University of Washington

Human Powered Submarine 2015

International Submarine Races #13

Design Report

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1. Introduction

The 2015 team has several very important goals that we are working towards. First and foremost our team has decided that we want to perform well at ISR13, and develop as a sustainable organization. Several subsets of goals have been established in the effort to attain our top level outcomes, which will be discussed further in this report. The culmination of our effort leads to the most aggressively designed submarine our team has ever produced.

Figure 1.1: General Design

Table 1.1: General Specifications

Dimension Specs	Hull Only (in)	With Appendages' (in)
Length	**96**	**103**
Beam	**20**	**43**
Draft	**25**	**43**
Crew Egress	**36**	**36**

2. Hull

The Hull Design was performed primarily in the 2013-2014 year by a senior AA student and the past captain. Their methodology was to first use biometric human measurements to constrain the minimum dimensions of the hull. The primary human measurements were the leg room around need to run the previous gearbox and the shoulder width. With the human constraints set, they generated several different concepts. It was agreed that the optimal design would maximize the speed achievable in the first 50 meters of the race course. To compare the concepts an equation was created by applying the basic equation of motion. This equation made velocity a function of mass, cross sectional area, and coefficient of drag. The coefficient of drag was determined by using CFD through ANSYS. The final design selected had large reduction in mass and a slight increase in drag coefficient compared to hulls from previous years.

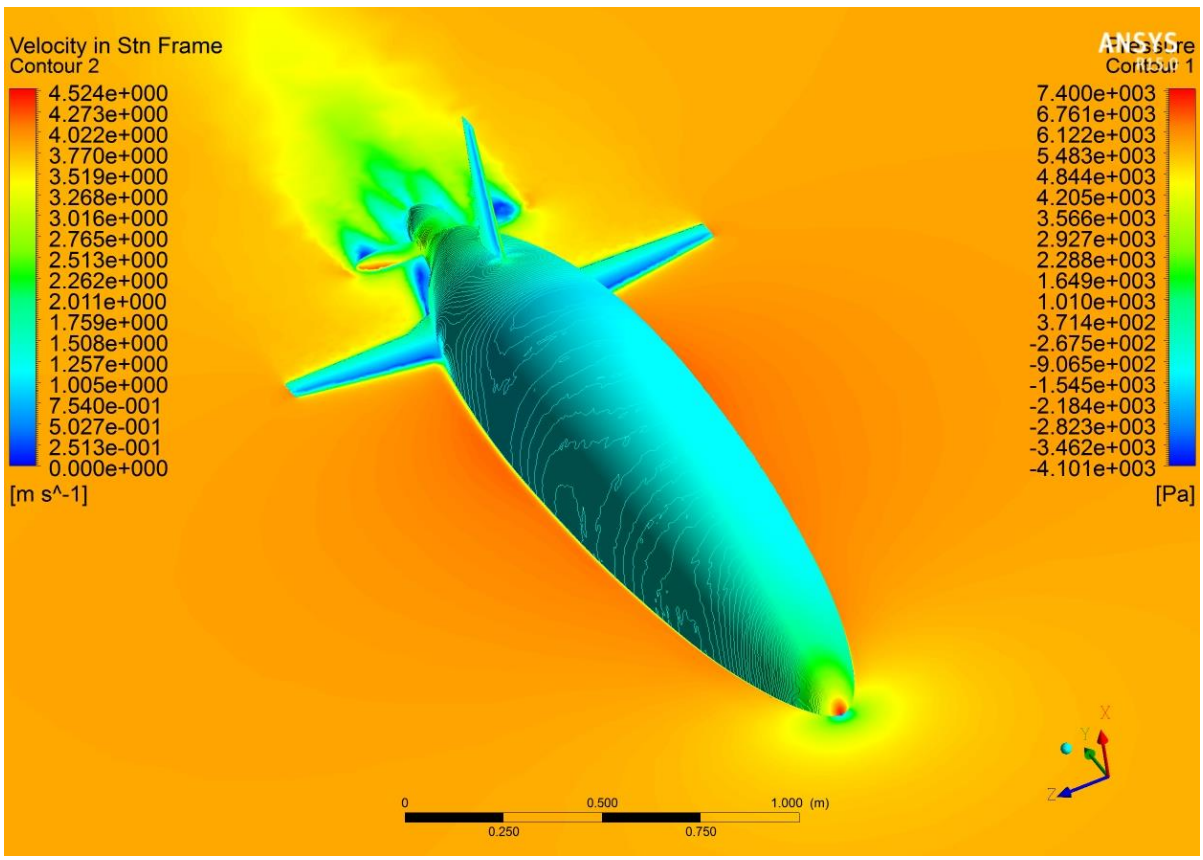

Figure 2.1: Sample CFD Analysis

In order to produce the hull, the team reached out to Janicki Industries as a sponsor, who assisted us in hull manufacturing in previous years. With large envelope 5-axis milling capabilities Janicki was able to mill us a female mold for the submarine with great precision and detail. The mold design chosen would extend one inch past centerline to allow a wax strip to be

laid along the top edge for the top half of the submarine. The intention was for this to make a uniform lip with would mesh with the other half in a lap joint. Also included was an offset lip in the front of the submarine as a mounting point for the window and a 45 degree flange around the entire mold to give a precise cutting edge and real estate for laying down the reinforcement fibers.

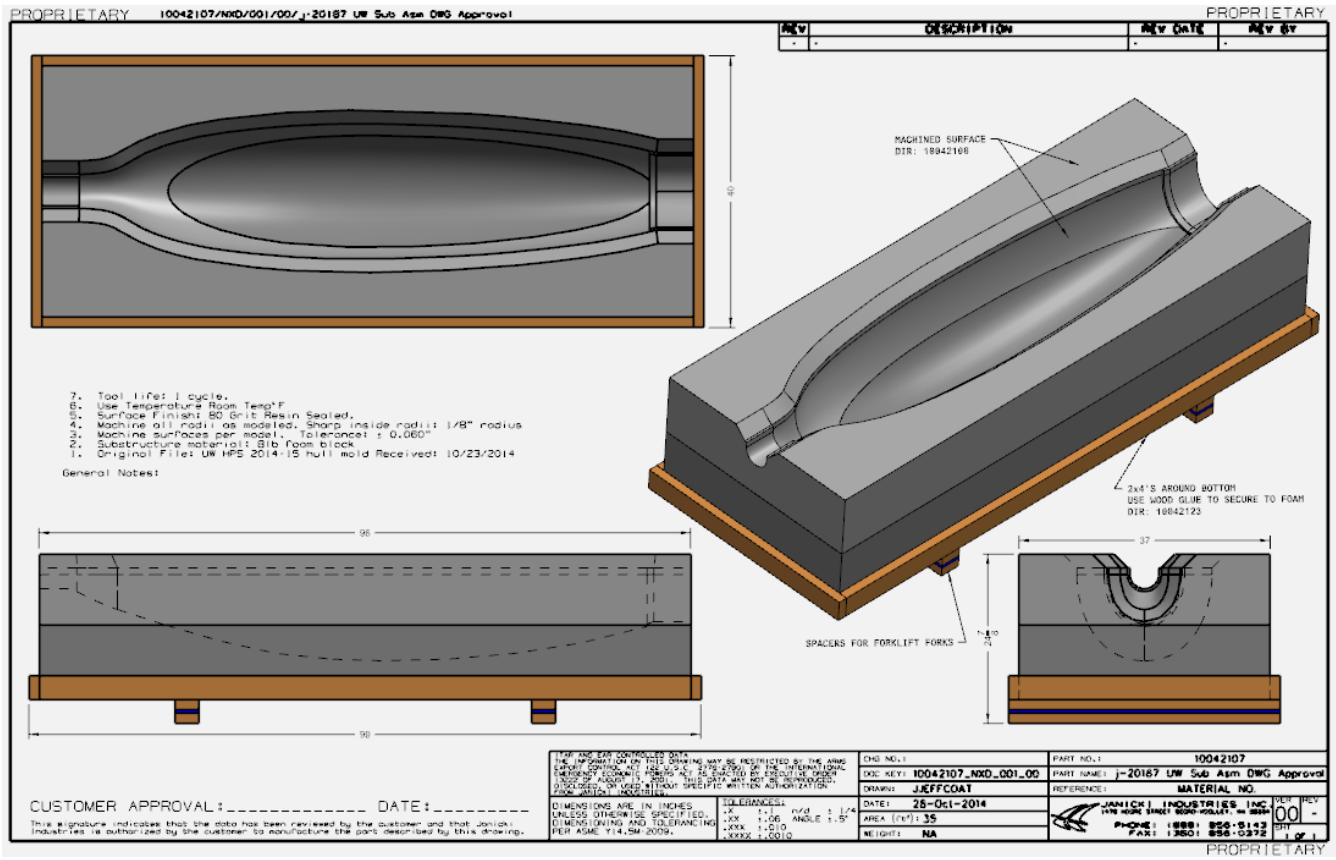

Figure 2.2: Female Mold Drawing

For the layup we chose to use 4 layers of fabric. One glass layer on the inside and outside and two layers of the carbon fiber on the inside with a foam “keel” between the carbon layers on the bottom of the submarine. The foam keel was primarily used to increase the moment inertia of the hull, to make the stiffer and so less like to bend while doing body work. The glass layers were selected for several reasons. First the glass layers would afford us the ability to do some bodywork, without touching the primarily structural carbon fiber in case we chose later to exhibit that later. Additionally the glass fibers have a greater ability to elastically deform then the carbon fibers. This meant that outside fibers are less likely to fail in case of a larger internal moment occurred.

Figure 2.3: Fiber Laying

While the mold was originally meant to be two halves, significant issues during the production process. When making the first half (the bottom half), the sealant applied to the outside of the foam mold was chosen incorrectly and actually bonded with the infusion resin. Unfortunately, this meant we had to destroy the mold to remove the half. In order to compensate we used the first half as a male mold instead of building a new mold due to time limitation. Using the first half as a male mold meant that significant body work and faring on the top half was required to properly connect and align the two halves.

Figure 2.4: Creating the Top Half

3. Propeller

In this year's competition, the UW team decided to design its first controllable-pitch propeller. This rotating functionality extends the optimal performance of the propeller into a broader range of operating conditions which is why it was selected over the traditional fixed-pitch propeller. The propeller blades were designed and optimized using OpenProp, a free Matlab code for Propeller design and analysis. The airfoil used was the NACA 65A010. The code required basic design parameters such as: desired speed, number of blades, rotational speed, propeller diameter, hub diameter and hull drag force at desired speed. To determine the drag force that the propeller must overcome, a computational fluid dynamics program via Ansys was used to simulate the underwater condition of when the submarine is traveling at 7.5 knots. The team took a conservative approach by attaching a "place-holder" propeller onto the model. The final design parameters are listed in Table 1.

Table 1: Design Parameters

Design Parameters		
Number of Blades		2
Desired Speed	[knot]	7.5
Propeller Diameter	[m]	1
Hub Diameter	[m]	0.127
Rotational Speed	[RPM]	200
Hull Drag Force	[N]	190

Table 3.1: Propeller Specifications

The Open Prop optimizes the airfoil shape for each blade section of the propeller and generates several efficiency curves for a range of angles (shown in Figure 2). The final design is shown in Figure 3.

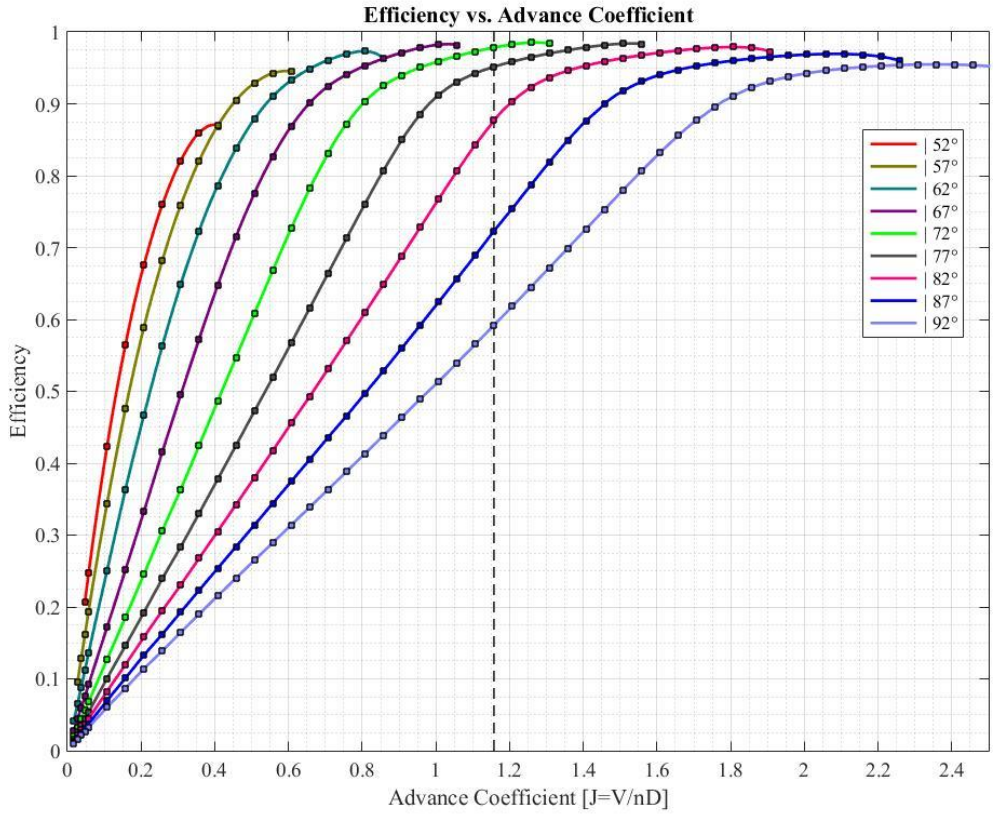

Figure 3.1: Efficiency Curves for the optimized Propeller.

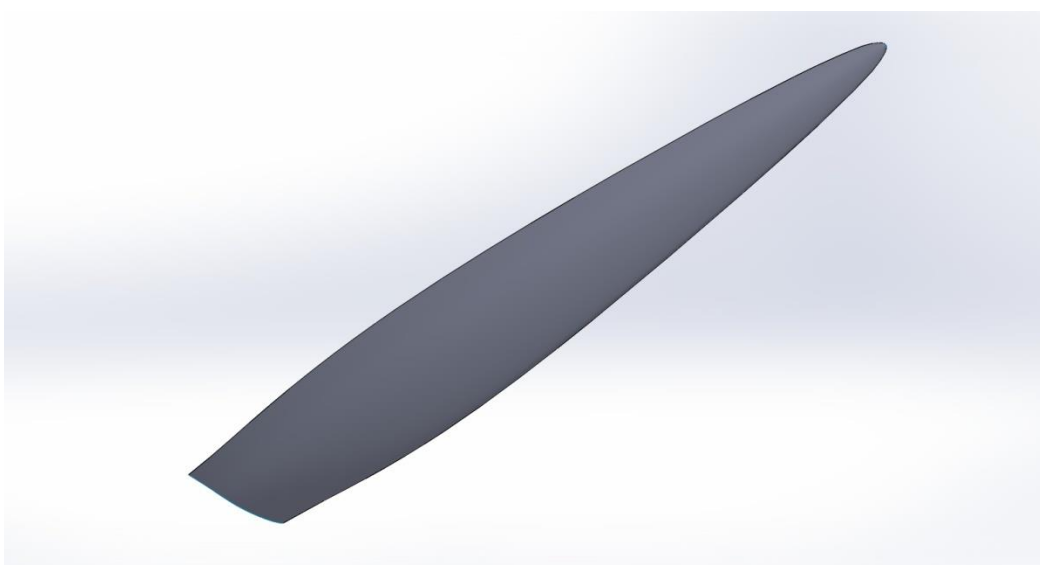

Figure 3.2: General Design

The addition of the rotating functionality of the propeller blades added new challenges, which was how to determine the most optimal blade angle at different operating conditions during the race. The team's solution was to develop an algorithm that sifted through thousands of operating conditions and selected the angle of rotation that would allow the blades to provide the most thrust given the power constraint from the pilot. A graphical representation of the result from this process is shown in Figure 4.

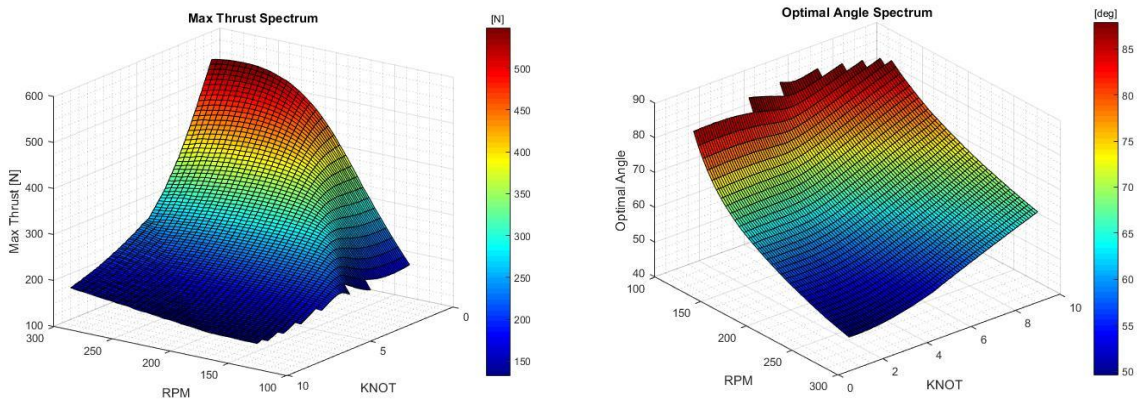

Figure 3.3: 3D plot of the maximum thrust (left) and corresponding pitch angles (right) that the propeller can produce at different operating conditions

4. Controllable Pitch Mechanism

4.1. Utility

Propellers are optimized for a certain angle of attack distribution. This angle of attack distribution is controlled by the pitch of the propeller and the ratio of forward speed and angular speed of the propeller (known as the advance coefficient). Unfortunately over the race, the advance coefficient varies due to the change in speed and the relatively constant rotation of the propeller. While we can do very little to control the advance coefficient, by using a controllable pitch propeller we can change the pitch as the advance coefficient changes. Thus with a controllable pitch propeller, we are able to maximize the efficiency of the propeller blade over the course of the race.

4.2. Requirements

Creating a mechanism to control the pitch of the propeller is difficult because the blade must be held securely yet be able to rotate about their axis. This is difficult because of the two uncontrolled loads:

- Friction between the blades and the mechanism holding the propeller in place
- Any Induced Moment caused by the flow of water over the blades

Additionally having a closed loop control system control the propeller would lead to better results than an open loop control system. This requires sensors that can accurately measure the rotational velocity of the propeller and forward velocity in real time and then use the collected values to maintain the optimal angle of attack distribution.

4.3. Design

In order meet the closed loop control requirements, an electronic system was used. An electronic system was used because it would be more flexible in the types of sensors used to collect data and motors used to control the rotation of the propeller. Additionally an electronic system would have more control in determining the optimal pitch. It was then determined that this electronic system would be completely contained in the hub, designed as a continuation of the hull foils. This is due the difficulty in maintaining a connection between any non-rotating parts not enclosed in the hub and the rotating parts enclosed by the hub.

To collect the data, a two axis accelerometer was used to collect both the rotational velocity and forward velocity. These are connected to one of our custom microprocessors which processes the collected data and sends the output to a relatively large high-torque stepper motor and then a 1:3 gear ratio bevel gear set was used to connect the stepper motor to both propeller blades. To power these electronics, two parallel sets of 10 standard rechargeable NiMH batteries in series which produce 12V and up to 2 amps.

Due to the use of electronics, waterproofing was required. In order to minimize the required parts for waterproofing, all electronics and batteries were placed in a single cavity. This cavity is accessible with the removal of a single large waterproof shell. To ensure the waterproof, the shell was 3D printed, then covered in epoxy. While not necessary for the structure or function of the hub, this allows easier testing and development of the electronic system.

Two primary concern areas for water entering the cavity were where the hub body and waterproof shell join and connecting to the propeller blades. To compensate for the former, an O-ring was placed at the location where the two parts join. To compensate for the later, a mechanical shaft seals was placed around the propeller blades shaft. Because of the inherent unreliability of waterproofing moving parts, a second mechanical shaft seal around the stepper motor drive shafts were used for additional reliability.

Figure 4.1: Exploded View of Controllable Pitch Propeller Mechanism

5. Gearbox

The Gearbox used is the only part that that was re-used from a previous years submarine. In the 2014 eISR the gearbox experienced a failure do to a design flaw it it's alignment. Since the system was otherwise quite robust and came in a highly modular setup it was used as a platform for the gearbox on the new submarine as well.

Figure 5.1: Complete Gearbox Before Alodine Coating

The original gearbox relied on dynamic oil seals to prevent water from getting inside and touching the gears and bearings. All parts also received a surface treatment with Alodine to prevent galvanic corrosion. The gearbox has now been updated with nylon bushings and dynamic double o-ring seals.

6. Control Surfaces

6.1. Control Surface Design

In designing the fin control mechanism the primary concerns were quality of waterproof seals, ease of manufacturing, ease of maintenance, and modularity with the rest of the interacting systems.

The final design chosen, as displayed in figure 6.1, consist of a central frame which is mounted to the hull from flat mounting points on studs. This frame holds each of the custom designed stepper motor housings on the front side, which connects to the control planes with an acetal pulley and belt drive offering an extra 1.6:1 ratio for added torque. The motor and torque specifications of this system are further outlined in section 7, with the other electronics.

Figure 6.1: Control Planes Mounted on Submarine

6.2. Control Surface Manufacture

The control planes in addition to providing control and stability protect the propeller in the event of a wall or bottom hit, so they must be sufficiently strong to take moderate impact and large enough to be effective in protecting the propeller. The material chosen is a Urethane casting. Although tooling cost is high, a new ready to use fin can be produced in less than one hour

Figure 6.2: Casting Control Planes

Class NACA 0018	
Mean Span (m)	0.354
Mean Chord (m)	0.119
Surface Area (m2)	0.0417
Taper Ratio 0.45	0.45
Root Chord (m) 0.163	0.163
Tip Chord (m)	0.073

Table 6.1: Control Plane Specifications

7. Electronic Controls

Being one of the only two teams in the world to successfully pull off using a fly by wire control system in eISR2 the team was looking for ways to further distinguish ourselves above our competitors this year. The three aspects that we decided to optimize were

1. Reliability and robustness of the electronic control system
2. Safety
3. Building a system capable of handling commercial application

All three of these goals led to the decision to completely scrap the old system of Arduino and servos in favor of a custom processors and geared and encoded stepper motors.

After only several days of racing in eISR the hi torque servos used were broken down and analyzed for wear. We found that even though only one servo burned out the entire week all servos showed significant wear on their internal circuit boards. It was determined that no off the shelf servo product would satisfy our minimum design requirements, so we developed our custom servo system. The motor chosen provides 416 oz-in of torque and is further geared at a 1.65:1 using a belt drive, which connects servos to fins for a total of 680 oz-in (3.5 ft-lb) of torque delivered to the control planes.

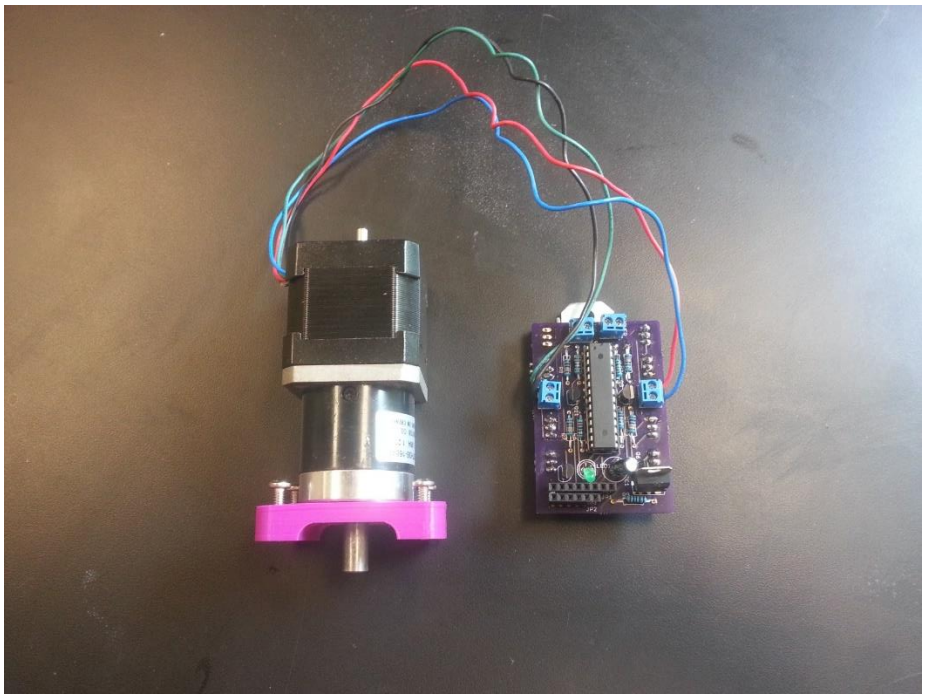

Figure 7.1: Stepper Motor and PCB Assembly

Each motor is connected to the system network through a custom built driver board running an 8MHz processor. With a simple Arduino running the power and feedback of fours servos the code would reiterate from the top every time a feedback was returned that did not match the desired output. This caused the code to lag during high demand situations, and caused “jitter” in the control planes even

when stationary. In the networked system the core processor monitoring the entire control system does not have to process any feedback, and only sends positioning information to the control planes. This extra feedback stage is off loaded to each individual control plane processor resulting in a system capable of handling the most demanding of physical situations at full power.

Another benefit of the networked control system is the water monitoring safety system. In the most basic design set ups detecting a leak in the system with a water sensor would shut off power to all parts of the system. With the networked design each water proof compartment can individually shut itself off to prevent total failure of the control system. This means even of one stepper motors was mechanically destroyed the pilot could still finish the race on three fins.

8. Safety and Life Support

8.1. Buoy System

The buoy system designed to fulfill the ISR guidelines is self-contained and pneumatically actuated by a dead-man style switch. Much thought was put into the buoy, as it has been the Achilles heel of the team in past years, and safety is our top priority. The design chosen is an entirely 3D printed casing which mounts the pneumatic cylinder and reel of line. 3D printing was our preferred method of manufacturing because if fine adjustments needed to be made to the design during testing phase new parts could be quickly and easily fabricated in less than 24 hours.

8.2. Driver Restraint

Due to the small shoulder area of the selected hull, a pilot harness restraint system was not needed. However clipless pedals are still used on the pilot's feet to allow for more stable and larger power output. The pedals chosen are Shimano SPD, which are cheap, reliable, and allow for power on the upwards and downward stokes of the pedaling cycle.

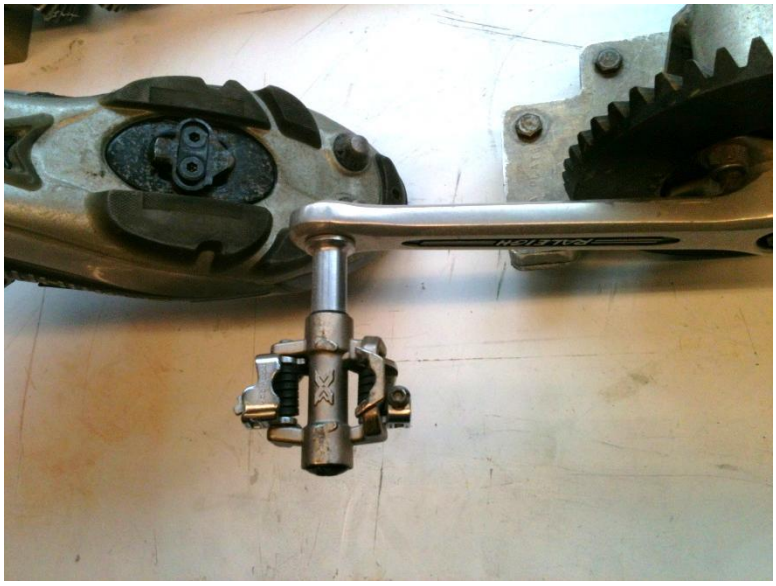

Figure 8.1: Clipless Pedals

The main pilot egress and ingress hatch is also considered part of the pilot restraint system. We chose a design very similar to one which had been used over the past 4 years do to it's track record of reliability. A 6 cubic foot pony tank was chosen to run to run the pneumatic systems (consisting of the hatch release and buoy) and it was calculated that the hatch could be opened X times before the tank dropped below the 100psi mark.

8.3. Air Supply

Much consideration was taken when choosing the SCUBA breathing equipment to be placed on board the submarine as well as its placement. A few functions were considered as primary and therefore un-comprisable: the ability for the pilot's pedaling motion to remain unimpeded, a parallel redundant tank/regulator setup, and the ability for the pilot's breathing to be largely unrestricted. A standard AL-40 tank was selected as the primary, on board air supply as it could support the pilot at 20ft for about 25 min based on a breathing rate of 1 CFM at 1 atm. It was estimated that the competition run would take about 1 min of intense activity with about 10 min of life support to submerge before the race and align the submarine with the race course. Assuming the pilot requires four times the air during the run, this would leave 50% air capacity at the end of a run which was deemed acceptable by the team. For context, even in a situation where the pilot was trapped and hyperventilating the extraction team would still have 5 minutes to pull the pilot out before we had to switch to his secondary air supply.

The secondary air supply chosen was a 3 cubic foot spare air bottle. Although smaller in air capacity then the 13 cubic foot pony used previously by the team, the secondary air supply needed to be much smaller so that the pilot could access it from his forward prone position the

submarine. At the stressed level of 4 CFM the spare air provides an additional 45 seconds of life support to extract the pilot.

Because space in the submarine is so tightly confined special consideration had to be made for the pilots second stage regulator and mask. The mask chosen was a low-volume Aqualung Sphera, which wraps around the pilots face giving more ability for him/her to move their head without interference with the window. The second stage selected is Poseidon XXX. This regulator is ideal because of it's low profile and side port exhaust.

8.4. Emergency Beacon

The emergency beacon used is a C-Strobe life jacket beacon. This beacon has proven successful in the team's past competitions and was mounted just aft of the hatch at the high point of the hull to ensure maximum visibility.

Figure 8.2: Emergency Beacon Rescue Egress

9. Team Finances

The University of Washington Human Powered Submarine team's financial report includes: sources of funding, how financial transactions are accounted for, a breakdown of this year's cash flows for purchases of each of the groups, and an income statement for this year's model constructed in fall 2014 and completed in 2015.

9.1. Sources of Funding

Our biggest source of funding comes from the University of Washington's Mechanical and Electrical Engineering departments. This year, they have contributed eight thousand dollars to our group for the construction of the submarine. Other sources of funding come from sponsors of our team. However, it should be noted that not all of the sponsors support the team via monetary aid. Boeing for example, gives the team a large enough shipping container, and ships the submarine to Carderock, Maryland for the international competition.

Although donated goods and services make up a large majority of the teams total support for the purpose of this report only cash flow will be analyzed

9.2. Financial Accounting

The system, by which financial transactions are accounted for, is a basic Debit/Credit (DR/CR) bookkeeping system. This system works by debiting and crediting accounts that are involved in a financial transaction. These accounts include: cash, inventory, accounts payable, sales tax, shipping costs and other expenses accounts. Financial transactions are chronicled by debiting and crediting affected accounts. For example, if Bentley (part of the hull group) made a purchase of inventory from Mc-Master Carr for $350 dollars, the inventory account would be debited $350 dollars to signify the addition of inventory, and $350 dollars would be credited to the Bentley's account payable. Each group has its own book to chronicle its own purchases.

Each book has two sheets, the first containing a general book of journal entries. These entries are very general and are meant to give the reader a general picture of the group's financial activity. The second sheet is a detailed list of journal entries. A reader of this sheet would be able to see exactly what was bought and the retailer it was purchased from. Going back to my previous example, instead of just debiting inventory for $350 dollars to a general inventory account, each individual purchase is debited and the retailer is specified. Sales tax and/or shipping cost is also separated and debited. Now for accounting purchases, these individual purchases do not have their own accounts, rather they are treated as a more detailed look at the inventory account, used to give the reader an idea of what exactly was purchased in that financial transaction. Sales tax and/or shipping costs are also debited as costs of inventory, and Bentley's account payable would still be credited.

It is assumed that all inventory purchased is all used toward the construction of the submarine. So for that reason there is no need to specify the inventory in a chain of accounts to describe the flow of costs and construction. This would be having three inventory accounts entitled Raw materials, Work in progress, and Finished Goods. It is assumed that everything purchased immediately goes through to

Finished Goods. The reason for this assumption is because we are not a company that sells what we make. So we do not have to worry about the use of our inventory affecting our costs of goods sold because are not even selling anything to have a cost of goods sold. Furthermore, for the consolidation of the income statement, we only use the contribution format in order to give an honest portrayal of our financial situation, separate the fixed and variable costs, and because there is no cost of goods sold.

9.3. Cash Flows

The total purchases made by each group are as follows:

- Propeller- $108.30
- Mechanical Hub- $313.20
- Gearbox- $355.24
- Electronics- $389.79
- Controls- $675.62
- Hull- $1,090.81
- General- $4,440.76.

This gives us a final cash balance of $2,626.28 remaining from our beginning cash balance of $10,000. There was a $600.13 variance in cash balances between the actual cash account reported by the college administration and the cash balance reflected by our own accounting system. This is not surprising because this system was implemented very late in the year. The variance is then accounted for in the adjusting entries portion of the general entries book as a debit of $600.13 to inventory and a credit of the same amount to cash. Previously, this variance was accounted for by proportionally distributing the variance among the groups, but it was decided that that amount would constantly change as the amount of money spent per group increased. So even though it is a more general way of accounting for this variance, we believe it is more accurate to leave it as an adjusting entry in the book of general expenses.

As percentages of the total amount of cash spent, the purchases made by each group are as follows (percentages are rounded to one decimal):

- Propeller 1.5%
- Mechanical Hub 4.2%
- Gearbox 4.8%
- Electronics 5.3%
- Controls 9.2%
- Hull 14.8%
- General 60.2%.

The vast majority of cash spent was for inventory in order to construct the submarine. Inventory was bought from the retailers: Amazon.com, Onlinemetals.com, Mc-Master-Carr, Tacoma Screw Products Inc. Hardwick's, Lighthouse diving center, etc. (All retailers can be viewed on sheet two of the each of the accounting books). The only group whose majority of purchases is not inventory is

the General group. The General group also is the group that spent the most cash. This is because our biggest expenses fall under the general group. These expenses include our Competition entry fee of $1250, and our travel expenses to send members to the competition in Maryland, $2350. These our most expensive purchases and is why our general account spends the most cash.

With our current cash balance of $2,626.28 we intend to spend it on any other materials we need to construct the submarine in order to make it competition ready, and on our christening ceremony, which we hold as a celebration for our members and as a thank you to our sponsors. Any excess of cash will be in excess of cash will be a favorable variance to our original budget because we would have spent less than we originally thought and therefore proved our efficiency in use of materials and labor throughout the year.

Next year we plan to construct a two-man submarine, which is approximately double the size of our current submarine. Therefore we will ask for double our budget that we got the year of 2014-2015. We still have yet to see if there are any variances in our budget but we do not expect to see any.

9.4. Income Statement

The following is an income statement for the submarine teams as of May 17, 2015 computed using the contribution format.

University of Washington Human Powered Submarine Team
Income Statement
For Period from October 12, 2014 to May 17, 2015

Cash Received from Sponsorship	**$10,000.00**
Less Variable Costs:	
Inventory from each group	
Propeller	**(108.30)**
Mechanical Hub	**(313.20)**
Gearbox	**(355.24)**
Electronics	**(389.79)**
Controls	**(675.62)**
Hull	**(1,090.80)**
***General/Administrative Expenses**	**(3190.82)**
Contribution Margin	**$3,876.23**
Less Fixed Costs:	
General/Administrative Expenses	
Competition Fee	**(1250.00)**
Net Income/Excess in Budget	**$2,626.23**

***This is the account which has the 600.13 dollar variance attached to it**

Appendix 1: UW Scientific Diver Guide

Guide to Becoming a Scientific Diver

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Introduction and Overview

To dive with the University of Washington Human Powered Submarine team, everyone must be certified University of Washington Scientific Divers. The process is fairly simple, but can take some time to complete. Though the team had certain requirements waived for the 2011 ISR competition, we should not rely on this happening again. Divers who wish to dive with the team should start this process as soon as possible.

Some of the expenses are being taken care of by our sponsors. Gear is provided by Lighthouse Diving Center (subject to availability) and before scheduling a dive with Samuel (Sam) Sublett, you should make sure that you can get all the required gear. All required training is provided by the University and is also free.

Sam Sublett is the University of Washington's Dive Safety Officer (DSO.) He is responsible for overseeing diving safety. He's got a big moustache and a great deal of diving experience (from Hawaii to under the North Pole) and we can learn a lot from him. In the past Sam has been more than understanding about everything so if you have any questions about this guide or certification, talk to the Dive Captain Tyler first and Sam second. Tyler is responsible for all diver coordination and planning.

Required Steps

- **Physical**
  - **This is scheduled with Hall Health and takes place over two days. The first day is general tests like sight, hearing and breathing. The second day is more of a general physical like you get on an annual basis to make sure you're in good health. The physical is good for five years if you're under forty, so you should only have to do this once.**
- **SCUBA First Aid and O_2 Class**
  - **The First Aid/ O_2 class takes place occasionally throughout the year. It takes a couple of hours and is comprised of a video and some hands on practice. Contact Sam for scheduling this, preferably through email. We will try to make announcements at the weekly meeting about upcoming classes when it comes time to get people certified.**
- **Written Examination**
  - **The written exam is a fairly simple review of what you learned in open water class combined with some additional information about diving with the UW. It has a take-home and open-book format. Try to complete all the questions before turning it in to Sam. The UW dive manual, available on the Submarine Team website, will be helpful. Remember to us Navy or NAUI tables!**
- **Check-Out Dive**
  - **This dive is scheduled with Sam Sublett. He teaches some basic rescue techniques (diver tows, in-water CPR) and double checks basic open water skills (mask clearing, regulator clearing, etc.) The 2009 dive took place in Lake Washington, but usually the location is negotiable.**
- **Registration**
  - **A simple UW registration website keeps track of divers and dives. Sam will ask you to register on the website at some point in your training to keep track your progress towards a scientific diver certification and to log your dives once you're certified. The URL is: http://washington.diveaaus.com/User/User_Login.asp**

Benefits to being an AAUS Scientific Diver

Besides being able to dive with the submarine team, being a scientific diver at the UW has certain benefits. The university offers free diving classes (rescue, for example) to all scientific divers. While these classes do not fulfill the requirements for national certification (ex. NAUI or PADI) they're useful and taught by our fearless DSO, Sam.

We also receive a discount with Pinnacle, a company that makes exposure suits for diving. If anyone is interested in purchasing a suit, they can get a top quality one from pinnacle at manufacturer's cost. This works out to about 60% off retail.

The reason we have to be scientifically certified is to take advantage of an exemption in OSHA rules that allows scientists and students to dive for a University without being certified as commercial divers. The exemption is regulated by AAUS (American Academy of Underwater Sciences) and it is possible to get involved in other scientific diving with the university and other organizations without having to get recertified.