

**PHANTOM 6**  
**TECHNICAL REPORT**



**VIRGINIA POLYTECHNIC INSTITUTE  
AND STATE UNIVERSITY**

**HUMAN POWERED SUBMARINE DESIGN TEAM**

**13<sup>TH</sup> INTERNATIONAL SUBMARINE RACES**

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## 1. Abstract

The following report details the conceptual design, development, fabrication and testing of Phantom 6, Virginia Tech Human Powered Submarine Team's (VTHPS) second newest submarine. Research and development regarding the decision for the side-by-side two pilot configuration was vital, since such a design had never before been constructed. Each major system plays a vital role in achieving the goal of maximum speed, while also providing for pilot safety. Phantom 6 features two systems of extreme innovation. The dual linear drive system decreases the cross-sectional area of the submarine and allows the pilots to combine their outputs through the differential. The advanced electronics system provides the pilots with a heads-up display (HUD) while allowing for data acquisition. Phantom 6 is the second most advanced submarine VTHPS has developed in its history, continuing the innovative spirit that has driven the team since its beginning.

This innovative spirit helped the team to take home First Place in Innovation at the 12<sup>th</sup> International Submarine Races despite not recording a speed during competition. However, because of this fact the team is able to return to the 13<sup>th</sup> International Submarine Races and compete with Phantom 6 for a second time along with her younger sister Phantom 7. Phantom 6 proved to be a great test platform for electronics integration and innovation and has helped to spawn the major improvements shown in Phantom 7, including variable pitch and autonomous control system. The goal for Phantom 6 at this competition is to set a new record speed for two-person propeller driven submarines.



Figure 1: Phantom 6 at ISR 12

## 2. Conceptual Design

Following the success of Phantom 5 and its innovative linear drive system, development began for Phantom 6. It became clear that the linear drive system had to be included as a major feature of the propulsion system. With this in mind, the team began to develop hull designs. It was decided that a two person concept was both challenging and provided room for innovation. The two hull forms that came out of the conceptual design phase were dubbed Orion and Typhoon.

The Orion hull form featured a long, slender hull that past submarine designs have utilized. This hull form features a small cross-sectional area to reduce drag. The design called for a pilot to control the submarine, and a propulsor, whose primary function would be to pedal. With the linear drive system, the sleek design of the Orion hull form could mimic that of Phantom 5. However, the overall length of the hull form was predicted to be difficult to handle and transport. In addition, the conceptual design showed that the safety system would be difficult to create. With this in mind, the Orion hull form was discarded in favor of the Typhoon.

The Typhoon hull form featured a much wider cross sectional area, while having a smaller length than the Orion hull. The major advantage that the Typhoon hull offered was the ability to couple two drive systems, one per pilot. While the cross sectional area is larger and increases the drag on the submarine, the power output allowed by a coupled drive system could overcome the increase, and allow for a two person submarine capable of achieving higher speeds than the others in its category.

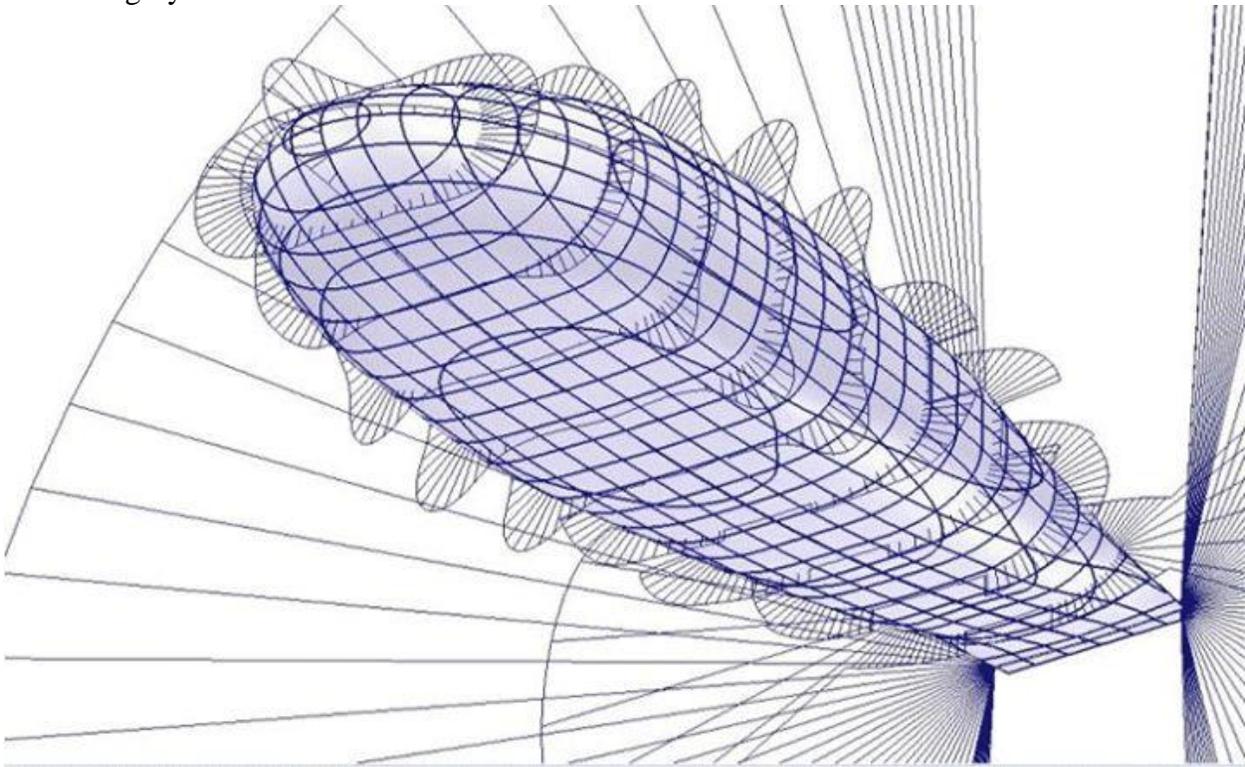


Figure 2: Phantom 6 Hull Form Conceptual Design

Phantom 6 also featured an electronics system at the ISR 12. This system was capable of logging and displaying in real time data such as speed, depth, pitch, yaw, roll, RPM, and battery life to the pilot via electronic displays. Due to the need for components in Phantom 7 the

electronics system in Phantom 6 has been removed, but the apparatus is still available and could be implemented back into the submarine if desired. As such, the report included a description of the electronics system before its removal.

The linear drive system mentioned previously had to be reimagined for the side-by-side configuration of Phantom 6. The team desired for each pilot to be able to move the submarine individually and have the power allocated to both propellers equally. As such, Phantom 6 features a summing differential to take the two pilot inputs and output them as one motion. This one output is then transferred aft to a shaft that will rotate each propeller equally and thus effectively reach the original goal set out by the team. Further details will be described in the Propulsion section of Phantom 6 below.



### **3. Phantom 6**

#### **3.1. Hull**

##### **3.1.1. Design**

As mentioned previously, Phantom 6 is a Typhoon class of submarine featuring a side-by-side pilot configuration. Design of the hull featured the use of computer programs as seen in Figure 2: Phantom 6 Hull Form Conceptual Design Figure 2. This hull was designed and sized to be consistent with previous Phantom models and to take into account the new ergonomic issues from the new pilot configuration. In final production the submarine is essentially slightly longer than a conventional one person due to the more complex gear box system and the overall beam of the ship is about equivalent to twice the beam of a one person submarine. The height of the submarine remains the same as a one person submarine.

##### **3.1.2. Construction**

The process of taking a concept design from a computer to a practical submarine hull is a long and complex process. The process begins by creating a submarine design using Autodesk Inventor. Once the design meets the requirements that are set for the submarine, the design is sent out to a company that will take the design and create a foam mold of the hull. Foam is chosen for the mold as it is easy to shape into the proper hull form.

Once the foam mold is returned back to the team, the mold is covered in fiberglass to create a rigid hull form. The fiberglass is a substance that is easy to apply and very sturdy. The foam mold is completely covered with fiberglass to create a full rigid hull. The hull is then sanded with a low density filler to create smooth finish on the submarine hull. The hull is then coated with a layer of wax to ensure further smoothness of the hull.

After the hull is smoothed out, the glass, peel ply and vacuum bags and vacuum tape are cut to shape the submarine and remove the portions of the hull that are not needed. Once all this has been removed, lay ups are performed and the vacuums are run for one day to complete the first layer of fiber glassing. This process is repeated for an additional layer of fiberglass, with layers of foam in the top half of the submarine. In areas that are predicted to need more structural support, such as the areas of discontinuity near the hatches, the hull is also reinforced with carbon fiber.

##### **3.1.3. Fairing and Painting**

Following the final layers of composites the low density filler is again applied to the submarine's outer hull. This is to remove any imperfections caused in the manufacturing process. Various grades of sandpaper and electric sanders are used to obtain the smoothest possible surface finish. Following the sanding process the submarine was taken to a local body work shop for painting. The paint used was intentionally chosen for stronger damage resistance and a smoother finish once the clear coat was applied. Finally, vinyl stickers were printed and placed on the submarine to alert support divers to pilot release locations and various no step or life support systems.

##### **3.1.4. Viewports**

In order to manufacture submarine windows for Phantom 6, 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.

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.

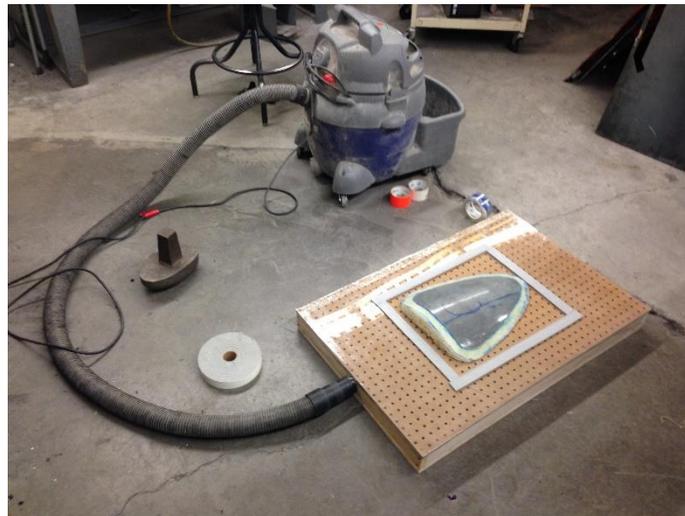


Figure 3: Vacuum Former System (Platum, Form, Vacuum)

## 3.2. Propulsion

The propulsion system of Phantom 6 is a highly innovative concept due to the new hull form. It features a complex system of gear and bearings to take the pilot's inputs as a total and output to the propellers equally.

### 3.2.1. Power Divider

Phantom 6's new power divider is functionally identical, but still an improvement to the previously used system at ISR 12. It still receives power via chain from the differential and splits it to the two propellers, turning 90 degrees with bevel gears. Instead of the original six pillars with press-fit bearings, the new "tray" mounting system has several distinct advantages.

1. All bearings are co-planar
2. Improved ability to align bearings
3. New bearings that move smoothly
4. Entirely bolted connections
5. Entire assembly can be removed

These improvements fall into two categories, efficiency and maintainability. The previous power divider did not have the bevel gears properly aligned, so it was noisy and vibrated which are both losses of energy. By constraining everything to the same plane and having the ability to adjust the bearings on the plane, these losses are minimized. With the new bolted connections, a hammer is no longer required to remove the driveshaft. While eliminating the cumulative damage incurred by this method of disassembly, it is also more convenient to work on specific components of the power divider without having to systematically disassemble the entire structure. This subtle change to the driveline of Phantom 6 greatly improves the usefulness of the drive.

### 3.2.2. Gear Box and Shafting

Phantom 6's drive train is one of the most innovative aspects of her design. With the success of the linear drive system from Phantom 5, the design called for a coupled system. This system would allow for both pilots to pedal simultaneously, and would potentially double the power output achieved by earlier subs. The gearbox from Phantom 5's drive system was adopted for Phantom 6, with changes only made to the gear configuration to allow input to the differential, discussed below. This familiar design allowed the team to easily fabricate the new gearboxes, and even use parts from Phantom 5 for a timely completion or for spares. Other minor changes to the gearbox were made to reduce weight, such as removing excess material from the bevel gears. The gearbox components were fabricated in the Virginia Tech Ware Lab by student team members, purchased online (in the case of the gears themselves) or professionally machined by the Department of Aerospace and Ocean machine shop.

The next, and arguably the most important aspect, of the entire power transmission system is the summing differential. This assembly allows for the power output from each gearbox to be combined and turn a common sprocket. Through use of a chain, this rotation is then translated to the aft section of the drive system, providing the same input into each propeller shaft. The differential therefore allows the pilots to pedal at different speeds, while maintaining an equal angular velocity, which prevents yaw problems that would exist should the system not be coupled through the differential. The drive system also forces the propeller shafts to counter-rotate, eliminating the roll moment produced by the torque reaction of a single shaft, which was a



prevailing issue for Phantom 5.

One concept newly implemented on Phantom 6 is the addition of a maintenance hatch. This hatch is attached via screws, and is located towards the stern of the submarine. While the hatch will never be opened during a race, it does allow for easy access to the entire propulsion system, and the aft section of the controls system for construction & maintenance purposes. This eliminates the need for two halves of the submarine to be completely separate, and allows team members to work easily and closely with the systems. This hatch also contains much of the added foam in the stern that is needed for buoyancy due to the weight of the gearboxes.

### **3.2.3. Propellers**

The propellers for Phantom 6 integrate a variable pitch system that is controllable by the copilot while the sub is moving. The copilot progressively releases a lever inside the cockpit to add more pitch. A cable running from the lever through the hollow propeller shafts actuates two pairs of cams in the propeller hubs. The final shape of the propeller hubs accommodates the spacing requirements for these cams while maintaining the smallest possible size and weight. The small size of the hubs and their interior slots for the propeller blade cams posed significant challenges for fabrication. The best choice for structural integrity, surface finish, and cost effectiveness was to have the propeller hubs sintered by ExOne using a blend of 316 steel and bronze.

The propeller blades themselves proved to be difficult to produce. Their twisted shape would have required that they be milled on a 4 axis mill, which for a set of 4 blades would have cost an estimated \$4000. To reduce cost and lead time, the team developed a working relationship with the Kroehling Advanced Materials Foundry in Blacksburg, Virginia, to have the propeller blades cast. This foundry is a new addition to the Virginia Tech campus. Students from the team made bonded sand molds on site, using an FDM pattern. Eight blades were successfully cast from aluminum 390, with 7 percent silicon added for increased stiffness. Overall weight per blade is 0.13-lb., and each measures 8.5 x 1.8 inches. Maximum thickness is 0.2 inches.

### **3.2.4. Improvements**

The propeller hubs for Phantom Six underwent a significant redesign to meet the new design requirements. The new hubs no longer needed the ability to interface with a variable pitch prop system, so the goals of the redesign were to create simple, cheap, easily manufactured hubs that allowed for the blades to be adjusted with minimal work. The solution was to have two Starboard circles sandwich the propeller blades, with the existing propeller cones on either side. The new design saves weight from the previous design and it is also machineable, which the original propeller hubs were not. The free spinning feature was also eliminated, to ensure the propeller blades remained in synchronization and reduce complexity. The end result is a simple, cheap, and functional propeller hub that is well suited for a down-to-the-basics submarine with a focus on maintainability.

As mentioned above, the variable pitch system was eliminated from Phantom 6 for a variety of reasons. The content above however remained in the report to showcase the capability that was originally planned for the submarine. Aside from this change, the only major improvement to the system was the reconstruction of the bearing support system described above.

### 3.3. Electronics

The electronics team's responsibility is to provide real-time sensor data for the pilots as well as store the data for system performance analysis. The following electronics section breaks down the design of the hardware and software system, and analyzes the performance of the current implemented system. The pilots developed the requirements for the electronics system since the system was created in order to provide them with accurate data about the vehicle and its environment.

- The vehicle must provide the pilot with roll, pitch, and yaw angles
- The vehicle must provide the pilot with the depth in feet and vehicle speed using a static and dynamic pressure reading
- Measure the RPM of each propeller
- The pilots must provide input with a waterproof button
- Log sensor data to microSD card
- Display sensor data with an onboard LCD and 7-segment displays

Software System:

- Languages: C++
- Compiler: MPIDE
- External Storage: Sparkfun Logomatic = 2 GB microSD card
- Microcontroller: Digilent chipKIT Max32 Microchip® PIC32MX795F512 (Arduino Compatible)

The electrical system is shown in Figure 4.

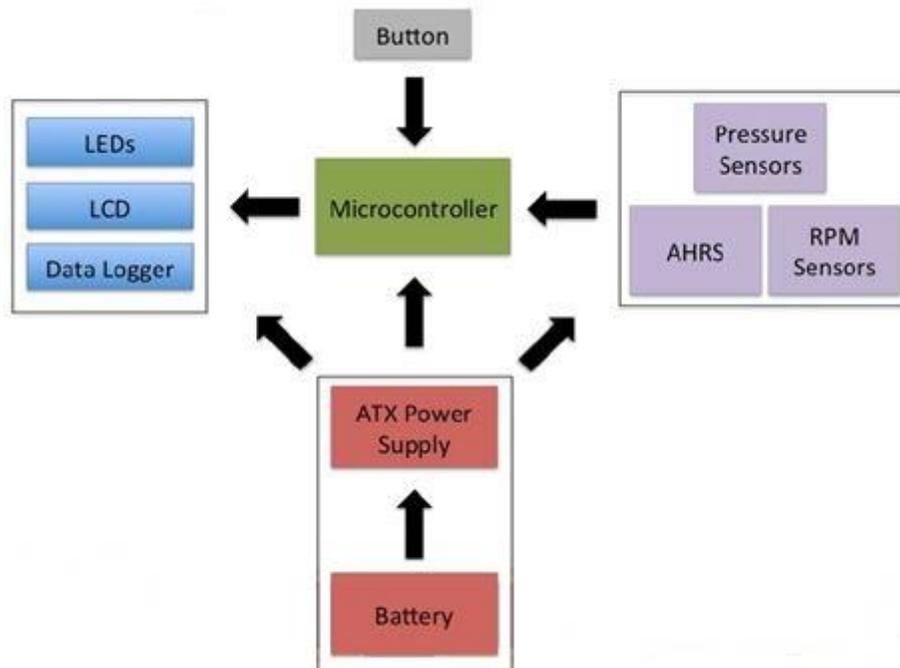


Figure 4: Electrical Integration Diagram

The red boxes that say “Battery” and “ATX Power Supply” depict the power system for the vehicle. The ATX Power supply is a DC to DC converter which takes the input battery voltage and converts it into a voltage that the sensors, displays, and microcontroller can utilize.

The purple boxes that say “AHRS”, “RPM Sensors”, and “Pressure Sensors” represent the various onboard sensors. AHRS stands for Attitude and Heading Reference System and is used to obtain the roll, pitch, and yaw of the vehicle. The RPM sensors are used to determine the RPM of each propeller. The pressure sensors are used to determine the vehicles depth and speed.

The green box is the microcontroller, which is the chipKIT Max32. The microcontroller receives data from sensors and displays it for the pilots.

The gray box is the button that allows the pilots to interface with the onboard displays.

The blue boxes represent the onboard displays and data logger.

The spreadsheet below shows the power budget for each component and was used when selecting a battery and power supply.

Table 1: Electronics System Characteristics

| <b>Quantity</b> | <b>Device Name</b>         | <b>Current (mA)</b> | <b>Voltage (Volts)</b> | <b>Power (mW)</b> |
|-----------------|----------------------------|---------------------|------------------------|-------------------|
| 1               | Data Logger                | 90                  | 5                      | 0.45              |
| 1               | chipKIT Max32              | 90                  | 5                      | 0.45              |
| 2               | Pressure Sensors           | 600                 | 12                     | 7.20              |
| 2               | Hall Effect sensors        | 18                  | 3.3                    | 0.06              |
| 2               | 7-Segment Display (LED)    | 1200                | 9                      | 10.80             |
| 1               | Crystalfontz Display (LCD) | 600                 | 5                      | 3.00              |
| 1               | CHR6DM (AHRS)              | 400                 | 5                      | 2.00              |
| <b>10</b>       | <b>Total:</b>              | <b>2998</b>         |                        | <b>23.96</b>      |

Since the vehicle needed to run for at least an hour on one charge, the battery that was chosen to power the onboard electronics was the NiMH 16.8V Battery Pack with 4.2Ah (55Wh).

$$\frac{4.2Ah}{2.998A} = 1.4 \text{ hours}$$

This means that the battery can supply the proper power to each device for over an hour. In order to supply the proper DC voltages to each device we chose to use a 12-25V input pico ATX power supply. This power supply contains 3.3V, 5V, and 12V rails, which were essential for the onboard devices.



Figure 5: Logomatic Serial SD Datalogger

### 3.3.1. Digilent chipKIT Max32 Development Board

When choosing which microcontroller to use it was between a BeagleBone and a chipKIT Max32. The microcontroller needed to collect, store, and display sensor data with I/O pins and serial ports. The decision matrix in Table 2 was created to compare the features of the chipKIT Max32 and the BeagleBone.

Table 2: Decision Matrix for chipKIT versus BeagleBone

| DecisionMatrix:<br>Microcontroller<br>Interface |                                 |               |   | <i>BeagleBone</i> | <i>chipKIT</i> |
|---|---------------------------------|---------------|---|-------------------|----------------|
| <b>CRITERIA</b>                                 | <b>Mandatory<br/>(Y=1/N=0)?</b> | <b>Weight</b> | <b>SCALE</b>                                  |                   |                |
| <b>Cost</b>                                     | 0                               | 10            | 3= Least<br>Expensive<br>1= Most<br>Expensive | 3                 | 2              |
| <b>Risk</b>                                     | 0                               | 10            | 3= Lowest<br>1=Highest                        | 3                 | 2              |
| <b>Power/Speed</b>                              | 0                               | 10            | 3= Most<br>Efficient<br>1=Least<br>Efficient  | 2                 | 3              |
| <b>I/O pins</b>                                 | 0                               | 20            | 3= Most Pins<br>1= Least Pins                 | 2                 | 3              |
| <b>Ease of<br/>Implementation</b>               | 0                               | 30            | 3= High<br>1=Low                              | 2                 | 3              |
| <b>Weight/Size</b>                              | 1                               | 20            | 3= Smallest<br>1= Biggest                     | 2                 | 3              |
| <b>WEIGHTED<br/>TOTALS in %</b>                 |                                 | <b>100%</b>   | <b>3</b>                                      | <b>73.30%</b>     | <b>93.30%</b>  |

From the decision matrix in Figure 2.3, it can clearly be seen that the chipKIT Max32 outclassed the BeagleBone in almost every category. The chipKIT Max32 earned a score of 93.3% while the BeagleBone earned only a 73.3% based on our criteria. Thus, the chipKIT Max32 was used for Phantom 6.

The chipKIT Max32 is compatible with the Arduino development platform, therefore, this microcontroller has the same functionality as an Arduino. The Arduino development platform was considered because it is easy to implement for beginners, is small and compact, and has low power consumption with high processing speed.

The features of this device are listed below:



- PIC32MX795F512L processor
- 512K Flash, 128K RAM
- Up to 80MHz operating speed
- 83 available I/O lines
- USB or externally powered
- 5 External Interrupt pins
- 4 Serial Ports



Figure 6: 2.4 chipKIT Max32

### 3.3.2. Calibrate Microcontroller's ADC:

The chipKIT Max32's ADC had to be calibrated because the voltage reading wasn't accurate when a known DC power supply was wired to the input of the ADC. This was a very important calibration because it would assure the microcontroller would read the various onboard sensors properly. Since the pressure sensors provide a change in output every inch in water, the ADC had to be very accurate or the depth reading would be skewed. To calibrate the chipKIT Max32, a known voltage from a DC power supply was used to compare it to the voltage that the chipKIT Max32 outputted. Using these data points, a trend line was created that would correct the chipKIT Max32's ADC error. The trend line plot can be seen below in Figure 7

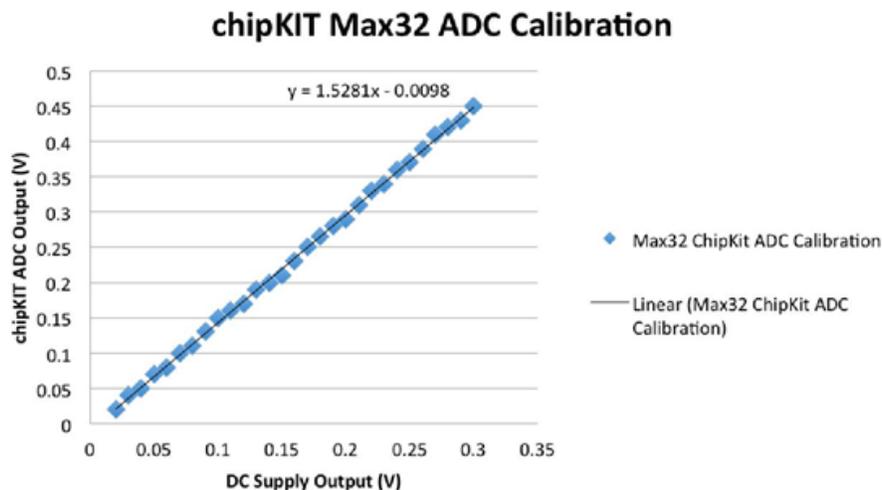


Figure 7: Trend Line for chipKIT Max32 ADC

### 3.3.3. Pressure Sensor



The pressure sensors that were used to calculate depth and vehicle speed were the PRECISELINE models donated by Keller America. These sensors provide an analog voltage from 0 to 5V and were mounted to the vehicle using the threaded end of the sensor.



Figure 8: Keller America Pressure Sensors

Two sensors were needed to calculate the vehicle speed. One pressure sensor was placed at the nose of the vehicle to obtain the dynamic pressure and another sensor was placed in the vehicle to obtain the static pressure. To obtain an accurate correlation between a voltage reading and the actual depth, the pressure sensors had to be calibrated.

#### 3.3.4. Calibrating Pressure Sensors:

To make sure that the depth readings were accurate within an inch, the pressure sensor had to be calibrated. The depth sensor was originally calibrated at the manufacturer's location, which was at a different elevation, making the voltage output of the sensor different than the specified datasheet output. Because of all these factors, it was deemed necessary to recalibrate the sensor, as well as, reprogram them for different voltage ranges. In order to calibrate the depth sensor, the voltage at every inch was documented from the surface to the bottom of the pool. After collecting the appropriate data, a trend line was set that accurately converted voltage to depth in inches. The trend line plot can be seen below in Figure 9.

## Depth Sensor Voltage Calibration

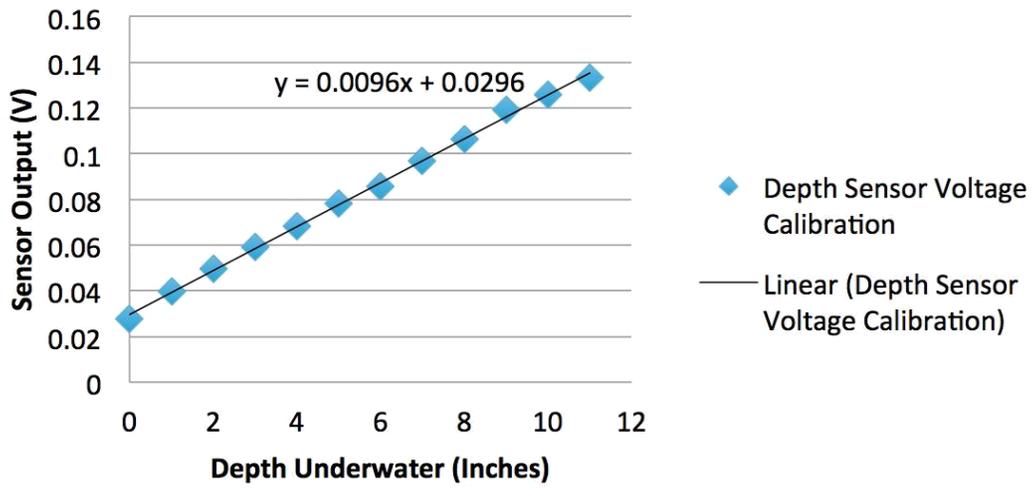


Figure 9: Trend Line for Depth Voltage

Keller America provided the software and hardware to reprogram the pressure sensor in order to change the output voltage range. The pressure sensors were reprogrammed to output 0 to 5 volts at 0 to 26 feet, respectively. Figure 10 shows the calibration software which allows the user to set a desired pressure range and voltage output.

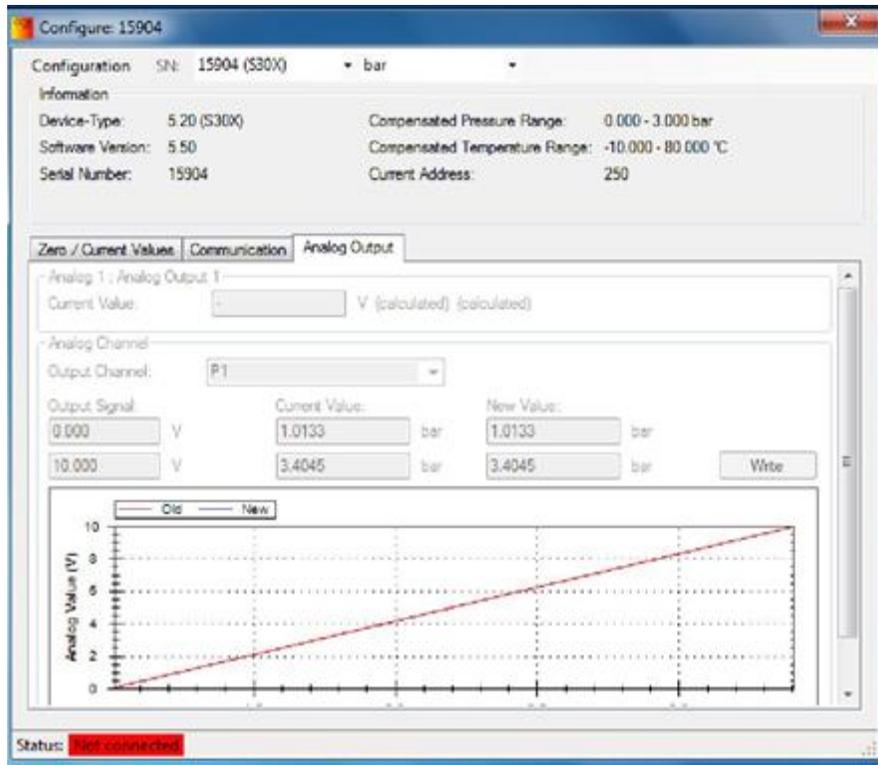


Figure 10: Pressure Sensor Calibration Software

### 3.3.5. 7-Segment Displays

Two SURE Electronics 1.8" Character Height 7-Segment LED Information Boards were used to display speed and depth to the pilots. The LED boards were secured in OtterBoxes directly in front of the pilots for easy viewing. The displays are supplied with 5V and communicate with the chipKIT Max32 via SPI protocol.

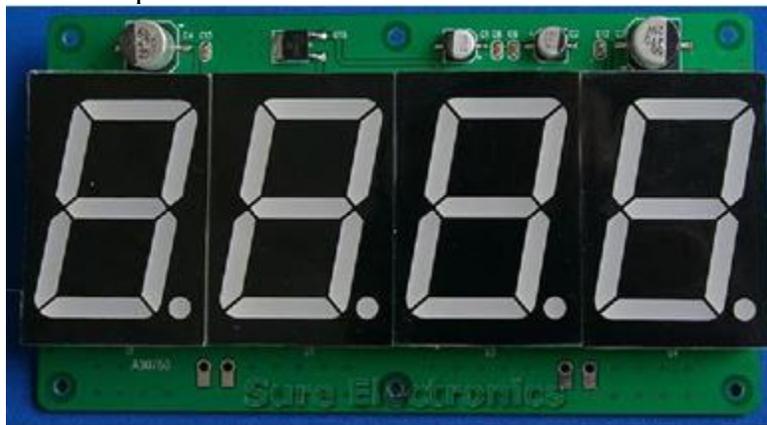


Figure 11: 7-Segment LED Board

### 3.3.6. Attitude and Heading Reference System (AHRS)

To measure the roll, pitch, and yaw of the vehicle the CHR-6DM from CH Robotics was chosen. This Attitude and Heading Reference System combines three gyro axes, three accelerometer axes, three magnetic compass axes, and a 32-bit ARM Cortex. A Kalman Filter is

applied onboard to combine the inputs from each sensor and calculate a roll, pitch, and yaw. The AHRS communicates the heading values through a serial interface at 300 samples per second. Figure 12 shows the CHR-6DM board.

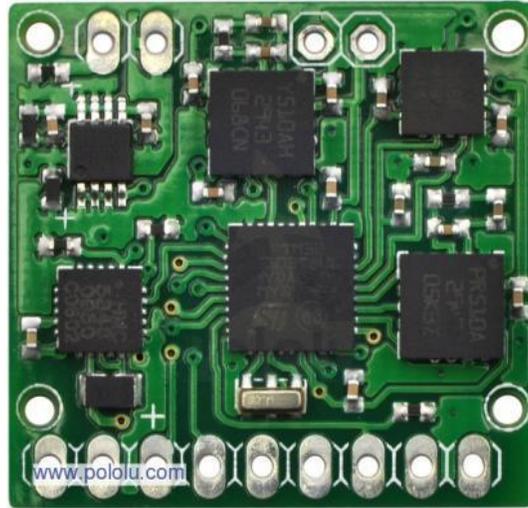


Figure 12: CH Robotics CHR-6DM

### 3.3.7. 20x4 Characters LCD

The LCD, which is located between both pilots, displays the current roll, pitch, yaw, battery voltage, speed, depth, and RPM. The display is powered with a 5V rail from the power supply and data is sent to the display through the chipKIT Max32's serial port.



Figure 13: Crystalfontz LCD Screen

### 3.3.8. Hall Effect RPM Sensor

To measure the speed of each propeller, a Hall Effect sensor was mounted next to each propeller shaft. The Hall Effect sensor is powered with 3.3V and has an analog voltage output pin. Since the analog output pin goes high as individual grooves on a gear go past the sensor, a circular piece of starboard with four screws attached evenly around it was attached to the propeller shaft for the sensor to detect the speed of each propeller. The output pin of each Hall Effect sensor is attached to the chipKIT Max32's interrupt pins. Every time the Hall Effect sensor detects a screw passing, it interrupts the microcontroller to enter a subroutine that updates the current RPM value.



Figure 14: Hall Effect Sensor

### 3.4. Controls

The control system for Phantom 6 is designed to effectively correct the submarine's attitude and depth while travelling along the course. It is based on previous Phantom models and integrated to be applicable for the new Typhoon class hull.

#### 3.4.1. Design

The controls for Phantom 6 were designed to be NACA 0012 airfoil shapes. The control surfaces are a 0012 for the length of the surface while the stabilizers are a 0012 shape tapered from a chord of around 8 inches to a chord of 3 inches. These were chosen to have a neutral lift component when held at 0° angle of attack. The controlling system was designed to utilize a series of cables with tensioners and a joystick utilized by the port pilot. Variable pitch was to be controlled by the starboard pilot.

#### 3.4.2. Manufacturing

The control systems on Phantom 6 contain multiple engineering achievements that help to provide the pilot and copilot have as much freedom as possible. The primary control system is comprised of the four sets of stabilizer fins and control fins attached to the aft of the submarine, two sets on the port and starboard sides as well as two dorsal sets. These fins were designed by shaping wooden molds into appropriate airfoil shapes and then pouring performance plastic into the molds. While solidifying in the molds, metal rods were placed in to attach the fins to the hull. After hardening, the fins were removed and sanded down to a smoother texture.

The next step was to mix low density filler (LDF) with epoxy. This LDF mixture, the same mixture that was used later on to cover the entire hull, was then spread over the fins and sanded down multiple times to provide a smooth outer layer to the fins. From here, the stabilizer fins, which were designed not to move, were ready to be attached to the hull. To do so, metal hard-points were epoxied to the hull with hollow metal rods. The stabilizer fins were then able to simply slide into place and are locked down with pins or set screws, depending on their location.

To attach the control fins, which are designed to move based on the control stick held by the pilot, a system needed to be implemented such that the pitch and the yaw of the submarine would be equal from both sets of fins. Since Phantom 6 is such a large submarine with a large beam-to-height ratio, she has passive roll stability, meaning active roll control was deemed unnecessary. This means that the control fins need only be responsible for pitch and yaw. To provide pitch control, the port and starboard control fins are attached to a single hollow rod that runs across the entire beam at the aft of the sub. The fins are then set screwed in order to prevent independent movement. To attach the control fins to the control stick, metal bike cables are run down the length of the submarine and attached to two moment arms on the rod. When the control stick is pushed forward or pulled backward, it pulls on one of these bike cables, which rotate the rod using moment arms, thereby rotating the control fins to a positive or negative angle of attack, as necessary. To control the yaw, a similar system was used, but a rod could not be simply run directly through the height of the sub as it would intersect with the horizontal control rod. Therefore, a custom-designed C-piece is attached to both control fins that allows the fins to stay in place, but move the vertical rod around the horizontal rod. This C-piece also serves as the moment arm needed for the bike cables to move the vertical control fins.

The other control system that is unique to Phantom 6 is the active variable pitch control system. This system is designed to provide a similar experience to gears on a bike. To provide the most thrust possible at lower speeds, the propellers are at a lower pitch, which provides less thrust,

but also less resistance, thereby allowing the pilot and copilot to begin pedaling much faster. Once the propellers reach their optimal thrust, pedaling faster means more energy is wasted by the pilot and copilot. Therefore, the copilot has a lever which is attached to a bike cable, similar to the control system. This cable runs approximately two-thirds of the length of the sub, where it then attaches to a ring. This ring is connected to two bike cables that run to each propeller hub. As the lever is released, this then increases the pitch of the propellers. The ring is designed such that the single bike cable is able to change the pitch on both propellers equally. By changing the propeller pitch, the props begin to create more thrust. At this point, the pilot and copilot have already built up enough momentum to overcome the initial resistance. This means that the propellers are constantly providing the optimal thrust at each stage of the run.

Initially, it was thought that the pilot would be responsible for both control systems, but this was changed for two primary reasons. The first was to prevent the pilot from being overloaded with information. If the pilot were responsible for the variable pitch of the props and control of the sub's attitude while simultaneously pedaling as hard as possible, it would be too much for the pilot to handle, especially if the copilot's only responsibility would be to pedal. It also became apparent that it would be challenging to the variable pitch control into the dead-man switch. The only other options would then be to either place both systems in the same control stick, which would only add to the confusion of the pilot, or to provide two different control sticks for the pilot. This would mean the pilot would have to move back and forth from each system and not be capable of using both simultaneously. Again, this was found to be counter-intuitive if the copilot was only pedaling. Therefore, the final decision was for the pilot's left hand to hold the dead-man switch for the diver safety system and the pilot uses their right hand to move the control stick for the control fins. The copilot then uses their left hand to move the variable pitch control stick while their right hand holds the copilot dead-man switch.

### **3.4.3. Improvements**

ISR 12 showed the team that the current control system left a lot to be desired in terms of range of motion. As such, the system was overhauled for ISR 13. The variable pitch mechanism was eliminated to reduce complexity of the system. The joystick and cabling was remanufactured and rerouted to provide a higher range of motion of the surfaces as well as to limit pilot interference. Further, the clamps that were used in the stern of the submarine were remanufactured through 3D printing. This allowed the team to include multiple attachment locations, particularly for the rudder, which could then alter the range of motion. Additionally, a spring was placed on the elevator controls to return the system naturally to a full starboard heading. This was done so that the pilot would need to actively use the joystick as opposed to relying on the system to maintain a direct course. While counterintuitive, the psychological impact of the necessity to actively use the joystick is intended to focus the port pilot's attention on heading for the length of the course and ensure a proper run. It was believed that reliance on a singular heading could potentially cause the port pilot to lose attention to the heading and thus cause a situation where the submarine left the course heading. The removal of the variable pitch allows the starboard pilot to fully focus on pedaling so the loss in power with the two changes should be negligible.

### **3.5. Life Support and Safety**

The diver safety system of Phantom 6 is an integrated system consisting of the buoy, release switches, hatch releases, harnesses, and the associated cables. The buoys, one for each pilot, are comprised of shaped insulation foam. This foam is very buoyant, allowing for quick ascension to the surface. The foam is covered in a layer of fiberglass, which adds structural stability so that the strobe light and latch could be attached. The latch is taken from a common doorknob assembly, which reduced construction time and cost. The “bolt” that secures the buoy in its place is made from lightweight plastic. This lightweight plastic, known as starboard, replaces metal for various components throughout the submarine in an effort to reduce weight without sacrificing structural rigidity. The housing for the bolt is constructed from the same plastic as well as aluminum. This provides a cheap, simple, and lightweight solution to a previous design that used the complex bolt and lock mechanism from the doorknob assembly.

The buoys are deployed by the pilots as they release a “dead man’s switch”. When released, the cable attached to the switch removes the bolt from the latch, and the buoys ascend to the surface, tethered to the submarine with high visibility string. This string can be easily re-spooled by use of a mechanism designed and built by the team that was inspired by a fishing reel. The dead man’s switch provides two distinct advantages. First, it is a form of passive safety, in that if the pilot should become unconscious underwater, their grip on the switch is released and support divers alerted. Second, each pilot has their own switch, enabling each to make a decision should either become uncomfortable or alert divers if one pilot is incapacitated without the knowledge of the other.

Accompanying the dead man’s switches are both internal and external hatch releases. The external release is clearly marked on the top of the submarine, and is activated by twisting the handle. The hatches that enclose the pilots are positively buoyant, and will clear the submarine so that the pilots can eject without interference. The internal hatch release sits forward of the pilot’s heads, and can be activated by either in case of an emergency.

#### **3.5.1. Dead Man Switch**

Originally the DMS was to be modified to accommodate a more comfortable system. However, due to difficulties in procuring the proper handles, the original DMS used during the 2013 competition was reinstated. The system involves two handles that expand via torsional springs. Attached to each handle is a set of bike cables and jackets. The cables were removed to allow for the new switches to be installed on the buoys. These have since been reinstated and the system tested for functionality.

#### **3.5.2. Buoy**



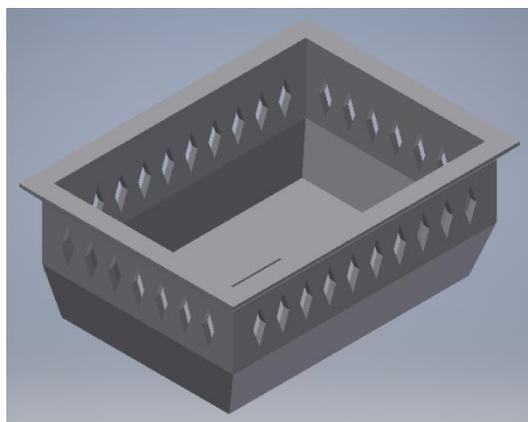


Figure 15: Buoy Pocket

The buoy pocket is pictured in Figure 15. 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 finger-sized switch that opens the release. When the string is pulled, the archery release loses contact with the buoy, and the buoy ejects.

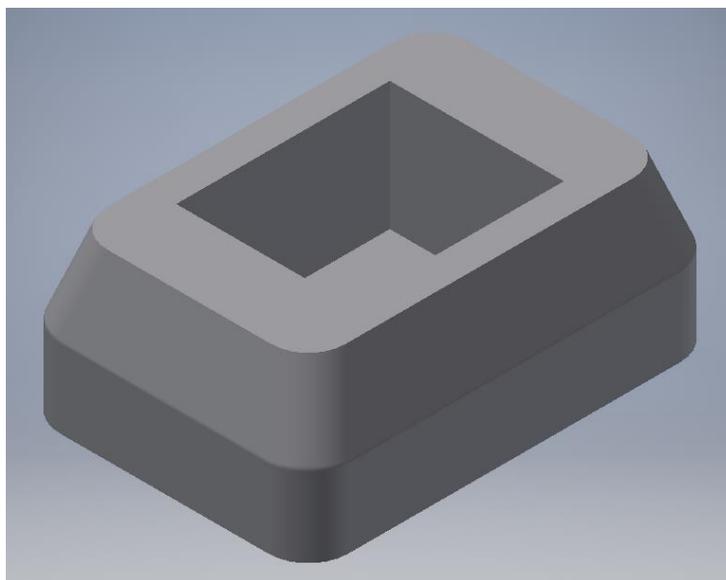


Figure 16: Buoy

Figure 16 shows the buoy itself. It was manufactured by gluing together foam board insulation and then CNC routing this conclusive piece. After this, the buoy was covered in

fiberglass and epoxied and allowed to cure. The fiberglass was sanded and voids were fixed with filler material. Finally, the buoy was spray-painted.

When the pilot releases the dead man's switch, consciously or unconsciously, the mayday buoy is released, alerting support and rescue divers. A mechanism is needed to hold the buoy securely to the hull until the dead man's switch is opened. Past designs have had problems with slipping (releasing the buoy prematurely) and sticking (not releasing the buoy when needed).

The design chosen consists of an archery release trigger mechanism enclosed in a housing attached to the inside of the hull directly underneath where the buoy sits. A hole was cut into the hull, and a plastic pocket was installed, to hold the buoy in place. Another plastic piece, which houses the trigger mechanism is secured in the bottom of the pocket. The buoy itself has a hollow bottom, fitting over the release caliper and housing. Through the hole in the bottom of the buoy is a .125" horizontal rod which aligns with the open caliper of the release. The release is able to slide up and down, allowing the force of the buoy being placed into the pocket to lock the trigger closed until the pilot releases it via the dead man's switch. The 30 feet of cord holding the buoy to the submarine is inside of the hole in the buoy.

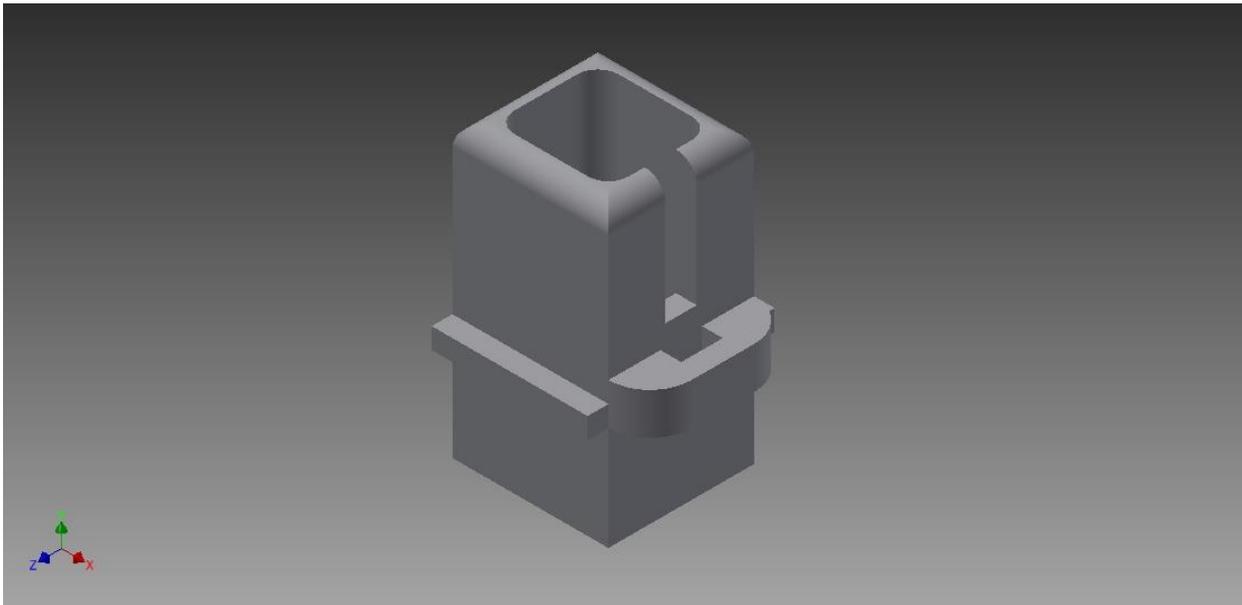


Figure 17: Housing Unit for Release Mechanism

### 3.5.3. Safety Light

Originally the lights were mounted onto the buoys themselves. However, the lights were less than reliable so we 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 cut into 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

In the design of the hatch release, it was decided that it would be best to make the hatches removable in order to better access the internal system. In order to facilitate this, standard stainless steel hinges were used, then the pins were knocked out with a hammer and chisel. These pins were then replaced with 4 x ¼ inch bolts and nuts, allowing the top and bottom sections of the hinge to be separated from each other, and thus detaching the hatch.

The final design consists of two hinges along each side of the submarine, approximately 5 inches apart, allowing the hinge's bolts to be removed easily and from the sides. Plastic starboard was used to distribute the forces acting on the hatch.

Due to an accidental over-milling of the submarine's sides, an additional piece of starboard was required to maintain hydrodynamics. This, along with the rest of the sub, will require repainting, not only to cover the bolts but also to fuse the bolts to the rest of the body. After this, it has been proposed to cover the gap with a flexible plastic gasket to preserve hydrodynamic properties.

### 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 can 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 18: Spare Air Tank Clamp

### **3.5.6. Harness**

The integrated harness system was designed to save space inside the submarine. Moving the tank directly underneath the pilots created more space underneath their legs, which in turn allowed for a more comfortable leg motion while pedaling. The other advantage of moving the tanks forward is the reduction of required hose length for regulators. This reduces the likelihood of snags on other aspects of the submarine or the pilots becoming tangled. The harness mount is made from starboard cut to fit a standard 40 cubic foot SCUBA tank made out of aluminum. Latches are placed on the three sets of starboard to attach the bottom and top halves. Along the top of the starboard there is an aluminum bar with T-slots used for adjustability of the harness location. The harness itself is made by laying up carbon fiber onto a standard marching snare drum brace. The harness is reinforced near the shoulders due to the high force placed by the pilot.

### **3.5.7. Ergonomics and SCUBA Integration**

As mentioned above the harness is adjustable so that the submarine can accommodate a range of heights for the pilots. The SCUBA tank is placed beneath the pilot under the harness and braced by the starboard. The first stage is placed underneath the pilot's face to eliminate the possibility of accidentally hitting the yoke off the valve. A short hose is used for the pressure gauge to decrease clutter underneath the pilot while a long hose is available on the second stage regulator. This allows for ease of entry into the submarine.

### **3.5.8. Improvements**

The improvements from ISR 12 to ISR to 13 are outlined above and consist of the dead man switch, buoy release, and hatch release. Both system description remain in the report (ISR 12 and ISR 13) to show the differences between the two system iterations.

## **4. Testing**

While finishing up the electronics installation and the hull surface finish, only a limited amount of testing could be performed for Phantom 6. As a result, the testing team prioritized test objectives necessary for each system, as well as overall objectives for the submarine. All testing was performed either in air at the Virginia Tech Ware Lab, or in water at Virginia Tech's War Memorial Pool.

### **4.1. Systems Testing**

#### **4.1.1. Propulsion**

In order to verify that the system could provide adequate thrust, it was necessary to observe the system both in air and in water. While an overall assessment of the system was performed in each case, there were three areas that were closely monitored.

The first was the gearbox itself. Careful attention was paid to the frictional resistance of the pedal shafts and bevel gears, along with gear alignment. In both the air and water cases, the gearbox seemed to function as intended, with no major issues. Small gear alignment changes were necessary to get the system to its optimum level.

The second aspect of the propulsion system analyzed during testing was the differential. This assembly is essentially the heart of the propulsion system, allowing for the summation of the two pilot inputs. Gear alignment within the differential is vital, along with no slippage on the input shafts from each gearbox. The differential performed adequately in air and underwater, with only one issue (a loose shaft) that was quickly corrected.

The third test if the propulsion system was the propellers themselves. In contrast to the other two systems, this test did not produce successful results, although it did reveal issues that are to be examined at a later date. The most prevalent of these is the pitch of the propeller blades. There was much discussion on the correct orientation of the blades in the hubs to produce the most amount of thrust. While not tested on the submarine, a mock propeller hub was fabricated and various pitch angles could be tested through use of this hub, a small connecting shaft and an electric drill, to provide necessary rotation. After noting the optimum pitch on this mock hub, the blades on the submarine were changed accordingly.

#### **4.1.2. Electronics**

Most of the electronics system testing was performed in air. These tests were mostly for functionality of the system, proving that sensors worked correctly and data was displayed in a readable form for the pilots. Waterproofing testing was conducted independently from the rest of the submarine, and was performed by leaving the containers at test depth (16ft) for a prolonged timeframe. Pressure testing was also performed by pressurizing a container with the electronics inside, to a local pressure of near 60 psi, well over the pressure limit that the system will encounter at competition

#### **4.1.3. Life Support and Safety**

The safety system is paramount for competition, to the point of disqualification should it not perform adequately. Therefore, it was necessary to closely analyze the testing of the system. The test was broken into two parts. The dead man's switch and buoy assembly was tested first. Both pilot and copilot assemblies were released while the submarine was submerged at 16 feet. Both systems proved to be successful as the buoys ascended quickly to the surface, without interference.

The second part of the test involved the pilot hatch releases. The twisting motion of the external release proved simple to operate and both hatches released without issue. The positive

buoyancy of both hatches was not as extreme as intended, but did provide a passive safety feature in that the hatches cleared the submarine and ascended to the surface, allowing for pilots to exit the submarine without interference. The internal hatch release was easily accessed from both pilot positions, and again the hatches ascended to the surface without issue.

#### **4.1.4 Controls**

Control testing was limited due to time constraints and the aforementioned problems with the propeller pitch. The team successfully demonstrated the response of the system both in air and in water by manipulating the joystick, but could not examine control authority in a dynamic environment. The variable pitch control could not be demonstrated due to issues with the propeller blades.

#### **4.2. Static Testing 2013**

The results of the 2013 static testing are described above.

#### **4.3. 12<sup>th</sup> International Submarine Races**

While at competition the team learned a great deal about Phantom 6. Several systems were remodeled in response to the results of ISR 12.

The hull at competition held up well. Buoyancy was easily compensated before and little changes were made. Of note: the drainage time was poor so new windows were created with a different mounting system allowing for drainage through the windows. Also, the hatches were essential in the buoyancy of the submarine and thus were permanently attached for ISR 13.

The propulsion system did not perform well at competition. This was mostly due to the set screws used on all shafts without keying. These changes were made for ISR 13 and the bearings that utilize set screws all have shafts that have been properly keyed.

The control system lacked range of motion and thus improvements were made to this area of the submarine.

The buoy release and dead man switch in general did not function as well as expected at competition and thus were redesigned for ISR 13.

The electronics system performed well in all testable areas at competition. The team's confidence in the system spurred the team to create an autonomous controls system for Phantom 7.

#### **4.4. Static Testing 2015**

Phantom 6 again went through pool testing in the spring of 2015. All systems performed as well as or better than expected. The buoy release mechanism released easily and efficiently. The only change made to this was the addition of a cable winding system for easily returning the buoy to the pocket.

The propulsion system performed well. The propellers were not attached during testing due to size limitations of the testing area, but as far as the team is concerned the keying of the shafts has removed all issues with the functionality of the gear box.

Hydrodynamic testing could again not be performed due to time and budget constraints.



The attached hatches worked better than expected. Closing the hatches underwater proved to require little force and the attachment points showed no signs of tearing or fracturing. The release system for the hatches on the exterior and interior both proved to be functional during testing. Attaching the hatches greatly reduced the issues previously seen with a significant loss of buoyancy that caused the breaking of windows at ISR 12.

## **5. Improvements Overview**

This section will provide a brief overview and description of changes implemented between ISR 12 and ISR 13. For a detailed explanation of each change please see section 3.

### **5.1. Hatches**

The hatches at ISR 12 proved to be essential to buoyancy. Thus, the fact that they were not attached to the hull meant that removal of the hatches caused the submarine to sink quickly. These were redesigned to be attached at the outermost beam of the submarine and to lift outwards from the centerline. This still allows for easy pilot ingress and egress and negates the buoyancy loss previously seen.

### **5.2. Viewports**

The windows in Phantom 6 were severely damaged at ISR 12. Thus, they were recreated by a new vacuum forming process the team began to use. In addition to manufacturing new windows, a new attachment system was designed to allow the windows to quickly be removed. The intention of this design is to allow the windows to be removed upon removal of the submarine from the water to facilitate quicker drainage time.

### **5.3. Propulsion System**

Shaft keying as well as new bearing support systems were installed in Phantom 6 to prevent issues experienced at ISR 12 that eventually led to the incompleteness of all test runs. The system is again fully functionally and expected to perform well during all dynamic situations.

### **5.4. Controls**

The control range of motion was improved and made adjustable by 3D printing manufacturing techniques and new design changes. The system now has a significantly larger range of motion in the rudder direction allowing for quicker course adjustments.

### **5.5. Life Support and Safety System**

The dead man switch and mayday buoy were reimagined and reconstructed to provide more reliable use. An archery release was added along with 3D printed and CNC machined buoy pockets and buoys. Static testing in air and water show that the system works effectively in all conditions and more reliably than previous installments.



## 6. Conclusion

In conclusion, Phantom 6 is a highly innovative submarine design that the Virginia Tech Human Powered Submarine Team has developed. Phantom 6 is a two pilot side-by-side design, which allows both pilots to input power into the dual linear drive system. This cutting-edge drivetrain allows each pilot to pedal individually while combining their power inputs. The combined power is transmitted down the drivetrain and outputted distributed equally to two counter rotating propeller shafts. The electronics system features a heads-up display that provides real time information to the pilots while during the race and allows for analysis later on. Although some aspects of the submarine remain untested and some areas could be improved, VTHPS believes that Phantom 6 will be successful in ISR 13 and has effectively spawned innovations in Phantom 7.



## Appendix A: Media

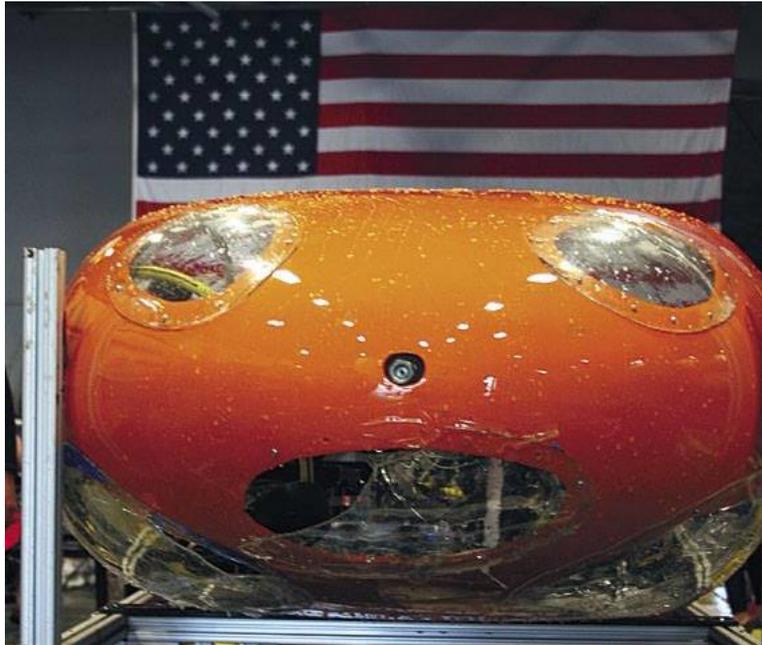


Figure 19: Phantom 6 at ISR 12

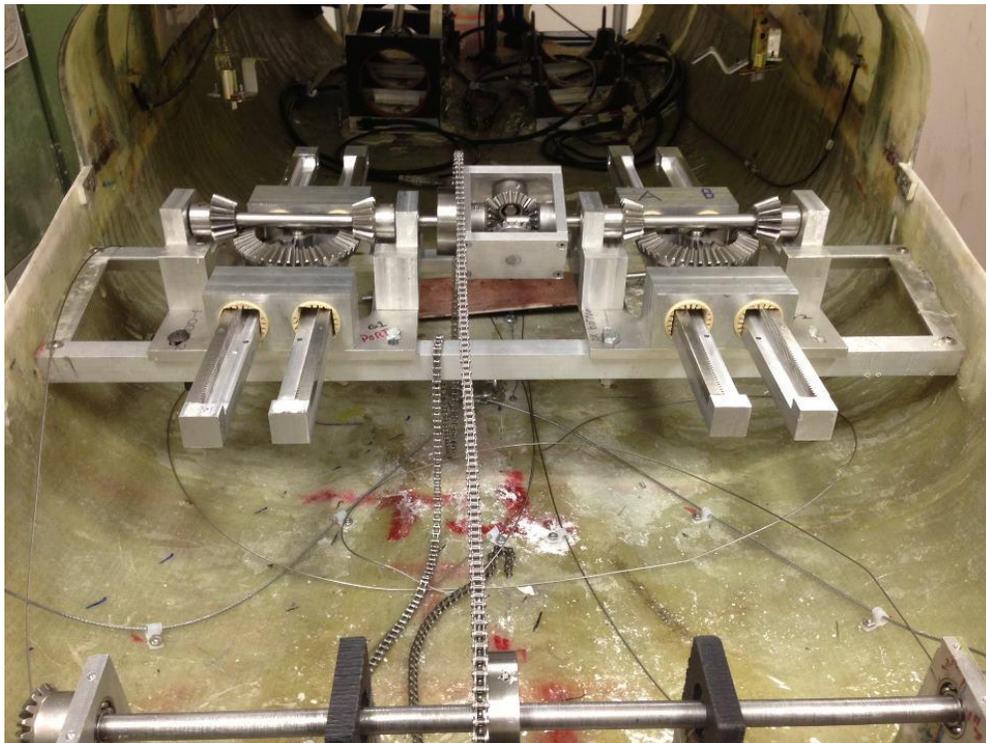


Figure 20: Phantom 6 Gear Box

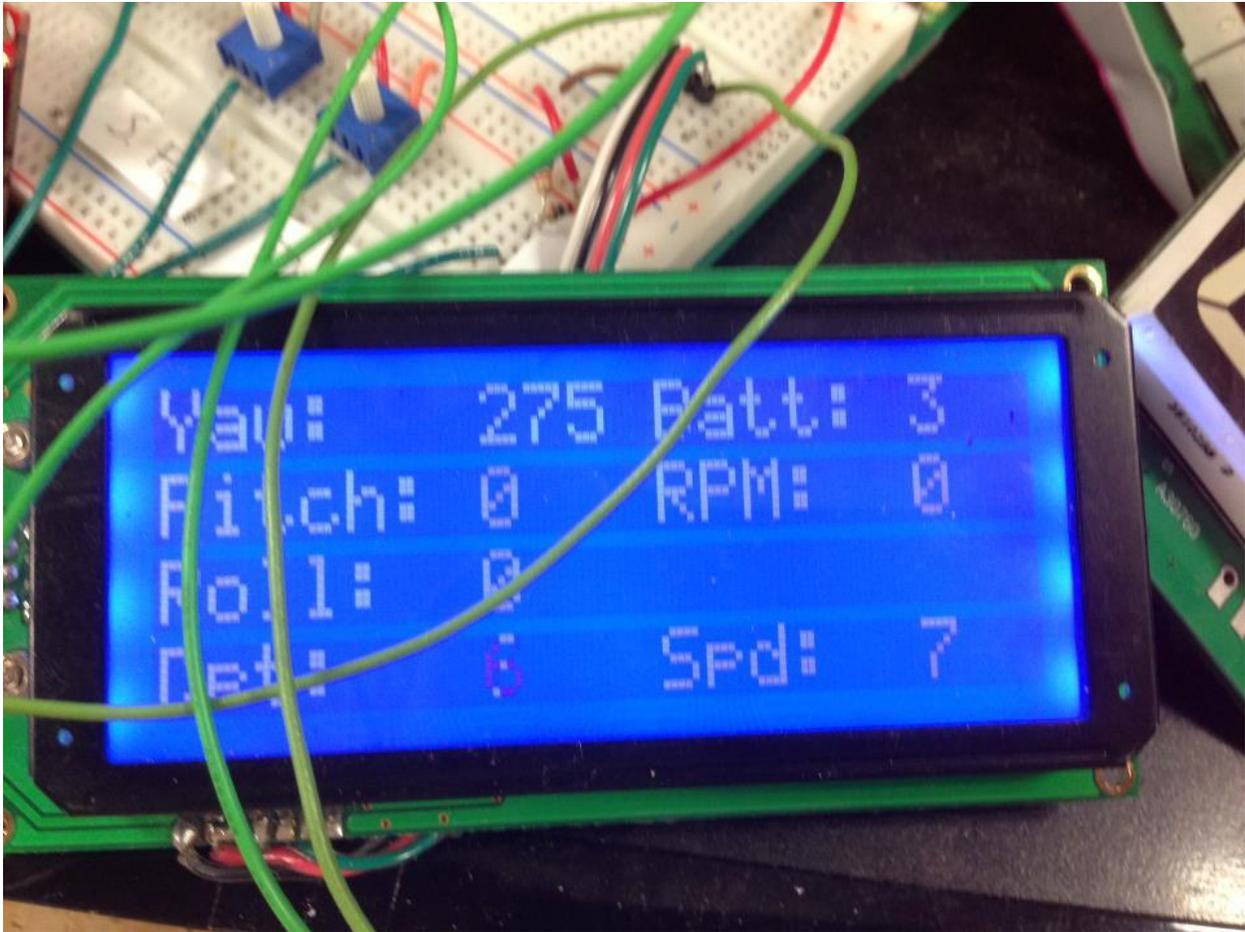


Figure 21: Phantom 6 LCD Display

Virginia Tech Human Powered Submarine is also on:

- Internet: [www.hps.aoe.vt.edu](http://www.hps.aoe.vt.edu)
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Department of Aerospace and Ocean Engineering Machine Lab

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*Thank you!*

