ISR #12 Final Design Report

I. Introduction

Submarines have been built by the Human Powered Submarine team (HPS) at the University of California, San Diego for more than a dozen years. The wealth of knowledge accumulated from each new endeavor is utilized as we strive towards more ambitious and efficient submarines, all with the goal of producing the fastest submarine. Students from all majors and backgrounds comprise our club, and an open and accessible atmosphere is something we pride ourselves in. As a result, the club is comprised of mostly new members who have made it their goal these past two years to produce the best submarine UCSD has ever seen.

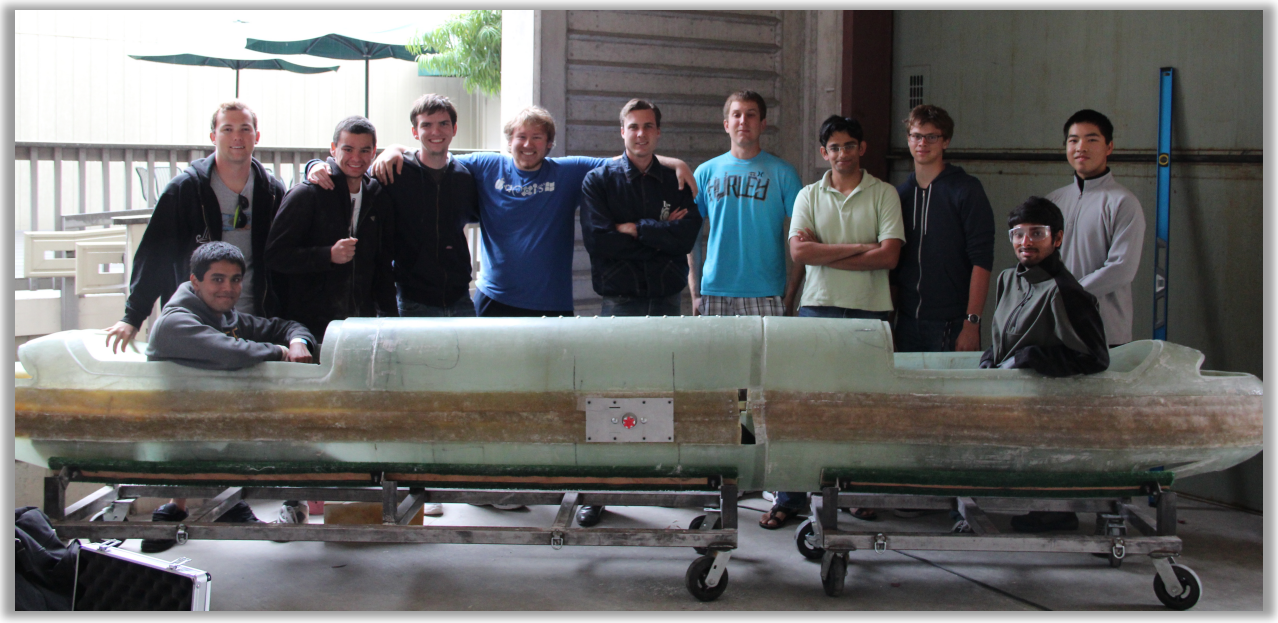

Figure 1: The HPS team with the completed hull

First place was netted from our previous efforts at the 11th International Submarine Races in the one-person one-manned propeller category with *Odin's Revenge*. Catastrophic failures during the first attempt at *Legasea* had forced us to instead just redesign aspects of a former submarine, *Odin's Rage*, to improve upon our previous speed record of 4.1 knots. Unfortunately this goal was not met, as our top speed was 2.5 knots, leaving much to be desired. However, the experience gained from redesigning *Odin's Rage,* and from the mishaps with the first attempt at building *Legasea,* was utilized in bringing *Legasea* to the 12th ISR.

II. Overview of Legasea

In the year following the 11th ISR, a transition from older leadership towards newer members and leaders occurred. This transition allowed for the team to break into more specialized roles as necessitated by the more intricate design of *Legasea*. *Legasea* brought forth

the greatest challenge our team has ever faced because it is the first two person submarine that we have ever produced. It is also the largest, coming in at 17 feet long with a total weight of over a ton with water inside. The new drivetrain design also brought new challenges as it is the first dual propeller submarine that we have ever made. All of these factors required the team to specialize into Propulsion, Steering, Human Submarine Interfaces, and Hull Production teams.

Legasea's larger hull demanded a much larger supply of materials than any of the team's former submarines. A total of 60 square yards of fiberglass, 7 gallons of Sunrez UV resin, 15 slabs of high density foam, several containers of mold wax, and several late nights were required to finish this hull. In order to allow access to the complex drive train section, the hull was designed to split in the middle and slide apart. The two separate halves were brought together through a system of draw latches and u-channel beams. The shear forces involved, created when a mass weighing over a ton comes to an abrupt stop, had posed another challenge in designing a latching system that keeps the submarine from buckling. A whole new drivetrain was engineered to accommodate a second pilot and was made out of u-channel to allow for ease of maintenance and construction. Stock propellers that most matched the profile we needed were bought for their optimum power to thrust ratio. After learning from the large, inefficient surfboard skegs on *Odin's Revenge*, smaller steering fins that fit the hydrodynamic profile of *Legasea* were made. To control these fins, a dual joystick design was incorporated with morse cables that run the length of the submarine. Due to the decreased size of the hull, custom knee bumps were implemented for their ability to deflect out of position when space is needed during peddling, and then return to a hydrodynamic position. Custom polypropylene hatches were made to act as both windows and exits for the pilots. Special harnesses were implemented to keep the pilots in place while peddling to ensure that all energy is expended on the drivetrain while also allowing for maximum mobility within the submarine.

III. *Legasea* Design and Fabrication

Hull

After *Odin's Revenge*, the decision to reduce the cross-sectional area by 18% was made early in *Legasea's* conception to reduce drag through the water. As a result, *Legasea* is considerably narrower than past UCSD submarines. This new feature had promised higher top speeds, but also had set a great space limitation.

Our first attempt at pulling *Legasea*'s hull had taken place mere months before ISR 11, and ended in catastrophic failure of our mold, which had halted all production. Poor choice in materials used for reshaping the mold to fit a new profile, an inconsistent layer of Polyvinyl Alcohol (PVA creates a "film layer" which prevents the fiberglass resin from bonding to the mold), as well as degradation of the mold's integrity after years of use, had caused the mold to weaken. Large chunks of plaster and Bondo were ripped from its surface after the first hull section was pulled. It was at this point that we had decided to completely scrap the old molds in favor of new ones created specifically for the new hull profile of *Legasea*.

After a gracious donation of high density foam, we were able to create new molds. Legasea's fabrication had required an elliptical nose cone, a middle elliptic cylinder section, and a tail conical section that could be placed in different configurations to get the correct overall mold required for the large pulls. Unfortunately, due to poor communication between the team and our sponsors, the mold profiles were made incorrectly, and mismatched when put together. As a result, the molds were returned to be reshaped into the correct profile. Afterwards, a large amount of Bondo was required to fill in the gaps that arose from machine inconsistencies. However, we were finally able to proceed with the new molds that, after weeks of prep-work, were finally deemed suitable with the correct specifications we needed.

The next set of pulls had progressed considerably smoother than the first due to enormous attention to detail and to the correct application of proper materials needed. After ensuring that the mold profile was correct by applying Bondo and sanding the molds a multitude of times, a primer coat of tooling gel was applied that provided the smooth surface we required for fiberglassing. Next a thin layer of Polyvinyl Alcohol (PVA) was applied that could later be washed away with water.

Once the prep work was completed, fiberglass was cut into the correct sections required to get the 4 pulls required for the two halves of the submarine. 16 oz. Tooling Cloth (a fine mesh of interwoven fiberglass fibers), Roving (a larger grid of fibers laid at 90 degrees to each other), and matte (random assortment of fibers) were all combined in different combinations to get the correct thicknesses needed for the top and bottom of the submarine. Due to an increased expected load on the bottom of the submarine, a total of 10 layers of fiberglass were used for the bottom and 8 layers for the top. This difference in layering allowed for the submarine to retain its structural integrity while saving on material and weight.

Figure 2: Two team members applying UV resin to the layers of fiberglass cloth

As mentioned previously, the submarine separates in the middle, so a way that meshed with this design, while still conforming to the tolerances required for aligning the two halves of the submarine, needed to be executed. As a result, precise leveling and stabilization of the molds was critical in ensuring that the 4 hull sections were aligned.

When laying up such large sections of fiberglass, a large amount of UV resin was desired to allow for a controlled curing time. Due to the nature of UV resin, work could be done for as long as we required without our batch of resin hardening prior to applying the vacuum bag. The vacuum bagging process was essential to creating the correct contour and

shape. Large sheets of flexible plastic were used and adhered to the edges of the mold through the use of double-sided tacky tape to create the airtight vacuum seal. Before the bags could be adhered, a layer of thick cotton or "bleeder ply" was placed around the rim of the vacuum bagging material to soak up resin without damaging the vacuum pump. The pump used was a venturi tube hooked up to standard shop air that provided the adequate change in pressure to remove any excess resin or air trapped beneath the vacuum bagging. A UV light, or sometimes direct sunlight, was applied to cure the resin and create the hard shell that we have now for our hull.

Once vacuum was pulled and the resin was cured, the bagging material was removed. Unfortunately, after pulling the first section, large pieces of the mold were broken and removed along with the fiberglass. We suspect that a poor combination of Bondo and incorrectly applied tooling gel is to blame for these mold failures. However, repairs were able to be made to fix the molds before the second, third, and fourth pulls.

After the four separate sections were completed, a torpedo band was applied with a slight offset to get more vertical space inside the submarine. The torpedo band was made up of many layers of matte fiberglass strips, laid lengthwise down the break between the top and bottom halves of the hull sections and coated with resin. A two-inch offset was desired to allow for more room inside the submarine.

Hull Connection

Due to the size of the submarine, it was decided early on that the hull would be split into two sections, one fore and one aft. The split design gave allowance for easy access to the drive train, situated in the middle. Priority was given to drivetrain access to allow future adjustments for differing pilot heights, as well as any repairs.

Logistically speaking, the split design of our hull made considerable sense as well. Due to the nature of UV resin, we were forced to layup indoors, meaning we had to fit our molds through several hallways and doors. This would not have been possible with a 17 foot long submarine. Additionally, storage becomes an issue when we are limited to the amount of space available to us. Finally, transporting the submarine across the country was made easier by this split in that it allowed us to use a smaller trailer and save on cost.

Drivetrain/Propulsion

Efficiency and maintainability were held as top priorities when designing the drivetrain. MATLAB code was used to design the propellers with NACA Airfoil parameters. The maximum thrust provided by the propellers was parameterized to a rotational speed of 240 RPM. The amount of thrust provided at this propeller speed was calculated to produce an end speed of 7 knots. Because 240 RPM is significantly faster than any realistic pilot would be capable of sustaining, a 4:1 ratio was introduced between the pedals and the drive shaft, reducing the required pedal RPM to 60.

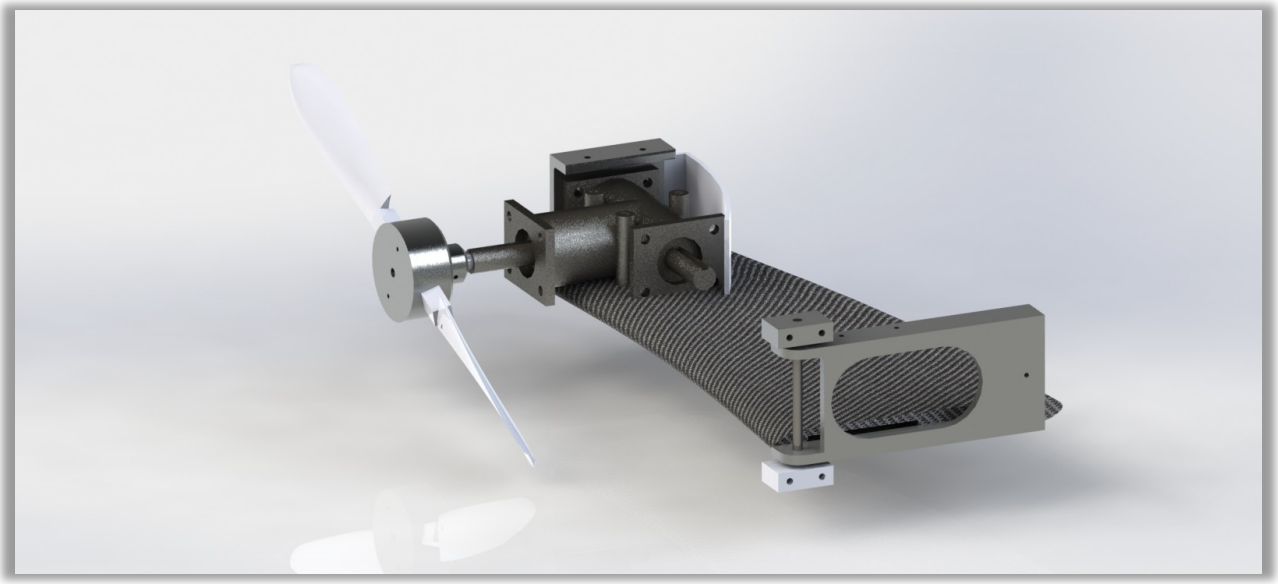

Figure 3: Stripped down CAD of the propeller–wing assembly. Shown is: the propeller, the gearbox, and the bottom wing. In the final assembly, there will be a wing on top as well.

Unfortunately, there were complications translating the propeller from the point cloud generated by MATLAB into a parameterized surface in SolidWorks. These complications in turn led to fabrication problems. Originally, a 3-axis CNC machine was intended to be used to shape the propellers from blocks of aluminum, but this was derailed when the only available CNC machine to was unable to use the SolidWorks models we provided. Ultimately, the decision was made to purchase similarly shaped propellers online, as it was determined that we would be unable to machine the propellers we had modeled.

The drivetrain itself was centered upon a single shaft located roughly in halfway between the nose and tail of the submarine. To afford input from both drivers, two sets of pedals were connected to the shaft by bicycle chains. Each set was oriented such that one driver faces upward and the other downward, allowing both to pedal the same direction. The pedals were mounted in aluminum blocks, connected via vertical u-channel beams to horizontal u-channel beams running across both the top and bottom of the submarine. The two gearboxes, located on the tip of each wing, were connected to the drive shaft. These gearboxes take the force from the drivetrain and rotate it 90 degrees with a 1:1 torque ratio. Due to the nature of the competition being a 100 meter sprint, it was determined early on that the gear ratio would favor acceleration over top speed to ensure that we reach maximum velocity before the speed trap at 60 meters. As a result, the torque ratio between the pedals and the driveshaft is relatively low to allow for maximum acceleration off the line.

Figure 4: The original drivetrain CAD. Shown is: the top u-channel beam, the mounting blocks for the pedals, and the driveshaft.

The drivetrain itself was primarily made of aluminum with certain components being made of steel, namely the gears connected to the pedals. The goal was to keep it as lightweight as possible while maintaining its strength.

Steering

Figure 5: A prototype steering fin. The flap at the top is actuated by the morse cables connected to the steering controller. The final version will be covered with a layer of fiberglass.

The steering mechanism of the submarine was designed to provide control for both pitch and yaw. Control is provided by four steering fins at the very rear of the sub, two in in each perpendicular plane. As the steering controller was to be located in the front of the submarine, while the actual steering fins are in the back, a method of connecting the two was needed. Morse cables were used to fulfill this task. Additionally, the cables split in the middle to accommodate for the hull disconnection.

The steering controller consists of two independent levers, each with one degree of freedom. The left-hand lever is used to control the submarine's yaw. Left and right movements of the lever are translated by a bell crank connected to the morse cable that runs the length of the hull. The right-hand lever controls the submarine's pitch through a separate

morse cable that runs the length of the submarine. The morse cables are attached to cantilever beams at the fins that provide the necessary torque required to rotate the fins. The driver's dead man switch is connected to the right-hand lever. Both levers are affixed to the hull with u-channel beams, which also provide the rails for guiding their movement.

Front and Rear Hatches

The hatches are were made to be attached and removed by latches and tongues, arranged in a triangle formation. Originally the hatch was intended to slide open on rails, but multiple problems had arisen with this design. Difficulties involved with the proper alignment of the rails, as well as mounting them securely to the hull, outweighed the benefits of a sliding hatch.

Ultimately, a simplistic design, consisting of a spring loaded bolt on the front and two short aluminum tongues on the rear of the hatch, was selected. The bolt was made able to be released by either one of two pull cords. The first is installed on the outside of the hatch, allowing easy external access, and the second is situated near the driver's hand via pulley. The tongues allow the hatch to be completely removed from the rest of the submarine.

Human Submarine Interface (HSI)

The human-submarine interface system consists of all features that safely join the human pilots with the submarine, such as harnesses, knee bumps, SCUBA equipment, and safety components.

The harness system was put in place to prevent the drivers from pushing themselves away from the pedals as well as to increase power input. These harnesses each consist of an anchored waist belt on each pilot that easily fastens and releases with buckles. The harness for the downward-facing pilot was oriented with two releases, one in front for releasing the belt himself and one on the pilot's back for rescue divers in case of an emergency. For the back pilot, only a buckle on the pilot's front is necessary, as both safety divers and the pilot can release it.

The submarine hull was made very narrow, allowing very little room for comfortable movement of the divers' legs when pedaling. The hull had to be somehow modified so that the divers' knees, toes, and heels could have a few more inches of clearance to pedal. To ease the divers' movement, holes were cut out of the hull. Then, neoprene patches were held tight across the holes by a metal frame and secured with nuts and bolts.

Due to the submarine being full of water, an air source from a SCUBA tank is required for both pilots. These tanks must be small enough to fit inside the narrow hull while allowing the room for the pilots and the various engineering components of the submarine. In the front, the SCUBA tank was positioned in front of the pilot's chest, and for the back pilot, the SCUBA tank was placed behind the pilot's back. Additionally, hoses were attached to the pilots' regulators to capture the exhaust from their breathing and vent it out of the submarine to prevent frequent air bubbles from affecting overall buoyancy.

Dead man switches were installed to ensure that in case of an underwater emergency, such as a pilot becoming unconscious, rescue divers could be notified and act accordingly. While inside the submarine, the pilots compress handles, keeping tension on modified bike brakes that compress the emergency buoys between two brake pads. When a switch is released, a buoy floats to the surface and alerts other divers of an emergency. The buoy can be quickly reeled back to its original position with a long fluorescent string connected to a mounted spool in the submarine.

Figure 6: The two submarine carts

Because the submarine was built as two detachable parts, two separate carts had to be made. The cart frames were made with steel beams welded together on locking wheels. Pivoting wood planks were attached on top of the frame, and then wrapped with AstroTurf to prevent the wet submarine from sliding. The two carts were also made to come together with u-channel beam to ease the connection of the two submarine halves.

IV. *Legasea* Testing and Training

With all of the new components and custom parts in *Legasea*, it was imperative that a variety of tests be performed several weeks before competition. These tests involved getting the various components of the submarine into the water for testing in an aquatic environment. A total of 6 pool tests were performed over the course of several weeks.

To test the stability of the drivetrain, it was first installed in a short prototype hull. The assembly was then submerged in a pool and pedaled. This test revealed structural instability with the pedal mounting. The initial design only had the pedal blocks connected to u-channel beams on the top of the inside of the hull, without any reinforcement to reduce vibrations. This lack of structural stability caused the u-channel beams that the pedals are attached on to oscillate, derailing the chain. We were able to fix this issue by adding in two additional u-channel beams on the bottom of the submarine to complete the stress loop and add additional structural rigidity in the hull. These new additions were tested once more with the prototype hull section and were determined to be satisfactory when the chain did not derail and the hull suffered minimal flexing.

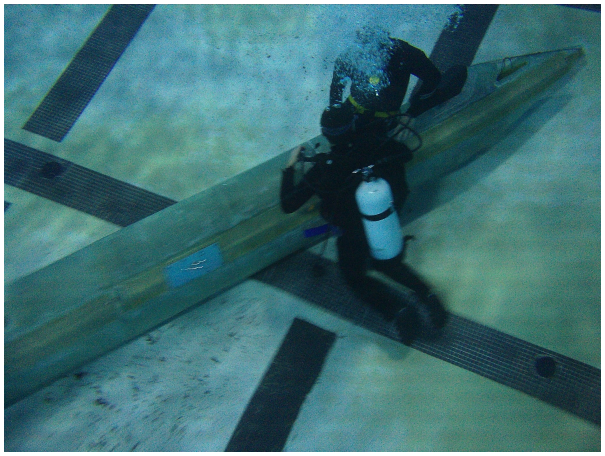

Figure 7: A support diver assisting a pilot into the submarine during a pool test

Our third pool test involved the completed hull of *Legasea* with the finalized drivetrain but no propellers attached. The purpose of this test was to roughly determine the amount of foam we would

require for ballasting and to familiarize new members of the team with getting pilots in and out of the submarine at depth. While testing our ballasting, we also determined where holes for knee and ankle bumps on the submarine should be placed as the hull does not provide enough space for pedaling without these bumps. Once this was determined and we made the submarine neutrally buoyant, we brought it down to a depth of 15 feet and proceeded to have every diver on the team practice getting in and out of the submarine.

For the fourth pool test, we finalized our ballasting for the submarine by using small increments of foam incased within small, sealable plastic bags, allowing for fine control over the amount of foam required. Tests were also performed to ensure that our pilots could safely and quickly release themselves from their harnesses and swim to the surface in case of an emergency.

The fifth and sixth pool tests are scheduled to take place a month before competition where we will check propulsion balance, steering, and alignment.