

University of Maine

Human Powered Submarine USS-UMAINE



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Introduction

The human powered submarine project has been developing over the years at the University of Maine since the 2001-2002 school year. The initial goal setting out was to test and use a non-propeller drive system, and throughout the years a propeller system has never been adapted at the University of Maine. Multiple submarine designs have been developed over the years with the latest being made in 2008-2009 to be competed in ISR 10. The hull and propulsion system being used this year is the same as used in 2009, but with some improvements made. In addition, this year's team has completely redesigned the control surfaces, control system and biomechanical systems.

University of Maine has competed in two human powered submarine competitions throughout the years including the West Coast ASME Human Powered Submarine Race in 2006, where they placed in the top three for most innovative sub design (first) and best submarine design (third). A few years later a team again competed at ISR 10 in 2009 at Carderock, where they took home third in speed for our class. This year the University of Maine intends to compete again at ISR 11 in 2011, with hopes of beating last competitions times and speeds. With this year's submarine, the USS-UMaine, our team has strongly emphasized driver safety, stability, and steering into the design process, retaining and improving the very effective Hobie Mirage drive system that has been used in previous years (discussed in detail on page 9).

Our team is comprised solely of mechanical engineering students here at the University of Maine and is divided into three sub-groups – an auto-pilot team, a controls surface team, and a bio-mechanics team. Our team's goal is to break the speed record and take home first place in our division this year at ISR 2011. Throughout the years, control of the submarine has been the team's largest problem in competitions, so it is crucial that this year we have a dead reliable control system in place that has been thoroughly tested for accuracy. We are also taking extra precautions by making the entire system into multiple components that can easily be replaced in the event of a failure so that another run may be completed while those parts are being fixed. In the event that no electronic components can be used due to extreme circumstances, we have also put extra attention into the manual control system and properly sized control surfaces to enable an easily maneuverable sub even at the lowest level of control system complexity. Lastly, to ensure a successful competition we will be putting in extra attention into the weighting and trimming of the submarine to ensure neutral buoyancy, stability, and easy maneuverability through the water.

Hull Design

Objective

Stability and speed were the top priorities in the design of the submarine's hull. The hull has been designed to be fast and easy to control and handle.

Drive System and Submarine Diameter

For the sub to achieve maximum power output and speed, the driver must have enough shoulder and leg room. Therefore, the submarine's drive system needed to be long enough to allow a maximum range of motion for the driver's legs.

The diameter of the hull needed to stay roughly constant around the area of the drive system. The submarine's diameter also could not be too large because this would increase drag and create a potential problem to the maximum output of the sub, but it could not be too small either because the driver needs ample room to complete a range of motion with his or her legs.

Because the shoulders are the widest part of a driver's body, and the driver requires a lot of room for their bending knees, the submarine's cross sectional diameter is greatest from the location of the pilot's shoulders and back toward his or her knees. In the past, careful measurements of the team members were taken to find the exact diameters required. Some extra room was added to ensure future groups could also use the submarine. The maximum diameter of the hull is 21.5 inches, and the design maintains this constant diameter from the driver's shoulder area to the knee area.

Size and Shape

A dimensioned drawing of the submarine's hull is shown in Figure 1.

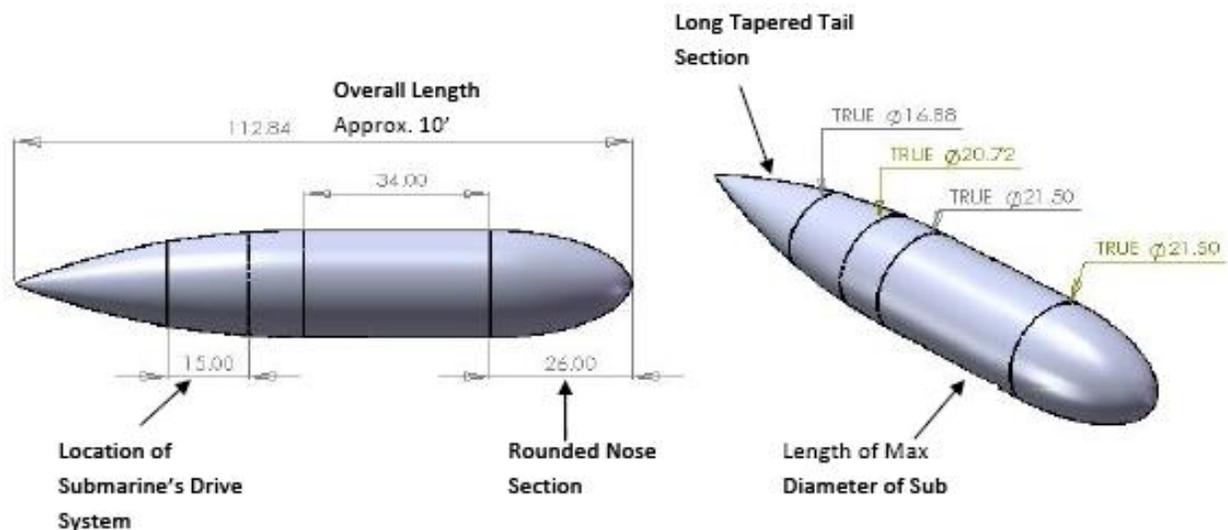


Figure 1 - Hull Design with Critical Dimensions

A circular cross-section along the length of the sub's axis was selected for the submarine's hull. This design improves stability. Since the sub is properly weighted, there is no force

perpendicular to the line of motion proportional to the velocity. This means that any yaw in the sub would not result in a different perpendicular force direction. This design also provided simplicity for the construction process.

The only two forces working against the submarine's propulsion system are the momentum and drag of the sub. The momentum is solely a function of the mass of the sub. Since the mass of the submarine must equal the mass of the water it replaces when submerged, the total volume of the submarine is all that contributes to momentum. Once the submarine reaches its maximum velocity and is no longer accelerating, the momentum is no longer an issue. Given the large "run-up" period before the timing gates, the momentum may not be a factor in the recorded time, but if the sub is light enough, it does not need to use the whole run-up length, which can help conserve the operator's energy.

The other force opposing the motion of the submarine is drag. Compared to momentum, the drag is not as large of a force in the overall run of the sub; however, in the timed section of the course while the submarine is at its maximum velocity, the drag is at its maximum magnitude and is the only opposing force on the submarine.

The length of the submarine from the driver's shoulders to the front of the sub was cut down from previous years' designs, which created a more blunt shape in the front. This reduced the volume of water in the submarine, while not greatly increasing the drag. The tail of the submarine was tapered to a point from the drive system in an attempt to avoid boundary layer separation and a significant increase on drag. Overall, a balance had to be struck between the weight of the sub and the hydrodynamic drag of the sub, since both were unable to be simultaneously minimized.

To create as high a righting moment as possible, the top half of the sub is constructed with fiberglass layers, a foam core, and an outside fiberglass layer. The bottom half is constructed from fiberglass, chopped fiberglass matt, and an outer fiberglass layer. Since the overall weight of the sub is only determined by the volume of the sub, the weight of the sub out of water is insignificant. Because the sub is a "wet" sub, there are few forces on the sub, especially in operation. The chopped mat on the bottom half of the sub will add rigidity and durability to the hull, which is helpful in transportation and final construction.

The hull is 10 feet in length and has a volume which corresponds to a weight of water of 986.57 lbs and the calculations for this are shown below.

Weight of submarine

$$W_{\text{Sub}} := 120.68 \text{ lbf}$$

$$1 \text{ in} = 0.0254 \text{ m}$$

$$W_{\text{Tank}} := 17.114 \text{ lbf}$$

$$1 \text{ lbf} = 4.44822 \text{ N}$$

$$W_{\text{Avg_Driver}} := 153.11 \text{ lbf}$$

$$g := 9.81 \frac{\text{m}}{\text{s}^2}$$

General Shape Equations for sub sections:

Front



$$r_{\text{front}} := \frac{22}{2} \text{in}$$

$$h_{\text{front}} := 19 \text{in}$$

$$V_{\text{front_cone}} := \frac{1}{3} \cdot \pi \cdot r_{\text{front}}^2 \cdot h_{\text{front}}$$

$$V_{\text{front_cone}} = 2407.50717 \text{in}^3$$

$$V_{\text{cylinder}} = 19956.96733 \text{in}^3$$

$$V_{\text{back_cone}} = 3611.26076 \text{in}^3$$

$$V_{\text{Total}} := V_{\text{front_cone}} + V_{\text{cylinder}} + V_{\text{back_cone}} = 25975.73526 \text{in}^3$$

$$V = m \cdot \rho \quad \rho := 998 \frac{\text{kg}}{\text{m}^3}$$

$$m = V \cdot \rho$$

$$m_{\text{Water_Sub}} := V_{\text{Total}} \cdot \rho = 424.8147 \text{kg}$$

Middle



$$r_{\text{cylinder}} := \frac{22}{2} \text{in}$$

$$h_{\text{cylinder}} := 52.5 \text{in}$$

$$V_{\text{cylinder}} := \pi \cdot r_{\text{cylinder}}^2 \cdot h_{\text{cylinder}}$$

Back



$$r_{\text{back}} := \frac{22}{2} \text{in}$$

$$h_{\text{back}} := 28.5 \text{in}$$

$$V_{\text{back_cone}} := \frac{1}{3} \cdot \pi \cdot r_{\text{back}}^2 \cdot h_{\text{back}}$$

Mass of Sub if it was full of water

Tank: The tank is treated as a cylinder

$$r_{\text{Tank}} := \frac{5}{2} \text{in}$$

$$h_{\text{Tank}} := 18 \text{in}$$

$$V_{\text{Tank}} := \pi \cdot r_{\text{Tank}}^2 \cdot h_{\text{Tank}} = 353.42917 \text{in}^3$$

$$m_{\text{Water_Tank}} := V_{\text{Tank}} \cdot \rho = 5.78008 \text{kg}$$

Driver: The driver is treated as a cylinder

$$r_{\text{Avg_Driver}} := \frac{10.82}{2} \text{in}$$

$$h_{\text{Avg_Driver}} := 68.89 \text{in}$$

$$V_{\text{Avg_Driver}} := \pi \cdot r_{\text{Avg_Driver}}^2 \cdot h_{\text{Avg_Driver}} = 6334.32858 \text{ m}^3$$

$$m_{\text{Water_Avg_Driver}} := V_{\text{Avg_Driver}} \cdot \rho = 103.59345 \text{ kg}$$

$$W = mg$$

$$m = \frac{W}{g}$$

$$m_{\text{Sub}} := \frac{W_{\text{Sub}}}{g} = 54.72355 \text{ kg}$$

$$m_{\text{Tank}} := \frac{W_{\text{Tank}}}{g} = 7.76013 \text{ kg}$$

$$m_{\text{Avg_Driver}} := \frac{W_{\text{Avg_Driver}}}{g} = 69.42627 \text{ kg}$$

$$m_{\text{Total}} := m_{\text{Sub}} + m_{\text{Water_Sub}} - m_{\text{Water_Tank}} - m_{\text{Water_Avg_Driver}} + m_{\text{Tank}} + m_{\text{Avg_Driver}}$$

$$m_{\text{Total}} = 447.35112 \text{ kg}$$

$$W_{\text{Underwater_Total}} := m_{\text{Total}} \cdot g = 986.57731 \text{ lbf}$$

Propulsion System

Hobie Drive System

The Human Powered Submarine Competition includes several different classes, defined according to the number of pilots and the type of propulsion system. UMaine chose the one person non-propeller-driven class, since the team felt the chances of performing well in competition were higher in this class than in the very well established propeller-driven class. In addition, the non-propeller-driven class allowed the team to focus on designing a unique propulsion system rather than on perfecting an already existing system.

A hydrofoil drive system was chosen similar to those that have been commercially available for kayaks for years. Hobie inc. agreed to donate two Hobie Mirage Drives for the University of Maine Submarine. The hydrofoil drive system has been proven to be very efficient even when compared to propeller-driven systems. The system works by converting a stair stepping motion from the pilot into a back and forth motion of the propulsion fins. This back and forth motion of the propulsion fins pushes water backwards forcing the submarine forward. To conserve symmetry, the team chose to connect two hydrofoil drives together with one on the top of the submarine and one on the bottom as seen in Figure 2.



Figure 2 –Propulsion System with two Hobie hydrofoil design systems

The two drive systems were connected together using two dual hydrofoil drive interconnection rods machined in Crosby Lab at The University of Maine. These connection rods were placed where the pedals had been for the individual drives, and the pedals were instead mounted on the connection rods as shown in Figure 3.

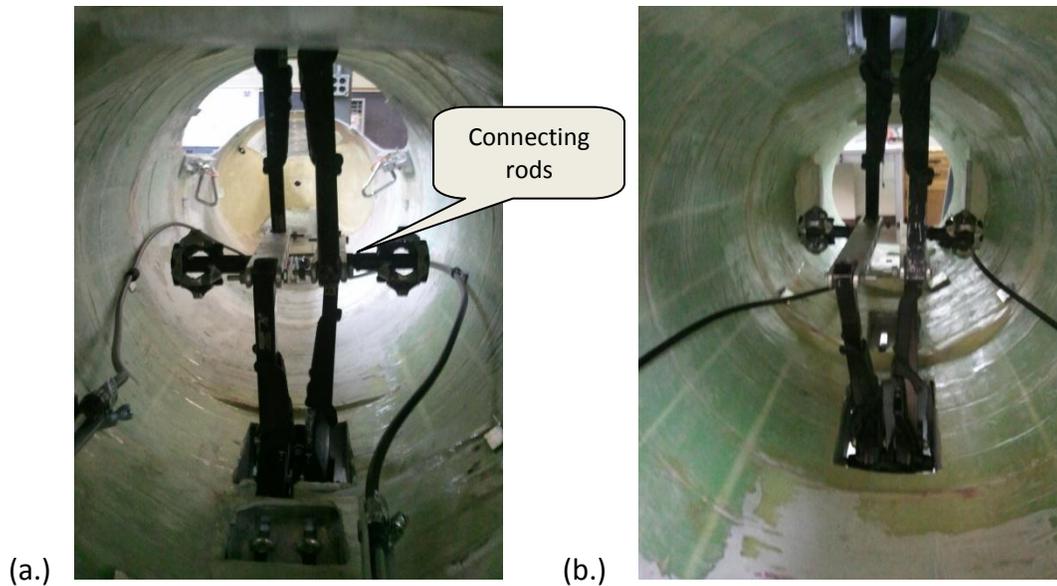


Figure 3 - Propulsion Drive System (a.) view from rear of sub (b.) from front of sub

Drive System Integration

The primary constraints for the drive system are its dimensions, its strength, and the accessibility of its parts. Metal reinforcement in the hull areas to which the drive system is affixed ensures a tight fit, reducing wear and tear in the system. To increase the structural integrity of the sub, the metal front stanchion is mounted directly into the hull, assuring a permanent, unwavering backbone to the drive system. Affixed to that backbone will be the two metal side panels that will hold the axle of the drive system. The last part of the integration is a movable metal rear panel. This will allow for the drive system to be removed easily for service. To ensure smooth operation and lessen the effects of wear, the rear panel will be tightened to the front backbone with long bolts. By having clearance holes in the rear panel and threaded holes in the front panel, the drive system can be firmly held in place as shown in Figure 4.

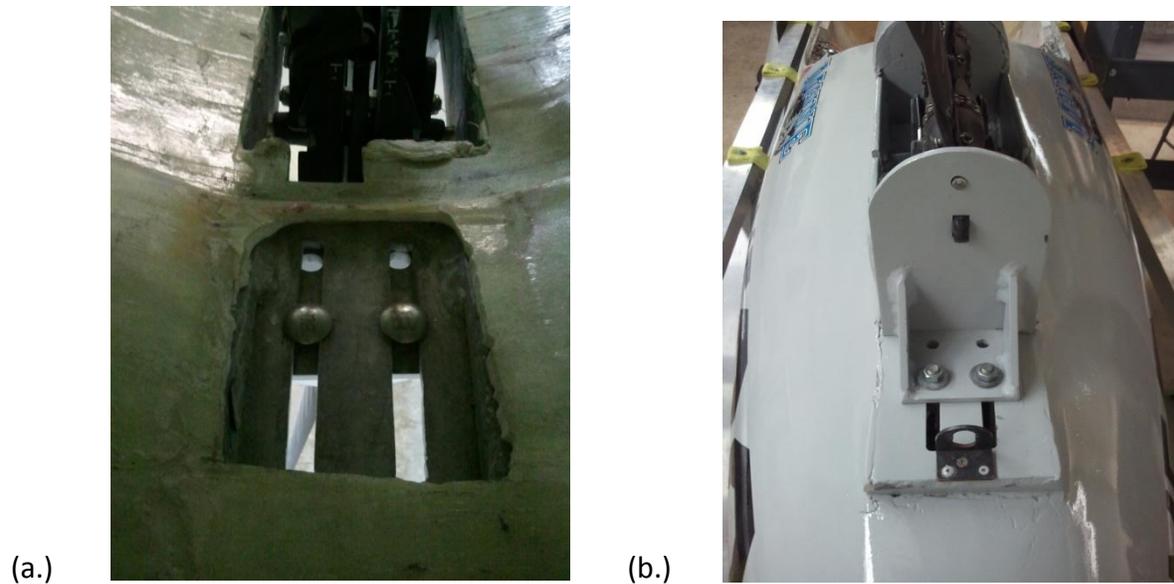


Figure 4 - Propulsion System Hull Attachment (a.) inside bottom of sub (b.) outside top of sub

Controls Surfaces and Actuators

Control Surfaces

After speaking with a naval architect about the size of the control surfaces, it was decided to construct them to four percent of the lateral plane area of the submarine. Therefore, according to calculations, the stabilizer fins should be 0.293ft^2 each, and the directional fins should be 0.586ft^2 . The team chose the National Advisory Committee for Aeronautics (NACA) 0009 profile for the control surfaces – a symmetric airfoil where the maximum thickness of the fin is nine percent of the total chord length of the fin. This means that the maximum thickness of the stabilizer fins will be 0.54in, and the maximum thickness of the directional fins will be 0.72in. Figure 5 shows a SolidWorks drawing of the new bow plane, Figure 6 shows a SolidWorks drawing of the new horizontal fin, and Figure 7 shows a SolidWorks drawing of the new vertical fin.

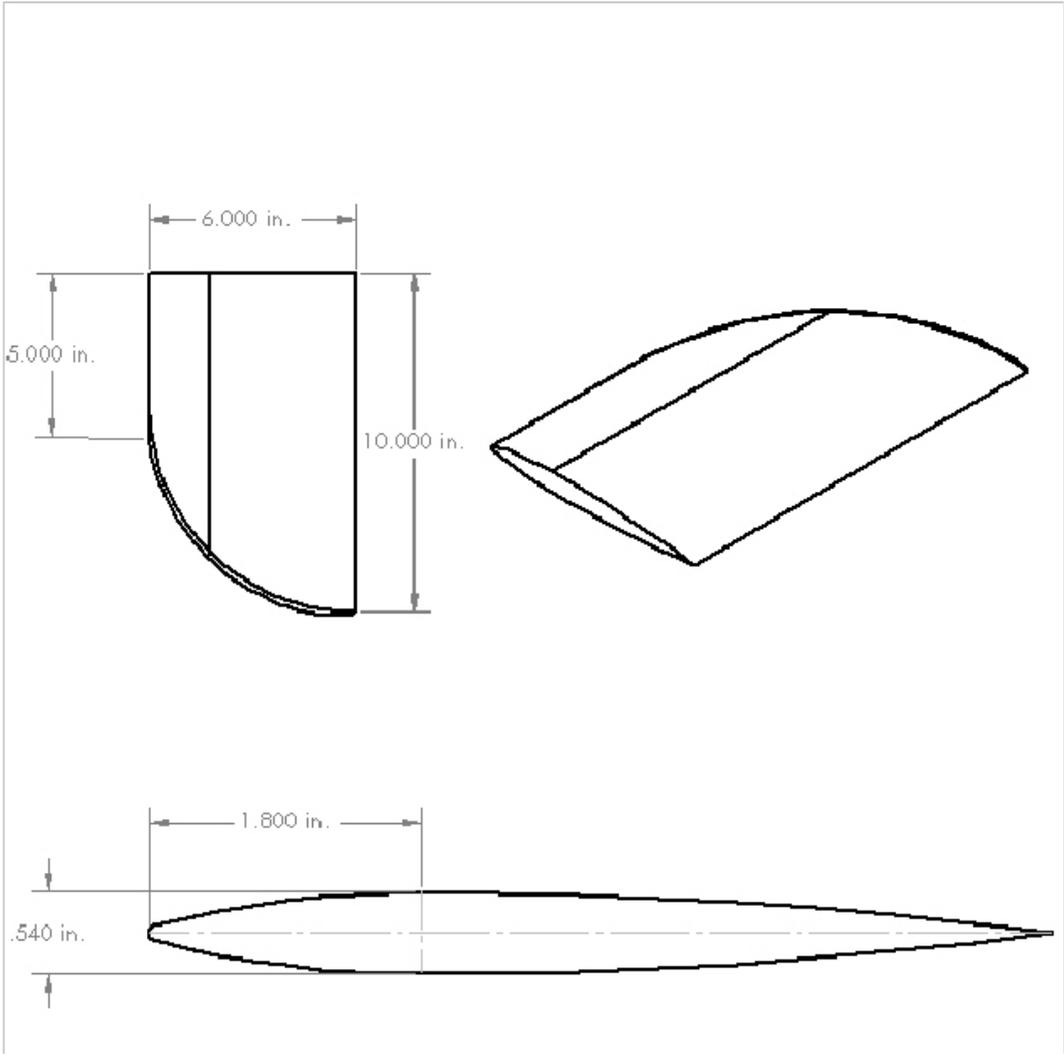


Figure 5 - New Bow Plane Design

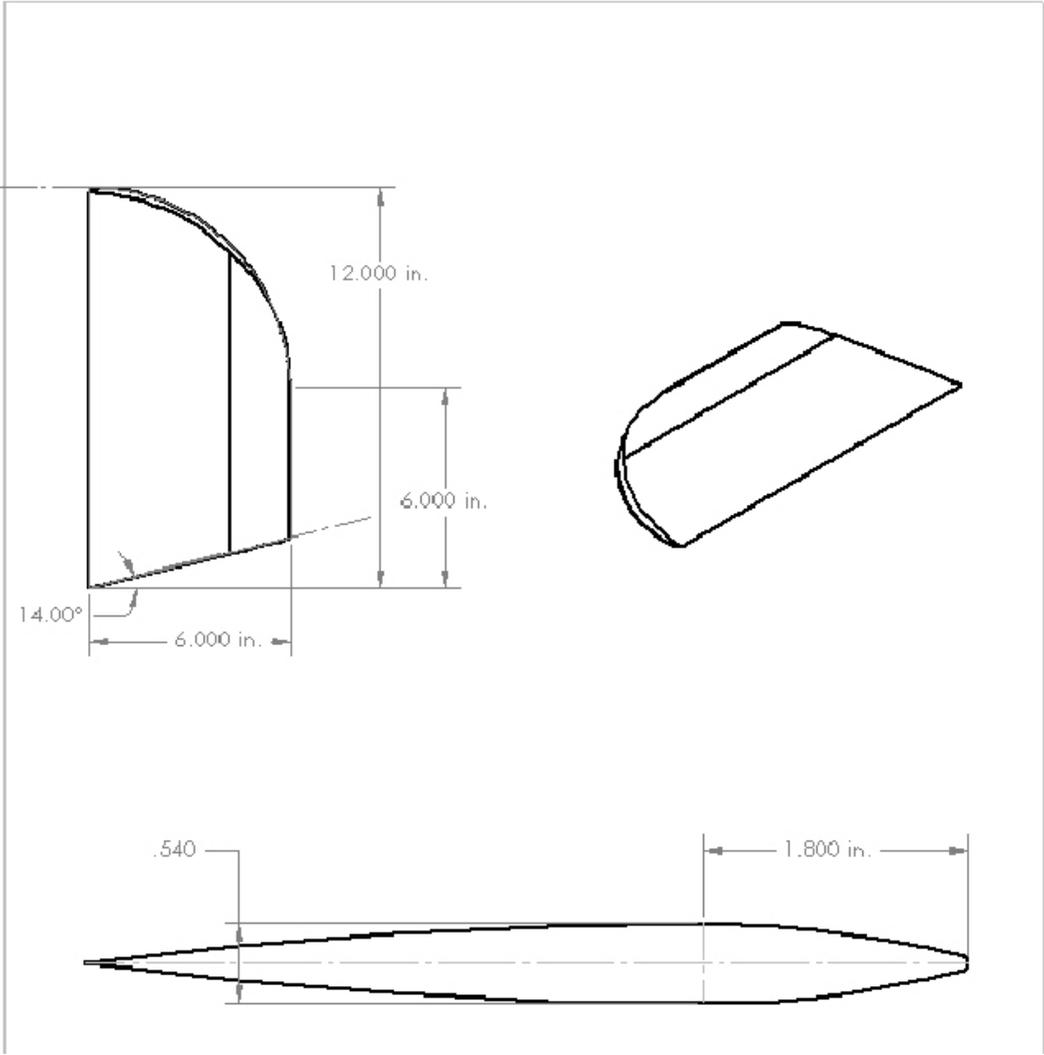


Figure 6 - New Horizontal Fin Design

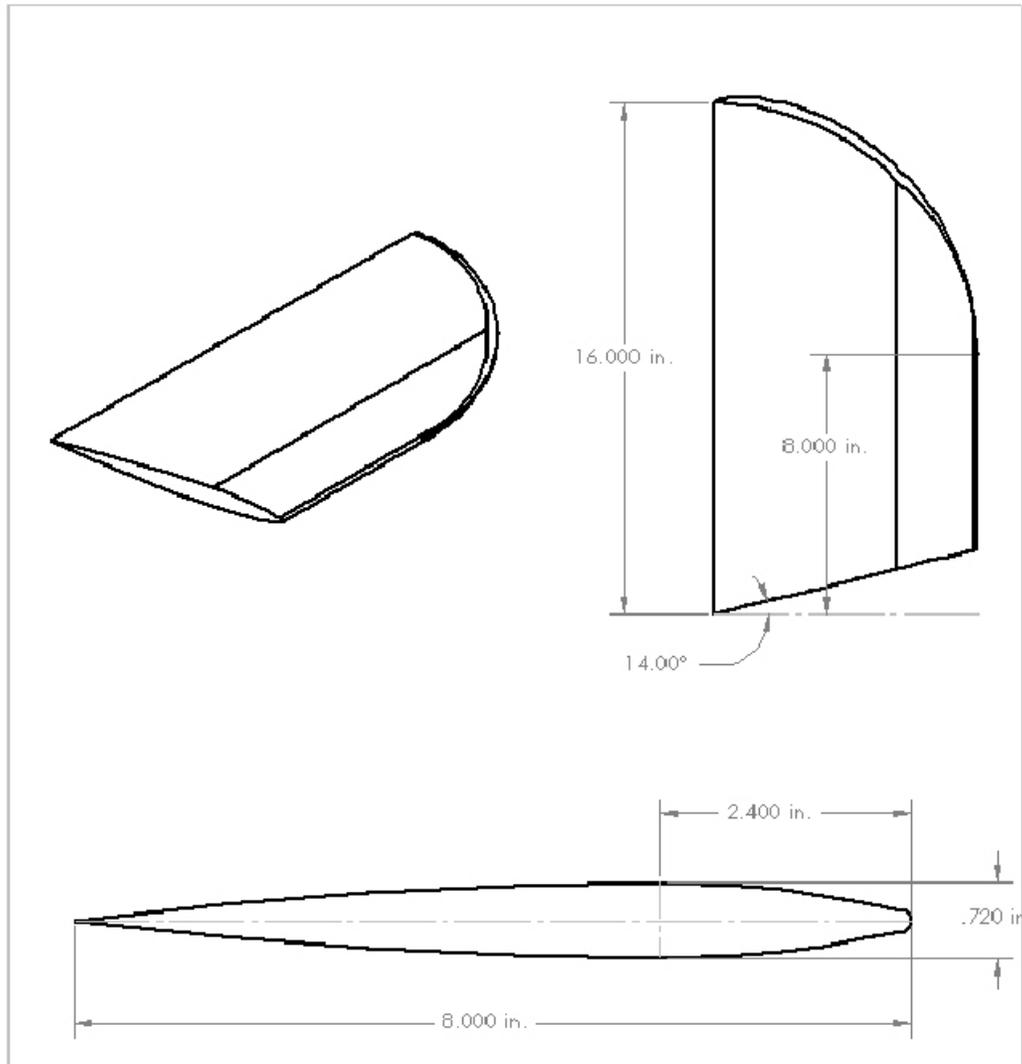


Figure 7 - New Vertical Fin Design

The control surfaces were constructed by tracing the NACA 0009 profile onto the side of a piece of pine, and then using a planar and a belt sander to achieve the profile. The arch on the leading edge of each fin was cut with a vertical band saw, and an angle was cut on each fin with a table saw so that the fins would butt up against the side of the submarine. Once the fin shape was acceptable, slots were milled in each fin and aluminum shafts were epoxied into the fins that will connect to the motors inside the submarine. While milling out the slots for the shafts, additional space was milled in the fins to add some lead shot in order to make the control surfaces neutrally buoyant.

Control Surface Actuators

The DC Motors that will be used to move the individual control surfaces are sized based on the required torque for the largest fin on the submarine being 45.929in-lb per fin at a maximum speed of 5 knots and an angle of attack of $\pm 8^\circ$. Gearboxes are also being used to increase the

output torque and decrease rotational speed of the motor as well as to prevent back drive. Shown below are the calculations made to determine this:

Water Properties

$$\rho := 1.69 \text{ lb/ft}^3 \quad \mu := 2.37910^{-5} \text{ lb/fts}$$

Free Stream Velocity

$$V := 8.4 \text{ ft/s}$$

Chord Length

$$L := \frac{2}{3} \text{ ft}$$

Fin Area

$$A := .611 \text{ ft}^2$$

Reynolds Number Calculation:

$$N_{re} := \frac{(\rho \cdot V \cdot L)}{\mu} = 3.98 \times 10^5$$

$$q := .5 \cdot \rho \cdot V^2 = 59.658$$

From NACA 0009 airfoil data, using the Reynolds number

When angle of attack $\alpha = 8$ degrees then $C_l = 0.60$

Note: change in freestream velocity would cause change in Reynolds Number.

Lift Coefficient (C_l) is a function of Reynolds Number and angle of attack.

Force of lift:

$$F_l := C_l \cdot q \cdot A = 21.871$$

Max Torque with moment arm $d := 2.1$ in

$$\tau := F_l \cdot d = 45.929 \text{ in}\cdot\text{lbf}$$

Since the lift coefficient, $C_l = 0.60$ from above is theoretical, the experimental lift coefficient will be found through tests in a tow tank at the University of Maine for better accuracy of the control system. Using the experimental lift coefficient, a more accurate maximum angle of deflection can be calculated for the motors. Based on the calculations above, DC Gear motors were selected to have an output torque of 50 in·lbs (seen in Figure 8).



Figure 8 - Control Surface Actuator (MOLON DC Gear Motor)

Controls Systems

Overview

The submarine can be piloted using any one of three main modes of control. The primary mode of controlling the submarine is through an autopilot system, where the depth of the submarine will be controlled by a custom designed computer system. If failure occurs, the secondary mode is a fly-by-wire assembly in which the driver will be able to control the sub using a joystick. The third and final mode of control is the manual control system in which the driver will use levers to move the control surfaces through a purely mechanical system.

The amount of human energy required to propel the submarine through the water as quickly as possible requires that the pilot be able to control the path of the submarine with minimum attention and effort. For this reason, it was crucial to design a control system that allows the pilot to focus primarily on generating power to propel the submarine. It is necessary that the control system allows switching between manual and autopilot modes in order to allow the driver to maintain a constant depth throughout all ISR races, while allowing the driver to choose to follow either a straight path or steer a slalom course.

Controlling the three principal degrees of freedom (yaw, pitch and roll) is accomplished using two control surface directions, horizontal and vertical. The vertical control surfaces are actuated to control heading, while the horizontal control planes will be actuated a) together to control pitch and b) separately to control the remaining effects of roll that are not eliminated by the submarine's physical structure. . Although the control system allows for the possibility of actuating horizontal control planes separately in order to control roll, roll has not been observed with the submarine, and thus implementing roll control using the autopilot system is not necessary.

The USS-UMaine's fly-by-wire control system allows the operator of the submarine to steer the submarine using a computer based steering mechanism (joystick). This level of control is further enhanced by a computerized auto-pilot system. The final computer control system, allows the operator of the submarine to choose between operating in fly-by-wire or depth controlled auto-pilot mode. However, because electronic control systems can fail unexpectedly during competition, it was also deemed crucial to have a back-up set of manual controls that can be installed quickly if needed.

Manual Controls

A working manual control system is essential to the control of the submarine in the event of electronic failure. The manual control system and the computer control (fly-by-wire, depth, and auto-pilot) system will not be interchangeable "on the fly." The manual control system will be separate from the auto-pilot system and will be installed if needed. Separate, interchangeable systems will remove some of the complexity of adapting manual controls to the control surfaces without working around the computer based control system.

The driver needs to be able to adjust the horizontal and vertical fins located at the stern of the submarine through the use of a control device located at the front of the submarine. The manual controls use two separate control levers, as seen in Figure 9, to maneuver the sub. The levers are attached to push-pull (control) cables that run to the central axial of the rear vertical and horizontal control fins, one lever controlling the up and down motion of the sub, the other steering it left and right. The push pull cables would be laid along the bottom of the sub, underneath the driver.

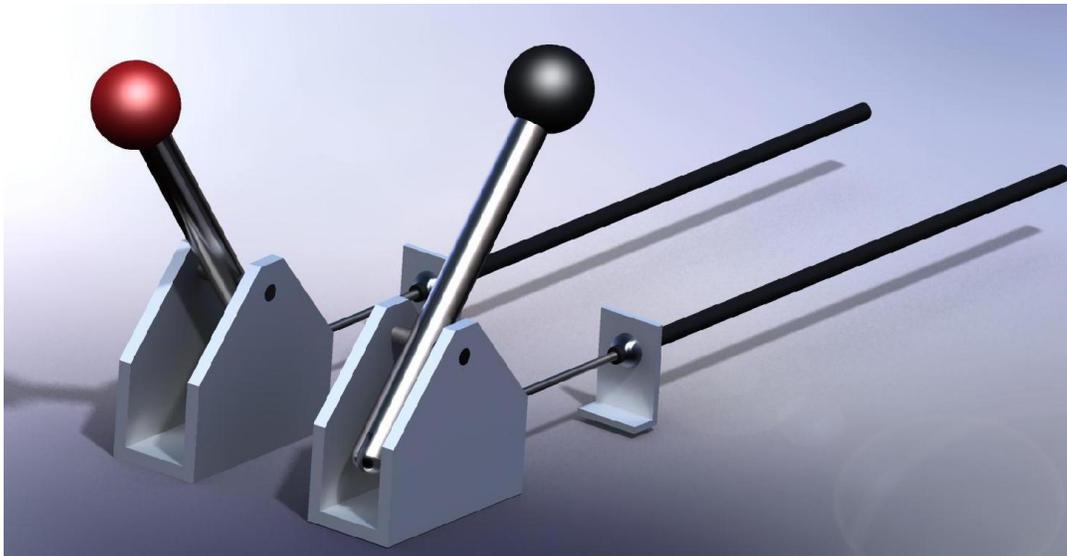


Figure 9 - Solid Works Model of Selected Design

Both levers have been mounted on to a common 6061-T6 aluminum panel that can easily be installed and removed from the submarine depending on whether the manual controls are in use. The lever shafts are constructed from stainless steel and everything in the system is

anticorrosive. Figure 10 shows the manufactured control levers installed in the submarine with the associated control cables attached.



Figure 10 - Control Levers with Cables Installed Inside of Submarine

This design will lend itself to future modifications and adjustments to driver input effort by changing the available mechanical advantage. By adjusting the fulcrum location or the control lever, the amount of linear travel experienced by the control cable can be increased or decreased. This increase or decrease in linear travel directly correlates to the amount of cable travel experienced at the rear vertical and horizontal control surfaces. In an effort to keep the sub easier to control, effort has been focused on making it less “twitchy” in order to prevent driver overcorrection that would cause losses in speed. To achieve this there will be an integrated reduction in the correlation between the angle input to the control lever and the angle output by the control surfaces.

Electronic Control System

Design Overview

The electronic control system will be used as the primary method of controlling the submarine. It has two main functions, fly-by-wire and depth control, designed to simplify steering for the pilot. The fly-by-wire system will utilize a joystick to take inputs from the driver, while the depth control system will depend on a pressure transducer to transmit the depth of the submarine to the autopilot control system.

Fly-By-Wire Controls

A fly-by-wire control system allows the operator of the submarine to steer the submarine using a computer based steering mechanism (joystick). The NI 9022 Compact RIO controller was chosen as the main computer controller for the auto-pilot system. The cRIO 9022 uses LabView programming language and its onboard Field Programmable Gate Array (FPGA).

During fly-by-wire operation, the cRIO receives an electronic analog signal from the joysticks' two potentiometers through a NI analog 9205 module. The cRIO then interprets the joystick signal and communicates the equivalence of the requested change in motion to the motors that move the control surfaces; an electronic signal is converted to mechanical motion through DC motors attached to the control surfaces. The fly-by-wire control system is designed to have minimal complexity.

A waterproofed human machine interface (HMI) housing the joystick and autopilot state switches as well as an on/off switch for the system is located at the front of the submarine for the driver to interact with and send signals to the controller when the fly-by-wire or autopilot control system is being utilized. The joystick box contains all of the necessary components for the driver to communicate with the control system (fig. 11). The human interface of the joystick consists of a 2-axis joystick used to control the direction of the sub as well as two toggle switches. One switch is used to turn on the electronics and the other is used to turn on depth control. These components are wired to small connectors that can plug into a custom circuit board (fig. 12). A buccaneer connector is wired to a circuit board where the joystick signals are transmitted to the control box. This box has been waterproofed and utilizes IP68 rating waterproof cable connectors.

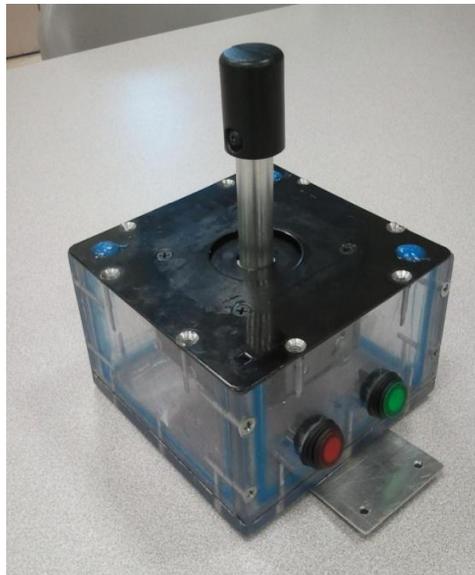


Figure 11 – Waterproofed Control System HMI

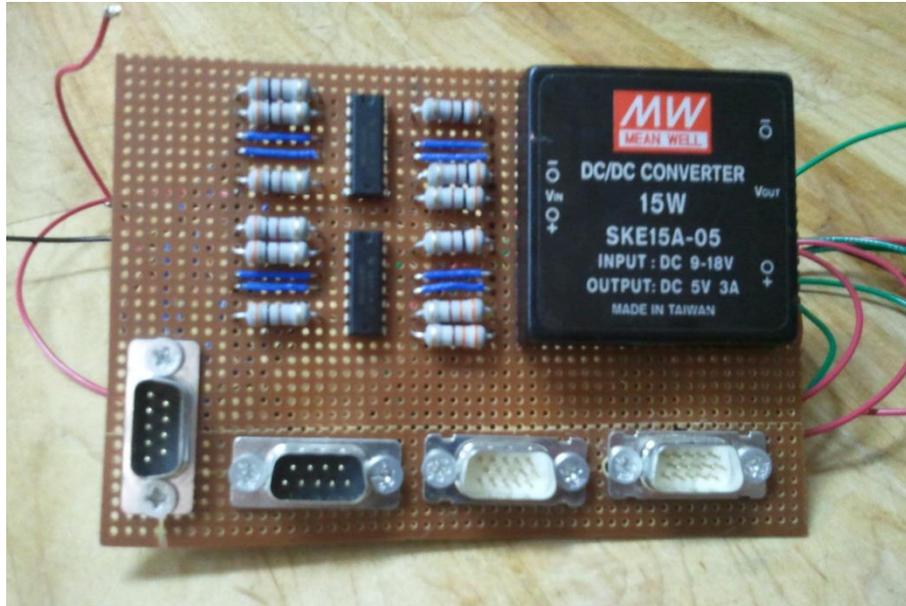


Figure 12 Custom control system circuit board unfinished

Auto-Pilot Controls

System Description

The auto-pilot system runs as a closed loop system receiving inputs from multiple sensors that replace the inputs from the joystick that the driver creates when executing in fly-by-wire control mode. The NI 9022 cRIO controller does all of the signal processing and sends out motor control signals based on sensor input.

The submarine's autopilot system uses a pressure transducer to give analog input signals that the autopilot computer system uses to maintain constant submarine depth. An Omega Engineering PX309-050A5V transducer was chosen to do the job. This specific transducer was chosen based on the operating range of depths that the submarine will experience. The maximum depth of operation of the submarine in the tank at Carderock is 22 ft, equivalent to 24.47 psia. The 0-50V range of the PX309, ensures operation of the transducer will be comfortably between the maximum and minimum of its range. An absolute pressure transducer is necessary for use in this application because of the inability to wire a gage pressure transducer's ambient sensor.

A LabView VI uses the relationship between depth and pressure, pressure and voltage to take voltage inputs from the transducer and convert them to measurements of depth.

The equation relating pressure and water depth is

$$P = P_{atm} + \frac{\rho g D}{g_c}$$

Where,

P_{atm} is the atmospheric pressure (psia)

ρ is the density of water at 60 °F. (0.03611lbm/in³)

g is the gravitational constant

g_c is the gravitational correction factor

D is water depth (in)

P is the water pressure reading from the pressure transducer (psia)

The PX309-050A5V operates over a pressure range of 0-50psia with an output range of 0-5V. The equation relating voltage and pressure for the PX309 transducer is

$$P = m * V + y$$

Where,

$$m = \frac{\Delta P}{\Delta V} = \frac{50-0 \text{ psia}}{5-0 \text{ volts}} = 10 \frac{\text{psia}}{\text{volt}}$$

“y”=offset. determined from calibration of the transducer.

Combining equations and rearranging, then solving for D, which directly relates transducer voltage and water depth.

$$D = \frac{g_c m}{\rho g} * V + \frac{g_c}{\rho g} y - P_{atm}$$

Where Depth=a*(Volt)+b

$$\text{and Depth} = \frac{g_c m}{\rho g} * V + b$$

Where,

$$a = \frac{g_c m}{\rho g} \left(\frac{\text{in}}{\text{Volt}} \right)$$

$$b = \frac{g_c}{\rho g} y - P_{atm} \text{ (in).}$$

In order to test and calibrate the pressure transducer used as a depth sensor, a test stand was built to hold water to a depth of 20 ft. The waterproofed transducer was lowered into the test stand at specified depths at which readings were obtained from the transducer. From the

calibration tests, the voltage-depth relationship used in the depth VI was manipulated by including the constant “ γ ” that was found as the error from the calibration results.

The Depth VI converts transducer voltages to equivalent water depths using the relations stated above.

The Depth Control VI takes an initial depth measurement when the autopilot system is powered on. The LabView Depth Control VI uses nested case structures and Boolean logic to control the motion of the servo motors based on inputs from the Omega Engineering pressure transducer. As long as the autopilot or depth control remains on, the submarine will attempt to remain at the approximate depth of the initial depth reading. If the depth VI senses that the submarine’s position strays from the desired depth, the depth VI sends a signal to the servo motors that controls the motion of the two horizontal control surfaces. The signal sent from the depth VI, to the servo motors will instruct the servos to adjust their position based on the degree of correction necessary to maintain the desired submarine depth. The greater the difference between current submarine depth and desired submarine depth, the greater the angle of deflection sent to the servos.

The operator of the submarine has the choice of operating using no automation (i.e. fly-by-wire), or auto-pilot depth control mode. Operating using depth control allows the submarine operator full control of the submarine in the horizontal plane.

Hardware

Electrical components included in the system include the following:

Controller:	National Instruments cRIO 9022
Analog Input Module:	NI 9205
Digital Output Module:	NI 9474
Pressure Transducer:	Omega Engineering PX309-050A5V
Magnetometer:	Honeywell HMC 6343-1048
Motor:	MOLON Permanent Magnet DC Gear Motor (CHM-1202-2M)
Power Supply:	12V DC battery pack

A National Instruments 9022 Compact RIO (NI9022 cRIO) controller was chosen to be the “brains” of the control system. It takes inputs from the various sensors of the control system, processes them and sends output signals to the control surface motors. A NI9205 analog input

module is used to acquire analogue inputs, and two NI9474 digital output modules are used to send outputs to the four servo motors used to control the control surfaces.

Each of these components will be sealed inside of a control box. Also sealed in the control box are a DC-DC converter that is used to take in 12V DC and output 5V DC and two Dual H-Bridges used to control motor direction. These smaller components are wired into a custom circuit board where the cRIO modules and instrumentation are plugged in using D-Sub connectors.

The instrumentation is plugged into the control box through a small junction box attached to the side of the control box. Sealed around this junction box are 5 400 Series buccaneer connectors into which each component of the system can be inserted. Two of these connectors are devoted to the motor box; one is devoted to each of the following: the battery enclosure, the pressure transducer and the joystick box.

The motor box encloses four DC motors. A potentiometer is attached to each DC motor in order to continually supply the electronic control system with the current position of each control surface. Each motor will be outfitted with a small connector that is plugged into a small custom circuit board. The “plug-and-play” option for the motors, allows the motors to be easily changed out in case of malfunction. The custom circuit board is wired directly to two cables that exit through the side of the motor box. The other ends of these cables are wired with buccaneer connectors that plug into the junction box that is located on the control box.

The battery system and enclosure desired to supply power to the entire electronic control system is fairly simple. A Great Planes Electrify 3600 mAh battery is enclosed in a section of 2” PVC pipe with two end caps. A hole will be drilled in one end cap for the cable to exit, and the entire enclosure will be sealed with PVC glue and potting compound. The buccaneer connector used to plug the battery into the junction box is attached to the end of the cable opposite from the junction box.

An Omega Engineering PX309-050A5V pressure transducer was waterproofed using PVC piping and potting compound to seal all necessary dry components of the transducer. A hole was drilled in one end cap for the cable to exit. At the other end of the cable, a buccaneer connector is used to plug the transducer into the control box. The wet area of the transducer is left exposed to the water at depth during submarine operation. The final waterproofed pressure transducer is shown in **Error! Reference source not found.3**.



Figure 13 - Waterproofed Pressure Transducer

Waterproofing

During competition the submarine and its operator are fully submersed in water, and as a result all electrical components must be waterproof. Maximum operational depth of the submarine at competition is 22 feet, so it is crucial that all electronic components are waterproofed to at least 22 feet of depth. Waterproofing requires extensive testing to ensure that there will be no leaks during competition. To make the waterproofing of the control system easier as well as to allow easier access to the control system, the rear end of the submarine was made removable to gain access to waterproof enclosures for the main computer control system (cRIO) and the motors. This design allows the entire control system to be easily removed from the tail end of the sub.

Three separate waterproof enclosures were made to seal off different parts of the control system from water. The first enclosure houses the NI 9022 cRIO and its modules, as well as other control system components. The second enclosure houses the motors, and the third enclosure is for the joystick. Some other small components such as a pressure transducer and battery packs were also individually waterproofed. All of these separate enclosures are connected by wires that are epoxied using potting compound around entry points as well as Buccaneer IP68 rating waterproof cable connectors. The control system is designed to be easily replaceable in case of failure of component or waterproof enclosure. If one component fails, back-up components are available to replace the failed one, allowing the submarine to make another run down the race course while the component at fault is being repaired. The design of multiple enclosures is also an advantage in the case that water leaks into one component, not all components will be ruined.

For the controller housing, an aluminum box was constructed out of 3/8 inch 6061 aluminum alloy sheets. This material was chosen for its strength, corrosion resistance, weldability and machinability properties; it is a high quality aluminum alloy. The aluminum sheets were TIG welded together by filling in the corners with material for a water tight seal on all edges. The box is enclosed on five sides for the controller box and circuit boards to slide in and out. There is a one inch lip on the open side of the box for the cover to attach to with a series of screws around the outer edge clamping the lid down to the box and compressing a gasket preventing leaks into the box. The box measures 8in x 4.25in x 8in with an extra 5/8 in. overhang on each side as shown in Figure 14(a). The box was made to these dimensions in order to maximum the box's size while conforming to the space constraints in the rear of the sub, as well as allowing the enclosure to be removable through the rear when the tail cone has been removed. A prototype was made initially out of scrap peg board (Figure 14 (b)) to ensure a proper fit within the rear of the sub as well as to encase the Compact Rio and custom built circuit boards.

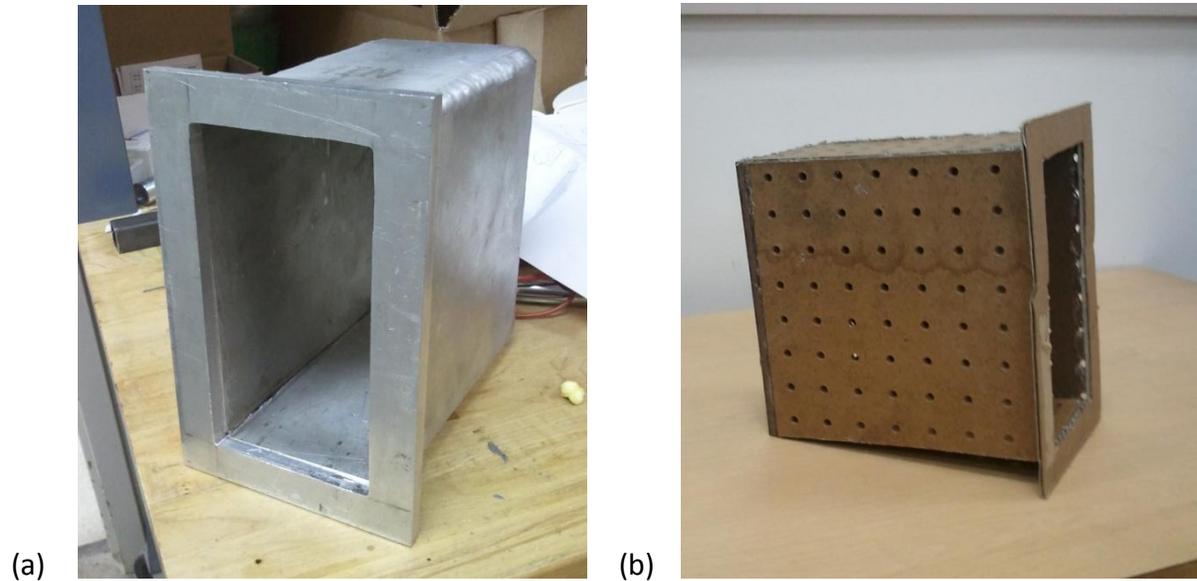


Figure 14 - (a) Electronics box enclosure unfinished, (b) prototype electronics box

Motors

Motor selection was made based on maximum load calculations that the control surfaces will experience. It was determined that geared DC motors with 50 in-lbs of torque are suitable to drive each individual control surface with no back drive. Potentiometers will be affixed to the output shaft of the gearbox as position feedback of the control surfaces to ensure that power to the motor will be cut if a control surface reaches the max deflection angle of ± 10 degrees off center. Finally, a set of four relays will set up in an H-bridge formation with each motor to allow for clockwise and counterclockwise rotation of the control surfaces.

An aluminum waterproof box has been fabricated to house four DC motors that will drive the rear horizontal and vertical fins. The bow planes will remain stationary. The box is 5.436in x 5.487in with four holes drilled into it for the motor shafts that will be waterproofed with latex tubing and hose clamps. The box was constructed by welding aluminum plates together. Wires to the motors also have waterproof connections to both the motor housing and the main computer system enclosure to ensure water is not able to pass through and to eliminate points for leaking into the electronic components of the main computer control system. Figure 15 shows a model of the box with motors enclosed and control surface shafts coupled to motor shafts. Figure 16 shows the actual motor box.

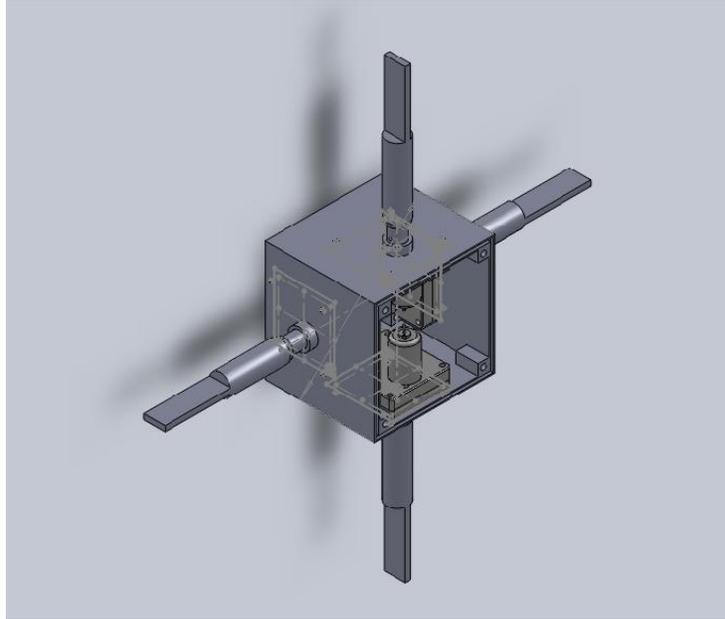


Figure 15 - Aluminum Waterproof Box for Electric Motors

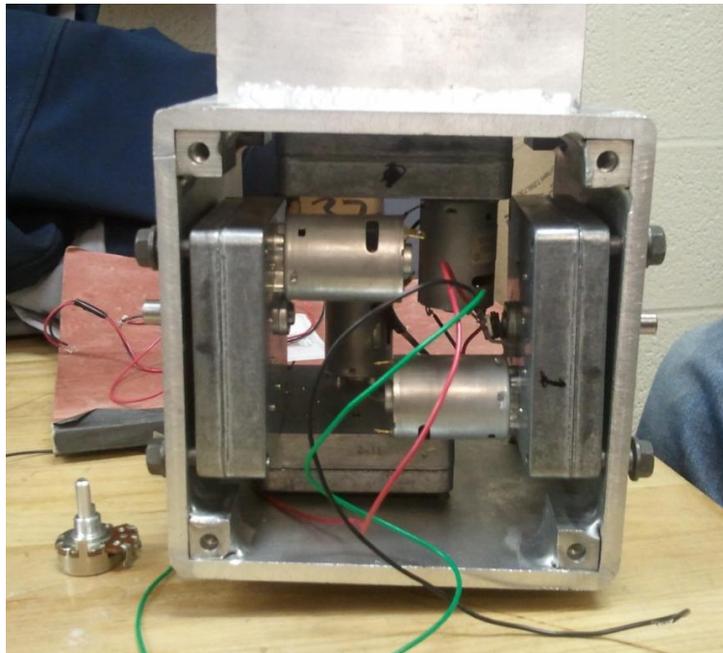


Figure 16– Actual Motor Box

Auto-Pilot Controller and Electric Motor Enclosure Air Protection System

Because the submarine's electronic systems require waterproof enclosures, an open loop high pressure air system was also designed and installed to help prevent the ingress of water. When the enclosures contain compressed air at higher pressure than the surrounding water pressure,

any leaks will result in air being exhausted at the spot of the leak rather than water being forced in. The water pressure experienced at the bottom of the competition pool was selected as a design guideline for this air system:

$$P = \gamma_{\text{water}}h$$

Where P is water pressure,

γ_{water} is the specific weight of water at 60°F (62.4 lb_f/ft³), and

h is the water depth.

$$P = 62.4 \frac{\text{lb}_f}{\text{ft}^3} \cdot 22\text{ft} \cdot \frac{1\text{ft}^2}{144\text{in}^2} = 9.53\text{psi}$$

As long as the enclosures are pressurized at least 10 psi above atmospheric pressure, a positive pressure is guaranteed within them at any depth in the pool.

A simple schematic of the air system is shown in Figure 17 below. A 48 cubic inch compressed air bottle with a 3000psi fill capacity was chosen for an air supply due to its small size and the availability of high pressure air. Several fixed and adjustable regulators are used to step pressure down to the desired value while pressure relief valves are installed to prevent over pressurization. Because both enclosures are supplied air from a common source through a tee fitting, they are essentially married into one volume of air. In the event of a leak larger than what this system is capable of protecting the enclosures from, check valves are installed to prevent water backflow from one enclosure to the other.

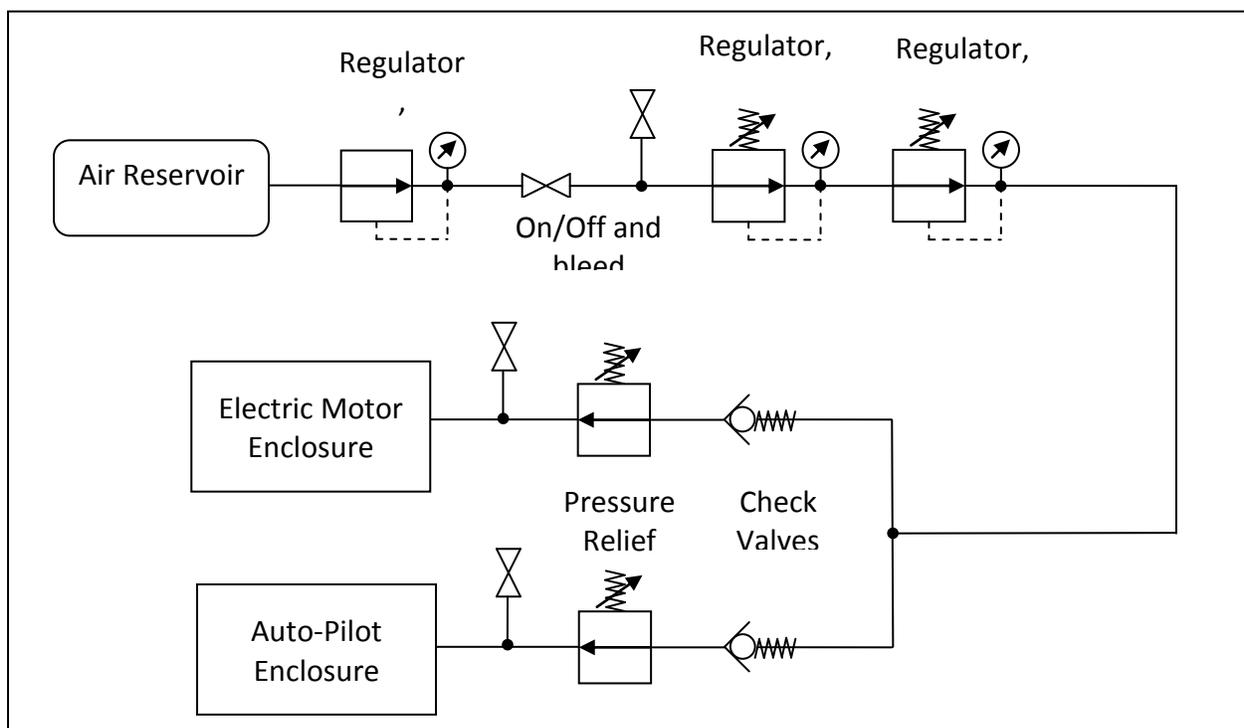


Figure 17 – High Pressure Air System Schematic

Safety Systems

Color Coding and Labeling

With safety being the number one priority for the human powered submarine races, all of the safety systems were painted with high visibility orange to denote that they are part of an emergency exit strategy. The submarine cover has been painted orange around the cover hand holds with the word “rescue” pointing to the exits. In addition to the submarine latch, the strobe light and emergency buoy were also painted orange to signify Emergency safety systems.

Strobe Light and Emergency Buoy

A strobe light and emergency buoy are required to be attached to the submarine as safety precautions. The team has chosen to have a strobe light attached to the top of the sub for maximum visibility as seen in Figure 18.



Figure 18 - Safety Strobe Light

The emergency buoy is also attached to the top of the submarine, only further back and behind to the propulsion system, shown in Figure 19.

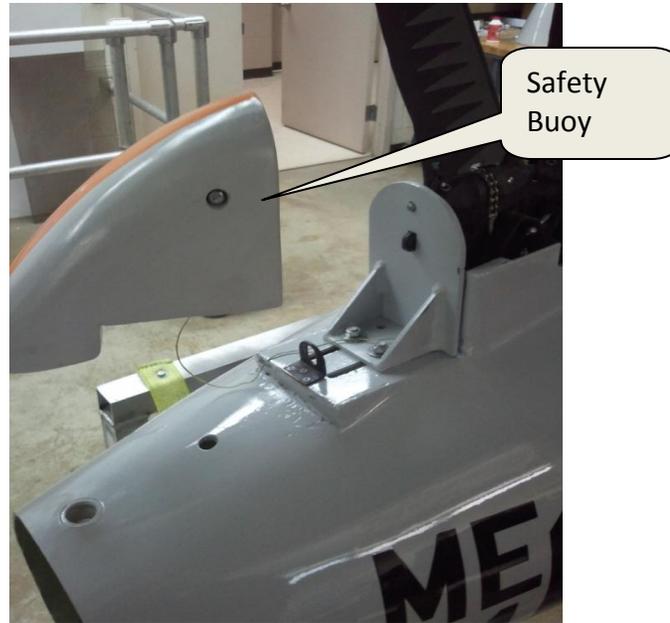


Figure 13 - Safety Buoy (detached)

The buoy mechanism consists of an electro-magnetic solenoid attached to a stiff spring. The solenoid pin will act as a latch that will hold the buoy in place during the race. The solenoid requires power to pull the pin in place; this is achieved through a battery pack installed under the buoy mount. While the solenoid is supplied with power, the magnetic force pulls the pin and latches the buoy to the submarine, completing the electric circuit. If and when power is lost to the solenoid, the circuit will be broken, and at this time the spring will pull the pin out from the latch releasing the buoy.

A cable is attached to the buoy and runs along the inside of the submarine, reaching to a dead man's switch that the pilot will hold in his or her hand continually throughout the race. If the switch is held down, power is sent to the solenoid. If it's not held down, power is instantly lost. In case of an emergency or pilot incapacitation, the dead man switch will be triggered, and the buoy will deploy. When the buoy is released, it will float to the surface of the water, signaling the rescue divers for help. The strobe light will act as a guide to help the rescue divers locate the submarine in case of an emergency. Another strobe light will be fixed to the driver so that the safety divers can quickly find the distressed pilot.

Pilot Restraint System

The pilot restraint system is made up of a harness worn by the driver that will be connected to restraints located to the driver's rear left and rear right. Restraining the pilot not only ensures a more ergonomic position for the driver, but also prevents a loss of energy to the drive system. Without the restraint system, the pilot would be pushed back and forth within the sub due to the pedaling motion, and a large amount of energy would be wasted.

The restraint, featured in Figure was milled entirely of machined 6061 aluminum to prevent rusting. The restraint also has rounded edges to further ensure driver safety. The device is attached to the submarine using a mixture of West System's Epoxy and their #105 resin. The adhesion strength of the epoxy for this application has a shear strength of 1800 psi and a tensile strength of 1400 psi. These strengths indicate that the risk of epoxy failure would be minimal as the total bonded surface area of the mounts is 28 square inches. Bond failure is unlikely to occur even under the condition that all of the driver's leg strength and thrust is somehow completely transmitted through the harness system and none of the power is transmitted to the propulsion system.

The harness system is also user friendly. The holes of the adjustable linkages are large and easy to align when repositioning the harness attachment for different driver heights. The harness attachment is held to the adjustable panel using quick release pins. These pins allow for the pilot to be held securely in place, but also allow for the pilot to execute a quick release in case of an emergency situation by pulling on the orange linkage between the two pins (see Figure 16).

The coated wire connecting the two pins has been dipped in orange Plasti-Dip, so it can clearly be seen as an emergency release.

A stainless steel carabineer has been placed through the large hole of the restraint to connect the driver's harness to the restraint. The complete installed device is seen in Figure.



Figure 20 - Pilot Restraint System (pictured without harness attached)

If the pilot's knees were to be flat against the bottom of the sub, it would be impossible to bend them in the manner necessary to push or pull on the driving pedals. In order to correct for this, the restraint system is positioned so that the driver's hips are elevated, thus providing a usable pocket of space for the required leg motion to take place. A carabineer is used on both sides of the pilot, connected to the harness, at the location circled in Figure .



Figure 21 - Location of Carabineer Attachment

Clipless Pedals

The human powered submarine has clipless pedals installed in the propulsion system. The pilot of the submarine will be wearing clipless sandals that connect to these pedals. This connection provides comfortable footing for the pilot and also allows for the best range of motion. Regular clip pedals like the kind used for bicycling do not cover the entire area of the foot. However, the clipless pedals used in the submarine cover the entire foot keeping the foot rigid and allowing for a greater transfer of energy to the propulsion fins. The sandals have adjustable Velcro straps that can fit to the feet of any potential pilot, allowing anyone to be able to clip into the propulsion system flawlessly. With the driver connected directly to the crank, there will be a greater amount of power output when compared to the general non-clipless pedals. The clipless pedals are also safe because they have an easy release arrangement that allows for the pilot to twist out of the pedals very quickly. Each potential pilot has been trained to clip in and clip out in an efficient manner before entering the submarine.

Diver Training

During the month of October, the Human Powered Submarine team worked towards becoming scuba certified. Enrolled in a PADI open water diver course, instructed by Randy Cook of Aqua City Scuba, based out of Waterville, Maine, the team met at Wallace Pool twice weekly for two hour sessions of confined water dives followed by two to three hours of classroom time.

During the confined water dives, group members began to learn basic dive skills. They were taught how to properly set up and use scuba gear. They also learned about how to handle underwater out of air emergencies, gaining experience with octopus breathing and making an

emergency ascent. Other skills, such as making proper water entrances and descents, clearing water out of a flooded mask, and underwater communication were also mastered.

In the classroom lectures, teammates began to develop an understanding of the basic principles of scuba diving. They studied things such as how pressure affects the human body, how to best control emergency situations, and what to consider when planning dives. Outside of class, group members read and studied the PADI Scuba handbook, which included daily homework assignments to further their investigation into the scuba diving world. Each class was concluded with a quiz of the information covered so far, in order to test each student's understanding of the material. On the final day of class, a comprehensive final exam was conducted, which all teammates needed to pass in order to move forward towards their certification. All students passed with flying colors.

On October 31, 2010, the HPS team made their first open water dive at Lake St. George in Liberty, Maine. Braving the chilly temperatures outside, and the even chillier water temperatures, they gained some real world scuba experience, performing many of the tasks they learned in the confined pool dives but in the deeper, darker environment. On November 2, the team made their final open water dive, this time in the ocean, near Acadia National Park in Bar Harbor, ME. Again they brushed up on their scuba skills, and learned some additional ones such as underwater navigation and how to cope with extremely limited visibility.

The skills the HPS team learned during this 5 week course will be essential for success in the International Submarine Race. Experience with using and setting up the scuba equipment will not only give the team the skills they need for successfully doing so in the competition itself, but it will also give them insight in how to best design the safest and most ergonomic set up for the diver-submarine interaction. Familiarity with the physical act of scuba diving and the health risks associated with it will help produce the most effective training program for potential submarine drivers. And finally, the team's understanding of the dangers related to diving, the skills necessary to prevent emergency situations, and the methods to manage them should they occur will be essential for the HPS team to safely compete in the submarine race.

In March 2011, the team worked towards achieving their Scientific Diver in Training certification, a requirement of the University of Maine needed in order to use the submarine at the campus' swimming pool facilities. During this course, instructed by dive safety officer, Chris Rigaud, the HPS team underwent a series of extensive swim tests, refreshed their scuba skills, and proved their ability to operate safely in the confined space of the submarine. The course consisted of five 3-hour pool sessions. A total of seven team members made it through the course and are now certified to use the submarine and scuba gear on campus without a dive instructor's supervision. This made it possible to test different components of the submarine as well as train for the competition.

Thrust and Drag Testing

By measuring the thrust output of the submarine as well as the drag force, it is hoped that clear conclusions will be drawn regarding the overall velocity of the submarine versus time and the total distance traveled by the submarine as a function of time. This was done by performing thrust and drag force experiments which are explained below.

A drag test was performed at the University's Aquaculture Research Tow Tank. The submarine was towed at a low known velocity. Using the Equation 1 below, the submarine's coefficient of drag was determined to be *approximately equal to .33*.

$$C_D = \frac{F_D}{\frac{1}{2}\rho AV^2}$$

Figure 22 below shows the submarine in the tow tank test setting.

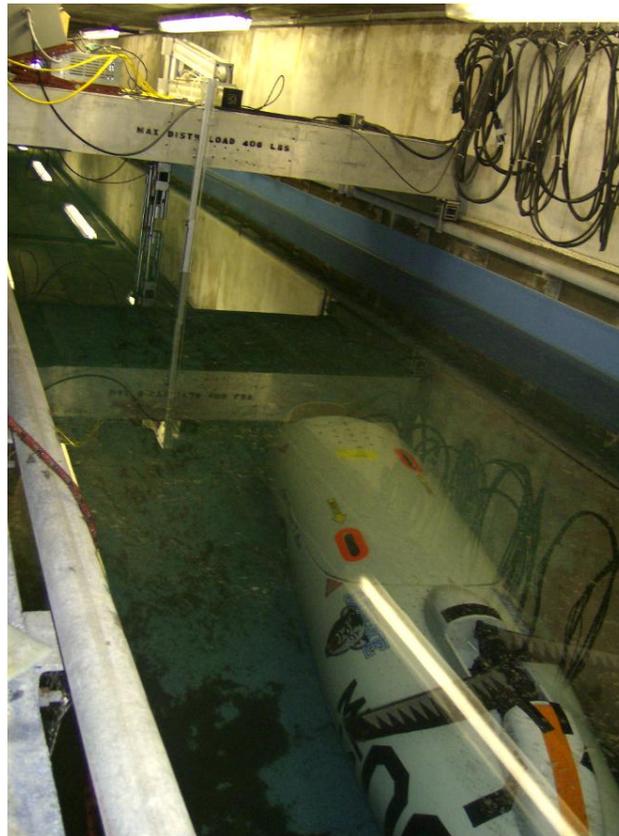


Figure 22: Tow Tank Drag Test

The thrust experiment took place in the University of Maine's Wallace Pool, using 6 different pilots. The submarine was placed in the pool and attached to the test rig detailed in Figure 23.

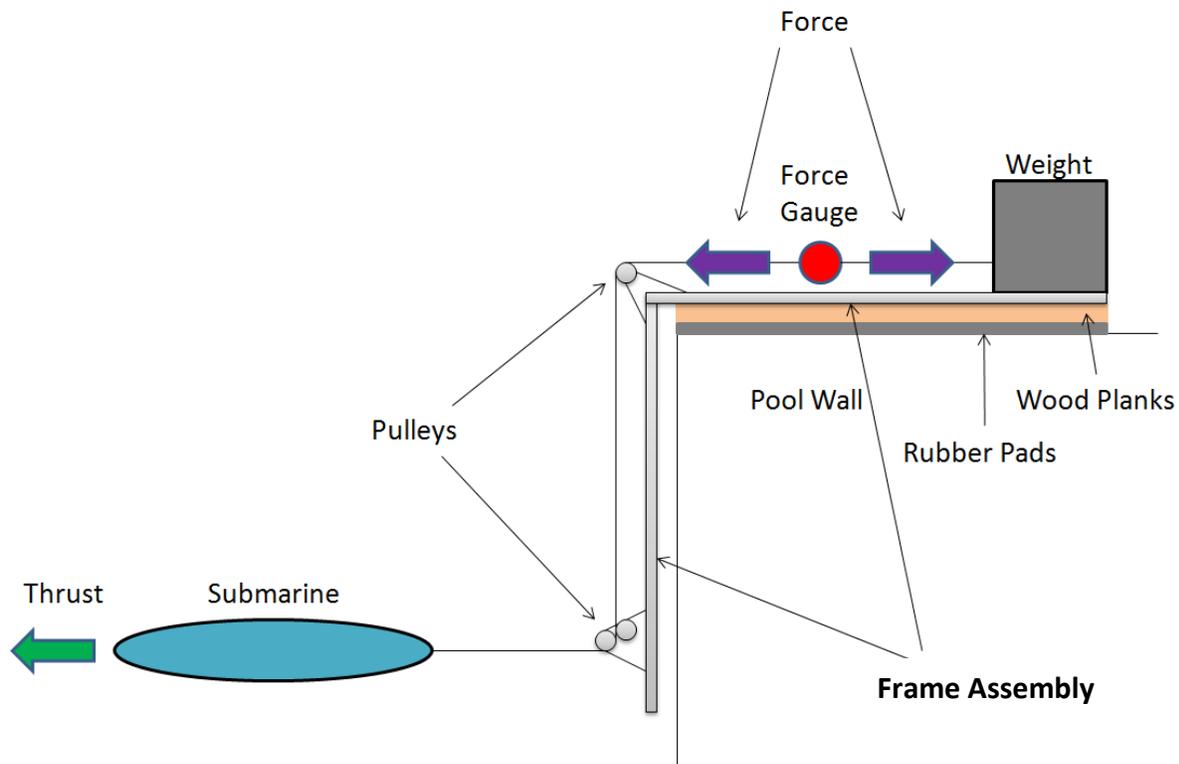


Figure 23: Test Setup for Thrust Test

A rope connected the stern of the submarine to the load cell via a series of pulleys. The load cell downloads the force of thrust as a function of time to a laptop computer interfaced with a LabView Data Acquisition System located on the pool deck. Each of the six potential submarine pilots entered the submarine and began pedaling under competition conditions. The acquisition system recorded the force produced by the submarine over a course of 60 seconds. Using the coefficient of drag found in the Drag Test, velocity can be found as a function of time using the following Euler Equation:

$$\frac{V_t - V_{t-1}}{\Delta t} = \frac{F_T - \frac{1}{2}\rho C_D (V_{t-1})^2 A}{m}$$

Using the data generated from these tests, plots were then be constructed representing Thrust vs. Time, Velocity vs. Time, and Distance vs. Time as shown in Figures 24 through 24 below.

Figure 24 below shows that most drivers tend to have the most thrust output at the very beginning of their cycle, the greatest output recorded at 60lbs. After an initial peak, the thrust for all drivers leveled out to a relatively constant value, ranging between 25 and 35 lbs, depending on the driver.

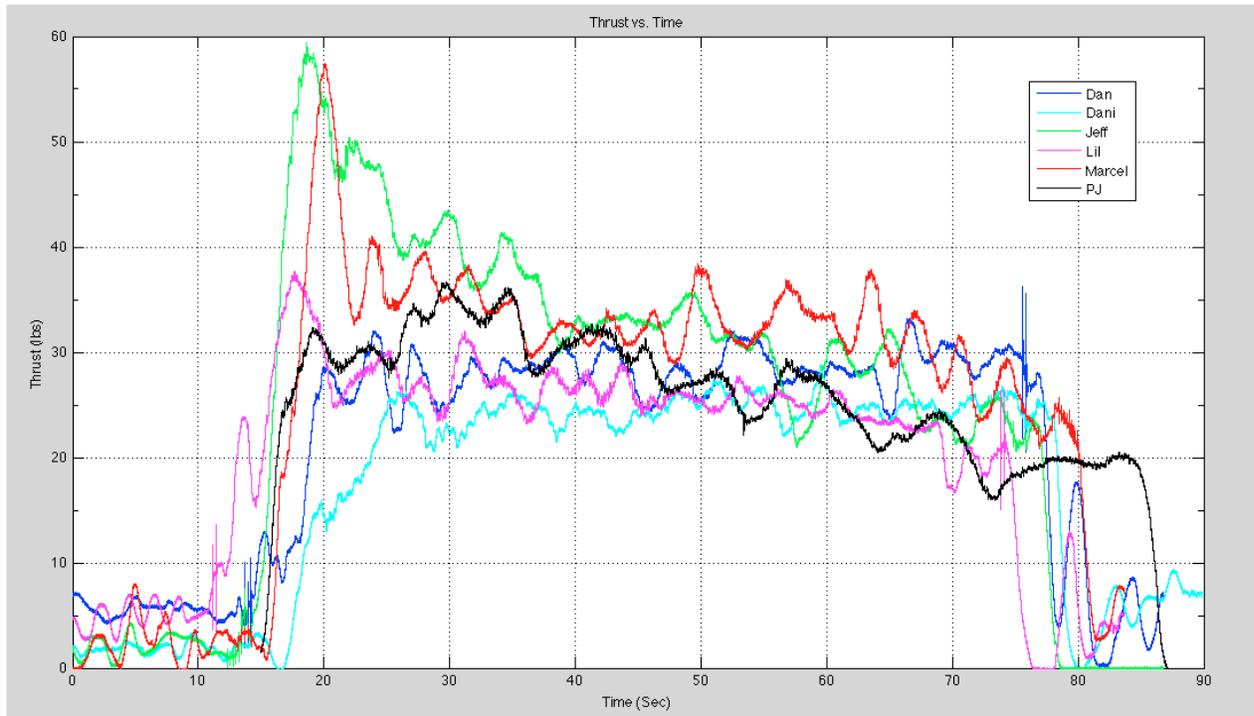


Figure 24: Thrust (lbs) vs. Time (s) for 6 different pilots

Figure 25 below shows each driver's velocity as a function of time. The maximum velocity achieved was approximately 4.15 knots, which surpasses the University of Maine's previous speed record of 3.996 knots. However, most drivers were producing much lower velocities in the 3.0 to 3.5 range. Considering that this test was one of the initial attempts most of the drivers have had powering the submarine, these figures are likely to improve with more experience and physical training.

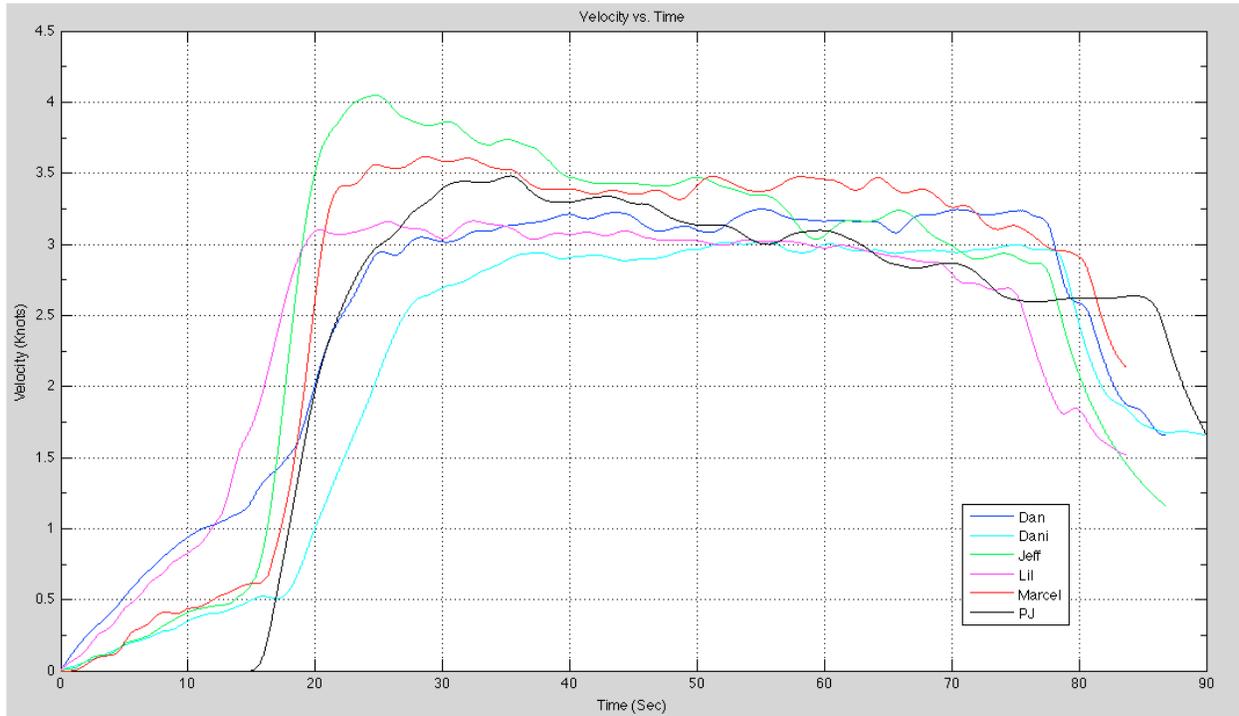


Figure 25: Velocity (knots) vs. Time (s) for 6 different pilots

Figure 26 below shows the theoretical distance the submarine traveled underwater as a function of time. The racecourse is 328 ft (100m) and from this it is possible to determine the fastest finishing time as approximately 70 seconds. This timeframe could be greatly reduced if the time needed for acceleration were to be factored out.

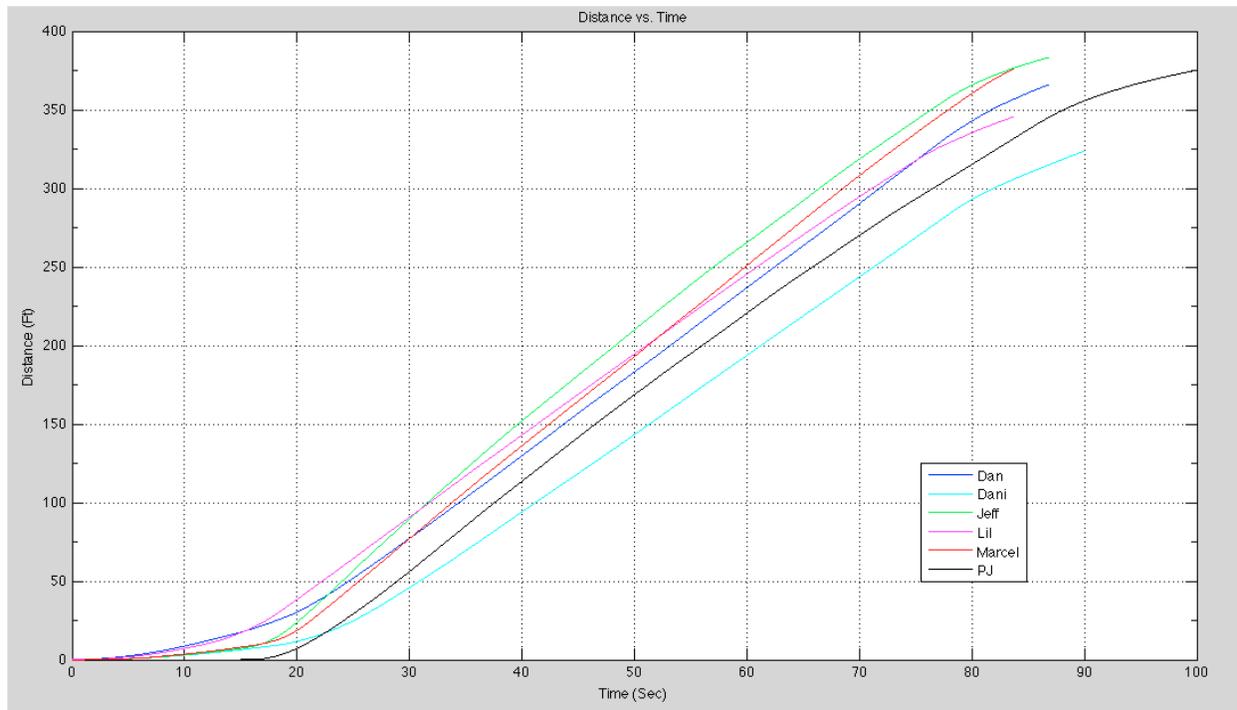


Figure 26: Distance (ft) vs. Time (s) for 6 different pilots

Budget

Auto-Pilot Team:

Compact DC Gearmotor - 6409K12	\$44.96
4 1/2" x 7/8" cut-off wheels - Model 05250	\$19.70
10k-Ohm Wheel Potentiometer	\$5.97
Description - CARD RELAY 4 RELAYS 24VDC 5A SPST	\$82.50
Servo Motor	\$19.99
Male PVC Plug - Item # 53292	\$4.98
Female PVC Plug - Item # 44863	\$11.64
1" or 2" PVC pipe	\$2.00
1" or 2" end caps for PVC Pipe	\$10.00
Clasps to hold on tail section	\$20.00
Analog Joystick with Standard Handle w5k Potentiometers Part Number: 50-2470-00	\$171.20
HP G72-259WM Refurbished Notebook PC - Intel Pentium T4500 2.3GHz, 4GB, 320GB HDD, DVDRW, 17.3" LED, Windows 7 Home Premium 64-bit	\$499.99
Part #: 780718-01, CRIO-9022, Real-Time PowerPC Controller for cRIO, 533 MHz	\$959.70
Part #: 780917-01, cRIO-9113, 4-slot Virtex-5 LX 50 Reconfigurable Chassis for cRIO	\$599.70
Part #: 182238-02, RS232 Null-Modem Cable, DB-9 Female to DB-9 Female, 2m	\$27.00

Part #: 182219-05 , E1 Ethernet Cable, Twisted-pair, 5 m	\$18.00
Part Number: 350100T-00 , Demo, LabVIEW 2010 Platform Evaluation DVD	\$0.00
Part #: 779357-01 , NI 9205 32-Ch ± 10 V, 250 kS/s, 16-Bit AI Module w/ DSUB	\$629.10
Part #: 779103-01 , NI 9933 37pin D-Sub connector kit	\$134.10
Pressure Transducer product no. PX309-050-A5V	\$245.00
Potting Epoxy 8 OZ	\$119.25
Joystick	\$171.20
Digital Module	\$500.00
Batteries	\$200.00
IMU	\$3,000.00
Compact DC Motors	\$359.68
Hookup Wire Rack	\$100.00
Year Total	
\$7956.00	

Bio-Mechanics Team:

Scuba Diving Lessons & Equipment Rentals	\$3,300.00
ISR Entry Fee	\$100.00
Quick disconnect pull pins 1/4" diameter, .8" long (part # 94975A153)	\$15.76
West System 105-A epoxy resin, 1 quart (part # 7480A41)	\$38.90
West System 205-A fast hardener, .44 pint (part # 7480A42)	\$19.57
West System 406-2 high density filler/additive, 1.7 oz (part # 7480A33)	\$9.33
T-Slot Nut and Stud Setup Kit - 3/8"-16 Stud, 7/16" Table Slot (part #3396A12)	\$64.78
Aluminum Rod (Alloy 6061), 1" Diameter, 12" Length (part # 9062K211)	\$14.50
Aluminum Slip-on Rail Fittings, Round, Fits 3/4" Pipe Size (part # 4698T52)	\$16.00
High-Strength Aluminum Tube, 36" length (Alloy 2024) 5/8" OD (part #1968T822)	\$27.61
Turcite Rod Blue, 1" Diameter, 12" length (part # 7521T16)	\$20.82
Carabiner: Type 316 Stainless Steel (Part # 3397T53)	\$22.22
Ball-end lever handle, 1-3/8" dia., 1/4"-20 thread (Part # 6046K16) BLACK	\$1.40
Ball-end lever handle, 1-3/8" dia., 1/4"-20 thread (Part # 6146K16) RED	\$1.93
Stainless steel lever shafts, 5" shaft length, 1/4"-20 thread, (Part # 8384K56)	\$26.54
7' length Teleflex TFXtreme control cable, universal marine (Part # 88806)	\$62.46
Plasti-Dip Create Your Color Kit. Part Number (38098)	\$16.70
4 foot heavy-duty cam strap	\$4.19
ISR Entry Fee	\$900.00
Various Mechanical Parts	\$350.00

Scuba Equipment Certification	\$300.00
Biomechanics Equipment	\$500.00
Team Jackets	\$560.00
Pool Rentals	\$840.00
Year Total	
\$7212.71	

Controls Surfaces Team:

Wood Plank	\$30
Metal Shaft	\$100
Waterproof Seals	\$75
Aluminum Plate	\$150
Misc.	
Parts/Accessories	\$100
Year Total	\$455

Total budget for all teams: \$15623.00

For more information on the entire project visit: <http://www.hyvmind.com/kellsey>

