Phantom 5 Design Report

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Executive Summary

A. *Team Overview*

The Human-Powered Submarine (HPS) Team is one of many student engineering design teams that are the pride of Virginia Tech's College of Engineering. The team's mission is to design, build, and race submarines propelled solely by human power. Although such a project can be accomplished relatively simply, to do it well requires the integration of many aspects of different engineering disciplines. Building a functional boat and competing each year requires the teamwork of many students who understand hydrodynamics, electronics, composite materials, biomechanics, machining, and administration. Participation on the team provides students a practical application of engineering and allows them to see the design progress from concept, to plan, to a functional boat, as well as experience the thrill of competition. The team's efforts are partially funded through Virginia Tech's engineering departments, but most of the material and monetary sponsorship comes from private companies.

B. *Phantom 5 Entry*

The Phantom 5 submarine project was started in the fall of 2003. A basic hull-shape was designed using computer-aided design software based on a volume and surface area minimization approach.

The hull and all systems used in Phantom 5 were constructed throughout the 2003-2007 school years with the ultimate goal being in the ISR races in Carderock, Maryland. Phantom 5 has previously competed in the 8th and 9th ISR, where it was plagued by electronic difficulties from its highly complex systems. These systems include a completely autonomous electronic control system incorporated in order to reduce pilot work load and increase overall performance. A vectored thrust system utilized to decrease the drag of the submarine by eliminating conventional control surfaces while maintaining a high degree of controllability. An electronically controlled variable pitch propeller system was used to maximize acceleration and minimize torque-over. After much hard work and innovative redesigns, the systems are nearly complete, but will appear at this competition as demonstration technology, not operational.

Phantom 5 is advanced mechanically as well, utilizing a linear drive system in order to hold the hull design philosophy of minimum volume and surface area. A self contained pneumatic safety system controlling the latches and the Pilot Emergency Beacon (PEB) allow for the safest Phantom submarine to date.

Phantom 5 was a significant step in comprehensive submarine design for the Virginia Tech team. The lessons learned from years of competition allowed for the design of the submarine to be completed with a more holistic approach. Historically, the approach has been top down, each system fitted into the already complete submarine hull wherever there was space and crews had little intercommunication. The new design made system placement a priority from the start and allowed the development and construction of Phantom 5 to be more efficient.

C. *Goals of the Project*

Safety of the pilot and divers associated is still the primary goal of this submarine team. The secondary objective for the Phantom 5 project was to increase the top speed of the submarine in order to be competitive in the speed category at the ISR 9 competition. This was accomplished by reducing drag and pilot workload while maintaining a high degree of safety for the pilot. Advancing the manufacturing processes and the technology used in the various systems remain important objectives for the team.

I. Introduction

A. Human-Powered Submarine Team of Va. Tech

Members of the Human-Powered Submarine Team of Virginia Tech come from many different backgrounds. Participation comes from the undergraduate and graduate students in various engineering disciplines. This year, the team has students from multiple different departments on campus. The team is subdivided into "crews" that are specialized in a particular system of the submarine project. The crews include the hull, propulsion, controls, electronics, propeller, life support/safety, and cart. The team president and vice president oversee the administration of the team and are to whom the crews report. Each crew is headed by an elected crew chief that sets the agenda for his crew. While each crew works on their own project, the submarine is still a team effort and all team members work where help is required.

B. History of ISR Involvement

The Virginia Tech team has a long history of involvement with the International Submarine Races. The team entered its original submarine, Phantom, in the 3rd ISR in 1993 in the waters off of Fort Lauderdale, Florida. This submarine never moved due to problems with the variable ballast system. Phantom 2 was raced at the 4th ISR in 1995, the first races held at the David Taylor Model Basin, as well as the 5th ISR in 1997. At the 6th ISR in 2001, the Virginia Tech team raced Phantom 3. With its exceptional maneuverability, innovative design, use of composites, and recorded speeds, Phantom 3 and the Virginia Tech team were presented with the award for Overall Performance. At the 7th ISR in 2003 Virginia Tech won 3rd place for speed in the single person propeller category, and 1st place for speed in the alternative propulsion category. And, of course, our latest, most advanced sub was entered in the 8th and 9th ISR. At the 8th ISR in 2006, the team placed 5th for speed in the one-man propeller category and received 2nd and 3rd place design awards. During the races at Carderock in 2007, Virginia Tech placed 5th for speed when Phantom 5 reached 3.77 knots.

II. Design Philosophy of Phantom 5

A. Volume-based Approach

A volume-based approach was used in the design of Phantom 5. The pilot of the craft acts as the sole power plant and must provide all of the energy required to accelerate the craft up to speed. This person's abilities are tightly restricted by factors such as their complete immersion in water and limited air supply. These challenges can be addressed, to an extent, through high flow regulators and other specialized technology and techniques. The largest restriction of all is the mass of the craft itself, all of which the pilot must accelerate to the final speed. Minimizing the volume of the submarine is the most effective way to decrease the mass since water fills all of the excess space inside the submarine. A smaller volume also generally leads to a smaller surface area and thus a lower frictional drag on the submarine. Form drag was also considered in the design of Phantom 5. While a laminar flow body would be ideal for a vessel with such low horsepower propelling it, the idea is not practical considering the regime in which the human-powered submarines operate. Phantom 5 operates in a turbulent flow regime so the effects of an adverse pressure gradient on the submarine would not be as likely to lead to separation.

B. Design Goals

The two main design goals of Phantom go hand-in-hand. By reducing the workload of the pilot, the team hopes to achieve a speed of 8 knots. Testing has shown that if the pilot can concentrate on propelling the submarine and not need to fret over the controls, greater speeds are achievable. It can be inferred that by creating an autonomously-piloted submarine, the pilot is then solely a propulsor. In the end, speed is the ultimate goal of the project but advancing the manufacturing processes and the technology used in the various systems remain important objectives.

III. Design and Fabrication of Phantom 5

A. Hull

a) Design

When starting the design of the hull for Phantom 5, all of the components that were required to fit within the structure were first considered. At this initial stage of design, the team determined the type of gear box to be used, how this gear box would attach to the rest of the propulsion system, and in what position the pilot would be able to most effectively provide power to the gear box. The team had also decided to use an electro-pneumatic control system and made initial estimates of the size of housings that would be required to hold the systems. Rough designs of all of the systems were developed and initial sizes for all of the components were determined.

In order to account for the pilot within the hull, several team members that desired to be pilots for Phantom 5 were laid down on paper in a position they considered to be comfortable and would allow them to effectively pedal the drive system. Their bodies were traced on this paper and several key reference points for the interaction of the pilot, the systems, and the hull were measured from these tracings. Examples of these reference locations include such distances as the maximum height from the back of the pilot to the knee when the leg is retracted during pedaling as well as the distance from the head of the pilot to the foot when completely extended during pedaling. The ability of the pilot to pedal effectively is of utmost importance in generating the maximum amount of thrust from the propulsion system, so it was necessary to have the pilot in a comfortable position. It was from these tracings that the overall geometry of the hull would be constrained in order to minimize the volume.

The solid modeling program Unigraphics was utilized to aid in the design of Phantom 5. The preliminary system sizes were used to generate representative blocks within Unigraphics that would represent where the systems would be able to fit. The components that were modeled included the control system computer box, the control system power boxes, the gear box, the pilot's air tank, the control stick and pilot display box. A mock up of a pilot was also constructed (cylinders and spheres representing major body parts) and positioned according to the data collected from the traces. Using the modeling program made it very easy to move components around and position them relative to one another and to visually see how everything would fit within the boat. The systems were eventually positioned in a way that allowed for the most streamlined shape and the minimum volume possible. A hull shape was then lofted over the systems in order to have the completed hull design.

When the lofting was done around the components, several cross-sectional locations were considered critical for the functionality of the submarine. One key location in the lofting process was aft of the gear box where a precise 6 in. circular cross-section was required in order to mount the vectored thrust system. The distance aft of the gear box for this location depended on the available space within the hull for mounting actuators and for ensuring that the slope of the hull was not too great to cause separation of the flow. An initial overall length for the submarine of 10 ft. was chosen to be consistent with other submarine designs – when this length was used in conjunction with the aft diameter restriction, a streamlined hull shape resulted and the issue was left at the time to be addressed by further analysis.

Since the vast majority of the systems that needed to be fitted within the hull aft of the pilot were rectangular in nature, the hull cross-sections that allowed for the minimum volume were also rectangular in nature. The cross-sections used were splines that were fitted around the rectangular components. The team had great success using rectangular sections with rounded corners in the past in order to minimize volume, and the splines were seen as a more advanced approach along the same lines. The cross-sections around the pilot were more conducive to ovular shapes and were constructed using splines that fit around the components in the forward sections.

Another critical cross-sectional area was what has traditionally been termed by the team as the "pedaling box" – the area that must be open to allow for effective pedaling. The choice for using a linear gear box (as opposed to rotary) was made based primarily on the reduction of internal volume in the pedaling box allowed by constraining the motion of the feet to 1 dimension. The largest issue with the pedaling box when using a linear drive is the space for knees as opposed to the feet, which was always the case when using a rotary gear box. The data collected from the traces specified that the largest pilot required a 22 in. tall cross-section at the location of maximum knee bending. The most effective cross-sectional shape for this area was also a rectangular spline shape. An example of this cross-section can be seen in Figure 1.

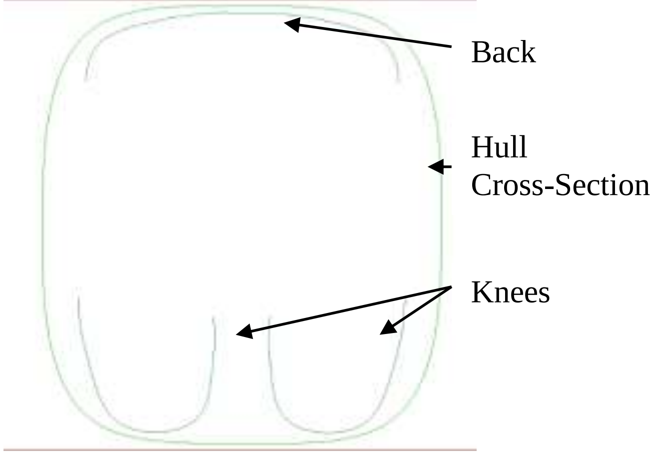

Figure 1. A representative "rectangular spline" used as cross-sections to reduce internal volume.

The space required by the feet during pedaling was not a limiting constraint – the gear box and computer boxes resulted in a highly rectangular cross-section at the feet location that was larger than that required by the feet during pedaling.

The final Unigraphics model can be seen in Figure 2.

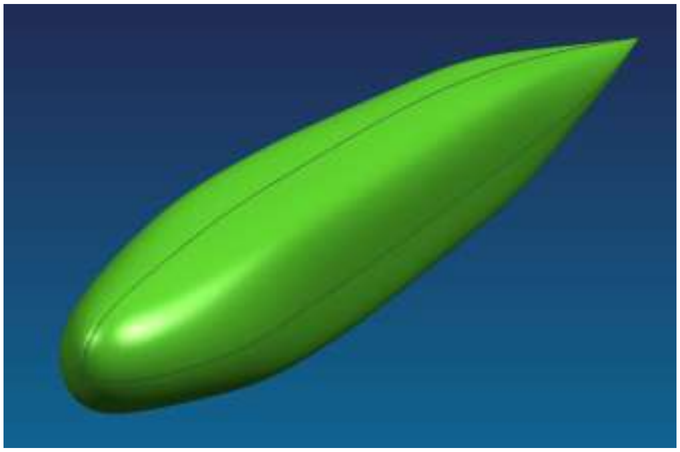

Figure 2. The Unigraphics model of the Phantom 5 Hull.

The design is symmetrical top to bottom and left to right. This design results in a total displacement of 1042 lbs of water, a surface area of 44.67 ft^2 and a volume of 16.69 ft^3. This displacement is 3.6 % less than Phantom 4's highly optimized hull and results in a more streamlined shape.

b) Analysis

Once the hull design was completed in Unigraphics, its performance was then analyzed. Since the hull was designed to meet the space requirements of the systems using a minimized volume and surface area approach, the most important factor to be addressed by analysis was whether or not separation occurred on the hull. The skin friction drag was already minimized by minimizing the wetted surface area of the submarine, so to further reduce the drag required the form drag to be minimized. The best way to ensure that the form drag was minimized was to ensure that separation did not occur in the adverse pressure gradient that is experienced over the aft portion of the hull. If separation were to occur, a low pressure separated wake would result in increased overall drag. If the flow remained attached, the pressure over the rear of the hull would remain higher than if separated, and the form drag would be reduced.

The pressure gradient over the surface of the hull is the main driver for the presence of separation and the pressure gradient is specified by the shape of the hull for a given flow field. In order to ensure that separation does not occur, the hull must be shaped in such a way that adverse pressure gradients do not become too large to induce separation – this is the idea behind streamlined shapes. The aft section of the hull, where separation is most likely to occur, was designed somewhat ad hoc using intuition and rough approximations based on previous designs. This was the critical section to be analyzed to determine whether or not separation occurred. If separation occurred, the hull design would have to be modified in order to increase performance.

The Virginia Tech Aerospace and Ocean Engineering Department has a series of JAVA based applets used for calculating fluid flows using 2-D boundary layer theory. A set of the applets must be used sequentially to analyze the flow field over the entire surface of the hull. All of the programs are only capable of 2-D calculations, so the vertical and horizontal cross-sections of the hull were analyzed independently.

The first program run was the Vortex Panel Method code which requires the hull offsets to be entered as inputs and uses inviscid flow theory to calculate the inviscid pressure distribution over the surface of the hull. The results from the Vortex Panel Method for the vertical and horizontal cross sections can be seen in Figure 3.

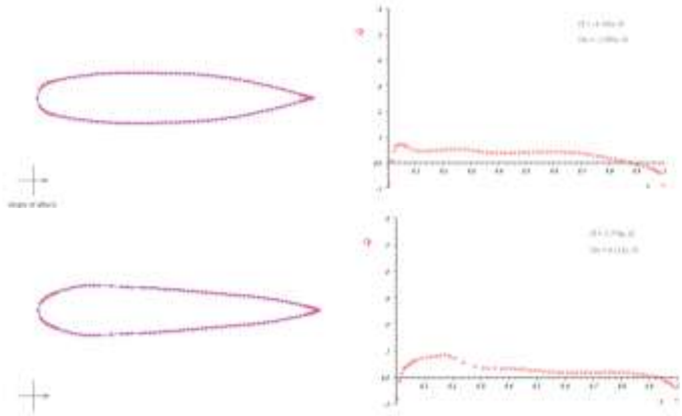

Figure 3. The vertical and horizontal cross-sections of the hull and their respective inviscid pressure distributions.

The surface pressure distributions are then entered in to a WALZ boundary layer code which is capable of calculating the skin friction coefficient, the boundary layer thickness, displacement thickness, and momentum thickness for laminar flows. The program is also able to determine if separation occurs or if the laminar flow begins to transition to turbulence. The WALZ program also requires several flow properties to be specified. The values input to this program were:

Dynamic Viscosity (m$^{2/}$s) = 1.758e-6
Freestream Velocity (m/s) = 4.2
Reference Length L (m) = 3.048
Flat-Plate Re (trans) = 2.5e5.

The freestream velocity was based upon the team’s expected speed during the competition of 8 kts, the reference length is the 10 ft length of the hull, and the flat-plate Reynolds number for transition is the value used to determine when transition from laminar to turbulent flow occurs. The value used in this analysis is a high value based on low freestream turbulence, but this is likely to give a more conservative estimate of performance. Due to the high Reynolds number of operation, $\text{Re} = \frac{\rho V L}{\mu} \approx 7.2 \cdot 10^6$, the flow over the hull will most likely be turbulent, which will be less likely to separate. By specifying a higher value for the Reynolds transition value, the flow will be analyzed as laminar over a greater percentage of the hull, leading to a more conservative analysis. The results from the WALZ program for the vertical and horizontal cross-sections can be seen in Figure 4.

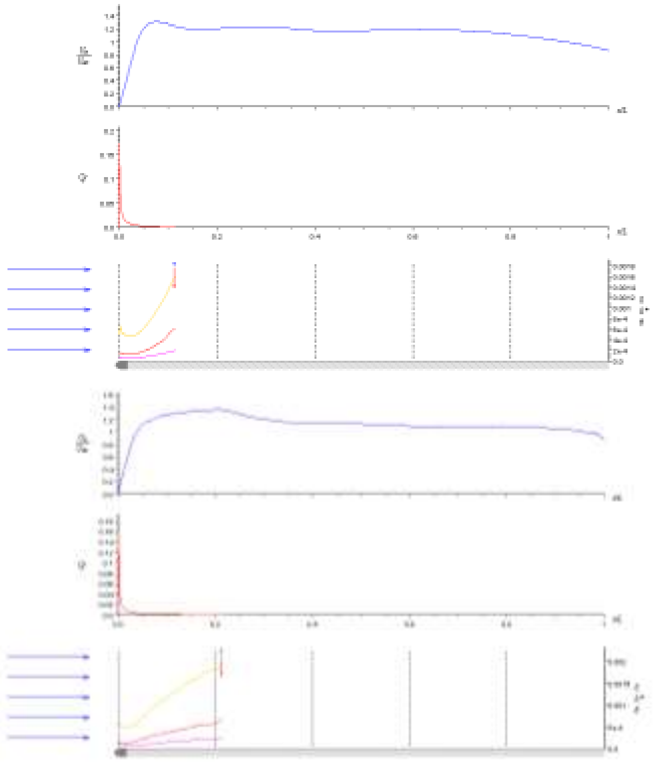

Figure 4. The WALZ output for the vertical and horizontal cross-sections showing the outer edge velocity distribution, the skin friction coefficient, and the boundary layer height, displacement thickness, and momentum thickness.

The WALZ program predicts the flow to transition to turbulent at approximately 10 – 20% of the hull length. Since the flow transitions to turbulence, another program must be launched from within the WALZ program in order to analyze the turbulent flow.

The MOSES program uses an integral boundary layer method to calculate the turbulent boundary layer. The inputs from the WALZ method are carried over to the MOSES method when it is run from within the WALZ method and uses the data from the final location of the WALZ method as the initial conditions. The results from the MOSES method for the vertical and horizontal cross-sections can be seen in Figure 5.

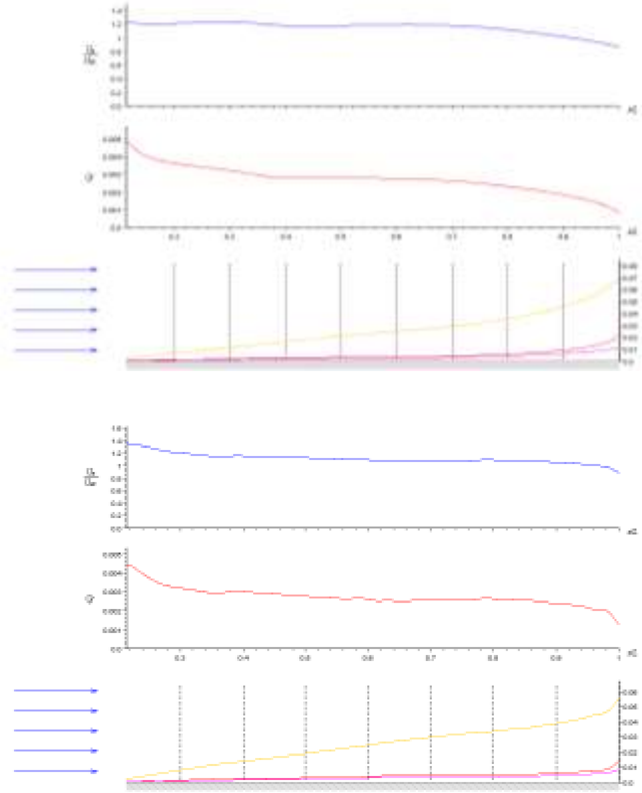

Figure 5. The MOSES output for the vertical and horizontal cross-sections showing the outer edge velocity distribution, the skin friction coefficient, and the boundary layer height, displacement thickness, and momentum thickness.

The MOSES method predicts that the flow remains attached over the entire surface of the submarine.

Another turbulent boundary layer program called ITBL can be launched in the same manner as the MOSES program from within the WALZ program and was used to compare the results from the MOSES program. This program allows for the option of either an eddy-viscosity model or a mixing length model to calculate the turbulent boundary layer over the submarine. The grid spacing for the models is set to have 2000 data points in the vertical direction across the initial boundary layer and the horizontal spacing is set to the initial boundary layer height. The total number of vertical spaces must be set to allow the boundary layer to grow over the length of the hull. The values used for this analysis for the vertical cross-section were:

Number of x steps = 2000
y step size (m) = 7.5e-7
number of y steps = 1e5.

The values used for the horizontal cross-section were:

Number of x steps = 1600
y step size (m) = 9.5e-7
number of y steps = 1e5.

The program was run using a mixing-length model. The results from the ITBL program for the vertical and horizontal cross-sections can be seen in Figure 6.

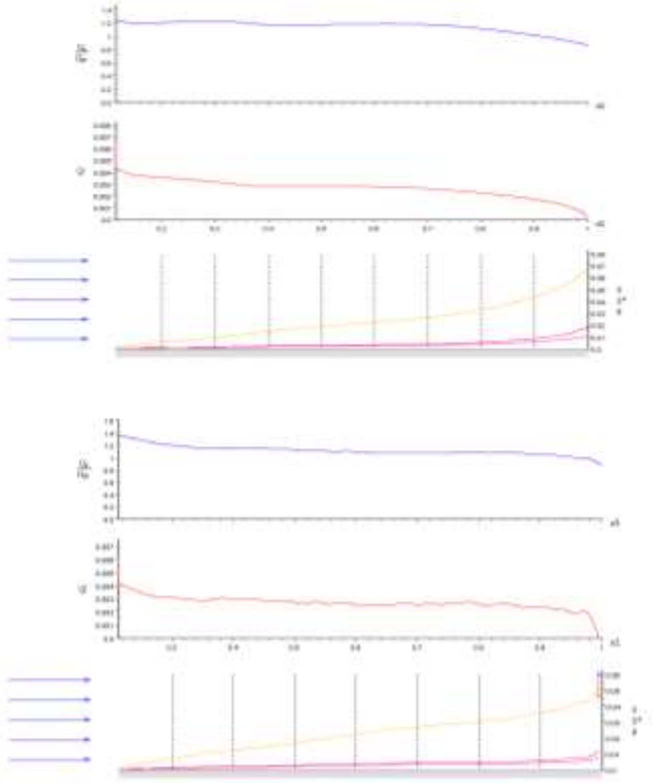

Figure 6. The ITBL output for the vertical and horizontal cross-sections showing the outer edge velocity distribution, the skin friction coefficient, and the boundary layer height, displacement thickness, and momentum thickness.

Both programs for the prediction of the turbulent boundary layer were in agreement that the flow remains attached over the entire surface of the hull for the vertical cross-section. The mixing-length model predicted that separation will occur at 99.5% of the hull for the horizontal cross-section. These methods only allowed for 2-D calculations and did not account for certain real world phenomena such as freestream turbulence and surface roughness; however, these effects would only serve to help transition the flow to turbulent and would aid in maintaining attached flow. The propeller also produces suction that increases the flow velocity over the aft section of the hull, and will also serve to maintain attached flow. The analysis showed that the initial hull design was successful and should not require modification. The flow at 99.5% of the hull will actually be located on the spinner, aft of the propeller, which is not of much concern for the general hull shape.

Using the results from the hull analysis and data for the surface area of the hull, rough estimates of the hull drag were calculated. The total drag coefficient for the hull was estimated to be $C_D \approx 0.0035$ and the total drag was estimated to be $Drag \approx 29\, lbs$. Though this is a very rough estimate of the total drag of the submarine, this is an 18% decrease in drag from Phantom 4.

c) Construction

The construction of Phantom 5 began with the construction of a female mold used to create composite lay-ups. The CAD design was sent to a company that manufactures boat hulls and has a large gantry mill for machining foam specifically for the purpose of a composite lay-up. Since the design for Phantom 5 is symmetric top to bottom, only one mold of one half of the submarine was required.

Fiberglass was used for the entirety of the hull construction for its strength, formability, ease of use, and low cost. The team has used carbon fiber for high stress areas in previous hulls, but this was deemed unnecessary, overly expensive, and overly complicated when the stresses incurred by the submarine are no where near the limits of fiberglass. Top and bottom halves were molded by a vacuum-bagging process. The advantage to such a process is that equal pressure is exerted across the entire surface by the vacuum, forcing the epoxy to distribute evenly throughout the fiberglass, creating a stronger product.

Historically, the team has permanently mated the two halves of the hull, and then removed sections for a pilot hatch and a propulsion system hatch. Using the Unigraphics model, it could be seen that the systems were so compactly placed in the rear of the hull and the hull was so closely formed to the systems, that hatches would necessarily be a large percentage of half of the hull. It was decided that, to aid in pilot ingress and egress and to allow for ease of working on the systems while mounted in the hull, the two halves of the hull would not be permanently mated, but rather would be able to be disconnected. The bottom half of the hull was reinforced structurally with more layers of fiberglass and it carries all of the structural loads of the submarine. All systems were mounted directly to the bottom half of the submarine. The top half of the submarine was divided into two sections – the pilot hatch and propulsion system hatch. The propulsion system hatch was bolted directly to the bottom half of the hull and can be removed when on the surface for easy access to all of the systems in the rear of the submarine. The forward section of the top half (the pilot hatch) was mounted to the back half (propulsion hatch) of the hull using a door-style hinge with a quick pin release system. The pilot hatch is directly attached to the bottom half of the submarine using the hinge and manual nose pin-jointed release system that can quickly release the pilot from the inside or outside of the submarine. By hinging the hatch, the pilot is able to easily ingress and egress from the sub, but the safety crew is now not responsible for holding on to a separate hatch when looking after the pilot underwater – the hatch remains securely fixed to the submarine. The hinge also limits the movement of the hatch, so it is much easier to close the hatch, which fits securely along a set of inner and outer flanges.

In the design phase of Phantom 5, it was estimated that a significant amount of floatation would be necessary to cause the submarine to be neutrally buoyant. This assumption led the team to the decision to incorporate foam in the initial composite lay-ups. Low-density, closed-cell foam was selected for its buoyancy and incapability of becoming water-logged, should water seep in. The flotation was incorporated in the top half of the submarine to create a stabilizing torque between the center of buoyancy and the center of gravity of the submarine. Since the bottom half of the submarine was the only section carrying any structural load, foam could be glassed in to the entire top section without regard to requiring any hard points to be mounted at foam locations. Hard points usually require a piece of metal to be imbedded in the composite. Placing such a hard point in foam is unadvisable because it acts as a stress raiser and it provides a location for water to seep into the composite and potentially become trapped inside, changing the ballast of the submarine. Having foam glassed in to the pilot hatch also aided in the hatch opening by being slightly buoyant. When the hatch is to be opened, the latches disengage and the hatch will float open on its own.

Aluminum hard points were connected to the hull by first embedding them in to the hull with a milled fiber-epoxy composite and then were glassed over using a vacuum-bagging process. Hard points for the gear box, vectored thrust mounting plate, vectored thrust pneumatic actuators, pilot restraint, pilot hatch hinge, and pilot hatch latching mechanisms were all glassed in to the hull.

The windows were formed in a process called vacuum forming. Polycarbonate sheets were heated to thermoforming temperatures then sucked into a negative mold. An entirely new front section mold had to be made from the male plug for the vacuum forming process. Since the submarine is symmetric about the top and bottom halves only one mold was needed. The mold had tubes run through the mold to allow suction on the polycarbonate sheet when it reached its thermoforming temperature. The thermoforming temperature of our polycarbonate sheet was 350-400 degrees F. Windows were then cut-out to match the shape on the hull.

The vectored thrust system is used to control the submarine, but without comprehensive testing, it could not be known if the system alone would be capable of stabilizing the submarine. It was decided that optional stability fins would be attached to the hull in order stabilize it if necessary. Commercial surfboard skegs were used as stability fins and their mounting blocks were glassed in to the hull and faired. The skegs can be easily inserted or removed from their mounting blocks as needed. The stability fins were also equipped horizontally to make a back-up manual control system like previous year designs.

The final stage in the construction of the hull was fairing the hull in order to reduce drag. The hull was coated with a thin layer of two-part marine fairing compound, which was subsequently sanded off to produce a smooth hull form. Any defects in the vacuum-bagging process were eliminated and seams between the hatches and windows were made as small as possible. Drainage and air-vent slots were cut in the hull to quickly drain water upon exiting the basin and efficiently vent the pilot's exhaled air to prevent air from being trapped in the submarine, which would negatively affect the ballast.

B. Propulsion

a) Objectives

The design and success of Phantom 5 relies largely on the innovative vectored-thrust propulsion system used to control the submarine. With one design objective being to reduce the hull volume, the use of a rotary (cyclic) gearbox was immediately reevaluated. A linear drive gearbox design conceived by the Propulsion Crew allowed the team to significantly reduce the diameter of the hull at the gearbox from 28 inches on Phantom 4 to 20.2 inches on Phantom 5.

b) Underwater Human Output Testing

The last several gearbox designs have used large assumptions in their designs. The design of the gearbox and propeller are governed by the power that is available. Unfortunately, the output of a human, underwater, on scuba, and peddling a bike is not well understood. Estimates of 0.25 to 1.5 hp have been found in literature, but none of these values were for this specific application or were based on the performance of an Olympic cyclist. In order to create an efficient propulsion system real data was needed. To solve this problem the team constructed a pilot-test tank which can be used to measure the power generated by out pilots over a range of rpm's and loads. The pilot test tank consisted of a water filled tank with the pilot restraint harness and an older generation of gear box mounted inside, as can be seen in Figure 7.

Figure 7. The pilot harness and gear box mounted inside the test tank.

The shaft of the gear box goes through the tank to the outside, where a fly wheel is mounted in order to measure the rpm and torque produced by the pilot. A frictional brake was applied to the fly wheel by having a cord loaded with certain weights and the torque was measured by a load cell connected to the frictional cord. The fly wheel, brake, and load cell can be seen in Figure 8. A Hall effect transducer was used to measure the rpm of the fly wheel, as seen in figure 9.

Figure 8. The fly wheel and brake used for measuring the torque produced by the pilot.

Figure 9. The Hall effect transducer.

Both the Hall effect transducer and the load cell were connected to a data acquisition system that recorded the data during test runs. The pilot was also equipped with an LCD screen that showed the time of the run (runs were conducted for 60 seconds) and the pilot's pedaling rpm. The pilot was to hold a constant rpm and the LCD screen was used to inform the pilot of his current rpm.

Preliminary data from the testing of one pilot is presented in Figure 10.

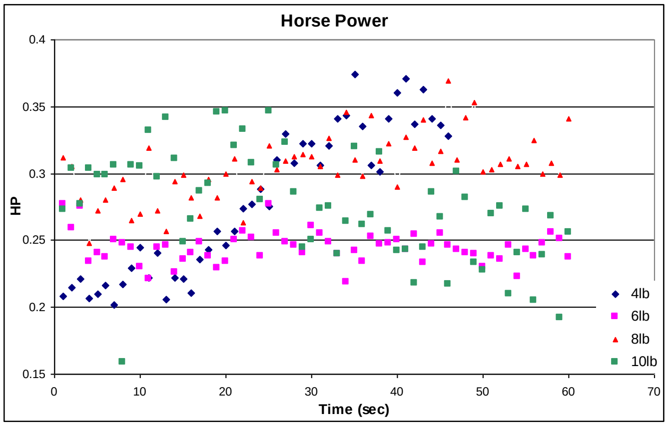

Figure 10. Preliminary data from a single run of pilot testing.

The figure shows that the pilot's horse power varied between 0.2 and 0.38 during the course of the run. A higher load on the brake generally lead to greater power output, as the pilot was exerting more effort in order to maintain a constant rpm. Other preliminary data showed that pilot power output can reach as high as 0.55 hp.

c) Gearbox Design

As this is the first linear drive propulsion system designed by a Virginia Tech team, it was not known how the underwater pedaling efficiency compared to a rotary system. Literature shows that a higher power output level can be maintained using a linear gearbox versus a rotary gearbox over the same interval. This promising information drove the motivation for the design. Using a linear system permitted the hull diameter to be smaller than in previous Phantom submarines. Rotary systems must account for pedaling space for the propulsor's heels and knees while not sacrificing efficiency by shortening crank arms. By contrast, a hull-shape that incorporates a linear system needs to account only for the propulsor's knees.

Traditional human-powered submarine designs use a rotary gearbox with a drive shaft on the neutral axis. By moving to a vectored-thrust design, the Virginia Tech team opened up many options for itself in terms of propulsion. Because the thrust-vectoring unit inherently changes its position from the neutral axis, the use of a single drive shaft was not feasible. This required the use of universal joints to connect several sections of the drive shaft, bringing to light the possibility of mounting the gearbox above the centerline. A centrally-located linear drive system wastes space above the propulsor's legs, but by positioning the gearbox above the centerline, the team could maximize the pedaling space for the propulsor's knees below.

The Propulsion Crew designed the linear drive system to be mechanically similar to the rotary gearboxes of the past. Our pilots have become comfortable with a pedaling speed of 60 to 70 RPM. This would provide the desired RPM and torque for the new propeller design. A 4:1 gear ratio has been found through testing to be optimum for performance during acceleration and while running at top speed. The design centers around two gears on a vertical shaft: One pinion gear that is driven by the racks, and a large bevel gear that drives the shaft. This compact design utilizes one-way clutches in the small bevel gears located on the drive shaft to allow for push-pull action. Because the two racks are linked via the small pinion gear, the propulsor is able to "pedal" using both the up stroke and down stroke. This is beneficial for three reasons. One, the propulsor is using different muscles in each direction; two, the gears are seeing more constant loading than if only one side of the pinion gear was being driven on each stroke; three, the design provides an advantage in the event that one of the propulsor's feet slips out of the pedal. The one-way clutches also permit the shaft, and thus the propeller, to rotate even when the pilot is not pedaling. This is crucial to the design because the gearbox essentially comes to a stop at the top/bottom of each stroke before moving in the opposite direction.

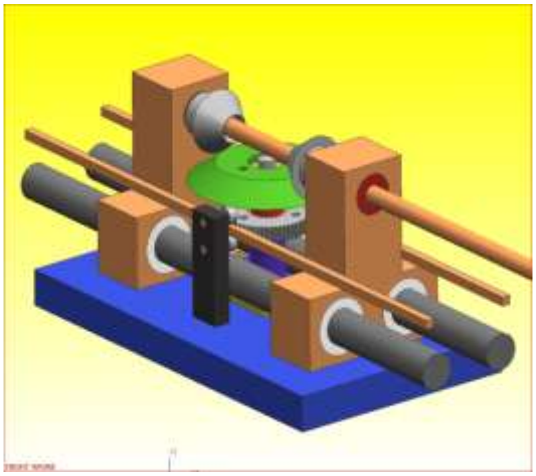
Figure 11. 2005 gear box design.

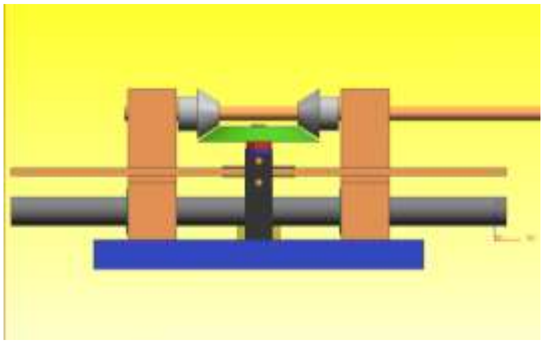
Figure 12. Side view of 2005 gearbox design.

After the design was created, and the CAD Model constructed, the team had the daunting task to machine the gearbox. Thankfully, Virginia Tech has several vertical mills and lathes at the disposal of the engineering design teams, and a few of the members of the team have access to the lab. Countless hours of machining go into the construction of the gearbox. All dimensions of the gearbox can be machined to 1/100th of an inch accuracy, and there are very few machining operations that the team is unable to perform. The gearbox was constructed mainly using Al 6061 because of its high strength, good machinability, and low cost.

d) Testing

Following the completion of the gearbox, extensive underwater testing was performed to ensure that the box performed as desired. We were mostly concerned with the proper meshing of the gears and that the propulsor felt comfortable pedaling in a new position. After extensive testing has been performed on the gearbox and the other propulsion components, the problems that arise will be corrected, and the sub should be fit for competition in ISR 9.

C. Propeller

a) Objectives and Constraints

The first step in designing the propeller was to determine its expectations and requirements. Since the intent of this propeller design was to maximize the speed of the submarine, a goal value was initially set and became the foundation of the entire design. The ISR 9 competition is a speed race, and the team wanted to be competitive with the fastest submarines. World records have been set around the 7-8 kts range, so a maximum achievable speed was set to be 8 kts. Keeping this design speed in mind, the other physical requirements and limitations were outlined. The team decided to use a variable pitch propeller system in order to maximize acceleration and to reduce the effects of torque-over when accelerating. The propeller optimization was conducted for the design point of fastest speed with constant pilot pedaling speed. It was assumed that the propeller performance at lower speeds with a pitch other than that of the design case would be efficient enough to accelerate the submarine to the design speed.

The vast majority of the propeller design was carried out in a propeller design and optimization program called JAVAProp. This program is available freely on the internet from its creator, Martin Hepperle. The optimization program contains a database of various airfoil sections and their lift and drag curves, which would become the sections from which to base the propeller optimization. The program also requires a wide range of input variables including the overall propeller diameter, hub diameter, the number of blades per propeller, the RPM of the propeller, the forward speed of the submarine, the power provided to the propeller, and the fluid properties of the medium in which the propeller will be operating. All of these attributes were considered during the propeller optimization process.

The diameter of the propeller was chosen based on the size of the hull and its ability to protect the propeller from any accidental contact with obstructions. A propeller that sticks out beyond the hull is more likely to be damaged by contact with the bottom of the basin and is also a safety hazard to safety divers and other competitors. A larger diameter propeller is capable of having a greater aspect ratio and being more efficient, so a propeller diameter of 22 in., the largest vertical size of the hull, was chosen.

The hub diameter was determined by past experience. The team had experimented with creating a variable pitch propeller system in past years, and knew that the mechanisms for varying the pitch could be effectively fit within a 3 in. diameter hub. The size of 3 in. for the hub was chosen for initial design considerations and required the hub to be fabricated to a 3 in. specification.

Experience has shown that a 2-blade propeller is highly efficient and the team has had great difficulty in manufacturing high quality propeller blades in the past. For these reasons, it was decided to utilize a 2-blade propeller in order to reduce the manufacturing requirements by limiting the number of blades that had to be produced.

After years of running Phantom 3 with a 3:1 gear ratio and a single propeller and Phantom 4 with a counter-rotating propeller with a 4:1 gear ratio, the team was looking for a change in the overall performance of the propulsion system. As mentioned before, the overall length of these races is extremely short, making acceleration vital. The decision was made by the team to increase acceleration at the expense of efficiency by making the blades shorter and operating at a higher rpm. Since a human pilot has a set range of pedaling speeds that is comfortable, the decision was made to increase the gear ratio from 3:1 to 4:1 in order to increase the rpm of the propellers. This would hopefully boost the acceleration of Phantom 5 and allow the boat to reach its design speed before the timing gates at the end of the course. Unfortunately determining the gear ratio was only half of this problem, the other half of the responsibility rested on the shoulders of the pilot. Since the output of a human is far from consistent, a goal RPM for the pilot to pedal had to be determined. From experience, this value was set to a conservative value of 60 rpm, though testing has shown that a value closer to 70-80 rpm is more comfortable. A higher rpm will result in more thrust, so the propeller was designed with a design rate of 240 rpm $(60 \cdot 4)$ for a conservative design.

A search of literature for human power output shows that top athletes can produce over 1 hp for certain activities. Considering that Virginia Tech Human-Powered Submarine team members are not world class athletes and that they are restricted by a wetsuit, confined to a small volume, breathing on a SCUBA tank, and pedaling in water, a very conservative value of 0.5 hp was used in designing the propellers. Pilot testing that was conducted verified this estimate of pilot power generation.

b) Optimization

In order to run the JAVAProp program, a set of 4 airfoils distributed along the span must be chosen as the initial starting design which JAVAProp then modifies and interpolates between to design the optimized propeller. These airfoils were chosen based on the highest lift to drag ratio, while having a thickness that was capable of carrying the large bending moments that are present on the blades (the thickness must increase closer to the root as the bending moment becomes greater towards the root). The initial airfoil distribution was chosen to be, from the root to the tip, an MH 126, an MH 112, an MH 114, and an MH 116. JAVAProp was then run and calculated the most efficient propeller based on the criteria input. The program modifies the distribution of the airfoil sections and calculates the chord lengths and blade twists that result in the most effective propeller.

The blade that JAVAProp returned was then analyzed to ensure that it would be structurally sound. Structural analysis, assuming properties of 6061 aluminum from which the blades were to be machined, showed that at several locations along the length of the blade, the bending moment was too large for the thickness of the propeller. The chord length distribution was then slightly scaled and smoothed in order to achieve a blade that was capable of carrying the loads, though with slightly reduced performance from what JAVAProp predicted. The propeller designed using JAVAProp, before modifications were made, was predicted to have an efficiency of 93% and a total thrust of 18 lbs. This value of thrust is less than the total drag estimate of the submarine at 8 kts, but this value is thought to be conservative since it is possible the pilot will be pedaling at a higher rpm. With a thrust of 18 lbs, the submarine should still be able to reach a speed of 6.4 knots, which is a very competitive speed.

c) Manufacture

The modified data from JAVAProp was then input in to Unigraphics to develop a solid model of the propeller (Figure 13). The known sections, twist, and chord distribution were used to loft the propeller blade.

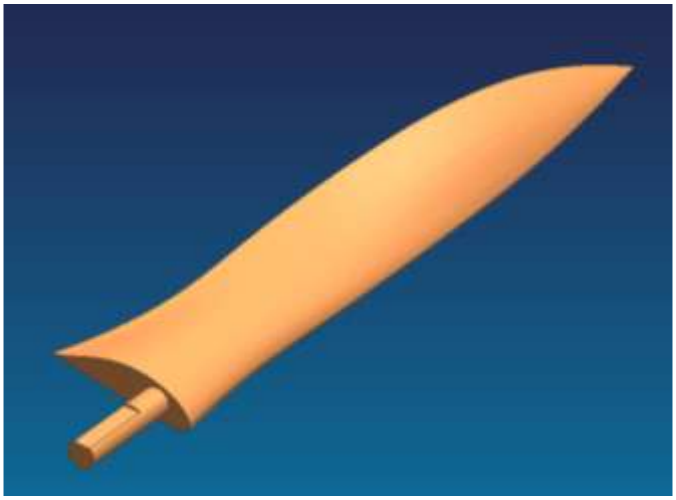

Figure 13. Unigraphics model of one of the propeller blades.

In order to operate in the variable pitch hub, a 3/8 in. shaft was to be connected to the blade. This required an increase in the thickness, and thus the chord, at the root in order for the shaft to fit. Since the blade was modified only in the vicinity of the root, where the blade is moving slowly and is producing the least thrust, the modification will not noticeably affect performance.

The purpose of the Unigraphics solid model was to CNC machine the blades out of 6061 aluminum, which was completed on a privately owned 5-axis mill in Febraury of 2007. The team has tried various techniques over the years to manufacture propeller blades, ranging from casting to composite molding, and has never met with a great deal of success. It was decided that machining the blades would be the most effective means of producing a high quality product. The finished blades were then anodized for added surface durability, while not compromising the shape of the precision surfaces (Figure 14).

Figure 14. Completed, anodized blades in variable pitch hub.

d) Testing

Propeller performance tests are important for understanding the operational characteristics of a propeller and determining the thrust and torque associated with respective advance ratios. We can use the performance data to determine the optimum pitch angle of our propeller for a given speed that will maximize our thrust while efficiently using the pilot's energy. We will calculate our optimum propeller pitches using a human power output of one-half horsepower to the shaft verified to be an accurate estimation by previous physical tests. The information gathered from a performance test can also be used to operate in special functioning propeller regions such as the air brake region for stopping and the windmill region for power generation. A commercially available aircraft propeller with similar characteristics to the submarine's propeller was tested in the Virginia Tech Open-Jet wind tunnel at various advance ratios using a six component strain gauge balance to measure thrust and torque. The data was used to create a performance plot representative of the submarine's propeller operation. The advance ratio was varied by adjusting tunnel speed and then rpm to ensure the thrust and torque coefficients stayed the same for equivalent advance ratios as theoretically assumed. There was a strong correlation of the non-dimensional coefficients ($r = 0.99$) indicating proper validity. The value of optimum thrust (K_T) = 0.0516 with a corresponding torque (K_Q) = 0.0035 was obtained for our preliminary constant pitch test. Using the non-dimensional equations below and expected shaft rotation of 300 RPM the thrust produced was 29.00 pounds with 3.61 ft-lbs of torque.

$$K_T = \frac{T}{\rho \times n^2 \times D^4}$$

$$K_Q = \frac{Q}{\rho \times n^2 \times D^5}$$

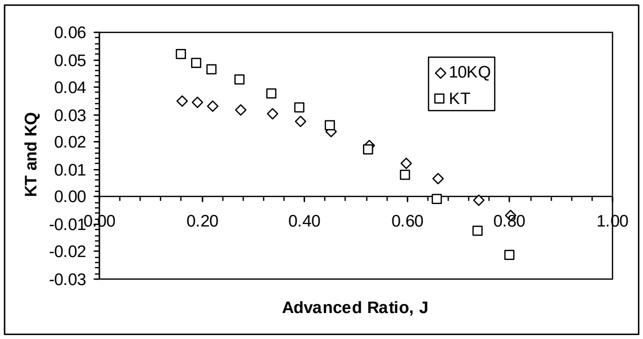

Figure 15. Propeller performance plot for the commercial propeller.

The torque and rotation measurements for this case correspond to an effective power of roughly 0.21 hp. If the majority of a pilots 0.5 hp is transferred to the propeller, the propeller should be able to generate more than 29 lbs of thrust. At lower rpm, the propeller generated much less thrust, approximately 18 lbs at 240 rpm (which agrees with results from JAVAProp). These measurements indicate that the propeller thrust, submarine drag, and pilot power are all at values that will allow Phantom 5 to be competitive at the 2007 HPS competition. Future tests will be conducted with the submarine's propeller at multiple pitch angles to determine optimum run conditions. We are developing a computer controlled variable pitch propeller that will adjust pitch angle automatically for corresponding advance ratios. The ability to change pitch angle during a run will increase the thrust effectiveness of our propeller giving our sub an advantage over fixed pitch propeller vehicles.

D. Controls

a) Objectives

The mission of the human-powered submarine team was to design and build a high-speed, controllable underwater vehicle. The team determined that the design of the control system must meet the following criteria: create as little drag as possible, function efficiently, and respond quickly to the pilot's signals, and allow for effective control authority Since the pilot is also the propulsor in Phantom 5, the system was to simplify all tasks. However, despite our best efforts, manually operated control fins will replace the vectored thrust system in this years competition. We include the following information as testament to our efforts thus far.

b) Design

The team viewed the vectored thrust system as an interesting challenge since it had never been attempted before in the human-powered submarine races. The vectored thrust system mainly allows the variable pitch propeller blade system to change orientation relative to the aft end of the submarine. The team has had a long history of successful control system designs and felt that the design and implementation of a vectored thrust system would be within the capabilities of the team. A vectored thrust system has several inherent benefits such as a reduction of overall drag by not requiring conventional control surfaces to deflect (which produce a high degree of drag) and has increased control authority. The only real drawback to a vectored thrust system is its increased complexity and sensitivity.

The controls crew searched for previous vectored thrust propeller systems and discovered a system in an autonomous underwater vehicle that was very similar to the characteristics of Phantom 5. The design of this system was basically recreated with a slight modification to the actuation mechanisms.

The design of the system centers on the concept of a gyroscopic propeller setup. Attached to the rear of the submarine is a three piece plate system that can rotate about the transverse and vertical axis relative to the submarine. The outermost ring is attached to the submarine while the inner ring holds the drive shaft through the center on the inside and the variable pitch system on rests on the outside. The variable pitch system is allowed to rotate freely on the inner ring. The full system can be seen in Figure 16.

Figure 16. Vectored thrust system with a view of the variable pitch system attached.

Testing in Weeki Wachee Florida has proven that the vectored thrust system requires a lot of force and precision that cannot be harnessed by the pilot manually so an electronic system was deemed absolutely necessary. The team created a very successful electronic control system in previous years which utilized pneumatic pistons to actuate control yokes on the moveable control surfaces. A similar system adapts very easily to the vectored thrust by replacing the control yokes with the gimbaled rings of the vectored thrust system.

E. Electronics

a) Introduction

The Virginia Tech Human Powered Sub Team has been using control by wire systems for the past few years. Past experience has shown that much of the pilot's energy and concentration goes into controlling the sub. Anything that can be done to reduce the demand on the pilot should improve the performance of the sub. The electronic control system requires very little force to operate and had the ability to automatically maintain the depth and direction of the sub. The reduced demand on the pilot allowed more of the pilot's energy to go into propelling the sub.

Please take note that only the input sensors and Pilot LCD display will be operational, not the actual controls. The team has acquired all the components necessary and does in fact have a nearly operational system, but was regretfully unable to complete it by the competition date.

b) Electro-pneumatic

The control of any mechanical system requires some form of logic and actuator. The form of the logic and actuator can be mechanical, pneumatic, hydraulic, or electronic. Electronic or computer based logic is the most versatile and arguably the easiest to implement. All of the controls courses taught at the undergraduate level focus on this method. There are a variety of sensors and transducers available, which can be easily integrated into an electronic control system. These sensors are used to provide the control and feedback signal for the control of the sub.

A variety of actuators have been used in the construction of human-powered subs. Most of them are based on some form of mechanical push-pull linkage. These systems are reliable, but are not easily adapted to computer control. The obvious choice for a control system with electronic logic would be an electronic actuator. This would require additional power and great care in sealing the system. The team has experimented with pneumatic actuators and found them to be a poor solution for several reasons:

1. Pneumatic actuators typically have slow response times because of the limitations of how fast air can be expelled.
2. The actuators require several switches and proportional valves which must be sealed.
3. Pneumatic actuators used were large and expensive.
4. Actuators are available with integrated displacement transducers, but waterproofing the electronic components of the actuators is extremely difficult.

After experimenting with pneumatics, the team has decided to use electric servos for control of the Vectored Thrust and Variable Pitch control. To accommodate the use of electric servos the sub's power system needs to be upgraded to ensure that the computer control will not crash due to a power spike. Servos control has several benefits:

1. Servos are known for fast response times.
2. The servos only require the wires and electronic components to be sealed.
3. Electric Servos have position sensing built in, which allows for fast development.

c) Computer Control

The core of the control system is a 1.0GHz single board computer (SBC) and a USB DAQ Card as shown in Figure 17.

Figure 17. SBC and DAQ Card

These components were selected for their small size and low power consumption. All of the required functions of the controls system; data acquisition, control algorithm, data logging, and the pilot display were written in Labview™7.1 and compiled into an executable program. This program samples the analog signals from the transducers, implements the required control functions, updates the pilot display, and logs the current data.

The SBC was equipped with an 802.11b wireless card. This allows direct control of the system when the sub is on the surface. Changes to the control program and analysis of the data from the last run can be performed without physically connecting to the sub, or opening the waterproof enclosure.

d) Automatic Depth Control

The automatic depth control of the sub was changed very little from last year. This part of the control system uses the signal from a depth transducer as the control and error signal. The depth transducer is shown in Figure 18.

Figure 18. Depth Transducer

Once the sub has reached the desired depth the pilot signals the control program to sample the depth transducer. This value is set as the reference depth. Under computer control, the depth transducer is continually sampled and the difference between the current value and the reference value is used to determine the control action. The greater the difference between these two values, the greater the control action.

e) Automatic Heading Control

The implementation of a fully autonomous control system also requires a method of controlling the heading of the sub. Several methods of determining the heading of the sub were considered including; GPS, inertial guidance, digital compass, and proximity detectors. It was determined that GPS is not accurate enough and will not work underwater. Inertial guidance systems are too expensive and proximity detectors will only function over short distances (low power units). This left us with digital compasses like the one shown in Figure 19.

Figure 19. Digital Compass Module

This module has a resolution of 0.5° and has an allowable pitch and role angle of 20°. The directional control algorithm functions in the same manner as the directional control. The pilot sets the reference direction and the control signal is based on the error between the current direction and the reference direction. The major difference is in the method used to communicate to the digital compass module. The digital compass communicates via a serial interface.

f) Pilot Override

Even though the control system will be fully autonomous, a pilot override was included in the design. This will allow the pilot to change the reference depth or direction during the run or take control of the sub entirely. In the event that this is not enough, the pilot has the option, via an advantageously located button, to shut down the computer, facilitating his/her timely egress.

Figure 20. Pilot control handle and dead-man switch.

Two strain gauges determine the position of the joystick. When the switch is depressed the transducer signal are used as the control signals. After the switch is released the current depth and direction is read and set as the new reference value. The computer then takes over control of the sub using the new reference values.

g) Pilot Display

Due to the complexity of the control system, it is necessary to provide information to the pilot. A small USB LCD display was mounted in the front of the sub as shown in Figure 21.

The pilot display indicates if the control system is functioning under computer control or pilot control. The reference depth and direction as well as the current depth and heading are also displayed. Additional information can be displayed such as the propulsion RPM and the speed of the sub.

Figure 21. Pilot Display

F. Life Support

The pilot life support system consists of a scuba tank, a regulator, and a pressure gauge. A spare air cylinder is also inside the submarine for emergency use.

The pilot of the submarine is working at a fast pace, and his body needs the maximum amount of air possible. To accomplish this, a high flow scuba regulator is used to supply air at a higher rate.

A scuba tank pressure gauge is located in visible range of the pilot. This allows the pilot to observe the amount of air in the scuba tank and to identify if a leak becomes present. In the event of a scuba failure, a spare air unit is easily accessible to the pilot that permits several minutes of emergency breathing time.

It is also important to note that only premium quality scuba equipment is incorporated into the life support system. All equipment is properly maintained by dive shop professionals.

a) High Visibility Markings

The submarine is marked with bright orange, high visibility markings in places that present a hazard as well as areas critical to the safety functions of the submarine. The markings are designed so that they will be easily seen underwater. They ensure that safety divers will not put their hands in a dangerous place on the submarine that will cause them harm. The tips of the propeller blades and fins are marked as well as the hatch release latch.

b) Pneumatic Safety System

The pneumatic safety system will implement a Pilot Emergency Beacon (PEB), Figures 22 and 23, that is designed to operate off of a self-contained pneumatic system.

The PEB consists of a releasable, buoyant buoy that contains a strobe light. The PEB is mounted flush on the top of the hull and is held in place by a pneumatic piston which is in series with a momentary "dead man" switch. When the pilot is inside the submarine, he holds down the dead man switch and arms the PEB system. Once the system is armed, the pilot must hold the momentary switch to prevent the PEB from deploying. If the pilot loses consciousness, the dead man switch is released. Once the switch is released, the PEB is deployed and floats to the surface to alert the emergency. A fluorescent tether is attached to the PEB which serves as a guide for rescue divers to find the submarine.

Figure 22. External view of the PEB

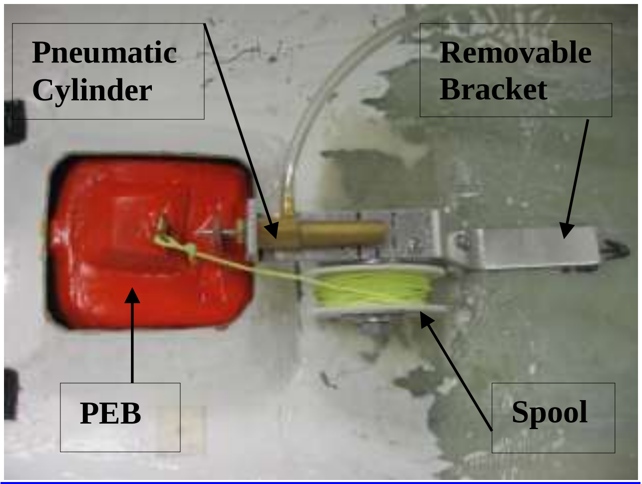

Figure 23. PEB release mechanism

Air for the system is provided by an independent 1800 psi tank. This tank contains atmospheric air and is regulated to 100 psi to run the PEB system. In light of the desire for the utmost safety and the fact that the pneumatic tank contains breathable air, an innovative safety system has been incorporated into the system. The device, called "3rd Chance Air," (Figure 24) consists of a small nozzle that is tied into the pneumatic system. In the event that the pilot encounters failures of the primary scuba system and the spare air cylinder, the nozzle can be accessed so that the pilot can breathe the air in the pneumatic system. It should be noted that this device is intended as a last resort and not a primary safety system. Since the device takes up an extremely small amount of space, it is included to maximize the use of the life support resources in the submarine.

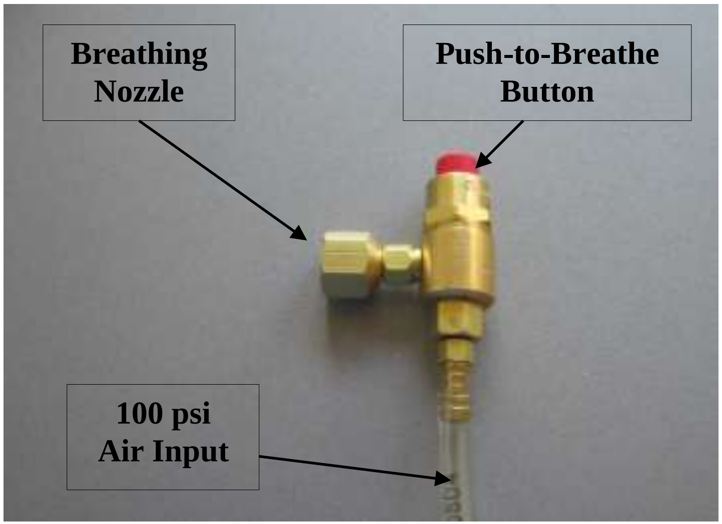

Figure 24. "3rd Chance Air" device

c) Hatch Release

The hatch release is accessible to both the pilot and safety divers. The hatch consists of the top, forward section (nose) of the hull. It is hinged at the top center of the hull and is latched in the very front center of the hull. A spring loaded pin is actuated to open and lock the hatch. Safety divers can open the hatch by pressing the release mechanism on the nose of the submarine. Once this is actuated the hatch's buoyancy will immediately open the hatch. The pilot releases the hatch by pulling a tether that is positioned within easy reach. Both the outside and inside release actuators are painted fluorescent orange.

d) Pilot Harness

When the pilot is pedaling the submarine, he needs as much support to push against as can be provided. This support is provided by the pilot harness (Figure 25).

Figure 25. The pilot restraint harness system.

This harness was designed with the safety of the pilot in mind. The harness uses a modified drum harness (donated by the Virginia Tech Marching Band) which is permanently secured to the pilot during racing. The harness itself is attached to the hull of the boat via a quick release mechanism. For pilot ingress and egress, the pilot simply slides the harness into the slot to lock him in place and pulls on the large orange release handle to remove the release pin. The release handle is marked in safety colors and is easily accessible to safety divers. If the pilot needs to be removed from the submarine by other means, the straps can be loosened from around the pilot and he can come directly out.

The harness system is highly adjustable, permitting the change in angle at which the pilot is positioned, the height the pilot is from the bottom of the hull, as well as the distance the pilot is from the gear box. This allows team members of various sizes to pilot the boat and allows the pilot to be positioned in the boat in a manner that maximizes power output and comfort.

e) Integrated Safety Features

Every aspect of the submarine's design has been approached with safety as a primary constraint. This approach has resulted in boat that has several safety features integral to the hull itself. The use of large area windows on both the top and bottom of the hull accomplishes two things. First, adequate visibility for the pilot is important so that the pilot has the best chance of avoiding obstacles. Second, windows on the top of the boat allow safety divers to clearly see the diver's head and shoulders so they can see the condition of the pilot. Perhaps one of the most serious safety concerns, which is often overlooked, is the potential for expelled scuba air to become trapped inside the hull and cause a rapid ascent. This rapid ascent could cause the pilots ears and nasal passages to be seriously damaged if the pressure change is too quick to permit equalization. A rapid and unexpected ascent could also cause the submarine to strike divers or dangerous objects. To guard against this hazard, venting holes are located on the top of the hull, directly above the pilots head. Several holes are also locate on the nose of the submarine as an added precaution.

IV. Testing

A. Systems and Dynamic Testing

Upon completion of the spring semester, the Virginia Tech team typically conducts a week of testing to evaluate the success of their work throughout the semester. Testing is conceivably the most important part of the entire design process as it sheds light on the designs that worked well and those that did not. It also provides the team with an opportunity to gain experience working together underwater and outside of the laboratory.

Testing consists of two subdivisions: systems testing and dynamic testing. The bulk of the testing will be conducted after the writing of this report, so specifics cannot be addressed here. In general, those systems going in Phantom 5 must first be tested to ensure their functionality and robustness. For instance, the waterproof boxes that will house the computer, batteries, and pilot display must be pressure tested by sinking them to the bottom of a pool. The electronics must also be working correctly out of the water, prior to installation in the submarine, so these must also be tested. If all systems are satisfactory, Phantom 5 will be assembled for dynamic testing.

In dynamic testing, the team has three main objectives: to ballast the submarine, make runs with the submarine to test all functions, and give some underwater experience to the pilot and support divers.

V. Training

A. Pilots

While HPS is more of an engineering competition, speed is the ultimate goal of every team that comes to Carderock. The top speeds at competition get faster every year and world records continue to fall. Although most of these advancements can be attributed to engineering, there is still a human inside providing all the power. This makes pilot training an important factor for a team's success.

Working with biomechanics professors at Virginia Tech, the team has learned how to train its pilots for the submarine races. While propelling a submarine, a pilot is pedaling at relatively low RPM (less than 75 RPM). On land, a bicyclist typically pedals 100 RPM. To properly train for this difference, a pilot should exercise by pedaling at very low RPM but high torque. Mountain biking, especially riding uphill, simulates this activity perfectly. It should be mentioned that the submarine races are sprint events. A mountain biker often sees a similar situation as he is riding relatively easily but is then faced with an uphill climb. This is essentially a sprint in that the biker is putting all his energy into the climb. To improve endurance, road biking is a good complement to the pilot training program.

B. Support Divers

Just as one must train to be a pilot, one must also train for to be a support diver. Diving is a skill that must be practiced for one to feel comfortable underwater. This becomes even more important when a diver must handle a submarine and provide support to the pilot. Approximately half of the Virginia Tech team took the submarine to Weeki Wachee, Florida to get some dive time and work on the submarine. This experience allowed them to brush up on their dive skills as well as practice the essential art of underwater communication. Equally important, was the experience gained working with the submarine in the water to perfect and practice various procedures. This trip was essential to prepare our support divers to operate effectively as a team and to provide the greatest level of safety to the pilot.

VI. Project Summary

A. Overview

The Virginia Tech Human-Powered Submarine Team entry for ISR 9 is Phantom 5. Phantom 5 is the fifth in a line of one-person, propeller-driven submarines that the team has constructed since its establishment in 1993. This is the third year that the Phantom 5 hull will be used and it is unique in many ways. Phantom 5 is controlled by a pair of servos used to actuate a vectored thrust system – a first ever for human-powered submarines. This system results in a highly controllable submarine with less drag than conventionally controlled designs. The pilot can also choose to use automatic depth and directional control while making runs, which effectively makes the submarine an autonomous vehicle and aids the pilot in reducing his workload. In addition, Phantom 5 utilizes a computer controlled, dynamically variable pitch propeller system – another first for human-powered submarines. The use of pneumatic safety systems and pilot restraint serves to make the new submarine the safest and easiest to pilot submarine to date.

B. Budget

The Virginia Tech team works very hard year-round both on the submarine itself and to secure funding and sponsorships to help pay for the project. To realize all of their objectives requires the support of many generous sponsors. It is only through material and monetary sponsorship that the VT-HPS team can function. Support comes mainly in the form of material donations from companies, some monetary donations from companies, monetary donations from several Virginia Tech engineering departments and monetary and material support from individuals. The budget shown below represents mainly the monetary value of materials donated. To pay for competition based costs, such as hotel stay and travel, monetary donations are used.

Table 3. Budget

Crew	Budget
Hull – fiberglass, resin epoxies, vacuum bagging materials, foam, female mold, hull fittings, hardware	$6,000.00
Electronics & Controls – pneumatics, hose lines, hardware, cables, control rods, fins, RTV mold materials, joystick controls	$4,000.00
Propulsion – gears, metals, hardware, bearings, shafts, propeller blades	$3,000.00
Life Support and Safety – scuba gear maintenance, Launch and Recovery Vehicle materials, Pilot Emergency beacon, harness	$2,000.00
Competition – entry fees, transportation, lodging, food	$7,700.00
TOTAL	$22,700.00
Material Sponsorship	$17,000.00
Monetary Sponsorship	$10,000.00

VII. Conclusion

A. Analysis of Design

By carefully integrating the various systems, the team was able to produce a more functional submarine with new, advanced systems. New technologies have created a more streamlined fabrication process and more intuitive pilot/submarine interaction.

a) Hull

The hydrostatics of Phantom 5 should allow for the fastest Phantom submarine yet. By using a linear gear box, the internal volume and surface area was greatly reduced from previous submarines and a more hydrodynamic shape resulted.

The development of the pilot hatch and rear hatch as separate and removable components has greatly aided in the construction and assembly of the rest of the systems within the hull and will be indispensable when working on the submarine at competition. Using a hinge on the pilot hatch will also allow for easier ingress of the pilot and will aid the support divers when inserting the pilot.

b) Propulsion

The weight of the gearbox was a major issue since we were no longer using a pressurized gear box. However, a computer box, which is very buoyant has been placed directly under the gear box and will offset a lot of the gear box's weight. Foam was also inserted into the hull to counteract this weight. The linear dive should result in good pilot comfort and performance.

c) Controls

The electronically controlled vectored thrust and variable pitch propeller system should result in the most effective and advanced system ever used in a human-powered submarine. Due to the low power output of human pilots, this power must be harnessed as efficiently and effectively as possible to allow the submarine to achieve high speeds in short distances. The electronic servo control system allows the submarine to do this. The system also lowers pilot workload and allows him to provide as much power as possible, and the autonomous capability should send the submarine straight down the course more effectively than a pilot ever could.