PHANTOM 7

TECHNICAL REPORT

VIRGINIA POLYTECHNIC INSTITUTE

AND STATE UNIVERSITY

HUMAN POWERED SUBMARINE DESIGN TEAM

13TH INTERNATIONAL SUBMARINE RACES

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1. Abstract

The goal of the Virginia Tech Human Powered Submarine team is to design, build, test, and race human powered submarines. Historically, Virginia Tech has been extremely successful at the International Submarine Races (ISR), placing in both the speed and design categories for recent designs in the Phantom (propeller driven) and Spectre (non-propeller driven) classes. Most recently, Phantom 6 won First Place for Most Innovative Submarine at ISR 12.

Phantom 7 is the newest submarine currently being produced by the Virginia Tech Human Powered Submarine team. Continuing with the innovation seen on Phantom 6, Phantom 7 possesses an autonomous control system, made possible through sensors and actuators controlled by an onboard computer. Phantom 7 will also strive to achieve speed awards. To meet this goal the team put forth extra effort in minimizing hull volume and weight, improving the propulsion system's efficiency, designing new propeller blades, and minimizing drag from control surfaces and other appendages. Conceptually, Phantom 7 is the most advanced submarine designed by Virginia Tech to date and her performance at ISR 13 is expected to be record breaking.

2. Conceptual Design

Phantom 5 was a largely successful submarine in measured values from previous ISRs. She set high speeds and proved to be one of the fastest submarines Virginia Tech had produced to date. Phantom 6, while so far lacking in the speed category, provided a great test platform for innovation with the propulsion system, electronics system, and overall submarine design. The team set a goal following ISR 12 to return to ISR 13 with a submarine capable of setting a new speed record. To achieve this, the team looked heavily back on what was learned through previous submarines. In short, these were the results:

- Single person submarines are quicker and easier to manufacture
- Single person submarines typically have higher speeds
- The electronics system was capable of being waterproofed
- The data from electronics was both accurate and measured frequently
- Controlling the submarine correlates to a loss in power
- Most previous propulsion systems were overdesigned and heavy
- Previous safety buoys were unreliable

In light of these ideas, the team set forth to correct all issues and improve on already sound systems. In doing so, Phantom 7 was born: a single person submarine with autonomous controls. The hull design is based on Massachusetts Institute of Technology calculations for the most streamlined hull shape. The gear box had large weight reduction design changes and new materials were used to reduce losses in efficiency. New propellers were designed based on cutting edge technologies using blade element theory. The life safety buoy system was improved upon to ensure reliable function in all conditions. Finally, and most importantly, the electronics system was scaled up to not only record and display data but to also control the submarine. Phantom 7 features autonomous controls system that will maintain the desired heading on the course. She also features a controllable pitch system, also controlled through electronics, to change the propeller pitch during the course of the race to aid the pilot in acceleration and finally attaining and sustaining top speed.

The detail design of each individual system is outline in the following section of the report.

3. Phantom 7

In order to be competitive with the top end teams at ISR, two main design goals were identified for Phantom 7:

- Reduce volume – By minimizing the volume of the hull, total surface area can be minimized, thus leading to a reduction in drag.
- Reduce mass – Minimizing the overall mass of the submarine means less weight for the pilot to accelerate through the water.

The hull for Phantom 7 has a very significant impact on weight and volume reduction. A major decision that effects the volume and mass of the hull is the number of pilots for the submarine. Based on experiences with previous Virginia Tech and competitor submarines, it was decided that Phantom 7 will be a single pilot design. With these goals in mind, this section will consider hydrodynamic shape, material selection, buoyancy and hydrostatics, and stability of the Phantom 7 hull.

3.1. Hull

This report details the development of a hull for Phantom 7, the newest submarine to be designed and constructed by the VTHPS team. By combining an ergonomic analysis with an exploration of the main submarine systems, it was possible to achieve minimum dimensions for the length and diameter of the submarine. Those dimensions could then be used in a mathematical model to determine a series of offsets that represent the hydrodynamic shape of the hull. Finally, an extensive calculation for hydrostatics was performed and should be maintained for the life of the submarine to balance and trim the vessel. The design of this model is then followed by the documentation of the construction of the hull for Phantom 7 and the resulting product

3.1.1. Design

The first step in determining the P7 hull shape was to examine the largest system to be onboard the submarine: the human. Measurements were taken with respect to the largest pilot currently on the team. Five separate measurements were used to determine the minimum ergonomic dimensions of Phantom 7: Total height, width at shoulders, 90° leg bend, width at waist, and head diameter. Figure 1 is a visual representation of these measurements, while Table 1 shows the results.

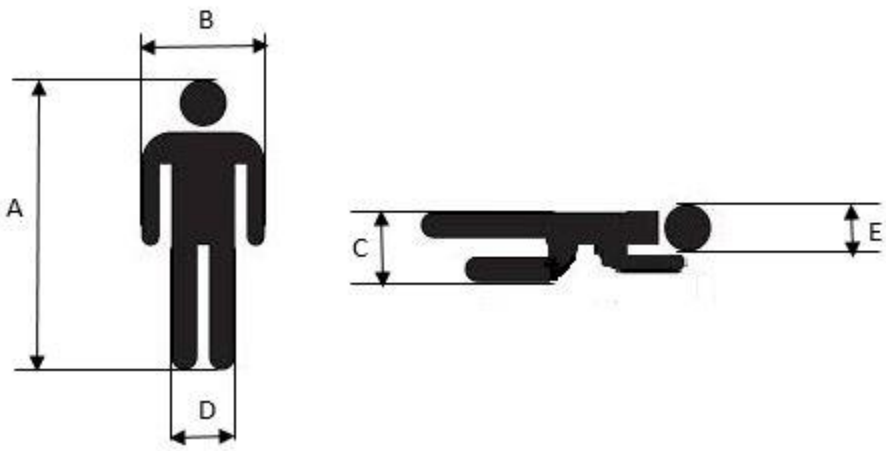

Figure 1: Ergonomic Measurements

Table 1: Ergonomic Measurements

Measurement	Measurement Description	Length (in)
A	Total Height	76
B	Width at shoulders	20
C	90° leg bend	24
D	Width at waist	15
E	Head diameter	7

Total height of the pilot will contribute to the overall length of the submarine, in addition to the propulsion system discussed in Section X. Width at shoulders represents the minimum "beam-wise" diameter of the hull in order to contain the human pilot. The 90° leg bend represents the minimum "depth-wise" diameter of the hull in order to account for the worst case scenario when the pilot is pedaling. It should be noted that previous examinations of Phantom 6 piloting show that a full leg bend is not typical. This depth is usually closer to 17". The width at waist represents a measurement that can be used for an aft beam-wise diameter. This will help to allocate space for the systems in the aft of the submarine, such as the drive train and electronic control system. Finally, the head diameter provides a minimum measurement for the forward part of the submarine. The pilot will likely have the need to move his or her head for situational awareness and comfort.

It is important to note that there is a possibility for smaller divers to pilot Phantom 7. A height compensator will be built into the chest and shoulder harness, or into the gearbox mounting system, and will not be considered in this section.

The next step in determining the shape of Phantom 7's hull form is a careful analysis of the large internal systems that will add to the total volume of the submarine. After all systems were considered, it was decided that major systems contributing to submarine volume would be the propulsion system, the electronics brainbox, air tank, and harness.

Virginia Tech's linear drive gearbox has been in use on VTHPS submarines since Phantom 5. The design has varied slightly over the years, but primarily has had the same functional envelope. The step shafts that transfer energy from the pilot's legs to the rest of the propulsion system are 22" long, so at full leg extension, the distance from the pilot's foot to the end of the gearbox is 22". It is also important to note that driveshaft must be directly on the centerline of the submarine. This offers a constraint on the y- and z- location of the gearbox. The maximum dimensions in the y- and z- directions are shown below in Table 2.

The brainbox is the next internal "system" considered, because of its importance to achieving the autonomous control system goal. In Phantom 6, the brainbox was located towards the bow in between the harnesses for the pilots. This was a sensible location, as most of the electronic components were located near the bow. On Phantom 7, the vital components of the system are the actuators moving the control surfaces.

Additionally, the brainbox needs to be in a secure location where it will not be jostled. Since the gearbox will be securely mounted near the stern, and must be high enough in the submarine so that the driveshaft remains on centerline, it was decided to place the brainbox directly under the gearbox. It is important to note that they will not utilize the same mounting system to prevent vibrations from the gearbox affecting components within the brainbox.

By the same placement logic, the air tank should be located close to the bow, where it is easily accessible by the pilot. The harness and tank will be integrated into one unit, similar to the design used on Phantom 6. This allows for more space for the pilot to move his or her legs within the smaller beam. Table 4 shows the final dimensions of the submarine systems used in the hull form analysis.

Table 2: Submarine System Maximum Dimensions

System	**Max length (in)**	**Max breadth (in)**	**Max height (in)**
Gearbox	22	4.5	3.625
Brainbox	8.8	5.2	4.2
Harness/Tank	24.8	9	8.25

By combining the ergonomic and submarine system dimensions, a final calculation of the minimum dimensions for the hull was made. Table 3 details which components and measurements comprise the final minimum dimensions for the hull.

Table 3: Minimum Hull Dimensions

Dimension	Components	Component #'s	Final dimension
Length	Pilot height, gearbox length	76" + 22"	98"
Beam	Pilot width at shoulders, pilot width at waist, gearbox width	20", 15", 4.5"	20"
Depth	90° leg bend, harness depth, head diameter	24", 8.25", 7"	24"

It is important to reiterate that these dimensions are the *minimum* dimensions for the hull. Of course, there are other space requirements that these do not account for. Examples of those requirements include space for the control surfaces, space forward of the pilots head for viewports, the heads-up display, and pilot comfort. After allocations for these and more factors, the finalized dimensions of the submarine are as follows:

Table 4: Phantom 7 Final Dimensions

Dimension	Value (in)
Length	120”
Beam	24”
Depth	24”

Now that the dimensions of Phantom 7 were determined, it was necessary to determine the hydrodynamic shape of the hull. The process used is based on the MIT model used in the Virginia Tech Ship Design class. This model describes the geometry of a “resistance optimum” teardrop shape for the hydrodynamic hull. The model separates the hull to an ellipsoidal forebody and a parabolic aftbody. For the “resistance optimum” teardrop, the forebody (L_f) is the first 40% of the overall length, while the aftbody (L_a) is the remaining 60%. However, consideration for where the maximum diameter should be located helped determine the actual percentages used for the forebody and aftbody. Additionally, a parallel midbody was added to create more internal space for the pilot’s legs. For P7, the forebody is the first 35% of the overall length, the midbody is the next 7.5%, and the aftbody is the remaining 57.5%. Next, the vertical offsets from the centerline are determined. Equation 1 represents forebody offsets, while Equation 2 represents aftbody offsets. Table 5 defines the variables used in the equations and Figure 2: MIT Model MeasurementsFigure 2 provides a visual of the measurements being made.

$$Y_f = \left[1 - \left(\frac{X_f}{L_f}\right)^{n_f}\right]^{\frac{1}{n_f}} \tag{1}$$

$$Y_a = \left[1 - \left(\frac{X_a}{L_a}\right)^{n_a}\right] \tag{2}$$

Table 5: MIT Model Variables

Variable	Definition
L_f	Forebody Length
L_a	Aftbody Length
L_{pmb}	Parallel midbody length
n_f	Forward fullness coefficient
n_a	Aft fullness coefficient
X_f	Forebody longitudinal location
X_a	Aftbody longitudinal location
Y_f	Forebody vertical offset
Y_a	Aftbody vertical offset

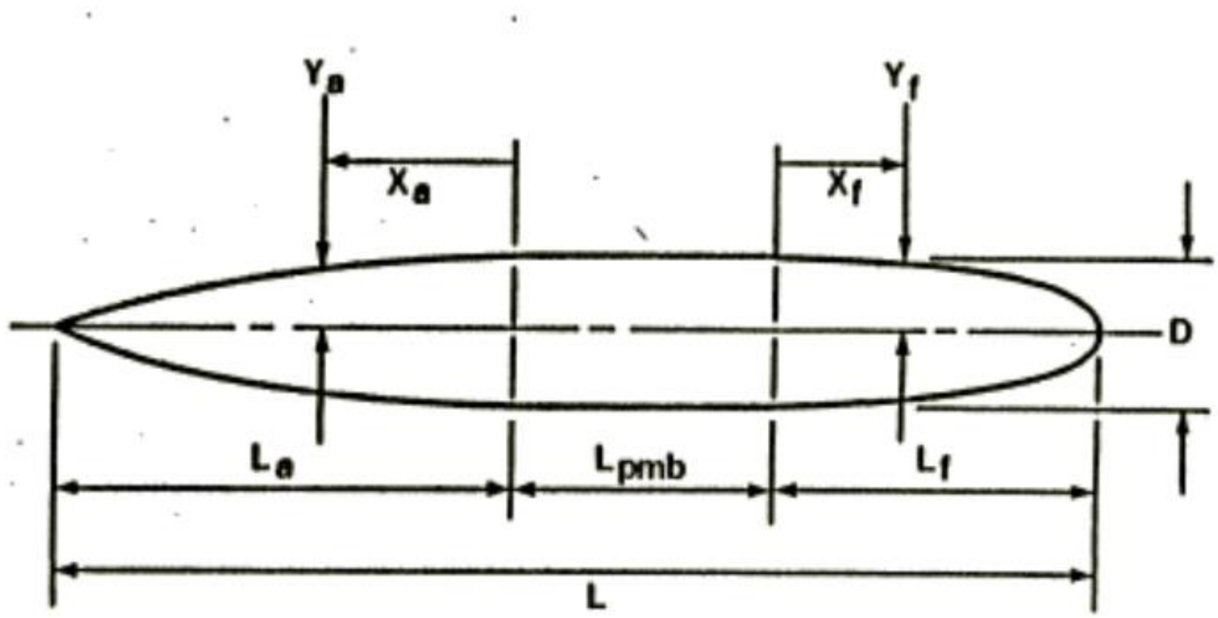

Figure 2: MIT Model Measurements

The fullness coefficients listed above effect the exact shape of the teardrop. Wanting to remain at the "resistance optimum" shape, the forward and aft fullness coefficients were set to 2.0 and 2.5 respectively. In future testing, these coefficients could be varied to explore the effect on drag and other properties. MATLAB was used to generate a series of points that could later be imported into Autodesk Inventor. The MATLAB code is located in Appendix A. Using the spline tool in Inventor, the series of points was transformed into a two dimensional curve. That curve was then revolved to create the three-dimensional, axisymmetric hull for Phantom 7. The final envelope volume and surface area of Phantom 7 are listed below in Table 6. Figure 3 is a rendering of the hull from Autodesk Inventor.

Table 6: Phantom 7 Envelope Volume and Surface Area

Envelope Volume (ft^3)	20.3
Surface Area (ft^2)	47.8

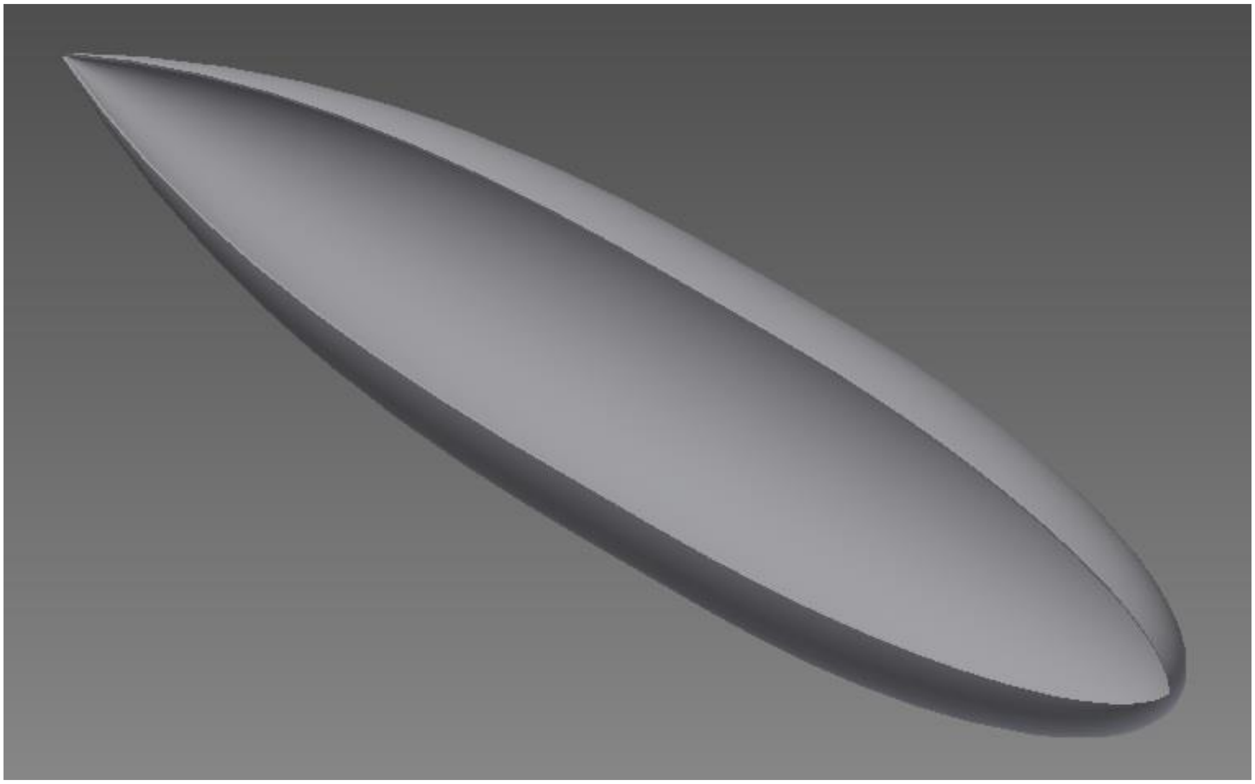

Figure 3: Autodesk Inventor Rendering of the Hull

The hydrostatics for Phantom 7 were approached with extreme attention to detail. One of the primary challenges of Phantom 6 and previous submarines was achieving neutral buoyancy in the design phase. By Archimedes' principle, an object will be neutrally buoyant in a fluid if its weight is equal to the weight of the fluid is displaces. Therefore, it is necessary to determine the weight and displacement of every component of every system in the submarine, as well as the weight and displacement of the hull itself. Additionally, all centers of gravity must be known for trimming the submarine in the pitch and roll modes. This task is best accomplished through the use of a database or spreadsheet. This document is most certainly a "living document", meaning it must be updated as more data becomes available, or if final products deviate from original specifications. An example page of the spreadsheet can be found in this section of the report.

3.1.2. Construction

The construction of the Phantom 7 Hull began in the first week of September 2014, and was completed in the middle of March 2015. The results of the operations are considered successful on the terms of the team, producing one of the best hull forms VTHPS has produced to date.

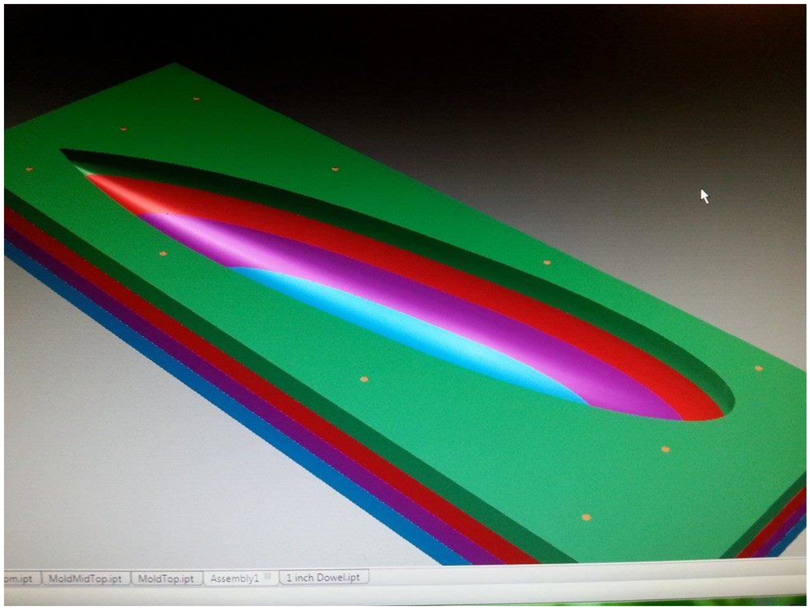

Figure 4: Visual Representation of Hull Mold Slicing

For the first time in the history of the Virginia Tech Human Powered Submarine Team, the mold to make the hull was manufactured entirely on campus. While the actual CNC milling of the mold is typically outsourced to a boat manufacturer, a new facility was made available on the Virginia Tech campus that would allow the team to perform this operation.

The mold was modeled in Autodesk Inventor using a negative of the initial hull model. Due to the z-axis limitation of the router to be used, the mold required splitting into four separate layers, shown in Figure 4, each of 4 inches in depth. Additionally, the x-axis limitation was brought into question, as it was exactly equal to the mold's cut length. It was decided that the pocket should be positioned at approximately a 15º angle in the plane of the stock material to move the pocket completely within the envelope of the machine. The first of these layers was the narrowest section, containing only the outer surface of the parallel mid-body. The two center sections were considerably longer, and were full depth. It was decided that the centers, as shown in Figure 4, would be left in the model to allow for less wear on the machine and shorter run times. The top section consisted of the top two inches of the hull shape, and an additional two inches of purely vertical sidewall to allow for imperfections such as edge bubbling and resin sagging. Additionally this edge would provide a smooth even surface for a clean cut to get the hull to the exact correct size. The layers would then be assembled into a block after machining using one-inch wooden dowel pins and alignment holes that were machined at the same time as the pocket. Machining the dowel holes and the pocket at the same time allowed for a proper relative alignment between layers regardless of the initial position of the machine head and stock on the table at the start of a layer. Finally, it was decided that the rear point of the submarine would be to square to be accurately machined by the router, and was turned to a half-inch radius to match the tooling selected for the operations.

Milling began on the afternoon of September 11, 2014. The operation was broken into eight components, a roughing and finish pass for each layer. The four layers took 70 hours in total to machine over the course of three weeks with varying run times for each pass. Roughing passes would step down at ¼" intervals and remove planes tangential to the curvature of the finished curve while operating only in the X-Y plane. The finish passes would use a raster design and move in either the X-Z or Y-Z planes in order to create sweeping curves. The strategy worked very well for the low angle curves of the bottom two layers; however, steep sides, tight curves, and the alignment holes were very rough, even after the finish pass. The finish pass was programed to never step below the final modeled surface so that any imperfections and tool marks could be sanded off for a smooth finish.

Once the mold was completed, the surface required a layer of fiberglass to create a more ridged interior finish that would support fiberglass work and provide a smooth surface finish. The surface of the mold was prepared by sanding tool marks off using 220 grit sandpaper. Gaps and divots were to be filled using a low-density filler of phenolic micro balloons, but this proved to be to fluid of a material, and cause significant running that required extensive grinding and careful sanding to remove without causing damage to the softer foam. A second attempt at filling was made using seam sealing compound for gypsum board seams, which proved both effective and easily sanded to match the foam mold surface. Once sanded the surface was ready to receive the fiberglass. Two layers of 6 oz. cloth were selected as the base coat, to be placed in sections along the mold's length, approximately two feet long and full width. These large sections of glass fabric were saturated in epoxy resin by dipping them in a trough and then the excess epoxy removed. This process proved difficult as it made the glass sheets very unwieldy and resulted in the less desirable end finishes discussed later. The two layers required a total of a half-gallon of mixed epoxy, which for the surface area of the hull is larger than should be expected. The glass was then covered with nylon release ply, and vacuum bagged overnight for 8 hours, however the vacuum was able to draw air through gaps in the foam blocks and was unable to seal enough to generate a pull on the pressure gauge.

Following a full five-day cure time, the vacuum bagging supplies were removed, revealing a number of bubbles, wrinkles, and other entrapped air pockets that had formed as a result of the poor vacuum seal. The major blemishes were removed using a Dremel tool and grinding stone to take them down to a more sanding ready state. Sanding then proceeded for three weeks to get the surface to an acceptable state, during which entrapped air pockets were continually revealed and required filling. Once the surface was free of major wrinkles, body filler was applied and sanded four times to level the surface to a uniform smooth surface. Once the smoothness met the satisfaction of the engineers, five consecutive coats of epoxy were thinned to a paintable consistency and applied with foam brushes to the surface to seal any exposure to foam and further smooth out the surface. Any remaining blemishes at this point were filled with Bondo body filler. This final coat was allowed two days to cure and then sanded with a vigorous regiment starting at 180 grit sandpaper to remove burrs, brush strokes, and other particles and proceeding up to 450 grit sandpaper before switching to wet sanding from 600 to two passes of 1000 grit paper. This final surface was polished using Partal Paste #2 chemical release wax with five consecutive coats of wax. The result was a fine glass finish that was ready for hull construction.

3.1.3. Fairing and Painting

Similar processes were conducted on the exterior of the hull for surface finish. Based on discussions with a local body shop and past experiences with Phantom 6, the team redesigned their fairing process. Much less filler material was used than in previous iterations and the overall sanding time was cut immensely. Following the fairing of the submarine the hull was cleaned off and all removable items were taken out of the hull. The interior was painted with a white coat while the exterior was painted with a team selected design. Sponsorship and safety decals were printed on vinyl and then placed at the appropriate locations on the submarine.

3.1.4. Viewports

A two window, ventral and dorsal, window design was selected for Phantom 7, as opposed to the five window configuration implemented on Phantom 6, due to differing requirements for 7 as outlined by former pilots. From interviewing past pilots, it was found that the central window on Phantom 6 was hardly used. The most used windows in Phantom 6 included the two, large, ventral windows and the two, smaller, dorsal windows on the submarine. The two ventral windows were used by the pilots of the sub primarily for positional awareness, and the two dorsal windows were used by the support divers to monitor the well-being of the pilots themselves. By addressing each of these two functions, attitudinal awareness and dive safety, via a single window for each, superfluous complexity is eliminated from Phantom 7 window scheme design. The single ventral viewport allows the pilot to monitor his/her attitude throughout the race, and the single dorsal viewport allows the support divers to monitor the well-being of the pilot.

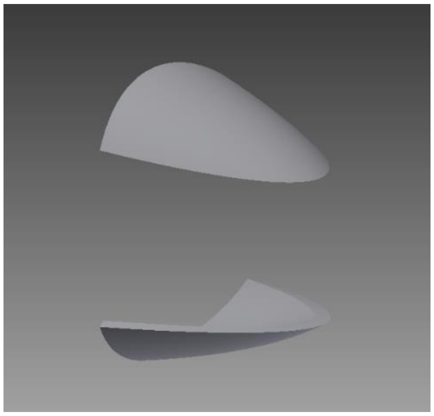

Figure 5: CAD Model of Viewports

Below is an early rendering of the intended viewport configuration as cut from the hull. This is provided to give a sense of the shape and relative orientation of the windows. The two aft corners of the cutout were rounded for the final design so as to reduce the number of stress concentrators introduced in the hull by each window. Additionally, the final window design includes a depressed lip encircling the viewable portion of the window. This lip is of the PETG plastic; it adds no structural discontinuities in the window and is introduced as a result of careful mold construction prior to vacuum forming. This feature is added to each window so that windows on Phantom series submarines may be installed from the inside of the submarine with a spring-loaded tab system, thus eliminating the need for bolts to secure the windows. The benefits of this new mounting design include a flush, more aesthetically pleasing finish, in addition to a theoretical reduction in drag across the hull.

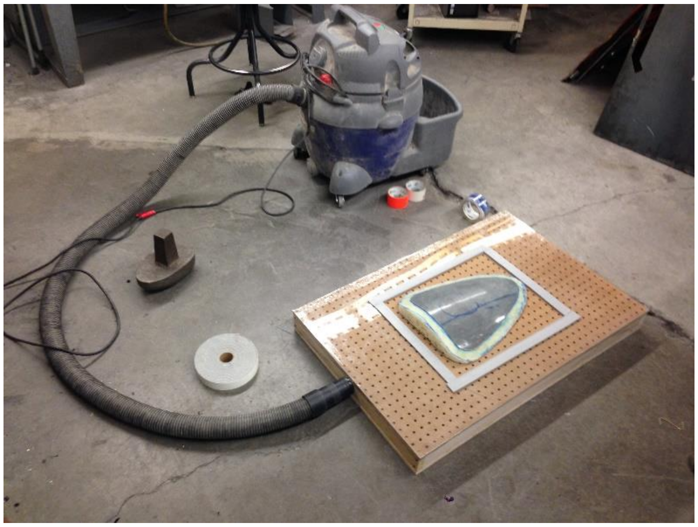

Figure 6: Vacuum Forming Process

In order to manufacture submarine windows for Phantom 7, in addition to those for future submarines, a vacuum former system and accompanying process has been iteratively prototyped. Vacuum forming is a manufacturing process in which a male form of the desired shape of a thermoforming plastic is fabricated; a sheet of said plastic is secured in a frame and heated; and the heated plastic is stretched down over a form-platum setup as shown below. A vacuum draws air through the platum, and helps pull the plastic down into its desired shape. This process was chosen with the reasoning that it inherently provided a formulaic, repeatable method for producing thin, plastic products in an infinite number of shapes. It naturally lends itself to window production, and the fact that it is in theory, repeatable, signifies that it could be used to manufacture spare windows in addition to primary ones, thus reducing the detriment during competition should a window fail.

To accommodate this manufacturing process, a thermoforming plastic suitable for the given application had to be selected. Originally, Acrylite FF was selected due to its relatively low cost. However, Acrylite FF was found to be too brittle for application as submarine windows, in addition to the fact that during heat treatment, it tends to form air pockets which introduce further structural weaknesses in the finished product. Subsequently, testing with Acrylite FF was discontinued and resumed using PETG plastic, an excellent thermoplastic with a formability temperature of 290-320 degrees Fahrenheit. PETG plastic was found to be much better suited for application as thermoformed windows due to its high elasticity relative to Acrylite FF.

Figure 7: Phantom 7 Windows

It has been empirically found that vertical edges are the most difficult features to attain when vacuum forming. As already explained in the discussion of design above, a vertical edge is necessary to the installation scheme of the windows. As such, much effort was afforded towards fine tuning the vacuum forming hardware and/or process so as to achieve the required edge definition for the windows. A successful proof-of-concept for the vacuum forming window manufacture method was performed during spring, 2014 using a single hole platum setup. However, upon recommendation from industry expert, Mr. David Collins of Sans Seriph Design, a multi-holed platum design was adopted that provides a more even air distribution during the drawing phase of the vacuum forming. This, in turn, provides the capability to achieve better definition in the steep features of a given form.

3.1.5. Weights and Volumes Spreadsheet

The spreadsheet breaks down the submarine into individual components. The level of detail can be determined by the user. For example, the user can either include the gearbox as one component, or break down the gearbox into aluminum, gears, and fasteners. Good engineering judgement and availability of accurate measurements should help determine this level of detail. Components are separated into five classifications: hull, propulsion, electronics, life support & safety, and auxiliaries. Again, a component's classification depends on the user. Any notes about specific components can be added to the far right of the sheet. Finally, the spreadsheet is divided into three colored sections, described below.

3.1.5.1. Gray Section – Box Volumes

The first section of the spreadsheet covered is the box volumes of each component. This section is very simple. By inputting the maximum length, breadth, and depth of a component, the spreadsheet will calculate the maximum box volume that each component will occupy

Table 7: Gray Section- Box Volumes

				Pha
Item	Max. L (in)	Max. B (in)	Max. D (in)	Box Volume (in^3)
Hull	120	24	24	69120
Stern bearing				0
Hull (fiberglass)				0
Control Surfaces	4	13	1	52
Gearbox	22	4.5	3.625	358.875
Driveshaft	38	0.5	0.5	9.5
Propeller				0
Brainbox	8.8	5.2	4.2	192.192
Misc. Elec				0
Harness	15	9	8.25	1113.75
Tank	24.8	5.3	5.3	696.632
Dead Man Switch				0
Buoy	5.5	2.75	2.75	41.59375
Drainage Hatch	8.25	5	1	41.25

Computing box volumes is useful for a number of reasons. Primarily, these can be used for internal arrangements, by creating the boxes in a modeling software and placing them in approximate locations within a hull. Since these volumes are over-estimated, fitting all box volumes into a true hull volume indicates that the hull might be too big. On the contrary, one can use this method to determine if the hull is too small as well.

This information is also useful when the true volume of a component is unknown. The box volume can be used to *approximate* the displacement. It should be stressed that in almost all cases, using the box volume will greatly overestimate the displacement, and should be replaced with the true volume as early as possible.

3.1.5.2. Blue Section – Weight and Displacement

The blue section of the weights and volumes spreadsheet is of vital importance when buoyancy in concerned. Once the true volume of a component is known, that is used to calculate its displacement. The component weight should also be inputted, and should be measured via scale or given by the manufacturer. Weights and displacements are summed over all components, and compared at the very bottom of the section in yellow. In the next column, the “water weight” of each component is calculated. This value is the displacement minus the weight. Therefore, if this number is positive, the component will be positively buoyant. Obviously, the component will be negatively buoyant if this value is negative. The water weights of each component are also summed and displayed in yellow. Ideally, this number should be as close to zero as possible, which indicates neutral buoyancy.

Table 8: Blue Section- Weight and Displacements

True Volume, V (in^3)	Total Weight, W (lbs)	Total Displacement, Δ (lbs)	Water Weight, Δ-W (lbs)
		Hull	
24353.39525		879.5662772	879.5662772
		0	0
	10.92	0	-10.92
		0	0
		Propulsion	
	14.8	0	-14.8
		0	0
		0	0
		Electronics	
192.192	5.4	6.941356644	1.541356644
		0	0
		Life Support & Safety	
		0	0
	19.4	0	-19.4
		0	0
		0	0
		Auxiliaries	
		0	0
	50.52	886.5076338	835.9876338

True volume and total weight should be calculated elsewhere to avoid over complicating this sheet by adding material densities and other values necessary for individual calculations. Displacements are calculated by simply converting the volume from cubic inches to cubic feet, then multiplying by the density of fresh water (1.94 slug/ft^3) and the acceleration due to gravity (32.17 ft/sec^2).

3.2. Propulsion

The propulsion system is designed to transfer the power supplied by our pilot into thrust to propel the submarine forward. Towards this end, three main sub-systems were devised; these include the linear drive train system, a controllable pitch system, and propeller blades. In short, the linear drive train system transfers the power supplied by the pilot to the propeller blades, which use this power to generate thrust. The controllable pitch system optimizes the state of the propulsion system via adjusting the pitch of the propeller blades such that the best propulsive efficiency is achieved at the current speed of the submarine.

3.2.1. Controllable Pitch

In order to gain more thrust at different times during the race, the team designed and implemented a variable pitch propeller system. When the submarine is stationary the blades need to be relatively flat. When the submarine begins to move and is gaining speed, the blades will pitch to a maximum 15 degree angle in order to increase thrust. Blades stall at over 15 degrees. The variable pitch works by first running a cable through the drive shaft. When the sub reaches a certain speed a linear actuator will pull the cable which compresses a spring in the propeller hub, which then twists levers attached to blades. When the levers twist, the blades also twist. Variable pitch is an excellent advantage to increasing our thrust and overall speed.

In addition to the analysis afforded during propeller blade design towards producing the best performance at the equilibrium condition of maximum speed, the operating state of the propulsion system at the range of speeds between rest and maximum speed remained to be optimized. Simply because the submarine blades are designed to have optimal performance at maximum speed does not imply that they will perform well during initial acceleration, for example. As such, the team intended to implement a system that performed the function of a car transmission, i.e. a system that would optimize the state of the propulsion system for a given velocity such that the best propulsive efficiency is achieved throughout the submarine's range of operating speeds. Naturally, the team considered a continuous variable transmission (CVT), a system common to many automotive vehicles. However, the team decided that controllable pitch was an alternative that performed the same function as a CVT, but inherently lent itself to operating in water.

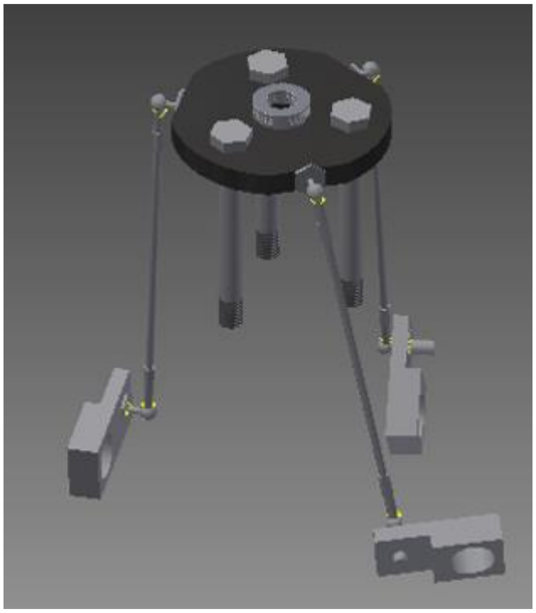

Figure 8: Variable Pitch Mechanism

The assembly shown in Figure 8 which changes the pitch angle of the propeller blades consists of the following. On the stern, guide rods protrude from the hull. Fastened to these guide rods is a metal plate such that a space is created between the hull and the metal plate. Between the metal plate (main plate) and the hull, springs encompass these guide rods. Attached to this metal plate are ball and socket joints. Attached to the end of each propeller blade is a corresponding step plate with a ball and socket joint. The ball and socket joint of each step plate is connected to its corresponding ball and socket joint on the main plate via a link arm. When the main plate is compressed into the springs, the link arms push the step plates. This creates a moment which turns the step plate, and resultantly, turns the propeller blade, effectually changing its pitch.

The linear actuator autonomously adjusts the pitch of the blades based off of the readings RPM sensors take of the gear spin rates. The drive shaft protruding out of the stern of the hull is hollow. Within this hollow space is a cable connecting a linear actuator to the main plate of the assembly just described. Based off of the readings taken by the RPM sensors, the linear actuator puts the cable in tension, which compresses the main plate and resultantly changes the pitch angle of the blades.

3.2.2. Gear Box and Shafting

The drive train constitutes the pedals, gears, housing, and drive shaft that transfer the power supplied by the pilot back to the propeller in the stern. What makes Virginia Tech's drive train system unique in relation to other teams is the fact that its drive train is linear. Many other teams implement a bicycle style drive train. However, oftentimes this requires that the hull geometry be widened to accommodate the circular motion of these bicycle drive train systems, which in turn, can lead to increased drag. By designing a linear drive train system, VT HPS does not encounter this problem.

3.2.3. Propellers

The stern of the submarine tapers to a point from which the drive shaft will protrude. Fixed at the end of this drive shaft will be our propeller blades which, when supplied with power from the pilot via the linear drive train, generate forward thrust. The propeller blades were designed using a rotor design and analysis software tool based in MATLAB called Openprop, which produces a 3D propeller geometry given user input.

Openprop allows the user to input such specifications as fluid density, ship speed, number of propeller blades, rotation speed, hub diameter, rotor diameter, and required thrust. These specifications were determined from physical and material constraints of our submarine and pilot. The hub diameter, for example, is constrained by the taper of the stern end of the hull, as it is desirable to maintain continuity at the interface between the hub and the hull. The rotation speed is constrained by the physical limitations of our pilot. Using data from Phantom 6, an estimate of the rotation speed generated was produced for the purpose of blade design for Phantom 7. Required thrust was found by analyzing the submarine when it has reached equilibrium at its designed max speed. Using coefficient of drag data from the hull design, total drag can be estimated. This drag must necessarily equal required thrust for the submarine to remain at this designed max speed, therefore required thrust is found.

In addition to the specifications described, Openprop also requires the input of blade design parameters. Specifically, it requires non-dimensional chord length proportions for incremented sections of the blade. Using trial and error, those proportions which produce the best propeller blade efficiency given our input design specifications were found. A 3D propeller blade geometry was produced, exported to Rhino, scaled to actual size, and then prototype blades were 3D printed. These 3D printed blades were taken to VT FIRE, an advanced materials foundry located on Virginia Tech campus, where the prototype blades were used to make molds and cast our final propeller blades. After sanding and polishing, our final propeller blades were produced.

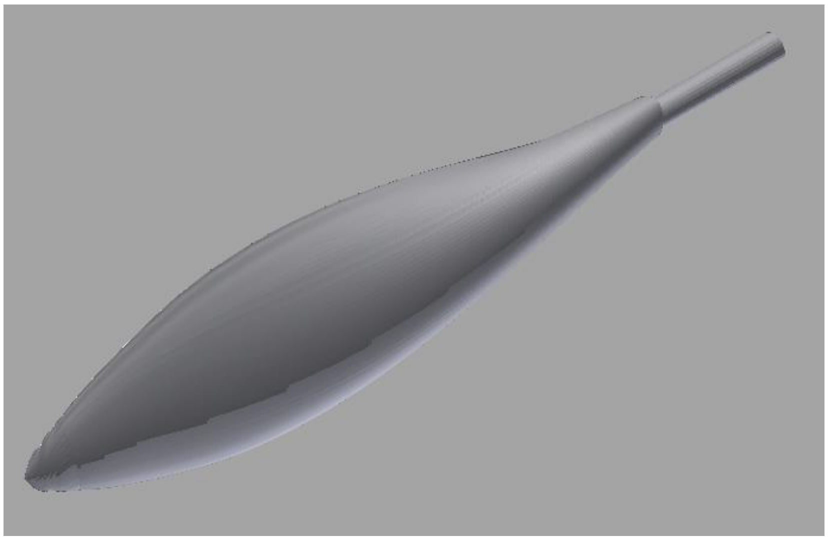

Figure 9: Propeller

3.3. Electronics

3.3.1. Introduction

Phantom 7's electronics system builds off many of the ideas and technologies that originated in Virginia Tech's previous submarine, Phantom 6, which was taken to ISR 12. This electronics system gathers data from an accelerometer, pressure sensors, and proximity sensors to determine orientation, depth, and speed. This information is then displayed to the pilot on a LCD screen so that he can better steer the submarine. This same information is also stored on a SD card via an onboard data logger. As a result, the performance of different pilots can be empirically analyzed. The pilot can also steer the submarine using a joystick that is integrated with the electronics system. The joystick sends signals to two linear actuators which move the control surfaces appropriately.

Phantom 7 is to be equipped with various instrumentation to help in her data reporting and autonomy. Onboard there is an RPM sensor, two pressure sensors, and a triple-axis accelerometer and gyroscope. The RPM sensor measure the rotation per minute of a particular gear in Phantom 7's gear box, and with that, the exact rotational rate of the propeller is calculated, displayed, and stored.

The two pressure sensors a located in such a way that both depth and speed can be calculate. With one sensor in the nose of the submarine, and the other in the middle of the inner hull, speed can be calculated by taking the difference in pressure between the two and plugging it into a few hydrodynamics equations. With this, fewer sensors are needed because one serves both purposes, which saves a great amount of time and money.

Lastly, the triple axis accelerometer and gyroscope work to provide the submarines relative position to the pilot and autonomous system. The culmination of both instruments allow for the computation of the submarines pitch, roll, yaw, and the rate of change on each axis.

Figure 10: Phantom 7's Accelerometer/Gyroscope Breakout Board

Table 9: Cost Analysis of Electronics System

	Unit Price (USD, $)	Quantity	Total (USD, $)
Arduino Mega	45.95	1	45.95
Otterbox 3500	22.89	1	22.89
Proximity Sensor(RPM Sensor)	4.50	2	9.00
Keller Pressure sensors	460.00	2	920.00
14.8V Li-ion Rechargeable Battery (5.2Ah)	71.99	1	71.99
Openlog	24.95	1	24.95
Sainsmart LCD module	13.95	1	13.95
Accelerometer	39.95	1	39.95
8GB microsd card	4.73	1	4.73
Arduino Micro	16.99	1	16.99
Switch	7.73	2	15.46
7-seg	6.06	1	6.06
pico-PSU	55.00	1	55.00
Joystick field sensor	5.99	1	5.99
Seacon wet-mate waterproof cabling	383.22	1	383.22
Linear Actuators	80.00	2	160.00
TOTAL			1,796.13

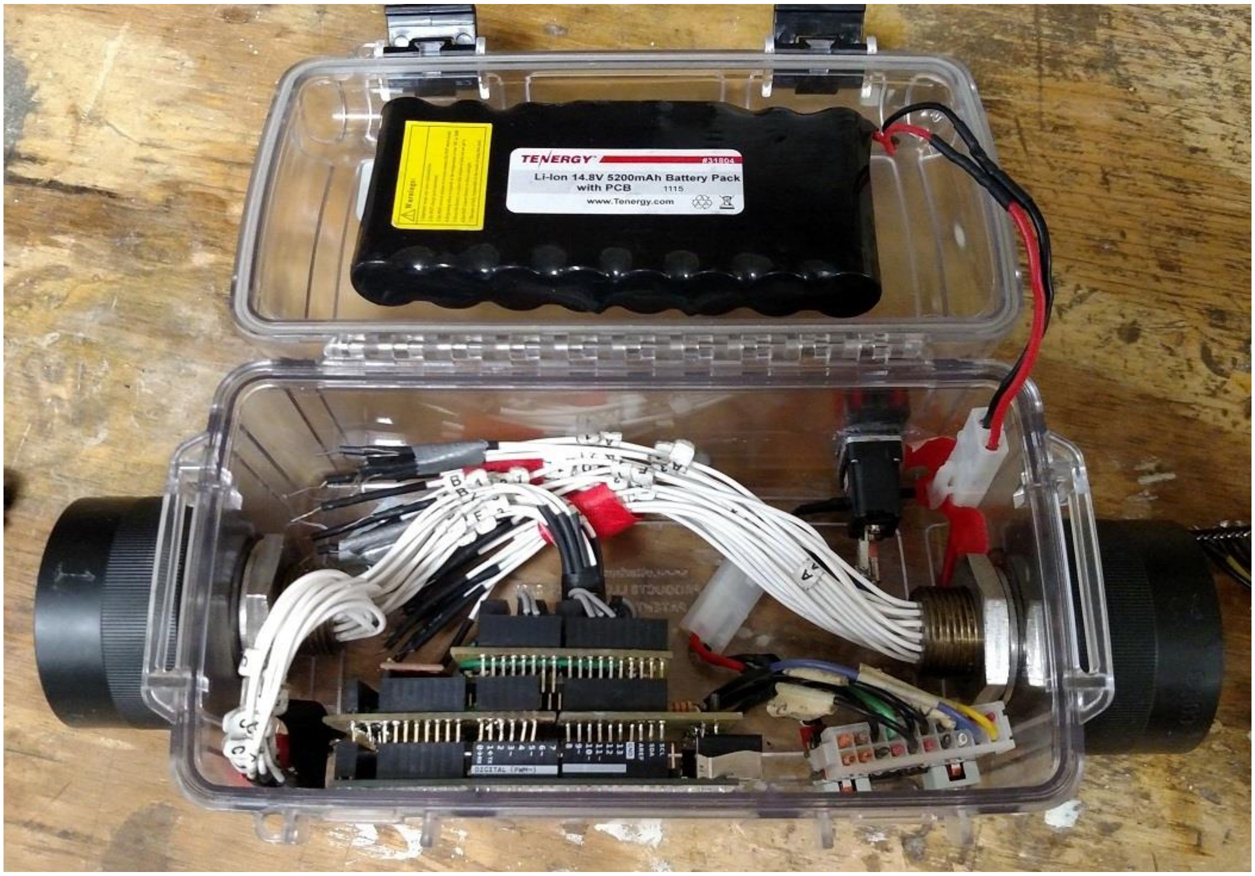

Figure 11: Contents of Brainbox

3.3.2 Brainbox

The electronics system is focused inside the "brainbox", a relatively large waterproof container located underneath the gearbox. The contents of the brainbox are seen in the Figure 11. Inside this box is an Arduino Mega, a 54 pin microcontroller which does the majority of the calculating and processing necessary for the electronics system.

The two custom-made "shields" that sit on top of this microcontroller board provide clean and organized circuits for a number of the systems that must communicate with the main microcontroller. These shields are shown in Figure 12 and Figure 13. The lower, longer board, as shown below, has a smaller microcontroller, an Arduino Micro, as well as an accelerometer and data logger. The accelerometer measures the yaw, pitch, and roll of the submarine. The data logger logs all of the information that the main system collects and stores it to be analyzed later by the team.

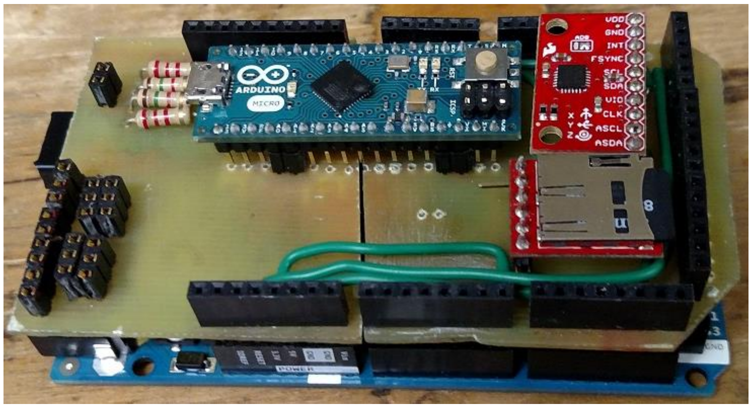

Figure 12: Arduino Mega with only the bottom shield installed

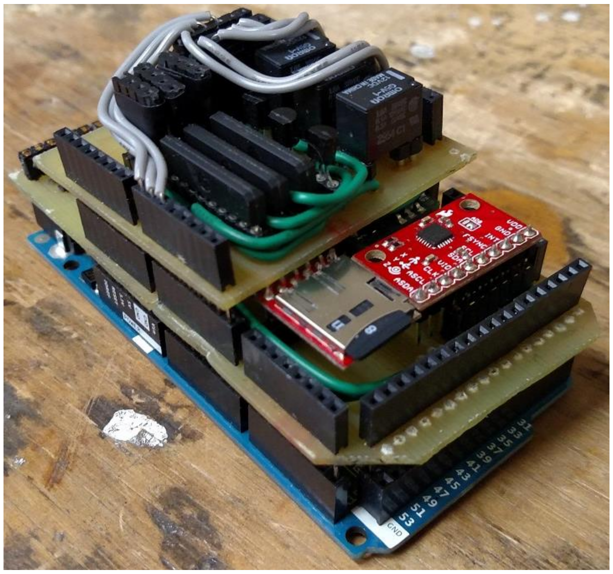

Figure 13: Arduino Mega with both shields installed

The second, smaller shield holds a very complicated circuit needed to move the linear actuators in a safe and smooth manner. This circuit takes full advantage of the space-saving attributes of printed circuit boards. Without a custom-made circuit board, it would be impossible to fit this circuit in the confined space of the brainbox.

Acting as the “Brain” of the system, the central computational and data storage unit processes the data from the various instruments, stores such data, operates the autonomous sub-system, and sends/received data from the control panel. Comprised of an Arduino Mega Microcontroller, and an OpenLOG datalogger, this sub-system acts as a complex logic machine to control the entirety of the other sub-systems.

The Arduino acts at the logical processor and is commanded via student written software. It is programmed to take data form each instrument, internally process such data, and then depending on the submarines state, either adjust its position, or simple display and record the results.

All data that is taken during every race is store on individual .txt files on the OpenLOG's microSD card. The main reason for including this feature in the design is so the team can analyze the pilot's and submarine's performance during each race, after the fact. This allows the team to not only improve the efficiency and speed of Phantom 7, but also determine which pilot is the fastest, and more suitable.

3.3.3. Battery

A 14.8V battery serves as the power source for the entire electronics system. An ATX power supply unit allocates power appropriately from the battery to the various components in the system.

3.3.4. Connectors

Unique specially made underwater electrical wet-mate connectors were purchased to connect the various sensors and systems to the brainbox. Two main female connections were installed on the side of the brainbox converting the male waterproof cables to smaller wires to be wired to the microcontroller. Figure 14 shows the male and female connections together.

Figure 14: SEACON Waterproof Connections

3.3.5. Heads-Up-Display (HUD)

A second waterproof box holds a number of components necessary for the pilot and system to communicate back and forth. A LCD screen provides the user important information that the system has gathered: the heading and speed of the submarine. The box also has a toggle switch that allows the pilot to change the submarine into different modes of operation. This feature is not used extensively in Phantom 7, but it is a place where new improvements will be added in a future submarine. Figure 15 shows the box in its entirety.

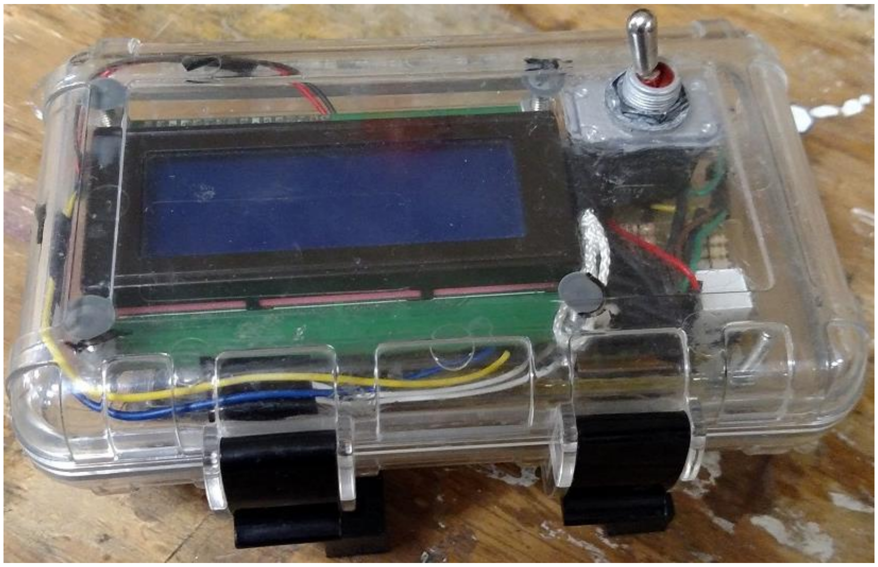

Figure 15: Heads-up-display box

This dashboard and control panel sub-system is mainly purposed to be used as the computer interface between the pilot and the entire electrical system. Complete with an LCD, rocker switch, and bi-color LED, the panel shows data and statuses, while providing a sense of control. This sub-system will be mounted in such a way the pilot can both view and interact with it during a race.

Specifically, the LCD displays submarine RPMs, speed, depth, pitch, roll, yaw, and state. The pilot can see whether the submarine is in autopilot mode or manual mode, as well as the output of all the submarines onboard instruments.

Furthermore, the pilot can quickly check the state of the submarine via the bi-color LED that is also incorporated in the dashboard. With a quick glance, the pilot can tell whether the system is in standby mode, or race mode.

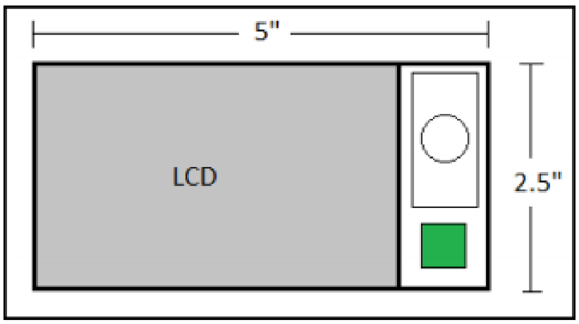

Figure 16: Dashboard/Control Panel Layout

Lastly, the panel has a rocket switched that allows the pilot to change the state of the submarine. He/she can choose to manually control the submarine via the joystick, or have the autonomous system take over and control the submarine for them.

3.3.6. Joystick

Phantom 7's joystick is fully integrated into the electronics system. The joystick arm contains a magnet, which alters the magnetic field around the sensor when it is moved. Below the joystick arm is a 3-axis magnetometer that measures the change in magnetic field around the sensor. When the magnetometer detects a change, it sends a signal to the microcontroller, which can react appropriately.

3.3.7. Linear Actuators

In Phantom 7, linear actuators control the yaw and pitch of the submarine. One actuator is connected to each control surface axis and is programmed to extend or contract depending on the desired angle of the control surface. The actuators will never be fully extended as the range of movement for control surfaces is relatively minimal. The linear actuators were the most difficult part of the system to waterproof, in the end the solution involved PVC pipe, a few clamps, and bike tubing. **Error! Reference source not found.** shows the final waterproof solution.

Figure 17: Waterproof Linear Actuators

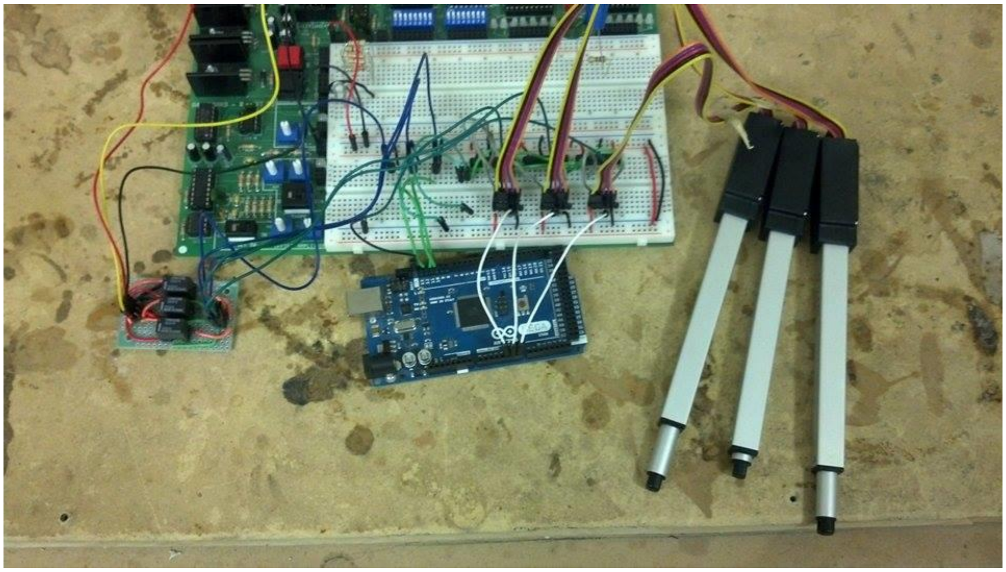

Figure 18: Partial Computational and Data Storage Circuitry with Arduino (middle) and Linear Actuators (right)

3.3.8. Autonomous Controls and Manual Override

Given that the submarine is autonomous with the option for manual control, a manual interface had to be designed to override the control of the autonomous system. Since the actuation of the control surfaces and propeller pitch is still done electrically, the manual control interface had to be electrical in nature. That being said, the current joystick is designed to use a magnetic field sensor and a magnet. The designed plan is for the manual joystick to have a small rare earth magnet attached to it and the B field sensor mounted directly under the magnet. This allows the computer to ping the sensor for the position of the magnet and adjust the control surface actuators accordingly.

Phantom 7's autonomous control sub-system maintains two different types of control. The first type of control is navigation, and as states above, is designed to take as much pressure off of the pilot as possible. This aspect of the autonomous control sub-system is made up of two linear actuators, the accelerometer/gyroscope mentioned in section 2.2, the microcontroller mentioned in section 2.3, and a PID controller circuit. The flow of data and logics is as follows.

First, data is collected from the gyroscope and accelerometer by the microcontroller. This data is then inputted into the PID controller's logic which determines how much to actuate the control surfaces to return the submarine's pitch, roll, and yaw to their initial, level positions. Such actuation is controlled by the aforementioned linear actuators, which are extended or retracted depending on the signal sent to them by the microcontroller. Moreover, the duration of the signal determines how far the actuator moves, and this value is controlled by the output of the PID controller.

The second portion of Phantom7's autonomy is the variable pitch propeller actuation. Just like the control surfaces, the variable pitch propeller mechanism is designed to be adjusted via a linear actuator. The data flow for this particular section of autonomous controls starts with the collection of RPM and speed data that is then passed into an equation which determines the correct pitch of the propellers. This value is then processed by the microcontroller and the linear actuator is adjusted accordingly. This process will run continually throughout the race and will appear as a completely responsive operation.

This sub-system comprises the wiring harness and enclodsure of all the sub-systems listed above. Given that the submarine is in a completely flooded environment, the wiring, connections, and housings must be waterproof to at least depths of 50ft. This will ensure operation of the system in locations other than the race tank.

In order to aid in the construction of the wiring harness and various connections, the design includes the modification of several waterproof consumer goods. SEACON sells very relieable and resistent waterproof cabling and connectors, and thus the wiring harness was designed to use SEACON's products. Additionally, OtterBox sells very resilient plastic cases that were incorporated to act as housings for the different sub-systems.

The Main Computer and Data Storage Unit is housed in an OtterBox case, and two 24 pin SEACON connectors run out from either end of the case. SEACON cables then interface with these connectors and divert power and data from inside the main OtterBox to the other sub-systems. One of these sub-systems, the Dashboard and Control Panel, is also housed inside a clear OtterBox case.

Through the watertight nature of these different products, the entire system is protected against the risk of water damage.

The autonomous controls system is still being completed at the time of this report's origin and is included for completeness. The team expects this system to be installed and operational by competition. If not, the manual override system described above will be used.

3.4. Controls

The controls system was designed primarily based on previous iterations on Phantoms 4-6. These submarines had ample control and in fact seem to be overdesigned after investigation. As such, the surfaces for Phantom 7 were scaled down in order to decrease the drag as much as possible.

3.4.1. Design

The stabilizer surfaces were designed and built to be symmetric in the horizontal and vertical plane. Both the horizontal and vertical stabilizers are positioned on vertical and horizontal planes respectively through the center of the submarine. The trailing edge of the stabilizers is placed 14 inches forward of the stern of the submarine. A lofted NACA 0014 airfoil was used for the geometry of the surfaces that tapers from an 8 inch chord to a 3 inch chord 10 inches away from the submarine. The trailing edge of the surface is perpendicular to the centerline of the submarine. The leading edge of the surface was placed tangent to the submarine and the remaining volume of space was lofted into a projected airfoil on the hull surface to create a stabilizer that contours to the hull. A CAD drawing of the Stabilizers as designed follows in Figure 19.

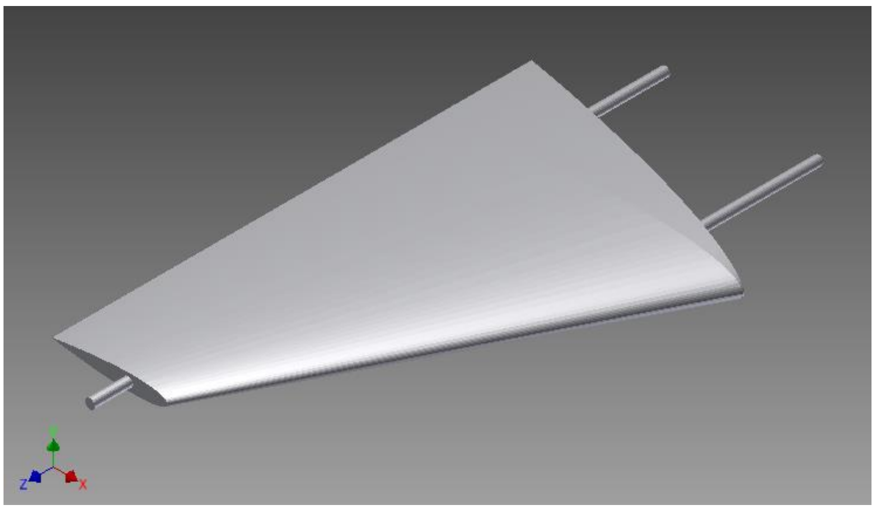

Figure 19: Phantom 7 Stabilizer

The control surfaces are a 10 inch long NACA 0009 airfoil with a 3 inch chord length. These will be placed aft of the stabilizers in order to maximize their effectiveness. With higher effectiveness, the control surface can have smaller dimensions which results in less surface area and drag. The control surfaces will also be perpendicular to the centerline and lofted to the hull to improve the flow over the hull and the control surfaces. A CAD drawing of the control surface follows in Figure 20.

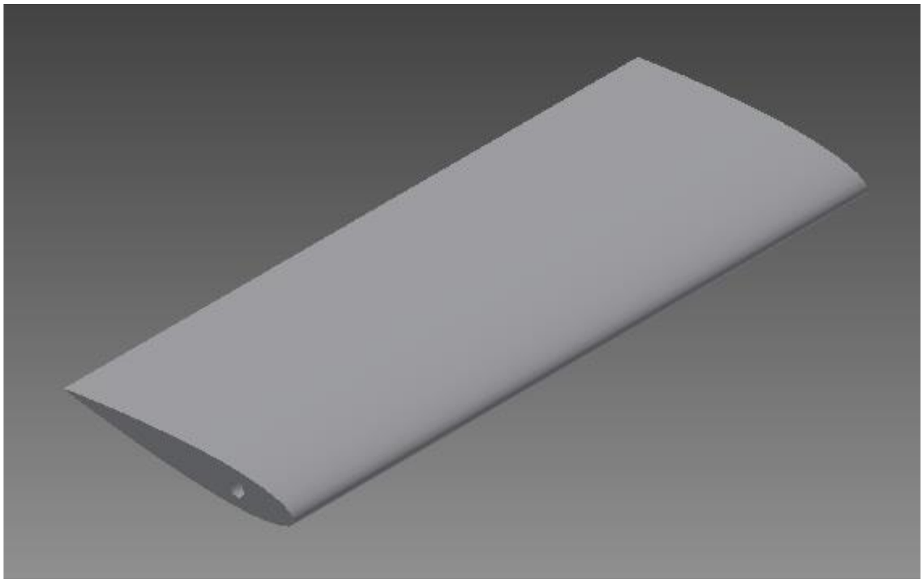

Figure 20: Phantom 7 Control Surface

In order to allow the control surface to rotate when required by the actuator, a stable point was required. This is the reason behind the rod extension out of the top (left) side of the stabilizer in Figure 1. An end piece in the shape of a NACA 0015 airfoil will be shaped out of starboard and epoxied to the top of the stabilizer and the rod coming from the stabilizer. A bearing will be set in the starboard around the rod coming from the control surface to allow for movement.

3.4.2. Manufacturing

Molds in the shapes described above were discovered in the lab and used to make these control surfaces and stabilizers. The mold for the stabilizer was in two halves which were clamped together as a negative and then filled with pourable foam to generate the stabilizer shape. Tunnels for the rods were drilled through the mold and the rods were set in the mold while the foam was poured. This same procedure was used with the control surfaces. Release wax was used to ensure that the foam structures came out of the molds easily and didn't break. Once the structures were out of the mold, they had to be strengthened before use. To this end, carbon fiber was layered up on the surfaces of the stabilizer and control surfaces and cut to shape. Airfoil shapes were also cut out of starboard for the bottoms of the stabilizers and control surfaces to ensure that the rods do not become detached from the structures. The surfaces were then inserted into the appropriate fittings and bearings already in place in the hull.

3.4.3. Autonomous Controls

Phantom 7 features an autonomous controls system. An electronic "brain box" will hold a battery and Arduino with coding and data taking ability to control the movement of the submarine. A pilot will be able to "zero" the submarine at a certain orientation in the water. Following this setting, the submarine will then autocorrect to maintain the desired path. Accelerometers, gyroscopes, and pitot tubes will be used to monitor the submarine's orientation. To control yaw, changes in the accelerometers will be measured continuously and the brain box will send signals out to linear actuators connected to the control surfaces to change their orientation and return the submarine to the proper heading. Roll will be controlled with proper ballasting and potentially electronic controls if dynamic testing shows the need is present. Pitch will be controlled based on pressure measurements. The electronic system will raise or lower the submarine in the water to maintain a constant depth. The linear actuators will be placed in waterproofed boxes that are 3D printed in house and fitted with proper housings for the electrical equipment. The actuators are connected to a lever arm that provides a proper and measureable amount of leverage on the stabilizers that will be adjustable in the coding of the Arduino based on testing and competition runs. If the pilot notices that the submarine is not correcting its course properly, a joystick will be available to override the autonomous system. A functioning autonomous controls system though will mean the pilot can concentrate on providing full power to the gear box and not need to spend mental and physical energy on maintaining a proper heading.

3.4.4 Mechanical Backup

In the case of electronic system failure, a mechanical backup was desired to allow the submarine to continue to race. In order to minimize the impact on the hull and hydrodynamics of the submarine, the mechanical system was designed to utilize the same connection points to the submarine as the electronic system. Metal wires along with a manual joystick with various angled pulleys can be attached to the hull to allow for manual movement of the stabilizers.

3.5. Life Support and Safety

3.5.1. Dead Man Switch

The key attributes decided upon for the buoy release were that it maximize comfort for the pilot, while maintaining a reasonable size. In order to facilitate the pilot's ability to power the submarine, it was also necessary for the dead man switch to be a hard point. The body of the part was designed as a rolled piece of steel, supported by four starboard pieces, on the back, bottom, and one on each side. On the side of the metal not covered by the starboard, a 3D printed plastic, rubber grip is attached to improve the comfort of the pilot. A bike cable is threaded through the top hole on each side of the metal, roped along the sub, and is then attached to the buoy release, which releases the archery release whenever the pilot releases his grip on the dead man switch.

Figure 21: Dead Man Switch Model

3.5.2. Buoy

The buoy pocket is pictured in Figure 23. The diamond shapes around the upper edge served simply to reduce material usage. The 45-degree lip at the top was initially made so that the pocket could be fiber glassed onto the hull. However, the team ended up simply bolting through this because it proved to be much simpler. There is a small cutout in the center of the bottom for inserting the buoy-release mechanism. The release mechanism is an archery release. It is a small clip that attaches to a rod that goes across the void in the buoy. The archery release has a fingersized switch that opens the release. When the string is pulled, the archery release loses contact with the buoy, and the buoy ejects.

Figure 22 is the buoy itself. It was manufactured by gluing together foam board insulation and then CNC routing this. After this, the buoy was covered in fiberglass and epoxy and allowed to cure. The fiberglass was sanded and voids were fixed with filler material. Finally, the buoy was spray-painted.

Because of the overall success of the buoy and pocket on Phantom 6, the team employed a very similar design on Phantom 7. The principal change made was adding a gradient to the top of the buoy and pocket. The reason for this was to allow the bottom of the buoy to remain level with the (longest) line directly through the center of the submarine. Because it is located near the rear of the submarine, which is steeply sloped, the buoy and pocket required the opposite gradient. Therefore, when the submarine is relatively level with the Earth, the buoyant force on the buoy acts almost entirely upwards. A minor change was the replacement of the lip on the upper edge of the buoy pocket with four extensions for mounting with bolts.

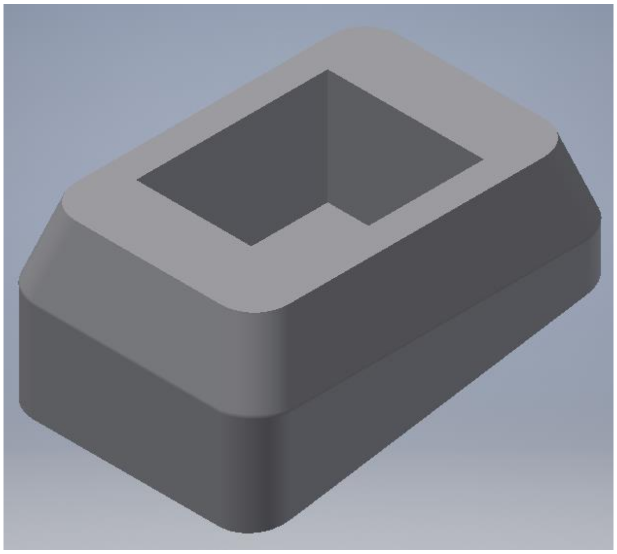

Figure 22: Phantom 7 Buoy Model

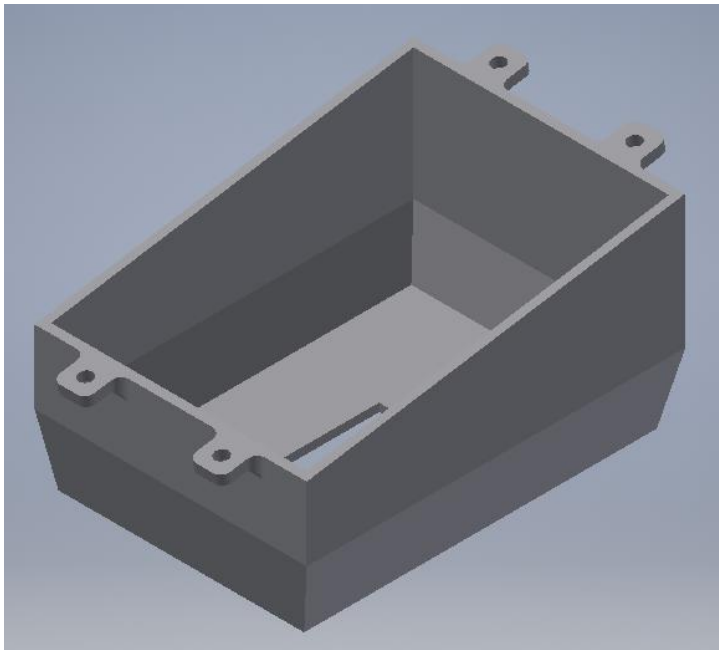

Figure 23: View Looking Forward at Phantom 7 Buoy Pocket

Figure 24: Side View of Phantom 7 Buoy Pocket

3.5.3. Safety Light

Originally the lights were mounted onto the buoys themselves. However, the lights were less than reliable so the team decided on an alternative. The light was altered (along with the buoys) to be more modular. The light can now be taken out more easily in order to replace batteries.

In order to mount the light, a hole approximately 2.75 inches wide was cute onto the top surface of the hull through the entire top layer. The hole exposed some foam for the ribs, however the exposed foam is not detrimental to the structural integrity of the submarine. The holster for which the light sits on was 3-D printed. It is mounted inside the sub on the ceiling of the hull, directly underneath and around the hole. The light has a magnet on the bottom that is screwed into the holster, while the magnet itself keeps the light fixture attached.

3.5.4. Hatch Release

The exterior hatch release of Phantom 7 features a simple design, consisting of a raised button adjacent to a handle flush with the hull. When the button is pressed, it pivots, allowing the handle to pop out, and when the handle is pulled a little farther, the hatch pops open. Once popped out, the handle is pushed back into the hull, pushing the button out of the way and locking in place, immediately ready for further use.

The exterior hatch release consisted of four different parts: the button, the handle, the exterior enclosure, and the interior enclosure. All of the parts were 3D printed using ABS plastic, as three of the parts featured curvature too complex for conventional machining. This curvature was obtained by "cutting out" a piece of the 3D model of the submarine's hull at the point on the hull where the handle would eventually be placed. All parts were modeled beneath this slice of the hull, so that when installed, the entire mechanism would be nearly completely flush with the hull, save for the button release, which is raised for ease of use. The exterior enclosure comes down from the outside, protruding into the submarine's interior and grabbing onto the outside of the hull with a thin lip. The interior enclosure's lip is flush with the interior of the hull, and its body slides into place alongside the exterior enclosure. The handle and button are then positioned properly inside the enclosures in a way that minimizes any parts extruding from the hull. Once positioned physically on the submarine, holes were drilled through the four-part apparatus and were locked in place with aluminum roll pins. A cable was ran from the underside of the handle along the hull's interior to the main hatch release mechanism.

The main criteria in designing the exterior hatch release for Phantom 7 were: ease of use, low hydrodynamic impact, and low weight.

The exterior hatch release occasionally has to be operated by a rescue team in an emergency, so it is important that the device is quick and easy to use, even while diving underwater. The raised nature of the release button, along with guiding signage, make the release mechanism extremely easy to locate and operate. The handle tends to pop out right into the operator's hand, leaving no confusion as to how to release the hatch.

Many hours were spent ensuring that the submarine's hull was as hydrodynamic as possible. Anything on the outside of the hull that deviates from the original design will increase drag experienced by the sub. Because most of the components of the exterior hatch release were shaped from the exact curvature of the hull, its hydrodynamic impact was kept as low as possible.

Any weight added to the submarine makes it more difficult to go faster. ABS plastic and aluminum roll pins are both incredibly light, and were good material choices to keep the weight of the hatch release mechanism as low as possible.

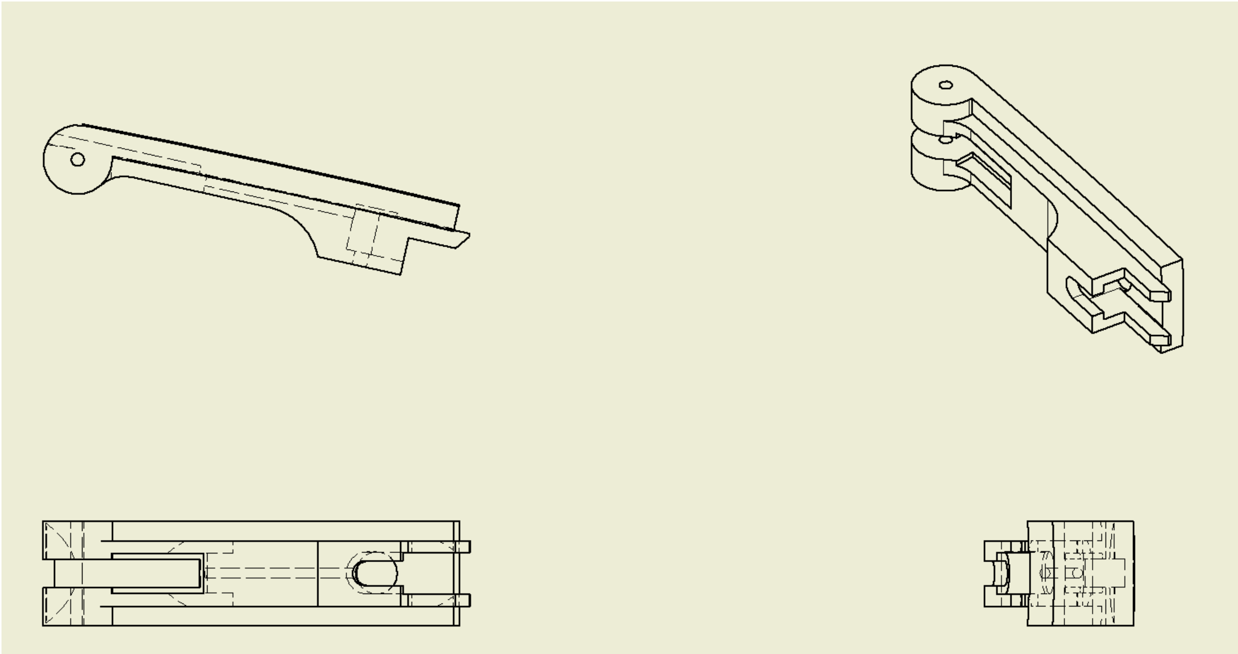

Figure 25: Exterior Hatch Release Handle

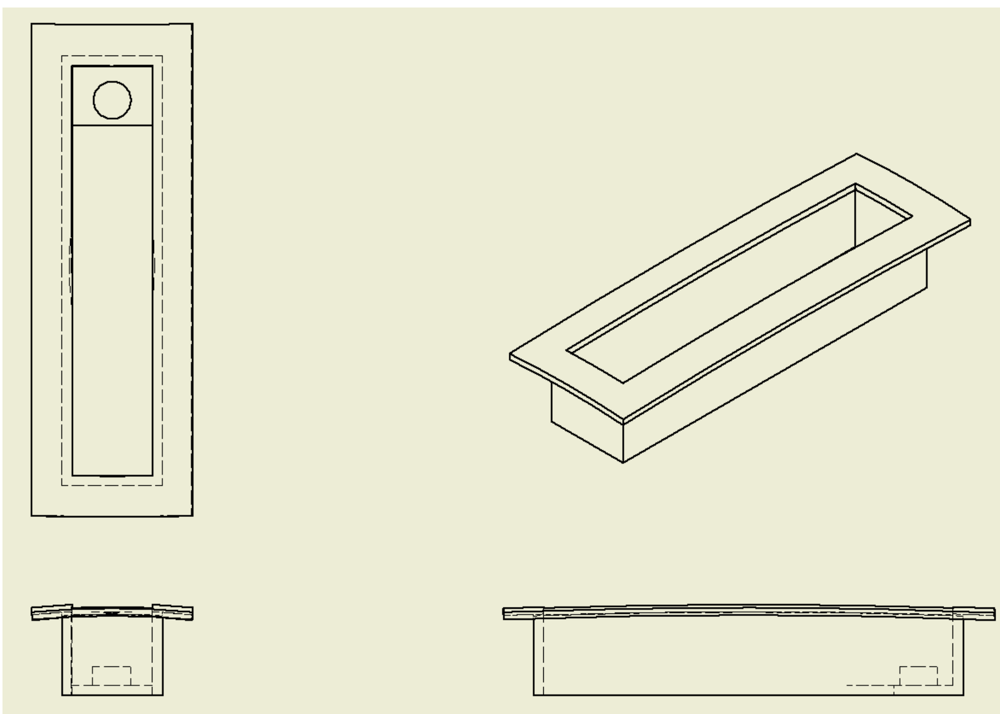

Figure 26: Exterior Hatch Release Interior Enclosure

3.5.5. Spare Air

The design for the spare air tank clamp is fairly simple, utilizing the concept of a “snap” clamp. The key factor in this design was ease of use, ensuring that the spare air tank cab be grabbed easily in case of emergency. Previous Phantom models required that the spare tank be carried on the pilot’s person, but mounting it to the sub’s interior offers the pilot additional mobility and clearance.

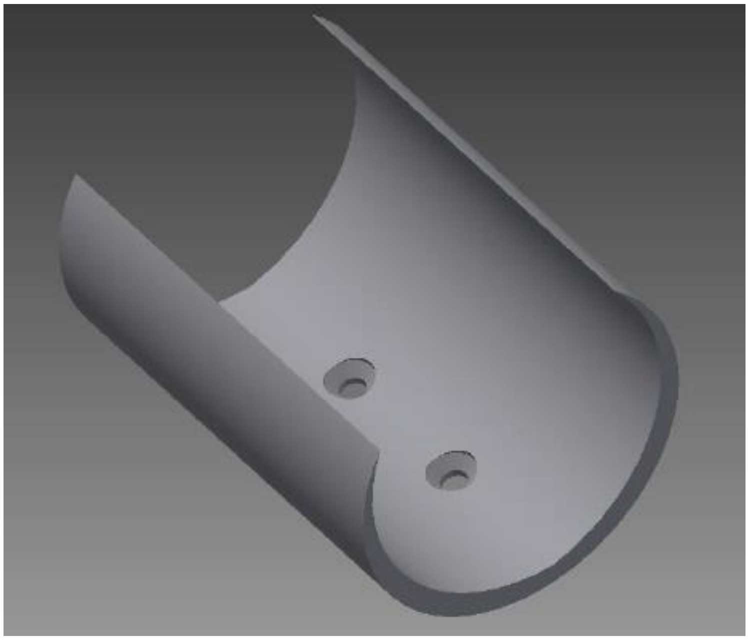

Figure 27: Spare Air Tank Clamp

3.5.6. Harness

Figure 28 details a few of the design alternatives discussed. Ideas ranged from spring latches to spring supports, rigid supports to rounded supports, rollers and non-rollers. The ultimate idea accepted features a height adjustable support towards the bow that is rigid in rotation (Figure 2). The aft support is adjustable in height, rotation, and location. Spanning these two supports is a longitudinal bar with adjustability along the length of the submarine for added pilot customization. 8020 was chosen as the material due to its durability, corrosion resistance, strength, and relative low cost (with discounted prices).

Figure 28: Harness Assembly

The harness portion will be laid up out of carbon fiber on the Remo drum brace mold with reinforcement vertically on the chest and on the shoulders.

Figure 29 shows Inventor calculations for center of gravity, volume, and mass. These values are calculated based on the default coordinate system of inventor and a generic material density of 1 g/cm^3.

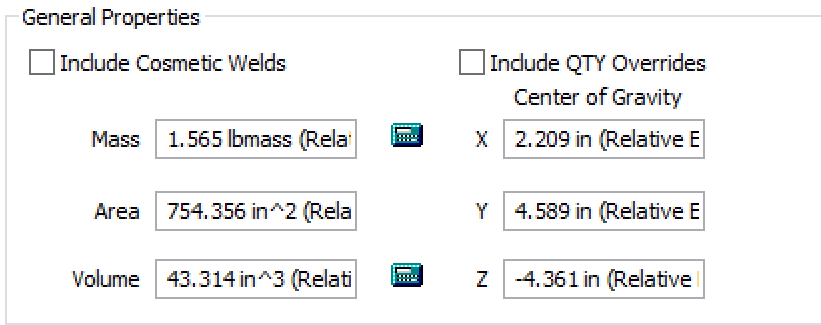

Figure 29: Harness Assembly Properties

Adjusting for coordinate system, proper density, and assuming a constant density (i.e. center of gravity is equivalent to center of buoyancy) the correct values based on a coordinate system with the origin at the center of the bottom span on the aft face:

Mass: 4.2107 lb

Volume: 43.314 in^3

VCG: 4.203 in

LCG: 10.514 in

TCG: 0 in

Buoyancy: -2.646 lb (negative implies a sinking object)

3.5.7. Ergonomics and SCUBA Integration

The submarine can fit a range of pilots due to the adjustable harness. Because the harness will not only move forward and backward but also up, down, and rotationally the submarine is the most pilot friendly built by Virginia Tech to date. The 40 cu ft SCUBA tank will be placed underneath the pilot and secured with bungee cords over a 3D printed mount. The tank will be situated with the first stage and valve facing aft. This is to decrease the clutter in the pilot's viewing area. A long pressure gauge hose along with a long low pressure second stage hose were purchased for this purpose. The cables will be routed beside the pilot from aft to fore and will have a large range of motion for pilot comfort.

4. Testing

As was the case in Phantom 6, Phantom 7 had limited in water testing. One static test was conducted to test for buoyancy on Phantom 7. However, many of the systems were installed and tested on Phantom 6 concurrently.

4.1. Systems Testing

4.1.1. Propulsion

The propulsion system for Phantom 7 has been tested in air and has seen no issues. The system itself is just a reincarnation of previous linear drive systems and thus is expected to work without any issues. The variable pitch mechanism has been tested and functions in air.

4.1.2. Electronics

To ensure the success of Phantom 7's electrical system, several tests will be conducted on different sub-systems in addition to the system as a whole. Such tests include verifying the resilience of the various housings to water, verifying the PID controller logic and successful autonomy, verifying the expected operation of the various instrumentation, and verifying the system's overall stability and operational abilities.

Due to the fact that the system is completely inoperable if it is to become wet, a watertight wiring harness is of the utmost importance. That being said, the wiring harness and its incorporated housings are to be thoroughly tested at depths that exceed the race conditions. This helps to ensure that not only will the harness keep water at bay during the race, but also during full submarine tests at various, deeper locations. Furthermore, the team already tests many of its waterproof seals in a pressurized chamber of water and air, which helps them create a realistic underwater environment to test all the connections that protect the entire electrical system from water.

In addition to the waterproofing verification, the PID controller and respective instrumentation will need to be tested to ensure efficient and successful control of the submarine. Since control is such an important aspect to Virginia Tech's rapid completion of a race, this sub-system will be thoroughly tested during several dynamic testing iteration. Moreover, the instrumentation that controls the autonomy, as well as provides the other data points that the pilot can monitor via the control panel, will be verified during the dynamic testing of the submarine.

4.1.3. Life Support and Safety

The dead man switch and buoy were installed in Phantom 6 and taken to static testing. These systems worked moderately well and only one improvement for reeling the wire up was added. The hatch releases were not installed for static testing but are functional in air.

4.2 Static Testing

Static testing was conducted in War Memorial Pool. The main purpose for testing was for buoyancy measurements and for pilot ergonomics. The submarine was exceptionally buoyant and as such about 20 lbs of lead were added to maintain neutral buoyancy. Pilot ingress and egress were non-issues and the submarine itself was relatively spacious compared to previous iterations.

5. Conclusion

In conclusion, Phantom 7 is a highly innovative submarine design that the Virginia Tech Human Powered Submarine Team has developed. Phantom 7 is a single pilot autonomously controlled submarine that allows the pilot to focus on the main portion of the race: pedaling. This innovation along with the numerous improvements to all sub systems of the submarine mark an exciting time in Virginia Tech's submarine design history. The team has optimized all systems to produce a submarine capable of setting speed records at the International Submarine Races and return Virginia Tech to the forefront of human powered submarine engineering design.

Appendix A: Hull Offsets MATLAB Code

```
clear all
clear clc

%Length 10ft, Diameter 24in
%Submarine Hull Shape
R=24/2; %Inches of largest radius
Lf=.35*12*10; %Forward Lenght (in)
Lc=.075*12*10; %Center Length (in)
La=.575*12*10; %Aft Length (in)
nf=2; %forward fullness coefficient
na=2.5; %aft fullness coefficient
iteration=1;
ya=[];
da=.2;
%Aft Portion of Submarine
for i=0:da:La
    ra=R*(1-((La-i)/La)^na);
    ya(iteration)=ra;
    iteration=iteration+1;
end
%Center Portion of Submarine
for i=La+da:da:Lc+La
    rc=R;
    ya(iteration)=rc;
    iteration=iteration+1;
end
%Forward portion of Submarine
for i=Lc+La+da:da:Lf+Lc+La
    rf=R*(1-((i-La-Lc)/Lf)^nf)^(1/nf);
    ya(iteration)=rf;
    iteration=iteration+1;
end
xa=0:da:La+Lc+Lf;
ya=real(ya);

yfinal=fliplr(ya);
xfinal=xa;
plot(xfinal,yfinal);figure(gcf);hold on
plot(xfinal,-yfinal)
axis square
axis equal
hold off
xf=xfinal';
yf=yfinal';
```

Appendix B: Media

Virginia Tech Human Powered Submarine is also on:

- Internet: www.hps.aoe.vt.edu
- Facebook: www.facebook.com/HumanPoweredSubmarine
- Twitter: @VTHPS

Figure 30: Vacuum Forming Process

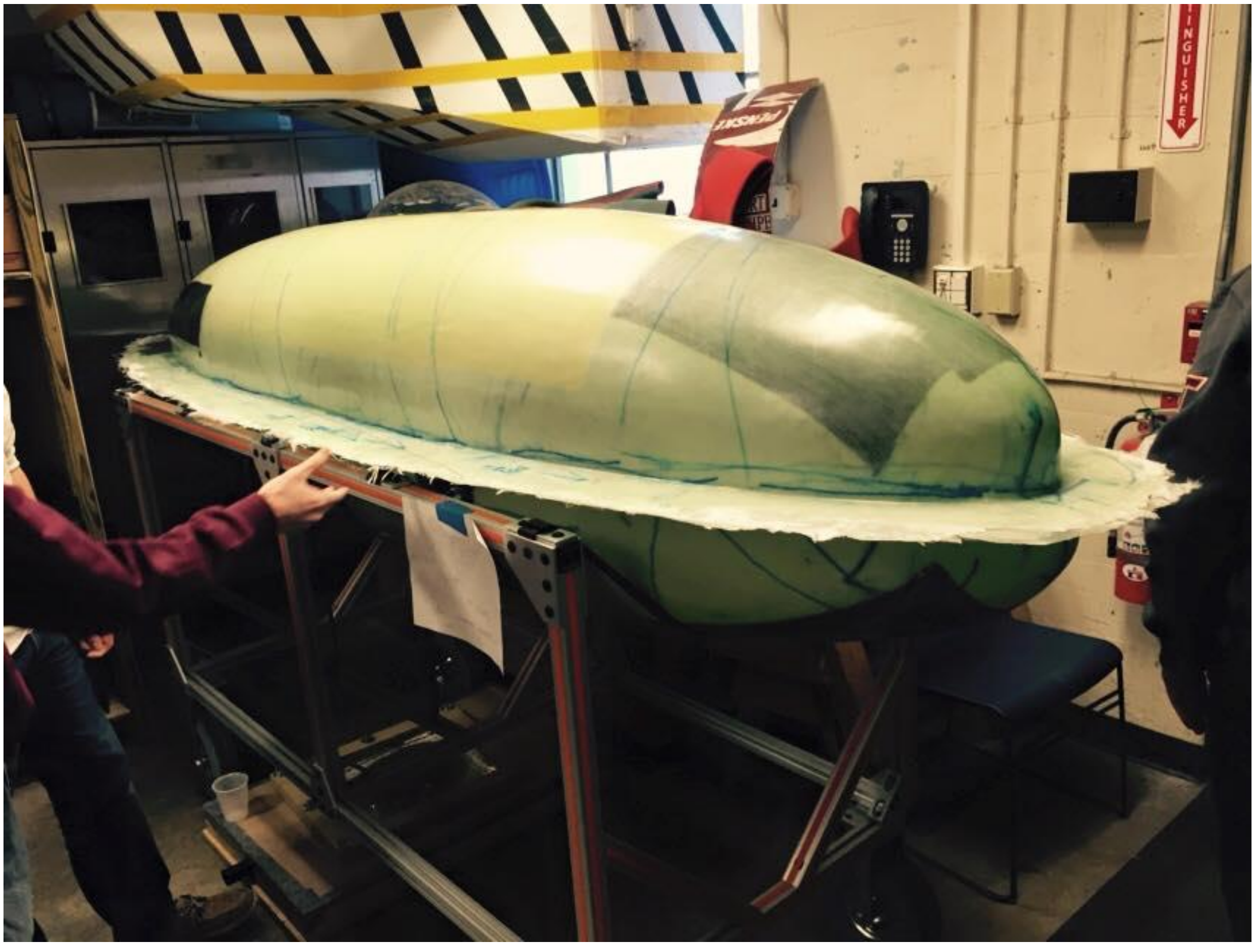

Figure 31: Initial Hull Forms from Mold

Figure 32: Final Hull

Figure 33: Static Testing

Appendix C: Sponsors

80/20

Boeing

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Lockheed Martin

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National Instruments

QTC

SEACON

Sub Station II

Tech Dive Center

Virginia Steel

Virginia Tech Department of Aerospace and Ocean Engineering

Virginia Tech Student Engineer’s Council

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Aerospace and Ocean Engineering Machine Lab

FRITH Engineering Design Lab

Virginia Tech Foundry

Virginia Tech Build Lab

Office of Naval Research

Naval Surface Warfare Center, Carderock, MD

International Submarine Races Committee

Thank you!