University of Washington
2011 Human Powered Submarine Team

ISR 11 Technical Report

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By

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The following report outlines the University of Washington Human Powered Submarine Team's 2011 submarine design *Dubs' Sub*, and the team's preparation for ISR 11. The material is more a summary of the work completed than a complete technical report, due to time limitations during manufacturing and testing. *Dub's Sub* has been tested in open water race trials twice, and was delivered to the Boeing Company on 18 June 2011 for shipment to the Carderock Surface Warfare Center. After failing to complete a run during ISR 10, the team's objective for 2010/2011 was simple: rebuild the engineering project to be able to successfully complete at ISR once again. In the process, the team has redeveloped a strong core of young engineers to lead the project into the future.

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I. Team Background and Objective

The University of Washington's Department of Mechanical Engineering has produced a submarine for the International Submarine Race since the early 1990s. The Human Powered Submarine Team (UW HPS) has continued to be an excellent project for developing design experience, but also creating an environment to learn a variety of manufacturing processes while collaborating with a team. Some teams have proven to have significant success, such as 2003's *Sirius*, which received the first ever Smooth Operator Award. 2007's *Dive Dawg* was recognized for performance, best use of composites, and best design report.

After 2007, the team experienced a decline in interest and organization. In preparation for ISR 10, UW HPS struggled to maintain a leadership core, and, as a result, suffered significant delays in manufacturing and testing. The resulting submarine, *Beluga*, was not capable of racing when it reached the Naval Surface Warfare Center. Despite its race failings, *Beluga* won awards for its use of composites and innovation.

After ISR 10, it was determined that UW HPS needed to undergo significant changes to serve its role as a successful engineering project. Three of the team's race participants decided to rebuild the team, and inspire a new interest amongst students to participate in the design, building, and testing of a human powered submarine.

The 2010/2011 team objective is to reestablish itself as a successful engineering program, both at the University of Washington and the International Submarine Race. In order to complete the objective, the team must set design goals that are tangible and realistic. By focusing efforts on manufacturing aspects of engineering, the team will garner the interest of underclassmen engineering students. A continued struggle in recent years has been team continuity, so it is crucial to build a team of multi-year participants.

In the climate of rebuilding an engineering project, It has been determined that systems design should be kept simple. Concepts already known to be successful have been pursued, and applied in a manner that will allow for efficient manufacturing, installation, operation, and maintenance.

As the team continues to regrow as an engineering tool and exciting project to be involved with, its capacity for higher-level engineering will be able to commence. Progress has been immense since 2009, and the result should be apparent in *Dubs' Sub*'s performance at ISR 11.

II. Submarine Design

Design for *Dubs' Sub* began in September 2009. Experimental designs for electrical controls and sensor systems were pursued, and eventually abandoned due to financial limitations. It was determined that designing and manufacturing a new submarine hull for ISR 11 would be unachievable, and the previous hull used for *Beluga* was suitable for systems design. All system designs were thus pursued as retrofit projects to the existing submarine hull.

Hull

The submarine hull was originally used during ISR 10 as *Beluga*. It was incomplete at the time of racing, and required considerable finishing work before testing for ISR 11.

The geometry is a modified airfoil loosely based on the body of a squid. Its aspect ratio has been adjusted to accommodate a diver, and the pedaling motion expected for propulsion (Figure 1).

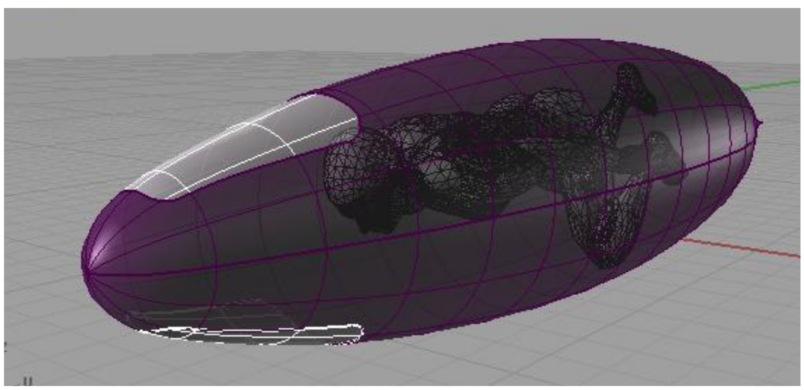

Figure 1 - Hull modeling in Rhinoceros®

The hull block dimensions are 116" x 28" x 24". It was expected that a diver of 72" would be capable of operating the submarine at this size, but the dimensions have proven to limit the submarine's capacity.

While most airfoils tend to taper out to the trailing edge in a concave fashion, this hull design carries the maximum foil thickness further aft, and remains convex to allow ample room for systems installation. It is expected that turbulent flow will be tripped well ahead of the after third of the submarine, so laminar flow over this area is not nearly as much a concern. The ease of systems installation was considered a priority over keeping flow attached towards the submarine's tail.

Controls

For interior pilot input, a simple mechanical pull-pull system is utilized. The system consists of two rotating handles near the pilot's head (Figure 2). One handle controls pitch, while the other handle controls yaw. Two cables run from each handle along the walls of the submarine, to half moon joining bars. Each half moon bar joins two exterior control fins in the after end of the submarine (Figure 3). These fins, a pair of rudders and a pair of elevators, serve the simple function of controlling the submarine's direction of travel by rotating it on its axes of pitch and yaw.

The concepts behind this system have been implemented several times for previous races. It was determined that, in going with the team's objectives to rebuild the team and return to the ISR successfully, that keeping the system mechanically simple was the best option.

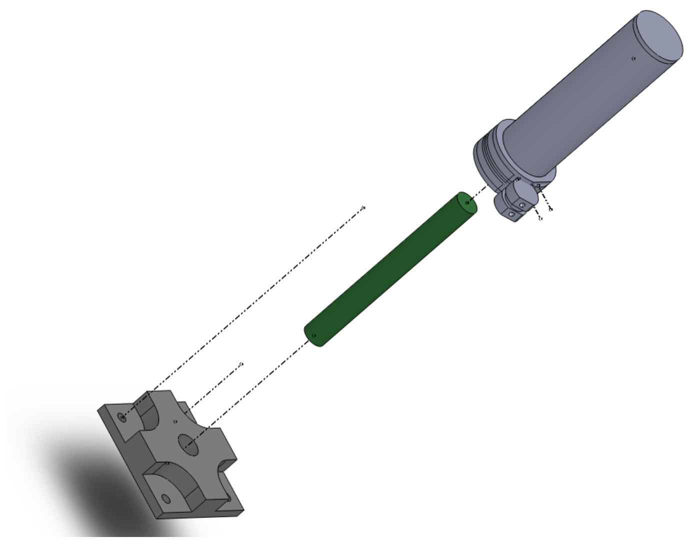

Figure 2 - Control handle and base

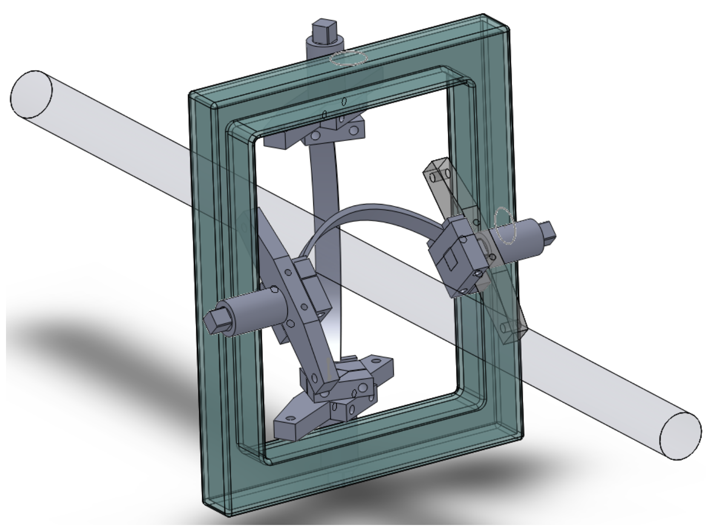

Figure 3 - Half moon control fin linkages

Propulsion

The propulsion design implemented for *Beluga* during 2008/2009 utilized turnbuckles for mounting the drivetrain structure to the hull. It was expected that small adjustments in drivetrain placement could be made with the turnbuckles, easing the alignment of the propulsion system with the submarine's stern opening.

In practice, turnbuckles proved to be extremely difficult to not only align the propulsion system, but keeping the mounting components free of the propulsion system's cranking motion. It was therefore decided to pursue a completely different method of mounting the propulsion system.

In keeping with the goal to keep system designs simple, the propulsion system is not highly innovative. It consists of a 3:1 taper bevel gear transfer, converting the rotation of bicycle cranks into the rotation of an aluminum shaft. The submarine is propeller-driven, with two propellers having a very small developed area ratio. The gear and propeller components minimize new design concepts. The system mounting, though, took considerable design thought. In order to avoid using a universal joint to ensure shaft alignment, a mounting plate capable of shifting in three directions was utilized (Figure 4). A bicycle bottom bracket is used to support the large bevel gear and pedal cranks. Bearing mounts supports the driveshaft. The mounts and bottom bracket attach to the same plate. The bottom bracket is capable of moving transversely in the submarine; the supporting plates are capable of moving vertically through the use of foam shims; the entire gear structure is capable of moving axially along its hull-mounting structure.

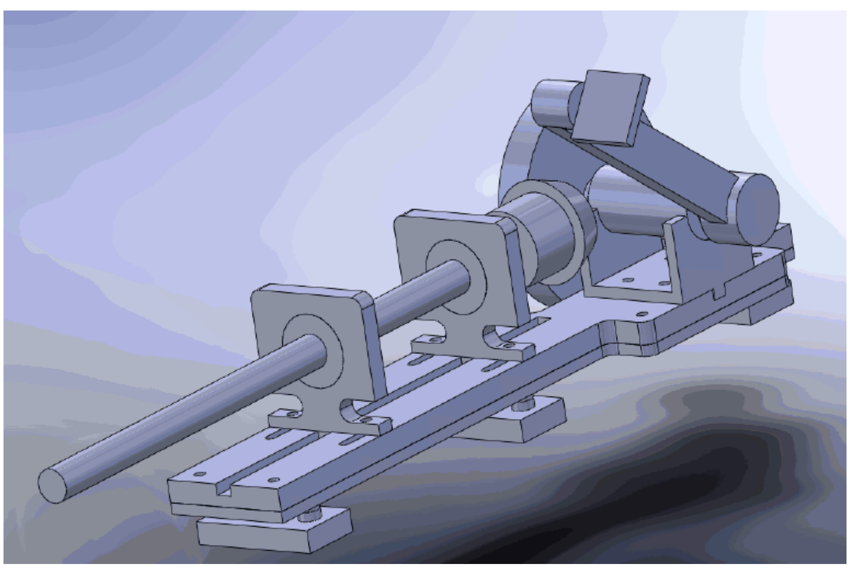

Figure 4 - Propulsion gear and shaft mounting

The entire gear and shaft mounting assembly is fixed in the submarine via an aluminum tube A-frame. This frame also serves as the mount for the controls system half moon bars.

It should be noted that further system design occurred concurrently with manufacturing, and was not well documented during the manufacturing period. All systems in the submarine vary from how they appear in this report.

IV. Manufacturing

The most critical objective of UW's 2010/2011 team was to build a group of engineers proficient in manufacturing processes. Where design processes were maintained to be simple, manufacturing became a focal point of the team's progress.

Hull

Manufacturing of the submarine hull occurred in spring 2009, with the assistance of Janicki Industries. Prior to hull manufacturing, the team constructed a foam plug, followed by a fiberglass female mold (Figures 5 and 6). Vacuum-assisted resin transfer molding (VARTM) was used to fabricate the hull. It consists of eight plies of carbon fiber, sandwiching a balsawood core (Figure 7). A ply of fiberglass was added to the interior and exterior to improve the hull's sandability. The hull was formed in two halves, which were then bonded together to form a seamless shell.

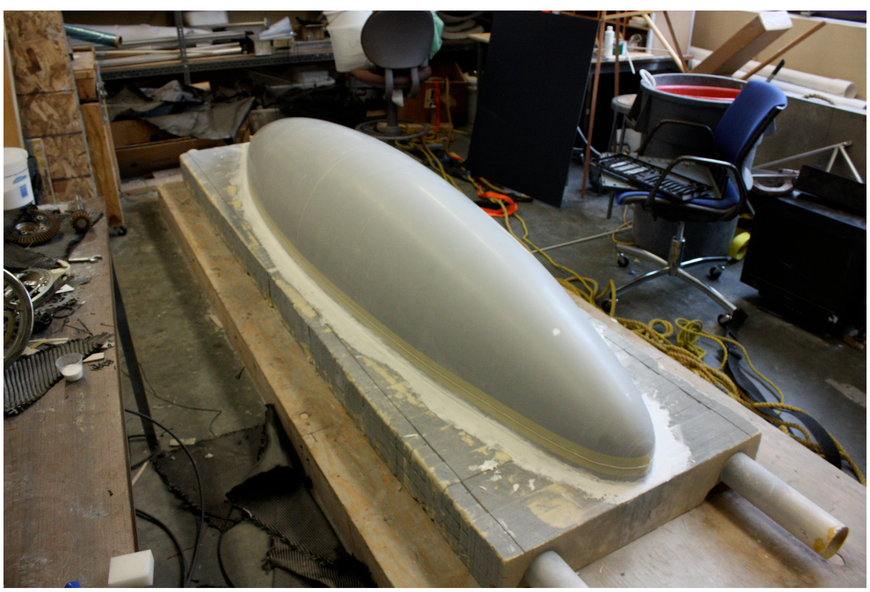

Figure 5 - Sacrificial male foam plug

Figure 6 - Finished fiberglass mold

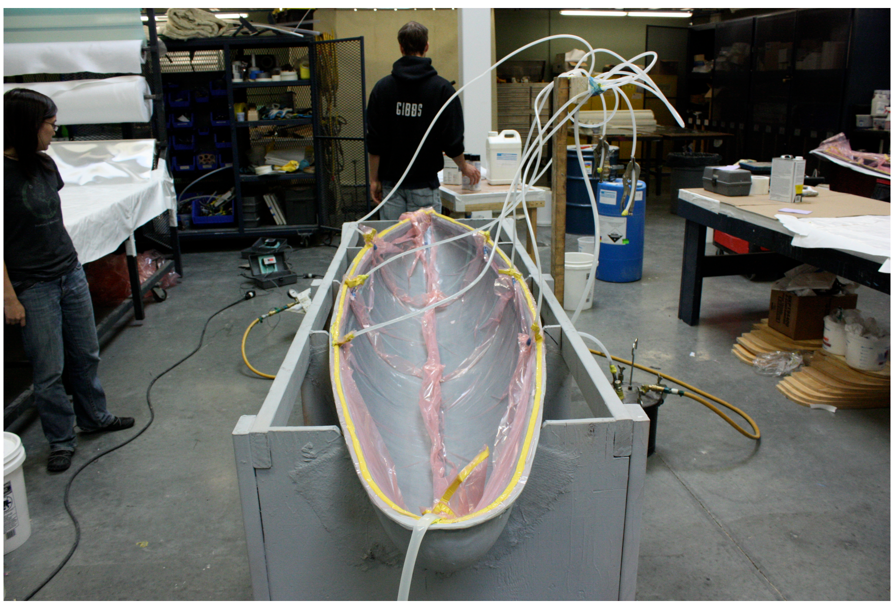

Figure 7 - Hull manufacturing with VARTM

All hull manufacturing occurred prior to ISR 10. In the time since, several other hull projects have proceeded in preparing the submarine for racing. One of the most important is window manufacturing.

Window manufacturing became an iterative process, both in method and material use. First, acrylic was vacuum-thermoformed into female plaster molds. This method resulted in moisture bubbling that required sanding. Difficulties in cutting the windows to shape were discovered, as the acrylic was very brittle and had a tendency to crack and fracture. It was decided that a new method should be pursued.

Next, polycarbonate was open-thermoformed over a large male mold. The polycarbonate was considerably more resilient than the acrylic, but required six hours of pre-drying (heating at a lower temperature than thermoforming) to prevent the formation of bubbles. The polycarbonate also required a higher thermoforming temperature. This increase in temperature had a tendency to crack the large plaster male mold. The polycarbonate also deformed as it cooled, not maintaining the expected geometry. This process was soon abandoned.

Both attempted window-manufacturing processes experienced issues with the window material and the mold material. Therefore, the window and mold materials were reconsidered. For window material, a polymer called Acrylite® was found. Acrylite® is an acrylic that has been modified to imitate several polycarbonate properties. It is highly resilient and easily machined, but does not require pre-drying and can be thermoformed at lower temperatures. In addition to the use of Acrylite®, a fiberglass male mold was manufactured. This mold is much stronger and robust than the plaster molds, and better suited for high-temperature molding.

A completely new process was developed to thermoform the Acrylite®. Acrylite® has a tendency to permanently fog when raised to very high temperatures (e.g. from contacting metal or other materials while heating), so it was decided to suspend the Acrylite® during heating. The window material was formed over the mold after it had reached thermoforming temperature to reduce the formation of moisture bubbles between the window and mold (Figure 8).

Figure 8 - Window manufacturing with Acrylite®

The results were spectacular. The window was not only bubble free, but was also easily machined and highly resistance to impact. After some process optimization, two race-satisfactory windows were manufactured.

Controls and Propulsion

Manufacturing of the controls and propulsion systems was heavy on machining processes. Material selection largely consisted of 6061 aluminum or 316 stainless steel for both systems, due to each material's strong resistance to marine corrosion.

During the 2008/2009 race year, less than half of the team was certified to participate in machine shop manufacturing, causing the submarine manufacturing to fall far behind schedule. An emphasis of the 2010/2011 team has therefore been to have a high rate of machine shop certification amongst its members. For propulsion and controls systems to progress in manufacturing at a regular rate, a weekly working period was assigned to each Saturday, from the hours of 11:00am to 6:00pm. The majority of manufacturing was done during this period between January and April. Several underclassmen pre-engineering students became vital to system manufacturing, making UW HPS an excellent place to acquire hands on engineering experience.

Several of the system designs were pursued during the 2009/2010 non-race year, and were not reviewed in detail until just prior to manufacturing in January 2011. It was thus required for the controls and propulsion systems to have several components redesigned as the manufacturing occurred. The joining of design and manufacturing gave all members ample opportunity to contribute to design modifications and become involved with the team on a more significant level.

V. Safety Systems

The pop-up buoy system consists of a simple push-button and cable linkage to rope reel system. The left controls handle contains a rod and button that is pushed out by a small spring. When the button is depressed, it holds a cable in tension, which in turn pulls a pin through the safety buoy. When the button is released, the cable loses tension, the pin comes out of the buoy, and the buoy is free to float to the surface. To ease buoy engagement, a hinged cover was placed over the button that could be fixed in place when the pilot is not engaging the buoy. Buoy setup will be much simpler with this addition to the system.

The main egress hatch, which opens via a sliding, spring-loaded shaft, is accessible by the pilot as well. A thin rod runs from the latch shaft up to a handle above the pilot's head. With a simple pull of the handle, the hatch can be pushed open from the inside. This has been tested extensively to ensure the pilot can egress safely on his or her own.

V. Testing

Submarine testing began with a buoyancy/diver familiarity dive on 1 April 2011. Following this dive, five test dives have been completed.

1 April: Tank Dive

The first test dive occurred in the UW Oceans Department saltwater test tank. The tank provides a controlled, isolated environment for preliminary submarine testing. Two main objectives were set for this dive: determine the submarine's weight in water, and get divers familiar with maneuvering the submarine underwater.

A crane scale was used to measure the submarine's dry weight, followed by its in-water weight (Figure 9). The submarine weighed 158 lbs out of water, and weighed 3.02 lbs in water. From these values, and in considering the density of saltwater compared with freshwater, an approximate weight for 10 lb/ft^3 foam was determined to be added to the submarine. It was found that 2.54 lbs of foam would be required to give the submarine +6 lb buoyancy.

The submarine's safety systems were also tested during this dive. Both the pop-up buoy and main hatch latch performed as expected, and were ready to be tested in a race environment.

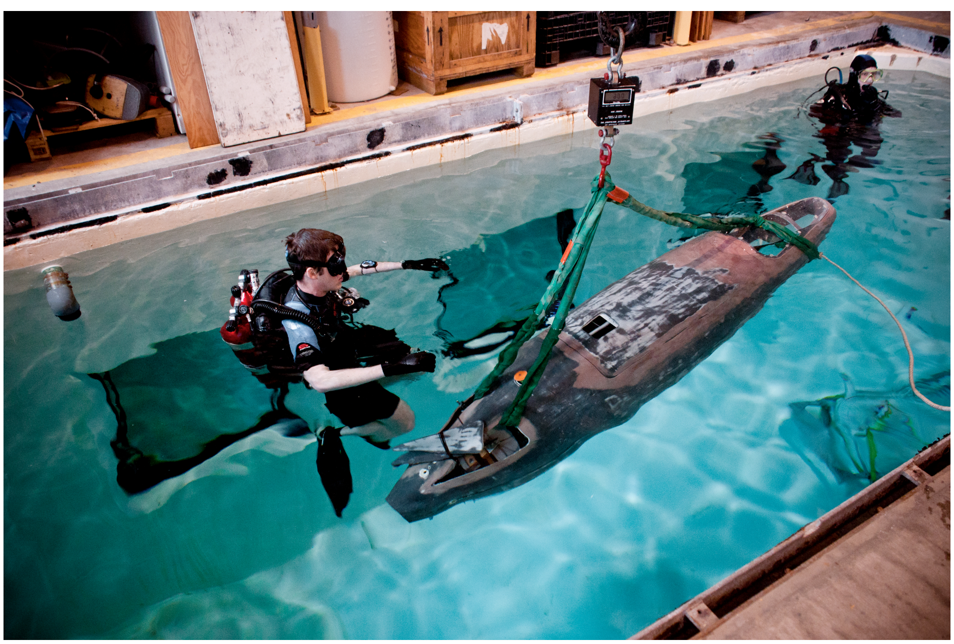

Figure 9 - Dive in seawater tank

17 April: Open Water Dive 1

The team hoped to begin achieving neutral buoyancy and properly trimming the submarine in open water. It selected Leschi Beach on the west side of Lake Washington, which has a protected swimming area between two docks. The submarine was brought into 15 ft of freshwater, and was ballasted with 3 lb dive weights. It was determined that the weights were not in small enough increments to properly trim the submarine, nor could their position be fixed properly. Lake visibility was poor, and there was considerable wave action due to boats in the water that afternoon.

The dive was largely unsuccessful, and the team decided to pursue buoyancy and trim tests in a more controlled environment.

8 May: Pool Dive 1

A pool dive was originally avoided for testing considering the expense necessary to achieve pool time. After the unsuccessful first open water dive, a pool dive became necessary. The submarine, now containing fully assembled and operating systems, was brought to UW's Hec Ed Pavilion Pool to properly achieve neutral buoyancy (Figure 10).

A new method of adding and shifting ballast weight was incorporated to the submarine. Velcro patches were attached to the submarine's interior walls, and painted steel plates were manufactured in one lb increments. Ballast weight was first added to the submarine without the pilot inside. It took seven steel plates to achieve neutral buoyancy. Once the submarine was neutral, weight was shifted forward and aft until the submarine was at equilibrium at a level trim.

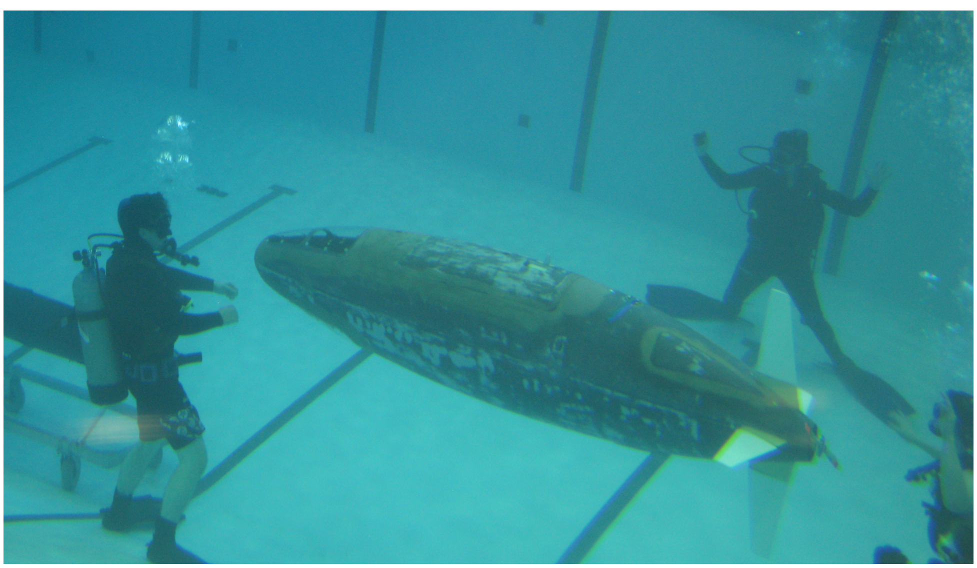

Figure 10 - Submarine achieving neutral buoyancy

After pilot-less trim was achieved, a pilot entered the submarine to check buoyancy with pilot in place. The venting of air from the submarine was inadequate, and the submarine had a tendency to rise at the bow once the pilot was in place. The addition of vent holes in both the upper window and the main hatch were added to allow for proper venting.

24 May: Pool Dive 2

Following the first pool dive, the submarine was delivered to the team's paint sponsor to be primed and painted. Following its return, a second pool dive for buoyancy and trim was conducted.

With the addition of venting holes, the submarine could be trimmed level with the pilot inside. With all systems installed and operable, the submarine was put in motion for the first time. Six 20 ft runs were successfully completed, with minimal input from controls systems. At this point, the submarine was ready for longer test trials in open water.

3 June: Open Water Dive 2

The submarine was put into the water at Magnuson Park, again on the west side of Lake Washington. Submarine trim was checked, as the submarine had previously achieved correct trim in chlorinated pool water. After a single steel ballast weight was added, the submarine was ready for test runs.

A 50 ft course was set in the lake sand, and two divers set the submarine position at one end. The submarine then successfully completed six 50 ft trials with only minor mishaps. Propulsion functioned properly, and controls kept the submarine on course. The maximum submarine velocity during these trials was estimated at three knots.

13 June: Open Water Dive 3

With a submarine shipment date looming, one more open water submarine test was attempted. Due to limited diver availability, only an evening dive was possible. With two hours to get into the water and test the submarine, a 150 ft course was set at the same location as before. Despite poor visibility and a small diving unit, the submarine successfully completed two 150 ft trials. The dive was called off early due to malfunctioning dive equipment and rapidly diminishing visibility.