effective way of turning, is when the UUV has zero forward velocity. Once the UUV is in motion the turning circle of the UUV becomes quite large, however this is not a major concern for this project since it was not designed to be nimble and agile.

The data produced by ANSYS indicates a total drag force of approx 9N is required to overcome before the UUV will move. This is validated via the video link. When testing the propeller thrust, it produced approx 30N of force. By analysing the video it can be determined that the UUV does travel more than 2m/s and therefore confirming that the total drag force produced by the UUV is approximately 9-10N.

XI. Recommendations

There are only two main areas that need to be addressed before the UUV is fully operational. First being the water tightness of the UUV. This problem is derived from the collar and bulk head. In order to overcome the leakage problem, the ordered aluminum collar is required to be installed. Once fitted the new locking mechanism of the threaded holes will provide enough force to seal the bulk head onto the polystyrene rubber. Future research can be conducted into another system to ensure water integrity to the dry compartments, whether that is by having a large dry compartment as in this UUV, or having individual components waterproofed, and the whole UUV being a flooded compartment.

The second issue is the control system. Although the present control system currently works to a certain extent, the system must be revised and altered to ensure that it has a variable voltage controller added to it, to able the user to alter the speed. This would ensure a safe working practice of the UUV. At present the control system is not robust and is definitely not reliable. One recommendation would be to assign an electrical engineer to the project to undertake the control system.

Future works that can be conducted on the UUV platform include a launch and recovery system. This would be highly desirable, due to the fact that the UUV is some 1.3m long and weighs approx 25 kilos. The size and dimension of the UUV makes it hard for man handling the UUV into, and out of the water.

Another future project would be to include access panels. To be able to design and manufacture water tight access panels, would allow an easier access to the dry components, and would enable the batteries to be recharged without removing them from the UUV.

One last research suggestion would be a propeller design. This would include fluid based analysis of the propeller, which would look at an angle of attack and the number of blades for efficiency. The propeller design could also research the possibility between shallow and deep water explorations blades. These research projects would help to improve upon the UUV platform developed in this paper.

XII. Conclusion

The aim of this project was to design and build a fully functional and operation UUV. The project began by researching current industry models and ideas. The current industry models were critically analysed for sustains and improvements. By using the information gathered from the literature research, this thesis analysed the current ADFA UUV proto-type's strengths and weakness. Then the latter part of this research set upon improving the proto-type to achieve the initial objectives before constructing a more efficient and effective model.

The first improvement for the proto-type UUV was to design and develop a new nose and tail cone which would reduced both the buoyancy and drag implications imposed upon it. This was conducted via the theoretical models, which were analysed using the ANSYS program which, basic drag profiles of a simple UUV are shown. Through inflation and refining the mesh, a clearer picture of drag around the tail cone was discovered. This drag also had the trend to decrease with the finer the mesh; which resulted in the most optimal results and an infinitely small mesh grid would be required. However this is near on impossible not to mention highly unpractical due to the amount of computational time and data that would be required. From these drag profiles the required thrust output was calculated to reach desired speeds and a clear trend of the higher the velocity the thrusters run at then the higher the total drag on the system increases. The behavior of the UUV with its thrusters off during motion was also shown. Using this information, future designs of UUV's can consider the drag profile around the tail cone as well as choosing propulsion systems that would be able to supply the required thrust for a given UUV profile.

After the theoretical analysis confirmed that the UUV had been modified so that the new shaft and propeller propulsion system would work, the next phase was the construction phase, which involved new and exciting challenges. Due to time constraints on specific parts not being able to be obtained, the final UUV constructed has two main downfalls: firstly, leaking via the rear bulk head into the dry compartment, although the flooding
is not catastrophic, it is enough to raise concern and secondly the control system of UUV. The control system is not robust enough, which rises safety concerns when operation in the marine environment.

Overall the project has been a success, the end result designing and developing an UUV which will be able to house optical equipment for underwater surveying. It achieved all the requirements specified in the aim section of the introduction of this study including the cost being less than $1500. Therefore it is a cost effective and time efficient device for surveying underwater, whether it be for oceanography or mine reconnaissance as opposed to using a small submarine.

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**Appendices**

A. Gandtt Chart
B. NSGA-II Matlab code