PHANTOM 8 TECHNICAL REPORT

VIRGINIA POLYTECHNIC INSTITUTE

AND STATE UNIVERSITY

HUMAN POWERED SUBMARINE DESIGN TEAM

15TH INTERNATIONAL SUBMARINE RACES

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We could not have achieved this goal without your help.

Thank You

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1. EXECUTIVE SUMMARY

Phantom 8, after a poor performance at ISR 14 in 2017, will come back to competition simpler than ever, with the intent of redeeming itself. A new, cable-controlled steering system and a manual buoy release system eliminate the need for electronics inside the hull. Extensive testing took place with Phantom 8 after it returned from competition proving that it can traverse the length of the test location. Learning from previous mistakes, the team now believes Phantom 8 has been improved and is now competitive. While Phantom 8 is not the focus of the team currently, this year's appearance at an ISR event shows that Virginia Tech is capable of the logistics required to bring two submarines to a competition.

2. INTRODUCTION

The Human Powered Submarine Team at Virginia Tech (VTHPS) is comprised of individuals with a passion for learning and engineering. The VTHPS team strives to design, produce, and race submarines against teams from all over the world. Phantom 8 is returning to the International Submarine Races to act as a proof of concept, train team members, and show that Virginia Tech can bring two submarines to the races. At ISR 14, Phantom 8 performed poorly. Large system failures resulted in the submarine staying out of commission for the entire week of the races. Since returning to Virginia Tech, Phantom 8's system has been overhauled and extensively tested. With the new improvements, Phantom 8 will return to ISR 15 for redemption.

3. DESIGN GOALS

Phantom 8 has been redesigned from previous years for simplicity, and to act as a test bed for future systems. The intention of repairing Phantom 8 was to train new team members on the VTHPS team. By fixing and replacing systems within the broken submarine, new systems could be better designed for future submarines. Many systems were repaired or replaced before the creation of Trident, which helped the new team members learn the functionality of human powered submarine systems and set the team members up for success in designing and building the new submarine.

4. HULL

During the manufacturing of Phantom 8, the team lacked the ability to keep and store notes on a drive for future use. This resulted in a lack of information regarding the hull design process. As a result, little is known about the hull design of Phantom 8.

4.1 HULL DESIGN

While Phantom 8's primary designed shape is like that of its predecessor, Phantom 7. The size was adjusted to allow for the autonomous control system designed to fit inside of the hull. The length was increased by one foot at the parallel mid-body to provide extra space behind the gearbox for electrical components and ballasting. The entire hull was constructed from a carbon-fiber laminate and features a textured outer layer, showing the carbon-fiber weave. The weight and strength of the hull were the primary reasons why carbon fiber was selected.

The shape of Phantom 8 mimics that of a teardrop, which was determined to be the shape that minimized drag for the team's purposes by past team members. The full length of the submarine is 11 feet, with a maximum diameter of two feet that occurs along the parallel mid-body of the submarine. The submarine has a surface area of 8066 in^2 , and the total internal volume of the submarine is 42610 in^3. When Phantom 8 is submerged, it will have a total mass of 1537 pound mass. The hull consists of six layers of carbon fiber, with a layer of Divinycell foam sandwiched in between. The outermost layer is a 7.2-ounce hex-weave carbon fiber. Three layers of 6-ounce bidirectional weave were also used to create the hull, along with two more layers of bidirectional weave that are cut at 45° angles from the other layers. These angled layers work to make the submarine's mechanical properties more consistent along all axes. The layer of $\frac{1}{16}^{\text{th}}$ inch thick Divinycell foam was placed in between the third and fourth layers of carbon fiber.

4.2 MANUFACTURING

4.2.1 MOLD

The manufacturing of Phantom 8 took place over two semesters from Fall of 2016 to Spring of 2017. The mold for the hull was cut out of Renshape using a computer numeric controlled (CNC) mill located in New Boston, Virginia. After the section of Renshape was cut by the CNC mill, the surface was finished with Duratec. The Duratec surface finish allowed the carbon fiber hull section to be removed from the mold after the resin cured. After the Duratec was fully cured and aired out, preparations began for the carbon fiber layup of the hull section.

4.2.2 LAYUP

Phantom 8 was laid up in two identical halves, the top portion and the bottom portion. Resin infusion was chosen as the layup method due to the smoother surface finish it provides. The carbon fiber layers were placed into the mold and resin was spread over the layers. A vacuum bag was placed over the entire surface and a vacuum pump installed using adapters. The pressure exerted by the vacuum bag presses the resin into all the gaps of the carbon fiber, and the curing process took place while the vacuum bag was still under pressure. The curing process took four days to complete. This process was completed again for the second half of the hull.

4.2.3 MATING THE HALVES

Due to layup of Phantom 8 being done in two pieces, a section of carbon fiber was applied to the seam using the same resin used to create the hull, to mate the pieces. The result was an enclosed tube of carbon fiber to be used for the hull. Since the hull was not designed to be separated once combined, holes were cut for windows and hatches to access the inside so that carbon fiber could be placed on the interior seam as well.

4.3 MODIFICATIONS

Starting immediately after ISR 14 in 2017, modifications were made to Phantom 8 to make the submarine functional. The electronics within the hull were scrapped and new mounts were created for a cable actuated steering mechanism. In the bow of the submarine, a joystick was created to actuate the cables. Cable routing and tensioning mechanisms were installed into the submarine to guide the cables. Larger supports for the main gearbox were built and installed to prevent flexing of the main gearbox during use. The hatch was also redesigned using magnets to assist in placement of the hatch.

5. PROPULSION

Phantom 8 uses a linear drive gearbox which was originally built in 2015. The drive system of Phantom 8 suffered many problems at ISR 14 resulting in a submarine which was unable to compete. Many of these problems have been addressed and fixed prior to entry into ISR 15.

5.1 GEARBOX

5.1.1 PRIMARY

The linear drive gearbox design present in Phantom 8 has remained unchanged during the previous Phantom line of submarines. The gearbox features a large gear located centrally on the mounting plate. The underside of this gear has teeth which mesh with the long slider arms the pilot uses to "pedal" the submarine. These arms slide through linear supports which contain recycled UHMWPE pads to reduce friction of the arms. These arms allow the gear central gear to rotate back and forth. A pair of gears mounted on a shaft in line with the slider arms contain one-way bearings which convert the alternating motion of the gears into a uni-directional rotation.

Figure 1: A rendering of the primary gearbox in Phantom 8

5.1.2 SECONDARY

The contra-rotation gearbox, or secondary gearbox, was designed to take input from one driveshaft and have two output shafts rotating in opposing directions. The original 0.5-inch shaft is located inside of a hollow one-inch shaft. The system is comprised of a total of four manufactured parts. Namely, the stern plate, the locking ring, the bearing boss, and the gear piece.

Non-manufactured parts include two spur gears, two pinion gears, and miscellaneous bearings and fasteners.

The secondary gearbox is attached to the submarine via a stern plate and a ring locks it in place as shown in Figure (3.3). Attached to the stern plate on the interior of the sub is the boss which allows for a bearing to be sandwiched inside. Using machine screws as standoffs, the gears are arranged inside attached to the drive shafts and held in place using the bearings and are used to space the gears. The gear piece is bolted into place and allows for a bearing to be placed around the shaft.

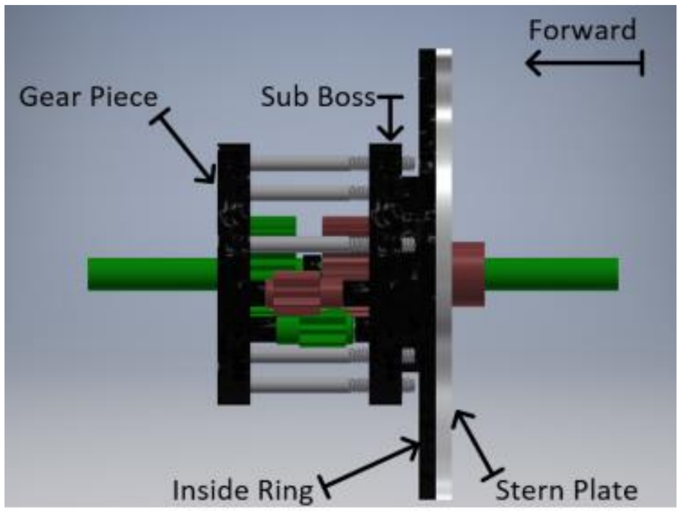

Figure 2: A rendering of the secondary gearbox system.

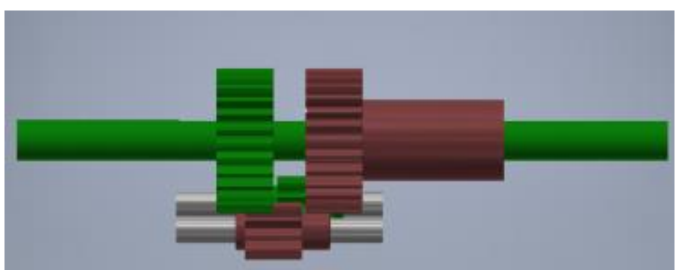

Figure 3: The green and red components rotate opposite of eachother to produce contra-rotation

5.2 PROPELLERS

The Phantom 8 racing in ISR 15 utilizes a two propeller, contra-rotating propeller assembly with fixed pitch. This was modified from the previous version of Phantom 8 since the variable pitch system was reliant on electronics which failed during ISR 14.

The design of the propellers for Phantom 8 was poorly documented. As a result, spare propeller blades located in the lab from previous submarines were used as replacements. The new blades functioned better than previous versions during pool testing, and it is estimated that Phantom 8 will achieve 2 knots during ISR 15.

6. CONTROLS

The controls scheme for Phantom 8 was rebuilt and redesigned using cables instead of the intended electronic controls. This system was designed to be simple, as the primary focus of the team was on Trident. The goal of the new system was to provide Phantom 8 with functioning controls for pool testing sessions during the semester so new members of the team could better train with a submarine in the water during testing sessions.

6.1 CABLE CONTROLS

A new control system was used in Phantom 8 due to the failure of the electronic components which controlled the original submarine. The new system consists of cables mounted to a joystick which connect to control arms in the stern of the submarine. Each control arm is permanently mounted to the control surface though the hull. The cables are tensioned in the middle of the submarine using turnbuckles. There are 8 cables routed down the submarine in order to control the 4 surfaces on the hull. These cables connect to a joystick that can rotate in 2 axes and allows the pilot the steer Phantom 8 with one hand. The cables are made stainless steel to prevent rust build up and utilize bicycle shifting housing to reduce friction in the system. Since the cables can stretch over time there are turnbuckles located in the parallel midbody of the submarine to increase or decrease cable tension as desired. Joystick was created with a 3 axis mill and aluminum plates to make for easy manufacturing and light weight ergonomic design. Additionally, padding was added to the help the pilot the grip the joystick.

Figure 4: The Joy-stick design in the bow of Phantom 8

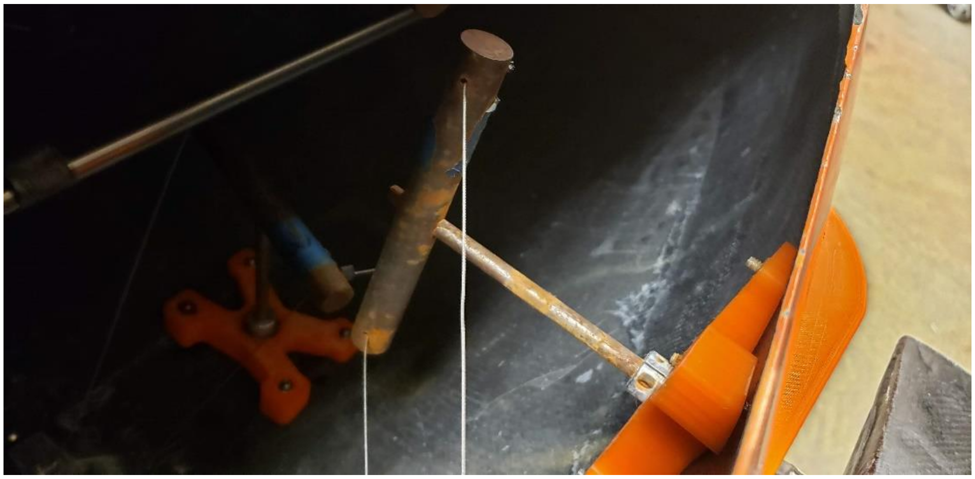

Figure 5: A control arm located in Phantom 8

6.2 CONTROL SURFACES

The control surfaces on Phantom 8 are original to the submarine. The functionality was never tested before ISR 14. After ISR 14 the team tested the surfaces and proved that they do turn the submarine while in motion.

6.2.1 DESIGN

The surfaces consist of a NACA 0015 airfoil shape, which was rounded over at the top for hydrodynamics. The NACA 0015 airfoil was chosen due to it symmetry and length. The control surfaces were designed to displace the large amount of water helping create reaction forces to steer the submarine.

6.2.2 MANUFACTURING

The control surfaces were to be made using a foam core with a layer of carbon fiber resin wrapped onto the surface. The shape was printed out and hand carved out of blocks of foam. Then a hole was drilled in the flat bottom section for the insertion of an aluminum rod. This rod was epoxied into place and the control surface was coated in a layer of carbon fiber. Inside of the hull, the control arms were J-B Welded into place to mount them permanently.

Figure 6: The control surface on the top of Phantom 8

7. LIFE SUPPORT SYSTEMS AND SAFETY

The VTHPS team takes safety very seriously. This year the focus was on Trident, the new submarine coming to competition. The team works diligently to ensure that our safety and life-support systems are tested and in working order before the submarine enters the water. The system present in Phantom 8 has been redone to be as similar as possible to Trident.

7.1 SCUBA SYSTEMS

The pilot's SCUBA system is comprised of an aluminum 40 air tank mounted below the pilot with the cylinder valve facing the stern of the submarine. This location is directly below the pilot and the valve are easily reached by the pilot or support divers to ensure the tank is open and that there is air flowing to the regulator. On the second stage inside of the submarine there is one 40-inch hose for the pilot's main regulator. Also attached to the second stage is the pilot's air gauge which is mounted in the pilot's line of sight. The team double-checks the amount of air within the cylinder before and after every test or run, to ensure that the pilot is not entering the submarine with lower than 1000 PSI in the tank. The pilot is equipped with a small "Spare Air" system which is in front of the scuba tank in the cockpit of Phantom 8.

7.2 BUOY

The safety buoy system has been redesigned in the Phantom 8. The system uses a fishing reel, so it can be easily set and reset. The system also incorporates a caliper that can be actuated to hold the string of the buoy while the pilot is holding the dead-man switch. The buoy holder is 3D printed and was designed to allow the string to pass through into the hull.

Figure 7: The buoy release mechanism in Phantom 8

7.3 DEAD-MAN SWITCH

The dead-man switch is located on the left side of the hull in Phantom 8. It is integrated into a pilot brace point that is not used for controlling the submarine. The dead-man switch consists of a bicycle brake lever mounted onto an aluminum handle. The dead-man switch is completely mechanical, reducing the probability of error and eliminating the possibility of electrical malfunction like the submarine experienced during ISR 14.

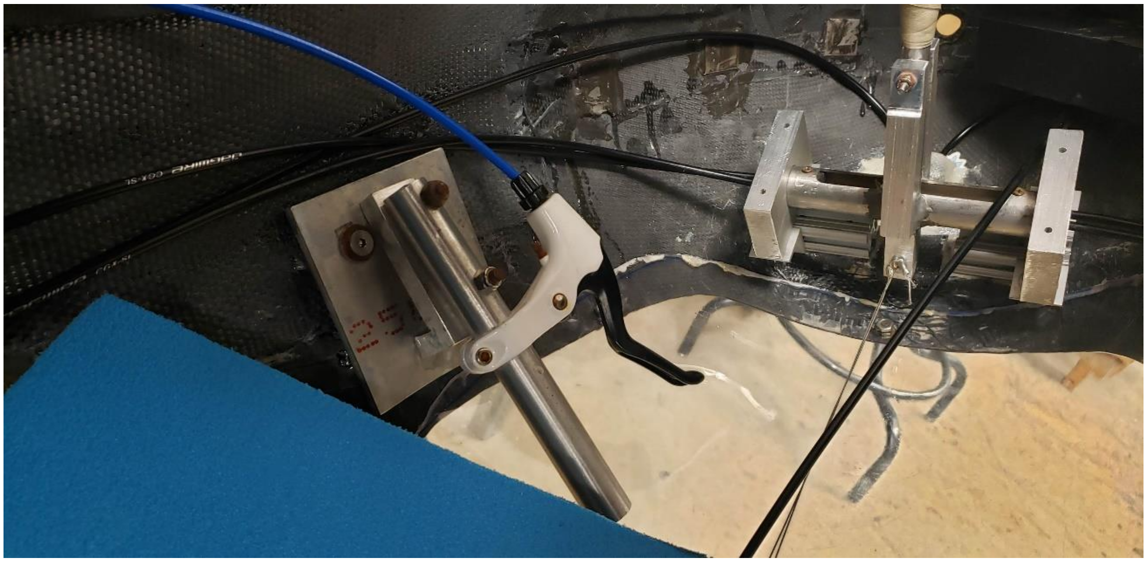

Figure 8: The dead-man switch in Phantom 8

7.4 HATCH RELEASES

The hatch release system consists of a lever which turns to lock the hatch into place. This mechanism is the original design present on Phantom 8. The design is functional, but the added handle contributes to the overall drag of the submarine. As a result, it is an inefficient system. The same mechanism is accessed on the inside of the hull and is located near the pilot's shoulder. There is a tongue and groove on the top side of the hatch to help hold the hatch in and making the support drivers job easier.

7.5 SAFETY LIGHTS

The safety lights used on Phantom 8 are circular waterproof lights with different modes for different visibility conditions. These lights have worked well making them a go-to choice for the team. The lights are placed in a 3D printed holder that is bolted to the inside of the hull. They have a magnetic base which is used to hold them in place. The lights are easily controlled from outside of the submarine.

Figure 9: A closeup of the safety light

8. CREW TRAINING

The dive crew consists of 18 divers. Each year the team works to get members dive-certified through a dive shop that sponsors the team. After they have finished the proper training, the new divers receive an "Open Water" certification, which allows divers to descend to 18 meters below sea level. These divers are then versed in handling the submarine at various testing sessions throughout the build-cycle. They are given the chance to practice with the submarine, carrying it, moving it, and steering clear of submarine related hazards. The team maintains a document that keeps track of certified divers and their certification levels. The team also keeps and maintains an extensive dive safety document which details the rules for diving with the team, safe diving practices, and hazards related to the VTHPS team.

Before every scheduled testing or dive, the team holds a safety briefing, conducted by the team's Dive Safety Operations Coordinator. The safety briefing includes going over the safety document and reviewing the sections that are specific to the testing location (the pool or the quarry). The submarine specific hazards are discussed (the propeller, being pinned by the submarine), as well as proper gear set up and the dive plan. The dive plan is written by the Dive Safety Operations Coordinator and details which diver is in the water at what time, and what they will be doing while diving.

During quarry testing, the team held multiple meetings with the divers to inform them of the layout of the quarry, the extensive plan that the divers would be following, and how to handle the submarine in a non-pool situation. These meetings also discussed the proper protocol for diving emergencies, such as entrapment, lost diver, and entanglement.

9. SUBMARINE TESTING

VTHPS tested Phantom 8 four times from November 2018 to May 2019. Shifting the focus of the team to testing and results allowed the team test, fix system failures, and improve the systems many times over. Multiple testing sessions also acted as trainings for our pilots and safety divers. The main goal of bringing Phantom 8 to testing sessions was to get the new members of the team comfortable with the submarine underwater.

9.1 POOL TESTINGS

The submarine was tested in War Memorial Pool on campus at Virginia Tech. Most testing sessions took around 4 hours and included doing trial runs of Phantom 8 in the pool. Another goal of the tests was to test the ballasting, and control surface function while in motion.

It was found that Phantom 8 needed a large amount of foam in the back of the submarine as well as weights in the front to properly ballast it. Velcro as well as racks for weights have been added to the submarine to make trimming the ballast easier and more time efficient. Due to the slow speeds experienced during pool testing session it was realized ballasting was especially important for Phantom 8 since it could not quickly adjust its position in the water. Additionally, the team found the closer to neutral the diver is the easier it is to adjust and steer the submarine

Additionally, high loads on the propellers would cause the primary gear box of Phantom 8 to bind and break. These findings lead to addition of several spacers in the system as well as universal joints in the drivetrain. The linear gearbox does allow for more room in the submarine but in pool testing it was discovered it created a pulsing in the propeller RPM leading the team to focus on a rotational based gearbox for the next class of submarines.

The largest benefit of testing Phantom 8 was the additional training of the team's divers and pilots. The divers and pilots had little experience prior to 2017 and hence their designs were reflective of that inexperience. As the team gained experience working with Phantom 8 and fixing its many broken systems, students learned what made for a good human powered submarine. The next class of submarine has proven easier to work on both in and out of the water due to testing in the pool with Phantom 8.

10. LESSONS LEARNED

The VTHPS team has grown as an organization over the past two years. Noticeable things have changed since ISR14. One major aspect of the team that needed changing was communication. The communication between team members and team leads in previous years was lacking, resulting in missed deadlines and issues with sharing ideas. Communication has been improved by increasing the occurrence of meeting times for everyone involved with a system, and having specific project channels made in our team communication app. While communication has been greatly improved on the team, there is still room for further improvement.

Regarding submarine design, the VTHPS team now documents design and manufacturing processes much better due to the lack of information regarding Phantom 8. After ISR 14, many members of the team quit due to the poor team dynamic. The team has tried very hard to turn the dynamic around and make the team an enjoyable thing to be apart of. VTHPS members are happier than ever.

Testing sessions are extremely important. Phantom 8 was never tested before competition and the result was sub-par. By training our divers in the water using Phantom 8 as a testing vessel, the team not only got Phantom 8 to move, but also gained experience working with human powered submarines.

Sponsors are a huge asset to the team. This year the team gained many sponsors who the team hopes to continue to work with in the future. Sponsor relations have led to improvements in the team's lifesaving dive equipment, improvements in submarine building materials, and improvements in communications with sponsors. It has taught the team how to speak with sponsors and ask for certain materials, as well as provide VTHPS with reliable support with the team's submarine building endeavors. Without our sponsors, the team would not be as advanced and as successful as it is today.

Along with learning comes change in operations. There are aspects about the team that VTHPS wishes to work on in the future. One improvement would be to recruit members in specific majors who can help the team achieve certain goals. Another would be to continue to foster communication both within the team and outside of it. The team would also like to expand outreach to the university community so that more people know about the Human Powered Submarine and what it does.

11. BUDGET

The budget for Phantom 8 was not recorded. Current team members estimate the total cost of the submarine to be near $25,000 due to the amount of carbon fiber purchased and the high costs associated with getting the hull mold milled. This number includes donations of materials, labor, and software donated to team through various sponsors.

The lack of a budget with detailed spending and donations for Phantom 8 was a large reason that the current team has very detailed spending lists.

12. CONCLUSION

The Virginia Tech Human Powered Submarine Team hopes to bring Phantom 8 back to competition to use as a training vessel. In the future the team wants to use multiple submarines to help with concept generation and testing while avoiding the consequences of committing to a design without ideas for change early in the design process. Additionally, freshman and sophomore members of the team have expressed interest in bringing two submarines to the ISR 16 event. By bringing Phantom 8 back to competition with modifications made to its systems, the team will have experience with the complications that two submarines in the water bring. Phantom 8 has never been more prepared for an ISR event.