Texas A&M University
Human Powered Submarine Team
"The 12th Mantaray" Design Report
ISR 2015

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Introduction

The Texas A&M Human Powered Submarine Team designed and built a new submarine, "Aggie Ray II", for the 13th ISR. The new submarine is a two-person propeller driven submarine where the passengers are side by side and both will power the vessel, Figure 1. A new drive train was designed to operate two contra-rotating propellers; one of the gearboxes is shown in Figure 2. The controls allow for pitch, yaw, and roll on all four control planes, Figure 3. Unfortunately, due to several setbacks this new submarine will not be completed in time for ISR 13. The Aggies will be racing "The 12th Mantaray", the same one-person submarine that was raced at ISR 12 with a few modifications. The team looks forward to racing Aggie Ray II at the 14th ISR.

Figure 1: New Two-Person Hull

Figure 2: Gearbox

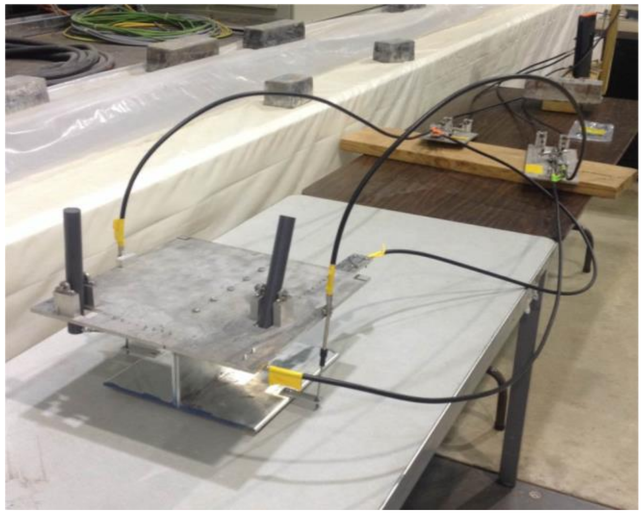
Figure 3: Control System

The hull for The 12th Mantaray was constructed during the 2006-2007 school year. The submarine was raced in the 9th International Submarine Races (ISR) in 2007, the 10th ISR in 2009, the 11th ISR in 2011 and the 12th ISR in 2013 at the David Taylor Model Basin in Bethesda, Maryland as well as the European International Submarine Races in Gosport, England in 2012. While the hull has remained basically unchanged since 2007, there have been many modifications made to the rest of the operating systems.

The hull design is based on the dimensions from the earlier one-person propeller submarine, "Ol' Sarge III", but was scaled up to allow for a pilot up to 5 feet 10 inches tall to pilot the submarine. The new control system is comprised of a throttle cable system that allows for roll adjustment in addition to pitch and yaw corrections. A new propeller has been added, and the drive shaft, gear box, and emergency buoy have been redesigned. A second strobe light was also added on the underside of the hull for additional safety. All designs for submarine controls and propulsion are in accordance with the specifications of the 13th International Submarine Race's rules and regulations.

Hull Design

The hull is a one-person propeller driven design. In the initial design of the hull, a pilot height limit was determined. With these limits known, a study on hull shape design was completed to determine the proper length to diameter ratio to produce a hull with the lowest possible drag coefficient. The Reynolds number was calculated for a 7.0-knot velocity to give an idea for the drag coefficient. Figure 4 shows the drag coefficient curves for various hull shapes.

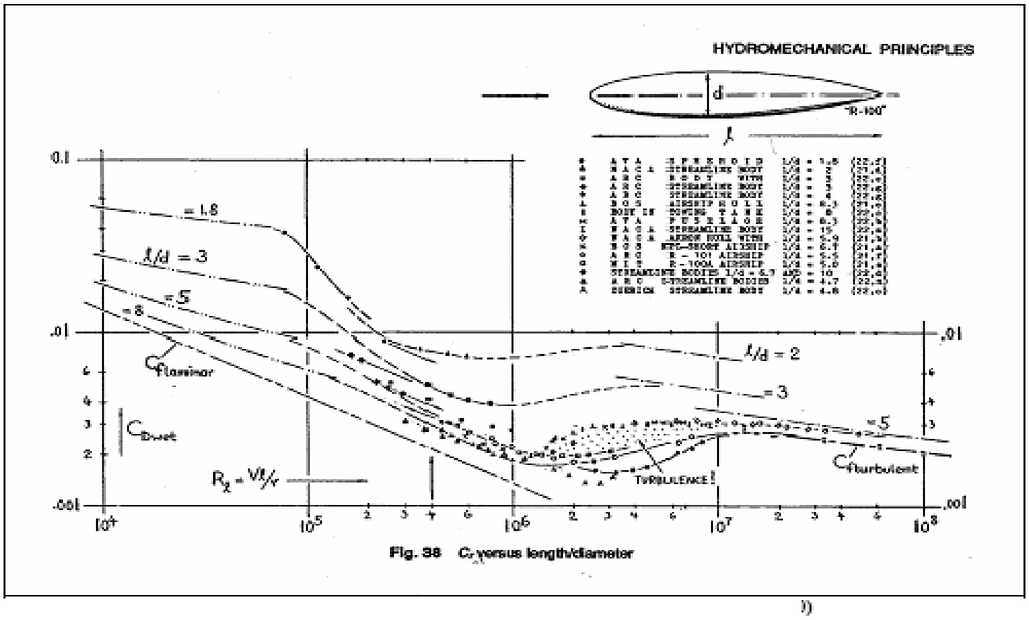

Figure 4: Drag Coefficients for Various Hull Shapes (Allmendinger, 1990)

The resulting length-to-diameter ratio of 5 correlates to a drag coefficient of 0.003. This ratio resulted in the shape shown in Figure 5 below. The shape in Figure 5 does not include the nose cone.

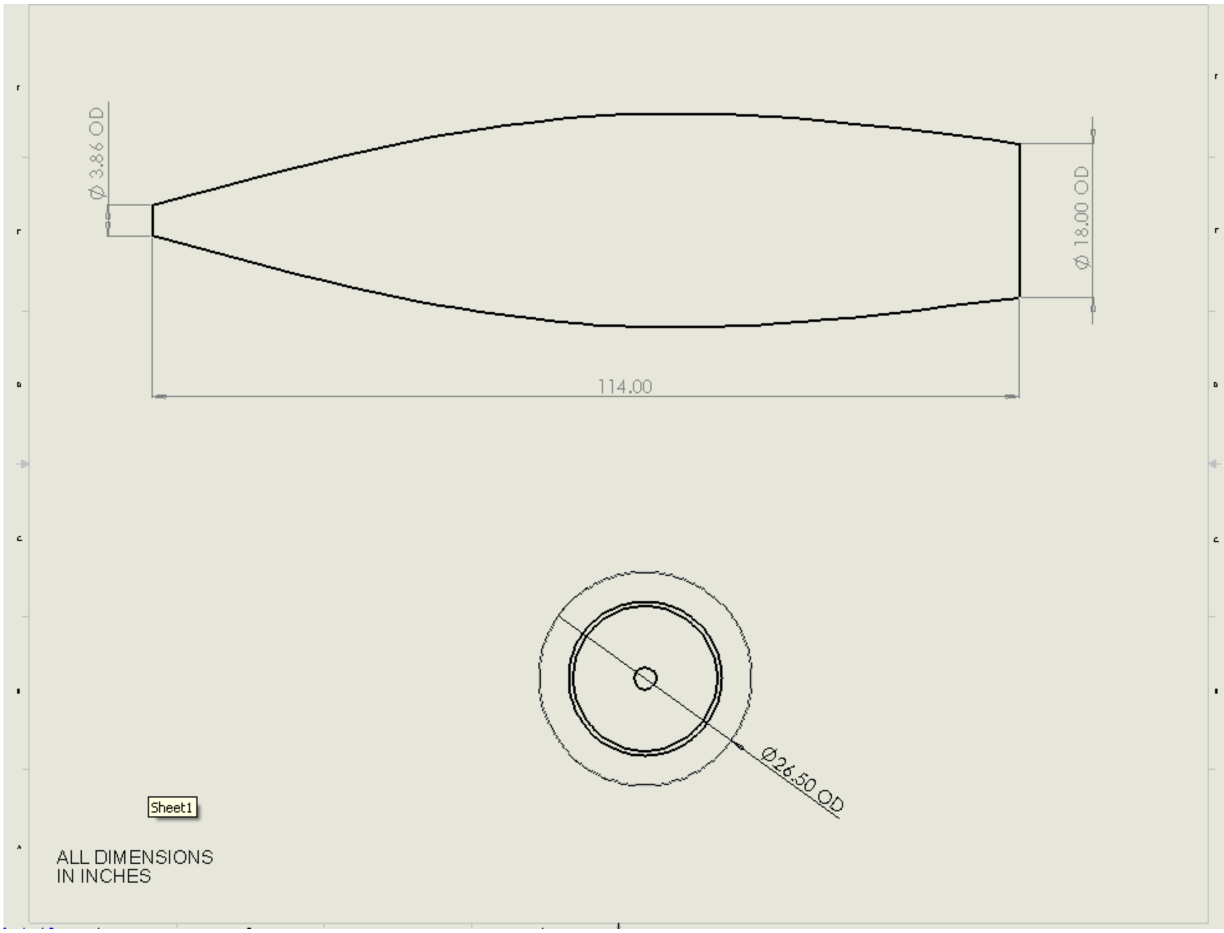

Figure 5: General Hull Design Dimensions

The position of the pilot is shown in Figure 6. The pilot is lying in a prone position with stomach downward and the head toward the bow of the submarine. An air tank is mounted to a solid harness underneath the pilot's torso. In order to ensure an optimum position for leverage on the drive system, a top-mounted shoulder harness was designed for the pilot. The harness is composed of four straps coming together at a central buckle and supports the pilot's shoulders and waist. Bicycle toe clips are used to ensure that the pilot's feet do not slip and have the ability to both push and pull while pedaling.

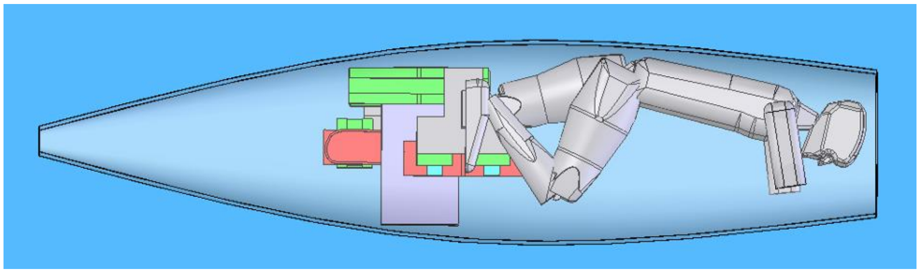

Figure 6: Pilot/Driver Position

Materials

The hull was fabricated using a fiberglass sandwich technique with Kevlar material and flexible syntactic foam. Various other materials, such as carbon fiber, E-glass, and S-glass were considered while brainstorming the design of the hull. Carbon fiber would have been a great option due to its strength and flexibility; however, it is a very expensive material in comparison to the team's budget. E-glass and its stronger counterpart, S-glass, were also both discarded. E-glass is not as strong as Kevlar and S-glass is also too expensive. Kevlar has the added advantage of superior impact energy absorption. After some consideration, Kevlar was chosen as the best material. Kevlar is a polymer made of aramid fibers. Hexcell Schwebel donated a sixty-yard roll of Kevlar material for the team to use. First, two layers of Kevlar were applied with resin onto the foam hull mold. Next, flexible syntactic foam was placed on top, followed by three more layers of Kevlar. The flexible syntactic foam was donated by the DIAB Group in 3ft x 4ft sheets at a quarter inch thickness. Figure 7 shows the composite layer cross-section. The details of the hull construction are discussed in depth in the next section.

Figure 7: Hull Layers and Thicknesses

Construction

Before submarine construction began, it was necessary to build a ventilation room in order to contain the fumes produced during the composite lay-up and priming stages. The room was built using 2x4 in lumber and 6 mm plastic and ventilated using a large fan that discharged the fumes and dust to the outside of the building. The wooden-framed lathe, shown in Figure 8, was custom designed by the team to fit the 120 inch foam block. A plywood template was used as a guide to shape the hull.

DUNA USA, Inc. donated a 30x50x114 inch, 4-lb/ft^3 density block of foam, which was used for hull construction. The block was cut in half in order to insert a 120 in long by 1.5 in diameter steel pipe through the center. The pipe, with a sidewall thickness of 0.5 in, was supported by two bearings on either side of the lathe. This setup easily supported the nearly 100 lb block that became the hull mold. A sharpened heavy-duty tile scraper was used as a chisel to shape the submarine mold until only 0.125 in of material remained and was removed by sanding. Figure 8 shows the mold after chiseling and sanding. The mold was then wrapped with cellophane, which was used as a release film.

Figure 8: Foam Block Lathing Set-up and Final Hull Form

The five layers of Kevlar were cut using cardboard templates. The alternating layers of Kevlar were cut at 0° and 45° angles in order to maintain rigidity and reduce stress. The order of hull material application was two layers of Kevlar first, followed by the syntactic foam, and then finally the last three outside layers of Kevlar. After the syntactic foam layer was applied, the hull was covered with the release fabric (cellophane). Subsequently, the hull was sealed with a vacuum bag, which was connected to a vacuum pump in order to remove the air within the layers, ensure hull smoothness, and to allow the resin to cure. A vacuum bag was used again after the fifth and final layer of Kevlar was applied. After ensuring that the resin cured sufficiently, the vacuum bag was removed and rough spots were smoothed out using lightweight Bondo and paint primer.

The original foam male mold was then carved out of the Kevlar, fiberglass, and syntactic foam sandwich hull. Hatches and holes were cut for control surfaces, propellers, and the acrylic nose cone. The main hatch measures 3.5 feet long and serves as the primary entrance and exit for the submarine pilot. The hatch, which is capable of being released from the inside or outside, is fastened with hinges at the top, and a latch at the bottom and is attached to the hull at all times. A secondary hatch, located on the rear starboard side, is used for maintenance access to the submarine drive shaft and control connections; it remains closed during operation and is not used for entry or exit. Finally, the hull was primed and sent to a body shop to be painted.

The testing of this submarine will be conducted on May 12 and 13, 2015, in the wave basin at the Offshore Technology Research Center at Texas A&M. Table 1 summarizes features of The 12th Mantaray human powered submarine.

Table 1: The 12th Mantaray Basic Specifications

Lightship Weight in Air	Dry, Equipped Weight in Air	Hull Thickness	Overall Length	Max. Diameter	Volume	Category
72.5 lb	233 lb	0.375 in	10.3 ft	2.2 ft	25 ft^3	One-person, Propeller driven

Nose cone

The nose cone used for The 12th Mantaray, shown in Figure 9, is molded of clear acrylic, made by Texstars, and cut to the proper length by the sub team. The use of clear acrylic enables the pilot to have visibility from the front of the hull. The nose cone is attached to the hull at a flared edge with a diameter of 18 inches. A one inch lip was added to the inside of the hull, and weather-stripping was laid around the lip in order to form a tight seal (Figure 9). Three rubber-tension latches (Figure 10) were spaced inside the nose cone and connect the nose cone to three small plastic notches on the inside of the hull to secure it to the submarine (Figure 10). This system is considerably safer for the pilot than previous designs.

Figure 9: Nose Cone and Weather-Stripping on Rim

Figure 10: Rubber-Tension Latches and Connection to Plastic Notch

Drive Train

Gearbox

The gear box is designed for a pilot input of approximately 50 rpm and has a gear ratio of 4:1. The resulting maximum propeller speed is 200 rpm. The gearbox is positioned in the stern of the submarine and is mounted in the hull using adjustable threaded rods (Figure 11). The threaded rods are expanded to provide compression that keeps the gearbox in place. The threaded rods allow for adjusting the gearbox height to better align the drive shaft. The gear box is restrained between an aluminum plate and to form-fit aluminum shims with receptacles for the threaded rods. The gearbox frame was redesigned in 2013 so that after the gearbox is disconnected from the output shaft and unscrewed from the frame, the gearbox can then slide out the front of the aluminum frame for easy access and quick repairs. This is different from previous designs where the gear box housing had to be removed from the sub before the gearbox could be removed.

New gears and bearings have been installed for the 2015 races. The output shaft of the gearbox is attached to the propeller shaft using a stainless steel rigid shaft coupling.

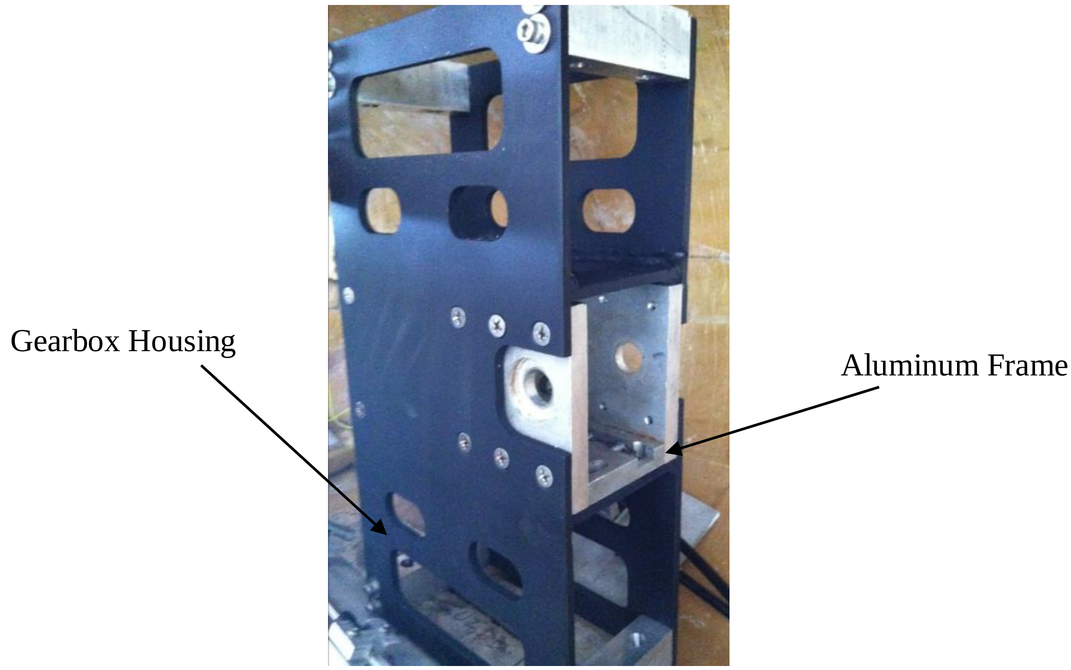

Figure 11: Gearbox Housing and Aluminum Frame

Drive Shaft

The team designed a drive shaft, which was constructed and donated by Oceaneering International, Inc. in Houston, Texas. The driveshaft shown in Figure 12 is made from MIL-A-8625 anodized aluminum with a rigid shaft coupling and misalignment joint. The driveshaft is 22 inches long with a maximum outer diameter of 0.97 inches, tapering to 0.623 inches at the gearbox. It is flanged at the hub end to mate with the propeller hub. The driveshaft passes through a bearing to outside the submarine where it is attached to the propeller hub.

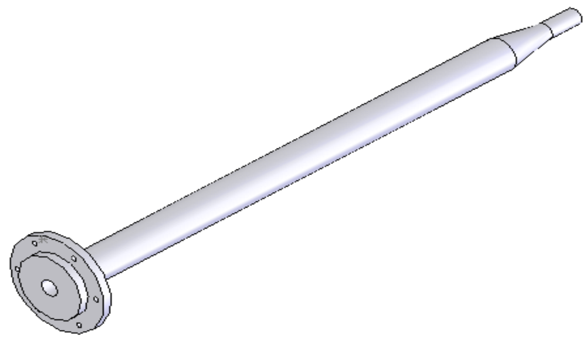

Figure 12: Driveshaft

Shaft Bearing and Completed Assembly

A bearing attachment fits inside of the tapered stern of the submarine (Figure 13). The bearing attachment holds two glass bead bearings securely in the stern through-hull, by clamping against the tapered hull. The attachment is made from nylon and clamped together using four Allen head cap screws. The completed assembly is shown below in Figure 14, which demonstrates how the final assembly fits together.

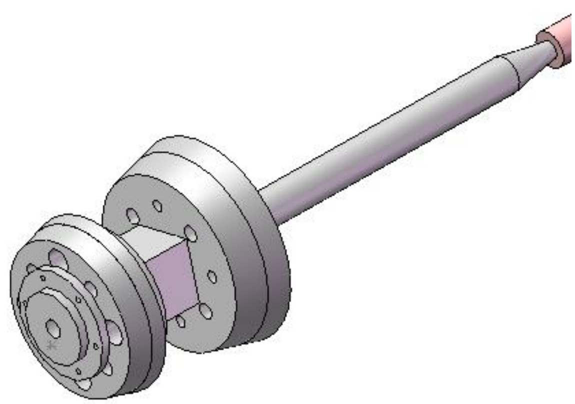

Figure 13: Bearing Schematic

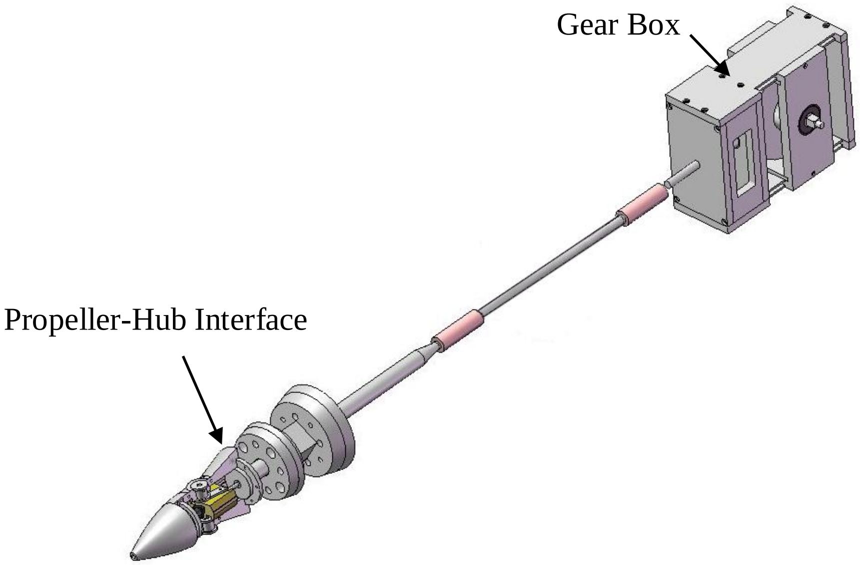

Figure 14: Complete Cyclical Drive System

Propulsion

Propellers

The team has three, two bladed propellers to insert in the variable pitch propeller hub (discussed later) that was designed by Texas A&M Submarine team members with the help of Oceaneering International Inc. The pitch of the blades can be altered before a race, but not while underway. The propeller blades were designed and fabricated according to the specifications of TAMU students by Baumann Marine in Houston, TX. The blades are optimized for an expected operator power output of 0.4 bhp and a design speed of 6 plus knots. Various propeller shapes have been tested in order to find the most effective design and best pitch setting. Figure 16 shows the two bladed propeller that will be used as the team's primary propeller for ISR 13.

Figure 15: Propeller and Hub


Figure 16: Secondary Propeller

Propeller Hub

The propeller hub, shown in Figure 17, was designed by previous Texas A&M Submarine team members, and then built and donated by Oceaneering International, Inc. The propeller hub allows for in situ adjustment of propeller pitch angle prior to each race, which previously required removing the drive shaft.

Inside the hub is a worm gear, which is turned by a nylon knob on the outside of the hub. This worm gear drives two cams that travel through downward angling grooves, forward or backward, which turns the blade attachments. The mechanism is shown in Figure 18.

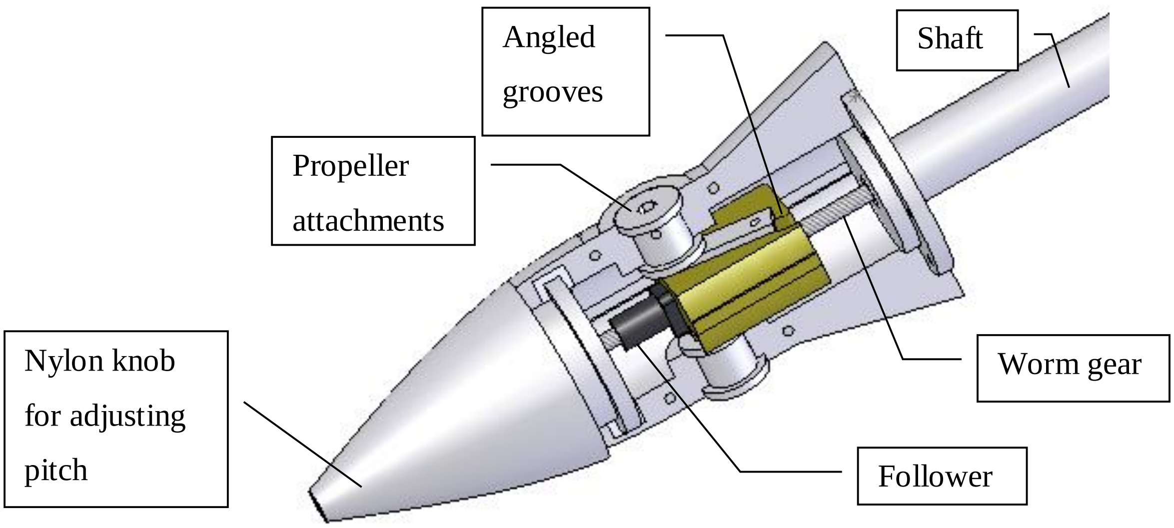

Figure 17: Propeller Hub

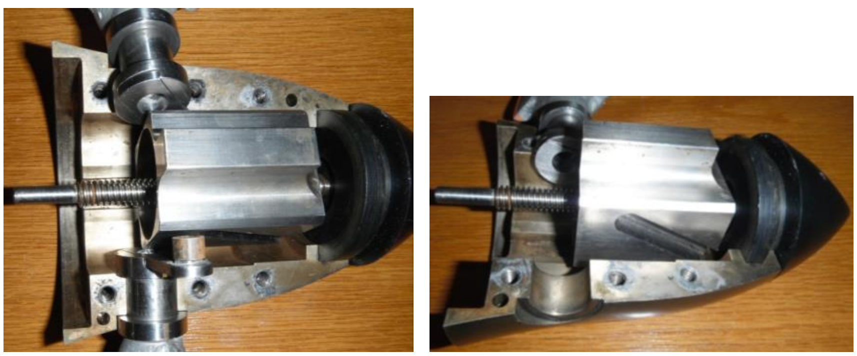

Figure 18: Hub - Top View (left) and Side View (right)

The blades are attached to the hub using tapered inserts that fit into the hub mechanism and are secured by a ¼-20 hex cap screw. The taper works like a Jacob's Taper on a lathe or mill and prevents the blades from spinning out of their attachments. Figure 19 and Figure 20 show the propeller-hub interface.

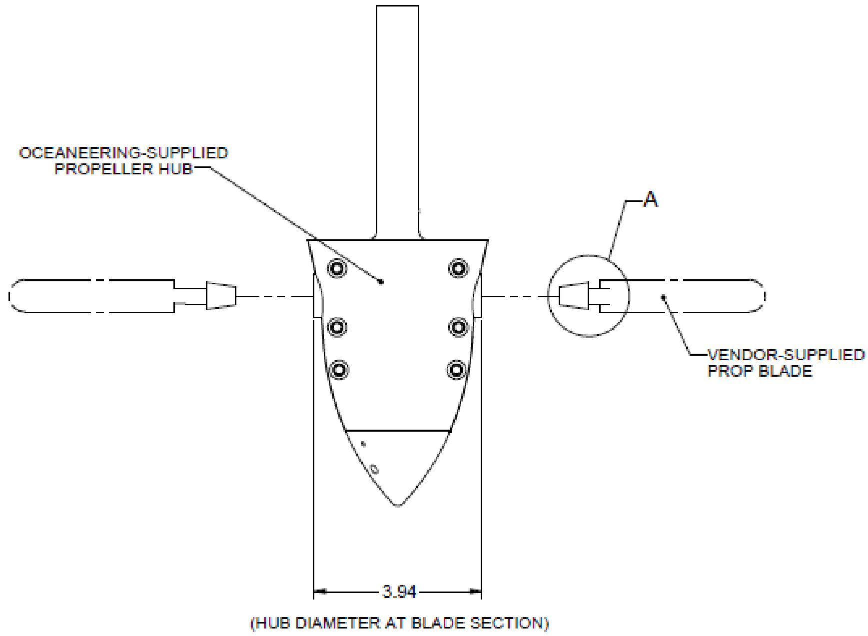

Figure 19: Propeller Hub Interface (Dimension is inches)


Figure 20: Propeller Interface

The initial pitch angle of the blade is set while the blade is unattached to the hub. Once installed, the hub allows for 15 degrees of rotation in both directions for easy adjustments. Pitch angle is determined from a line drawn on each blade and measured with an angle locator. The propeller blades are initially set to an angle of 35 degrees in the hub, which allows for a pitch angle adjustment of 20-50 degrees.

Control System

Control System

Control and stability is achieved through the use of four control planes mounted at 90-degree increments near the stern of the submarine. The two horizontally mounted planes control pitch, and the two vertically mounted control planes control yaw and roll. Movements of the control planes are governed by a system of tensioned cables routed between the steering mechanism mounted forward of the pilot, shown in Figure 21, and a pair of slide plates mounted in the stern shown in Figure 22. Each stern mounted slide plate is connected to two opposing control planes. These connections provide for both concurrent and opposing motion of the control planes. This system allows for the correction of yaw, pitch, and roll. The ability to control the roll of the submarine allows the pilot to counter the torque imparted by the propeller. The control planes are one-piece airfoils as shown in Figure 23.

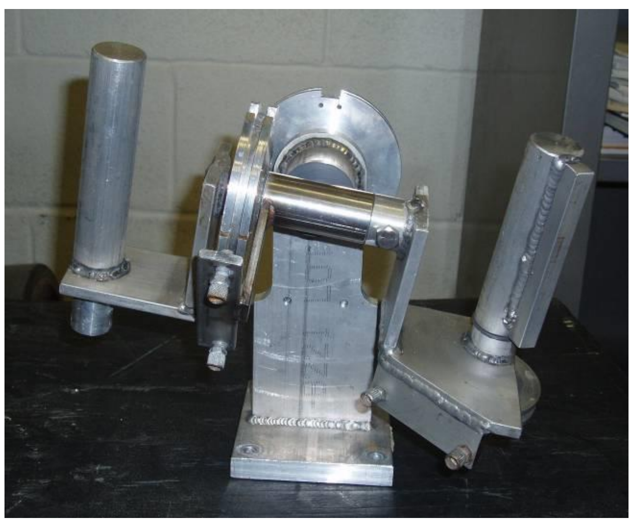

Figure 21: Steering Controls

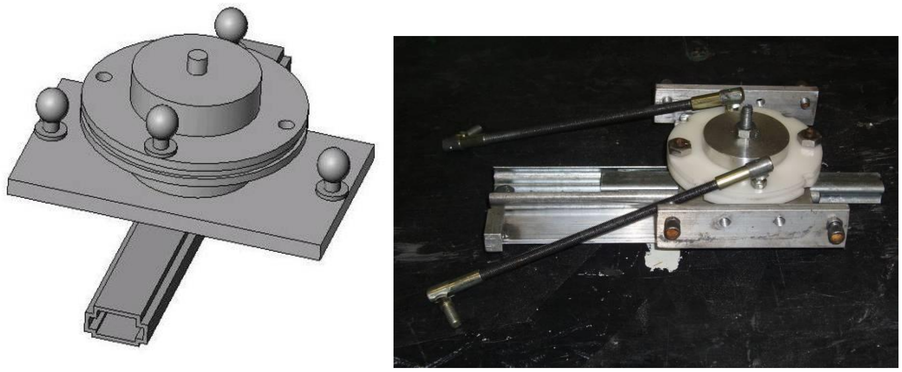

Figure 22: Control Plane System (left) and Slide Plate (right)

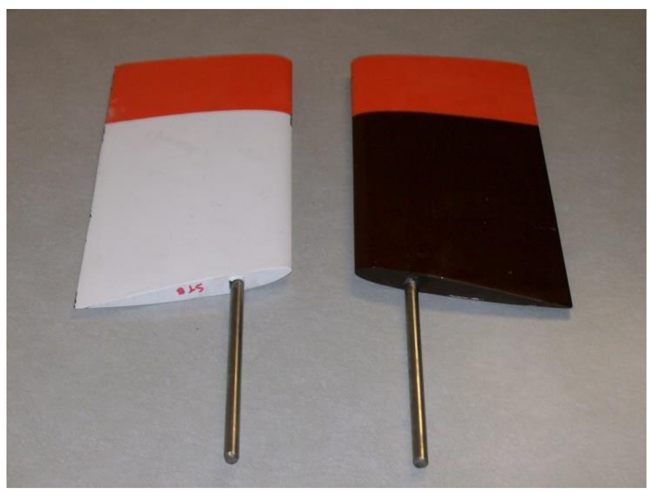

Figure 23: Control Planes

Braking

Braking is performed by reverse pedaling, which switches the direction of the propeller and causes the submarine to slow. Also, the pilot can bank into a turn to decrease momentum when space is available.

Life Support and Safety

Life Support

The air supply requirements satisfy the guidelines in the ISR Contest Rules and Regulations. The air supply, with a minimum of 150% reserve for each crewmember, is used primarily for life support while underwater. All breathing air is compressed, normal, atmospheric air. The primary air supply (60 ft^3 cylinder) is located under the pilot's torso. A secondary air supply is attached to the pilot, and each support diver is equipped with an octopus regulator. No air tank supply is allowed to fall below 500 PSI.

Air Supply Requirement

The duration rate of air supply is dependent on a pilot/diver's consumption rate, depth, and the capacity/ recommended minimum pressure of the cylinder(s). Temperature is not considered because it is only an important factor under extreme conditions. The duration of air supply for the proposed cylinder, may be calculated using equation 1.

$$C = \frac{D+33}{33} RMV \tag{1}$$

C is the pilot/diver's consumption rate in standard ft^3/min (scfm), D is the depth, and RMV is the diver's respiratory minute volume (scfm).

Table 2: Driver RMV and Consumption Chart

Level of Exertion	RMV	C
Heavy	1.7	2.16
Moderate	1.3	1.65
Light	.065	0.83

In order to calculate the capacity of air that is available to the pilot/diver, as opposed to the total capacity of cylinders, the equation on the next page is utilized:

$$V_a = \frac{V_c N (P_c - P_{rm})}{P_r + 14.7} \tag{2}$$

where V_a is the is the capacity available (scf), V_c is the rated capacity of each cylinder (scf), N is the number of cylinders, P_c is the measured cylinder pressure (psig), P_{rm} is the recommended minimum pressure of the cylinder (500 psig), P_r is the rated pressure of the cylinder (psig), and

14.7 is the standard atmospheric pressure (psi). To calculate the duration in minutes, the capacity available is divided by the consumption rate using the following equation:

$$Duration = \frac{V_a}{C} \quad (3)$$

To solve for the air supply and the consumption needs of the pilot, Tables 3 through 5 were used in association with the equations provided.

Table 3: SCUBA Cylinder Information

Rated Capacity / Rated Pressure	60 ft^3 / 3000 psi
Absolute Minimum Air Pressure	500 psi
Capacity Available per Cylinder	49.76 ft^3

Table 4: Time Calculations (all values in seconds unless noted otherwise)

Time to secure hatches and setup for run (max)	827
Time to accelerate to 6 knots in 150 feet	31
Time to transit gate area (100 meters = 328 feet)	32
Time for deceleration	10
Total time from setup to completion of run (min)	15

Table 5: Air Consumption and Available Resources

Case	Crewmember	RMV (scfm)	Rate of Consumption (scfm)	Duration of Air Supply (min)	Available Reserves (%)
A	Operator	1.70	2.16	22.41	153.58
B	Operator	1.30	1.65	30.16	201.05
C	Operator	0.65	0.83	59.95	399.69

These calculations demonstrate that even when conditions are harshest (case A); a 153.58% reserve is still maintained. These calculations are estimated for a speed of 7.0 knots.

Emergency Buoy System

The emergency buoy is constructed from a square cutout (Figure 24) of the top of the hull toward the stern of the submarine. The buoy contains a spool of 30 feet of 1/16 inch highly visible line. The spool is located on the buoy to reduce failure rate due to the line getting caught inside the hull of the submarine. The spool system is also made to quickly install a new fully wound spool in seconds. This is possible through the use of the cabinet hinges used to contain the rod for the spool. The purpose of this buoy is to provide indication of possible pilot distress by automatically releasing if the submarine pilot should lose consciousness.

Figure 24: Emergency buoy

In The 12th Mantaray, a quick release shackle is connected to the release mechanism which is wired to a bicycle brake handle on the steering column. During the race, the pilot depresses the handle and will release the handle when distressed. When the pilot releases the handle, the spring activated release lever pulls on the quick release shackle and frees the buoy to a positive ascent.

Submarine Markings

External markings follow the procedures outlined in ISR 2015. The submarine is painted with contrasting maroon and white colors, with silver accents. The submarine name, logo, and team sponsors are also located on the hull. The propeller tips, emergency buoy, hatch release, harness belt release, rudder guard, and control plane tips are marked with orange paint for visibility and safety.

Strobe Light

There are two strobe lights, shown in Figure 25, attached to the hull for safety purposes. One is attached on the top of the hull, the second is attached on the bottom of the hull near the keel of the submarine. With these two strobes, a flashing white signal is visible from 360 degrees in both the horizontal and vertical planes. The lights flash once every second and are visible for thirty feet under normal visibility conditions.

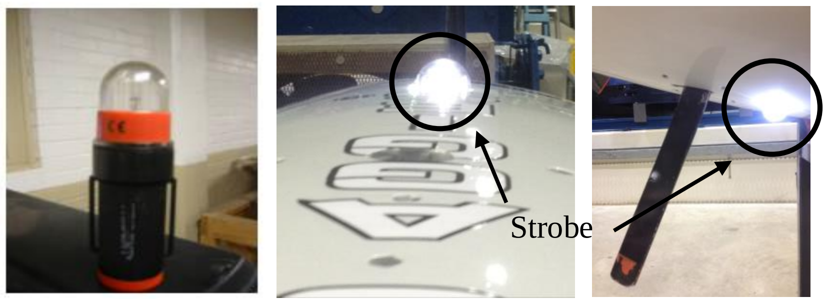

Figure 25: Emergency Strobe Light

Pilot Restraint

The pilot is harnessed into the submarine in order to position the pilot in a manner that produces effective pedaling (or horsepower). The new restraining strap is a four-point harness that supports the pilot’s shoulders and waist. The four straps come together at a single twist release that is easily visible to safety divers seen in Figure 26 and accessible by the pilot. In order to satisfy safety requirements, all harnesses and toe clips are visibly marked with orange paint. In addition, the pilots all practiced self-egress maneuvers during testing at Offshore Technology Research Center.

Figure 26: Pilot Restraining Straps

Pilot Visibility

The only window, or view port, on this submarine is the nose cone. However, the pilot is positioned to look straight out of the nose cone while pedaling and maneuvering the submarine.

Figure 27: Forward View

Rescue Egress

A four-inch orange patch displaying the word "Rescue" on the outside of the hatch marks the location of the latch release. There is also a release on the inside that is accessible to the pilot. The hatch is attached to the hull using the mechanism shown in Figure 28. The securing plates tuck under the hull of the submarine to assist in setting the hatch in place. Two retractable pins at the bottom of the hatch secure it in place. The pins retract and release the hatch when one of the rescue handles is depressed.

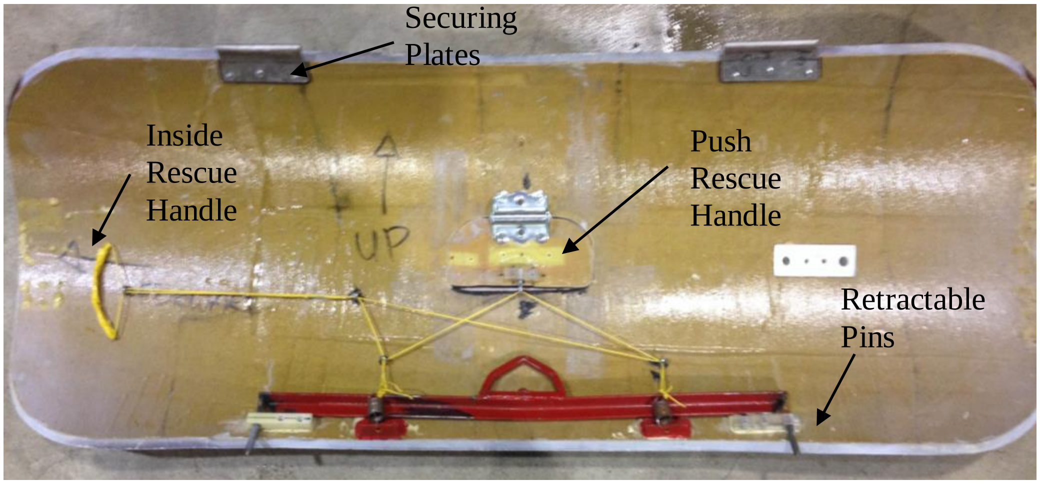

Figure 28: Pilot Egress

Testing and Training

Testing is conducted in the wave basin in the Offshore Technology Research Center (OTRC) on the Texas A&M University campus in College Station, Texas. Testing was performed on May 12th, 13th, and 21st of May, 2015. The OTRC wave basin is 150 feet long by 100 feet wide by 20 feet deep. Full speed is not attainable within these dimensions. However, safety features, ballasting, and proper functioning of the submarine is checked to determine what adjustments need to be made prior to the races. Pilots are trained for egression to the surface with assistance from support divers. The pilots are also trained on general piloting skills through short test runs. In addition the support diving crew is trained for launch and recovery of the submarine.

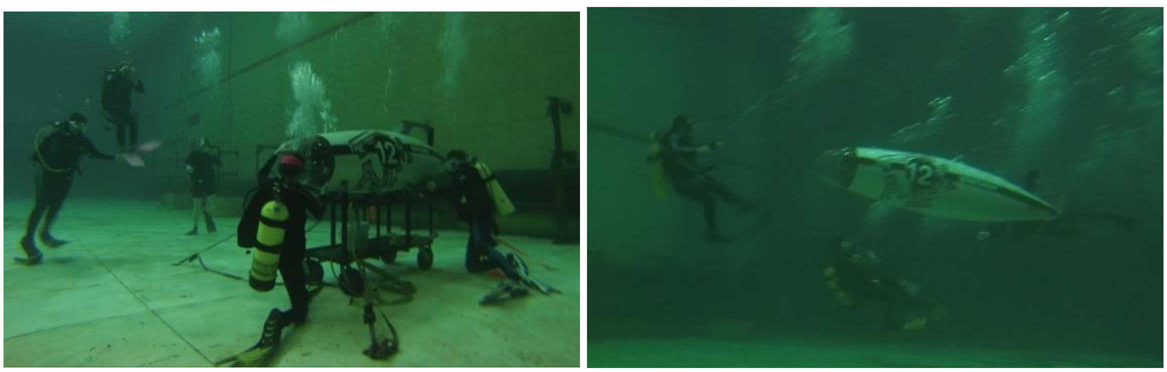

Figure 29: Underwater Testing at OTRC

Finances/Budget

The Texas A&M human powered submarine team finances the design, construction, and race participation through cash donations and in-kind donations of services/equipment. A departmental account was established in 1991 for the human powered submarine team. This account is used for depositing cash donations and paying expenses. The cash income for the 13th ISR is $15,740 and the estimated in-kind donation is $15,500. In-kind donations are parts and labor (e.g. propeller, propeller hub, wave basin testing, rental truck for transporting submarine, use of CNC machine, etc.) from various organizations. The total income is $31,240. The estimated expenses for the 2015 races are $30,536. These expenses include: hull construction, drive system, control system, transportation/lodging at races, scuba equipment rental, testing in wave basin, safety items, race registration, materials/tools, etc.

Summary

Texas A&M University Ocean Engineering students designed and built The 12th Mantaray to compete in the One Person, Propeller-Driven category at the 13th International Submarine Races, held at the David Taylor Model Basin in Bethesda, MD.

There have been many improvements made to The 12th Mantaray during the 2014-2015 academic year. The team made improvements in the hull to increase its structural integrity, optimized the emergency buoy system, refurbished the gear box, installed new gears, and added an additional safety strobe. The submarine is outfitted with a new safety harness and a new propeller. The hatch release mechanism is a new design. The overall length of The 12th Mantaray is 10.3 feet, maximum diameter is 2.2 feet, with a hull thickness of 0.375 inches. With these recent improvements, the team is confident in The 12th Mantaray's success in Bethesda, MD 13th ISR and its ability to exceed the Aggie speed record of 5.50 knots. The estimated overall cost of participating in the 13th ISR for The 12th Mantaray submarine is $30,000.

Sponsors

The Texas A&M University human powered submarine team would like to give special thanks to the sponsors who contributed to the 2014-2015 race year. Without their help the team would not be able to attend these races.

- Alan C. McClure Associates, Inc.
- Baumann Marine Services, Inc.
- Baxter & Knoll
- Classic Collision Repair and Restoration
- Deep Down Inc.
- Diab Group
- Duna USA, Inc.
- Marine Technology Society (Houston Section)
- WoodGroupKenny
- Ocean Engineering Former Student Reunion
- Oceaneering International, Inc.
- Offshore Technology Research Center
- Society of Naval Architects and Marine Engineers (Texas Section)
- Tasco Auto Color
- Texan Scuba
- Texas A&M Ocean Engineering Program
- Texas A&M Zachry Department of Civil Engineering
- TexStars Inc.

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