

Kids Into
Discovering
Science (KIDS)



www.KidsInScience.org

A 501c3 non-profit organization promoting STEM activities for kids



International Submarine Races 13
Design Report

May 2015

Abstract

We are a team of families from Charles and Prince George's Counties, Maryland, inspiring our students to love science, who designed and built a one man, human-powered, non-propeller submarine to compete in the 13th International Submarine Races at the David Taylor Model Basin in Bethesda, Maryland in June 2015. The fiberglass, wet hull is driven by a screw whose design is based on the Fibonacci sequence. This report outlines our efforts, focusing on the scientific methods we employed and nuggets of knowledge acquired on our journey.

Table of Contents

Mission	4
Previous Submarine	4
Team Construct	4
Engineering Tasks	
Hull	6
Propulsion	14
Steering	17
Buoyancy	23
Emergency Systems	27
Finances	
Cost Breakdown	29

Mission

Our mission for ISR 13 is to design and build a one man, non-propeller, wet submarine that will go faster than 1.32 knots., attempting to manufacture as many of the components ourselves, staying within a set budget and cross the finish line without breaching.

Previous ISR Experience

Our first experience racing in the International Submarine Races was ISR 12 in June 2013. The team was primarily made up of six students (ages 8—16) and their parents.



IL Calamaro was constructed of fiberglass, driven by a propulsion system that employed a pair of book-like paddles that opened, providing thrust when the pushrod extended and closed when the pushrod was retracted. The paddles were able to act in tandem or independently. We manufactured the components of IL Calamaro ourselves.



Not only did we achieve our goal of successfully crossing the finish line, we also received two awards: first place speed for Independent, non-propeller (albeit the only team to compete in the category) and *Best Spirit of the Races*.

Team Construct

Team members from IL Calamaro regrouped in June 2014 to assess if they would attempt to compete in ISR13. Over thirty children joined in the meeting to learn about the effort. Due to the overwhelming turn out and the age of the children (majority in elementary school), we realized we needed two things near term: (1) an age appropriate, hands-on project to develop the fundamental engineering concepts needed to construct a wet submarine and (2) a more formal organizational construct.

After some research, the group identified the SeaPerch program as our initial training platform. SeaPerch is an “underwater robotics program that equips teachers and students with the resources they need to build an underwater Remotely Operated Vehicle ... Students build the ROV from a kit comprised of low-cost, easily accessible parts, following a curriculum that teaches basic engineering and science concepts with a marine engineering theme.” We received a grant from AUVI through





www.SeaPerch.org for 7 kits and used training material developed for the program by MIT. This significantly helped decrease the learning curve of many of the children. We also used the SeaPerch platform to prototype and test scaled versions of the propulsion ideas the team later developed (see discussion in the propulsion section for further details).



Once we had commitment from a core group of families, we sought to codify the organization by creating a non-profit the children named K.I.D.S - Kids Into Discovering Science. In November 2014, we filed for and received approval for incorporation as a 501(c) 3 organization. We have learned however that timing is everything. We must now build up our activities and accomplishments to successfully compete in the future for STEM-related grants. Much like Il Calamaro, funding for Team Nautilus is provided by family and friends of the team members, as well as material donations from local companies.

Managing a team of more than 40 people, the majority of whom are very active students ages 7 and up, is challenging. We approached the challenge by breaking the group into eight “sub-system” groups: hull, buoyancy, propulsion, steering, emergency systems, pilot training, logistics, and transport. Each sub-system group had a primary adult mentor, student lead and at least four other team members. Starting in October 2014, all members of Team Nautilus met Friday evenings from 5:30 to 9:00 p.m. to participate in a number of project management activities. In subsequent months this entailed each sub-system briefing a series of charts to the rest of the group, highlighting the progress they made during the week, dependencies they identified with other teams and any other issues. Each sub-system group was also expected to meet in their small groups at least one time between the Friday integration meetings. Twice a month the group met at a local high school pool to test various in-water issues.

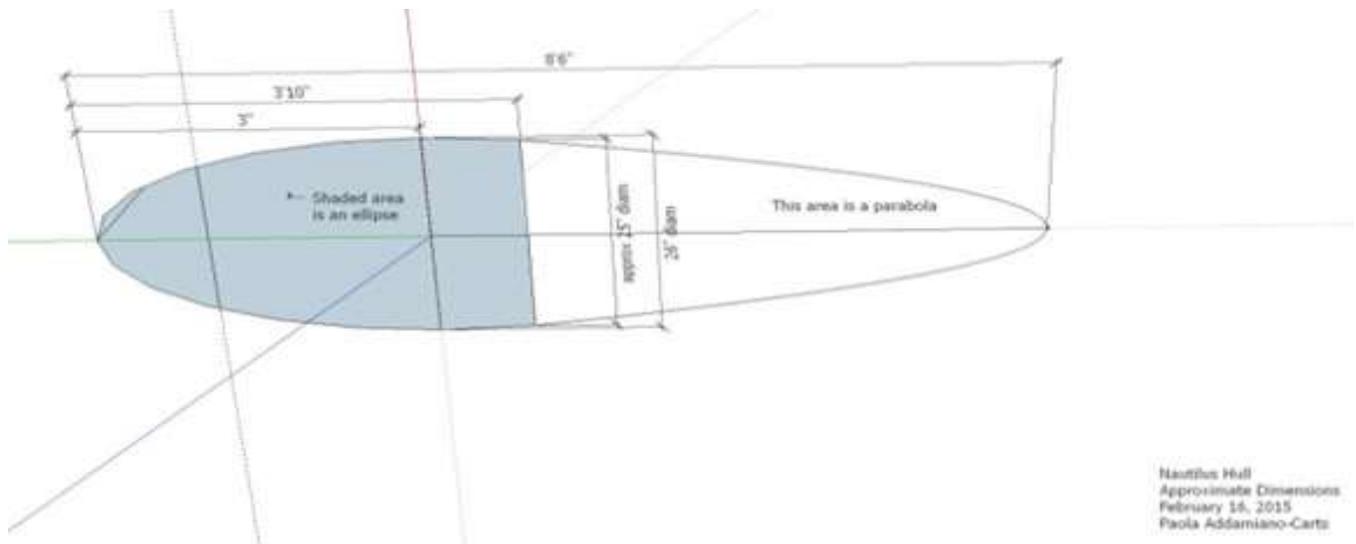
With a group this large, communication was also key. We maintained two web-based platforms. Rallyhood was used for internal communication such as calendar events, group messaging and file and photo sharing. Our primary mechanism for sharing progress with supporters and other external stakeholders was www.KidsInScience.org through Weebly.



Hull

Design Concepts

Several team members participated in our previous submarine, Il Calamaro. They were interested in keeping manufacturing simple, but improving skills, particularly fiberglassing, window forming and painting. Thus, we decided to keep a symmetrical cross-section and use a geometry similar to Il Calamaro, drawing on the Australian Navy report [1] which tells us that an ideal hydrodynamic shape has an ellipsoidal nose and paraboloidal tail. Additionally, the buoyancy sub-system group asked that we attempt to manufacture a neutrally buoyant hull/propulsion system. Later, the propulsion sub-system group asked that the tail on the sub be made removable to provide easy-access to the screw and driveshaft. This would also make it easy to access the rudder assembly.



Nautilus Hull
Approximate Dimensions
February 16, 2015
Paola Addamiano-Carta

Pilot Considerations

The submarine team met to consider pilot positioning. Recumbent and prone positions were compared. Safety, pilot visibility, pilot comfort, implication to hull manufacturing method, propulsive movement, and hydrodynamics were discussed. The submarine team decided on a prone pilot position. [See photos at end of report.] The propulsion sub-system determined that the pilot would be using rotary foot motion, similar to a bicycle. Armed with this information, we asked several pilots to lie down on a large sheet of paper and we traced their outlines. These tracings were used to determine critical dimensions for the hull. The dimensions, in turn, were used to determine the size and profile of the hull. We also recommended a pilot restraint system for efficiency of power stroke.

Safety Considerations

The ISR Contestant Manual requires windows so that the Navy divers can see the pilot's head. Also, the pilot needs to see the race course. We made patterns out of paper. The older submarine was nearby and we used it to help make the patterns. Then we placed our patterns on the hull plug to see if they fit and to get pilot approval. We made some modifications based on this feedback.

The hull sub-system is responsible for the interior hatch latch opening. The emergency systems team is responsible for the lights, buoy, deadman switch, latch, safety markings, etc.

Material Considerations

We chose fiberglass because it's an easy to use, easy to acquire, low cost, and strong composite. Also, some team members were very interested in improving their fiberglass technique. By calling around, we found a mentor in Mr. David Whitley, owner of Fusion Fiber, a local marine services company. He visited the team, gave advice and gave lessons to two team members. Based on Mr. Whitley's suggestion we opted for the following fiberglass lay up schedule:



Next we chose the type of resin we would use. We compared epoxy and polyester resins. Parameters we considered were cost, safety, availability, ease of use, pot life, and workability. We decided to use polyester resin. This was purchased from US Composites.

For the windows, we considered acrylic, polycarbonate and PETG. Availability, material properties, formability and cost were compared. We practiced oven forming acrylic to better understand how these plastics behaved. Our mentor, Mrs. Carts, was able to go to the University of Washington Human Powered Submarine team and ask for their input. They recommended PETG for its toughness properties. They kindly gave us two of their nose cones, a unique carry-on item, Mrs. Carts reported. The PETG sheet we purchased came from Piedmont Plastics.

To produce a smooth finish and increase our skill set, we originally wanted to use gel coat, but time constraints required us to make some changes (see Construction Method). An early color scheme concept is shown below. Orange was a big team favorite, but we thought having an orange submarine would make emergency markings less obvious. Our research indicated that bright green and blue were the best colors for deep water visibility. [2] Finally, we opted for a bright green and blue design. We intend to paint the submarine with a spray gun.

One option for the hull plug was to make it out of polystyrene, just like we did for *Il Calamaro*. Two of the team members went on a field trip to cellofoam in Winchester, Virginia, to see their capabilities. Cellofoam manufactures expanded polystyrene blocks, boards and shapes. We determined that we could obtain a large foam block or close-to-final submarine shape, if needed. We also looked at EPS and extruded polystyrene board, comparing cost, availability, ease of use to build up plug, sandability, clean up ease. In the end, our decision was made easy because a local contractor, Macia Construction, offered us free 2" thick polystyrene board. We knew the polystyrene was not compatible with polyester resin, but planned to protect the foam from the resin by coating it.



The figures demonstrate the maximum depth (represented by color-coded lines) at which different colors are no longer visible due to the absorption and scattering of different wavelengths of light. Turbid systems, like Green Bay, favor greens and yellows over blues, and dull the intensity of colors (on the left). Lake Michigan is clear and its effects on color are presented on the right. The top line on each graph shows the percentage of light at different depths, with all the light (100 percent) to little light (1 percent) at greater depths. As the total light diminishes with depth, the numbers and intensity of colors are also reduced.

Credits: UW Sea Grant Institute

Construction



The sub hull was to be constructed in the Carts garage. In anticipation of this, one of our younger team members dedicated a day to “getting this job done” and decluttering the garage. Her dedication to the job was astounding and made everything else we did possible.

We considered the one-off construction used on our previous submarine. In this method, we cut foam discs, stacked them like pennies and skewered them on a spindle. This was sanded to shape and fiberglassed over. However, we also looked at using a mold as shown in the 2013 Archangelo design report. After comparing cost, time, and build location, we decided to use the one-off construction method, but this time we would do it better and smarter than we did for *Il Calamaro*. Inspired by the Texas A&M design report [3], we built a lathe. This is one of the smartest things we did. Sanding the plug was so much easier and the results so much finer than when we hand sanded *Il Calamaro's* plug.

Once the plug was sanded to the desired configuration, we spackled holes, and re-sanded. We also planned where we would cut the tailcone and hatch. We decided to make stiffening ribs on either side of these cuts to ensure a nice, stiff hull. Thus, we routed a 1/2” deep channel about 2” from each proposed cutting line. These would be formed by inlaying fiberglass and thin strips of Divinycell foam.

Diameter every 2"	distance from nose	diameter	radius	bevel
0	0	0	0.0	
1/2	4.73	4.73	2.4	
1	6.66	6.66	3.3	
2	9.33	9.33	4.7	67
4	12.97	12.97	6.5	42
6	15.60	15.60	7.8	33
8	17.68	17.68	8.8	27
10	19.38	19.38	9.7	23
12	20.80	20.80	10.4	20
14	21.99	21.99	11.0	17
16	23.00	23.00	11.5	14
18	23.83	23.83	11.9	12
20	24.51	24.51	12.3	10
22	25.06	25.06	12.5	8
24	25.47	25.47	12.7	6
26	25.77	25.77	12.9	4
28	25.94	25.94	13.0	2
30	26	26	13.0	1
32	25.94	25.94	13.0	-1
34	25.77	25.77	12.9	-2
36	25.47	25.47	12.7	-4
38	25.08	25.08	12.5	-6
40	24.68	24.68	12.3	-6
42	24.28	24.28	12.1	-6
44	23.88	23.88	11.9	-6

Portion of the spreadsheet documenting diameters at various points along the hull.



We researched how to protect the polystyrene plug and opted for painting it with latex paint since we had a gallon of fuschia paint on hand. Our mentor, Mrs. Carts, had been vying for a lipstick pink submarine, but she got a lipstick pink hull plug instead.



Knowing that we had one shot at getting this right, we decided to conduct a test to make sure that our internet research was correct and that latex paint would indeed protect the plug from undergoing a chemical reaction with the polystyrene. We were glad we did this, because we got unexpected results. Our testing showed that the latex paint mitigated the corrosive effects of polystyrene, but there was still considerable damage—too much for our



purposes--to the underlay. Future testing could be conducted (cure time on latex paint, number of coats, etc), but we were in a time crunch. We had also read that packing tape would protect the foam. Our tests confirmed this, so we decided to cover the plug in packing tape. It was hard to conform the packing tape to the small routed channels where the stiffening ribs would be, so we used blue painter's tape there.

Finally, it was time to lay down fiberglass. The layup went much faster than for our previous submarine, in part because we developed a

pattern, in part because we worked with more experience under our belts, and also because the core of our hull was built up from two layers of 1708 fiberglass, rather like craft felt in stiffness, was much easier to use than the five slippery layers of 10 oz e-glass we used in *Il Calamaro*.



The finished hull was lumpy. The places where we'd overlapped the 1708 fiberglass were noticeable ridges. Mr. Whitley showed us how to sand down the ridges. He suited up in protective clothing, stressed the issue of safety, particularly in not getting the dust in your eyes or lungs, and put his sanding wheel (36 grit paper) to the nose of the sub. White dust flew everywhere. We were surprised at how aggressive one can be in sanding fiberglass. He did just a small portion, knowing we wanted to do the job ourselves. He also demonstrated how to use body filler to fill in the voids. In just a few minutes, he made the front of the sub look beautiful. We tried our hand at it after he left and soon discovered applying body filler is harder than it looks. It is quite easy, however, to work too slowly—the filler sets in 5 minutes—to apply it too thickly and end up with a rough, globby mess. Fortunately, one of the team dads had a lot of experience with drywall mud and was able to help us smooth out the worst spots. After several repetitions of sanding and applying thin layers of body filler, we declared the hull ready to paint.



The body filler we used would absorb water if submerged, or so we read, so the hull needed to be

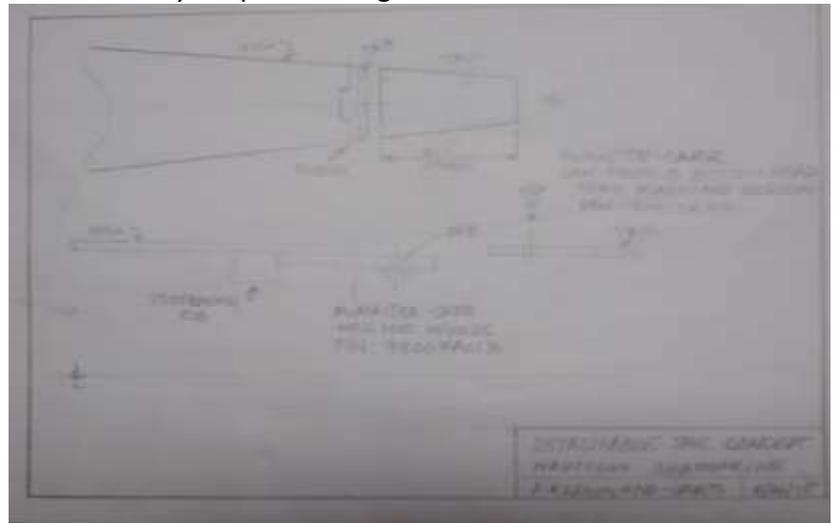
protected if we were to test it in the local pool. If we primed the sub, we couldn't use gelcoat. If we used gelcoat, a more expensive option, we figured we would not have the time to sand it through the many courses of sand paper grades necessary to make it look beautiful. We consulted with our local West Marine store and opted for a one-part polyurethane primer (Interlux Pre-Kote) and paint (Interlux Brightside). It helped that West Marine gave us a nice discount. We coated the hull with two coats of Pre-Kote, sanding in between coats, and declared the hull ready to take off the spindle. We would do a final sanding and painting of the hull just before Race Week.

To remove the hull from the spindle took several days. We used a grinding wheel to separate the tailcone from the hull body. We used the grinding wheel to cut the hatch, opting for a jigsaw at the rounded corners. The hatch did not pop off easily. In fact, it took four people and about 20 screw drivers to pry it off. When it finally came off though, it was rigid and beautiful. We were so happy that one of our primary goals had been met!

Next we had to remove the polystyrene plug. A Sawzall proved to be the best tool around to cut the foam out. This took a lot of man hours, nonetheless. Future plugs, if we used this method, could be constructed from solid disks periodically, but spaced with rings to make removing the plug go faster. When the last bit of foam was finally removed, the hull team work crew broke out in cheers. This was such a huge visible sign of our team progress.

The hull was transferred over to the waiting cart and ready for pool testing that same week.

The tailcone interface was designed so that it could be assembled/disassembled by using tools on the outside only. By looking through the McMaster-Carr catalog, we discovered fasteners specially designed for using with resin and fiberglass and ordered these. Later, we discovered these were manufactured by Rotaloc and that many more variations are available [4].



Other Components

Hatch

One of the most frustrating things about the *Il Calamaro* hatch is that it never quite fit the hull. Once it was cut from the hull, it sprang open, and we could never get it to conform again. Our fiberglass consultant, Mr. Whitley, recommended that we rout a channel into the plug 2" inside the outline of the hatch. Fiberglassing into this channel would provide a stiffening rib that would help the hatch stay put.

Sizing of the hatch was based on feedback from the local *Il Calamaro* pilot and support divers. The pilot

said it was bigger than it needed to be, and the support divers thought it was cumbersome to move through the water. Thus, we reduced the size, cut out a pattern, taped it to the hull for evaluation, and decided the new size was good. The dimensions are roughly 18" x 32", a 20% reduction in surface area from our last hatch.

Also, the hatch is designed to be hinged on the top side with a spring loaded latch at the bottom edge. In order to facilitate opening, the bottom edge of the hatch has a wide strip of Divinycell added to it so that the bottom edge will tend to float up when the latch is opened.



Hatch Latch

Team members were tasked with researching latches and bringing specification sheets to a team meeting. We were particularly interested in understanding how the Omer latch worked. We studied their design [5] and obtained a Southco lever latch. We also obtained a simple (but large) spring-loaded gate latch.



Southco Lever Latch



Spring--loaded Gate Latch

Hatch Hinges

Team members were tasked with researching hinges and bringing specification sheets to a team meeting. We narrowed down possible hinges to a few and made cardboard mock-ups of the hinges, to see how much they would stick out or protrude into the hull. These ranged from a simple cloth hinge to a pricey concealed hinge. Our final decision was to use a set of robust flush butt hinges like the one shown below. Ours were purchased through eBay.



Pilot Restraint



Sprint Training Strap

In order to assist the pilot in transferring power to the drive train, we elected to use shoulder stops. Various ideas we considered were a harness similar to a sprint training strap, a clip-in vest, a marching band drum harness and padded shoulder stops. Our pilots preferred an easy-in, easy-out method, so we opted for the shoulder stops. These were made from bicycle handlebars. A plea for used bicycles on a team member's neighborhood forum resulted in a deluge of used bicycles, so we had plenty to choose from.



Bicycle handlebars we adapted for shoulder stops.

Windows

Windows were formed from PETG purchased at Piedmont Plastics in Elkridge, MD. The mold for forming was made once the hull was complete. The windows were designed to be small enough to be formed in a kitchen oven.



Early experiments in forming acrylic



The Big Lathe

The lathe was powered by recycled parts: washing machine motor, garage door opener pulley, bicycle wheel and hub, ballistic shell casing, and tractor and lawn mower belts. The design was executed by Stanley L. Carls, Jr., a friend of the submarine project.

Slowing Down a Trommel With Pulleys

Instead of using a speed reducer, Paul, the YouTube guy, rigged up a machine using the trommel's center rim for speed control. "I used a 21-inch bike rim as a pulley wheel to step down the rpms of the motor," he says. Other trommel builders use a 1,750-rpm motor with a 2-inch pulley (A) going to a 10-inch pulley (B), then a 2-inch pulley (C) going to the 25-inch trommel frame (D).

With that information you can easily calculate the output rpm with this incredibly simple equation:

$$\text{OUTPUT SPEED} = (A/B) \times (C/D) = (1750 \times 0.2) \times 0.08 = 28 \text{ rpm}$$



This illustration from Popular Mechanics, October 2014 issue, shows how we reduced our motor speed (1750rpm) to about 60 rpm by using pulleys.

Resources:

1. *Some Aspects of Submarine Design, Part 1, Hydrodynamics* by Prof. P. Joubert. 2004
2. <http://www.seagrant.wisc.edu/Home/Topics/FishandFisheries/Details.aspx?PostID=1702>
3. <http://www.isrsubrace.org/docs/SS-Rowdy-HowdyTAMU-Final-Design-Report.pdf>
4. http://rotaloc.com/products/bonding_fasteners.html
5. <http://isrsubrace.org/docs/OMER-8-design-report-ISR-2013.pdf>

Propulsion

Objective

The objective for the propulsion sub system was to build and manufacture an innovative, non-propeller propulsion system that exceeds the speed of 1.32 knots, which was the speed of our first submarine “Il Calamaro” in the 2013 races.

Design Concepts

We pursued 3 primary propulsion concepts. The first concept we looked into was a jet drive. In order to investigate this concept we acquired a broken jet ski to take apart. When we located the impeller, which is a device that creates thrust by pushing water through a smaller tube creating a Venturi effect, we became concerned that the impeller might be considered a propeller design. Our systems integrator sent the information to the race officials and they said that it might be a propeller design. From the research in this design concept we learned about the Venturi effect and Bernoulli’s principle, which we used in our final design.

The second concept we looked into was a lobe pump, which is a type of positive displacement pump. Water flows in through an intake pipe and moves through the pump by lobes (bi-lobe and tri-lobe) and then squirted out through the exhaust pipe. For a while this was our main focus, but the cost for manufacturing this design was in excess of \$15,000. Due to its expense we decided to move on from this idea, but we are keeping it in mind for future races. We also considered a vane pump, but opted not to pursue this design because we were concerned debris would get into the springs and then the pump would not work.

The third concept pursued was a Fibonacci Screw. We chose the Fibonacci screw because we were looking for innovative ways to have a non-propeller design. The inspiration for this design is the Fibonacci sequence, or golden ratio (1.61803398875), which is a number sequence that found everywhere in nature, such as flower petal patterns, the pattern of a nautilus shell, or even the bones in fingers. The Fibonacci sequence is never ending, providing us a wide variety of data that we could use to make this screw. We decided to use the beginning of the sequence, since the numbers were not so drastically different that they would choke the flow of the screw.

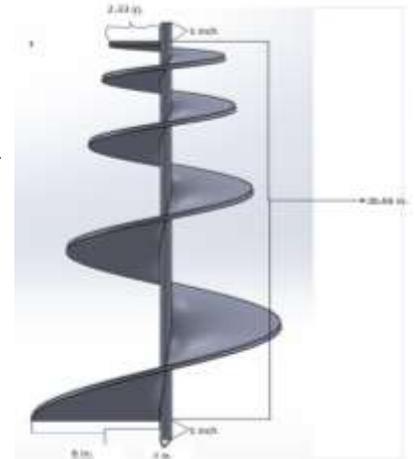
Prototype

To test the Fibonacci screw we started with a proof of concept, we created a basic screw by hand using U-Mold, a plastic that becomes malleable in hot water, on a straw and attached it to a Sea Perch robot, just to see if this concept would work, which it did! For the next test we 3D printed a CAD design we made on Solidworks using ABS plastic. We attached this prototype to a twenty-two inch hull model that the hull sub system fabricated for us to test with. The first test utilized only half the hull on the surface of the water, which made the hull seem more like a boat

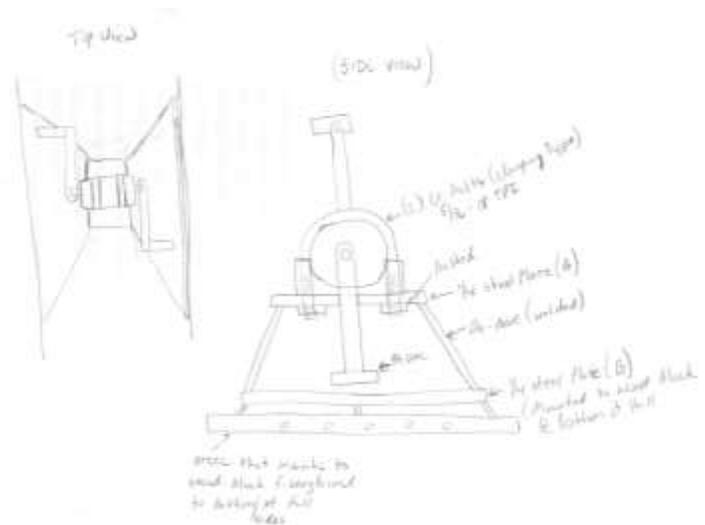




than a submarine. Then when we had the top half of the hull we combined the two halves and cut a 1 inch diameter intake at the front of the hull and a 1 inch outtake at the back of the hull. We spent a lot of time trying to establish neutral buoyancy in the scale hull. We discovered with this test that the screw oscillates, which makes it difficult to fit it against the hull. We also learned that the screw works best when completely submersed under the water.

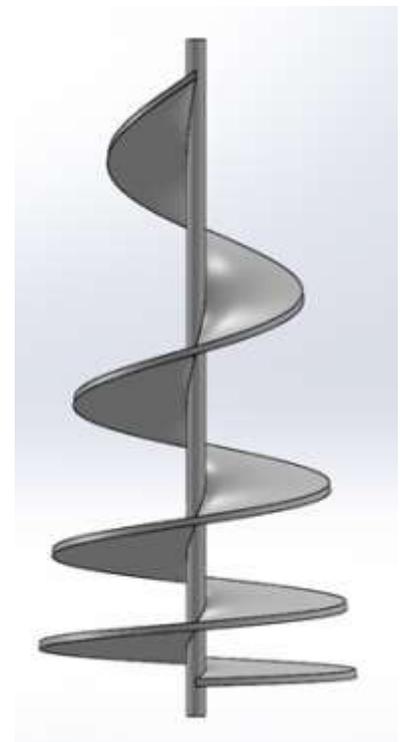
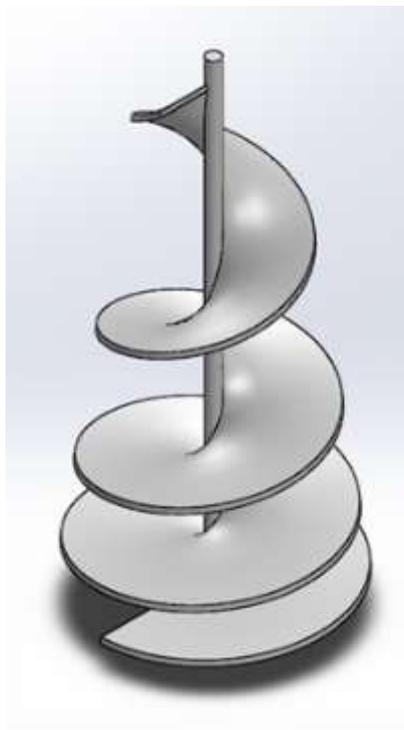


To power the screw we are using bicycle cranks attached to a gearbox with helical bevel gears at a specific ratio to give us the most speed possible. The driven bevel gear will then turn the output shaft and the universal joint attached to the end of the shaft. There will be a specific shaft attached from the u-joint, to the screw based on the pilot's height. The screw will turn clockwise and propel the sub forward. The alternate design we are looking at is purchasing a retail bicycle driveshaft system. We are trying to find gears and the manufacturability of the screw. We are hoping to reach at least 1.5 knots with this Fibonacci screw design.



Final Design

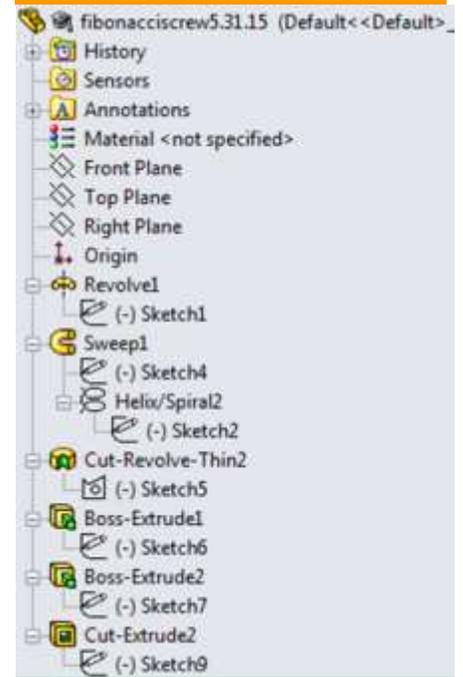
In the final design the screw makes 4 full turns, all with different pitches according to the Fibonacci sequence. In the final design, the beginning of the sequence segment we are using is at the beginning of the screw, at the top of the taper. The shaft diameter is 5/8 inch so it will match up with the drive shaft. As the numbers in the sequence get larger the length of the blades gets smaller.



Construction

We have 3 manufacturing processes, our primary process was to get the screw 3D printed on a metal 3D printer. We were unable to find a company or school who had a big enough build volume that could make it for us within our budget and time frame. We are still working to get the screw printed in ABS Plastic, then coat it in Fiberglass or nickel plating. Both of these options would give it more durability and a smoother finish. One of the problems with plastic printing is that we will need to develop a new way to attach the screw to the drive train, since our first Idea was to weld it together. Currently we are working with John Hopkins University and their Applied Physics lab to get our screw 3D printed. We have also made several frames of the screw, each one better than the last, out of metal conduit and wire that we weld in place, than we coat the blade of the frame in duct tape, which we than fiber glassed over. Our final manufacturing process we are looking into is carving the screw out of a 30' by 30' Styrofoam block and then coating it in fiberglass.

Steps in SolidWorks to create screw.



Steering

Objective

The steering system for the Nautilus submarine is responsible for controlling the submarine steering in the port and starboard directions. The steering system will also be responsible for controlling elevation steering of the submarine if it is necessary to make corrections during piloting the submarine to dive or surface. The basic design concept includes a rear situated rudder on the top and bottom side of the submarine. Dive planes will also be situated in the fore section of the submarine.

Research & Design Concepts

The steering team first conducted an exercise called Q-Storming to brainstorm ideas and ask questions that we think need to be addressed when developing the steering system. The team's Q-storming exercise resulted in the questions in the box on the right. A list of dependencies was also generated with regard to information needed from other subsystem teams

Hull Team

- Can Hull team build dive planes/rudders from molded fiberglass?
- Can Hull team build into the hull, Collar supports for hull intrusion of pole supports for Dive Planes/ Rudder
- Can Hull team build into hull interior eyelets for steering cable runs
- Position of pilot within Sub needed to determine dive plane, steering control mechanism location
- Can rudders be detachable for transportation

Propulsion Team

- Size/location of propulsion system/drivetrain/gearbox needed to determine final design of aft positioned rudder

Using this set of information and questions, the steering subsystem team then visited the public library to research different steering designs on submarines and surface vessels. We conducted this research by using Internet searching tools. We also started creating basic designs on a whiteboard by drawing subsystem components and where we thought they would be

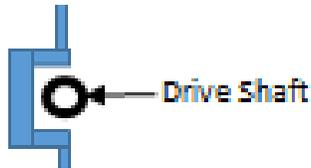
Design Concept

- Port/Starboard steering with rear situated rudder controlled by cables attached to a handlebar like steering mechanism
- Elevation steering bar connected to dive planes for up/down control of sub
- Port/Starboard steering and Incline planes will be controlled by one integrated mechanism via pilots hands
- Completely mechanical design (no electrical components)

Q-Storming

- Where will the steering mechanism be placed in the sub
- How big will the steering mechanism be
- How will the steering mechanism work left/right
- What is our budget/cost of materials
- How will we make the steering system (materials)
- What are the main components of the steering system up/down
- What are the main components of the steering system port/starboard
- How is the pilot going to control steering
- What is our schedule/timeline
- What is the basic design of the dive planes
- What is the basic design of the rudder
- What is the hull size, shape or diameter in front and back
- Where is the rudder going to be placed on the sub (front or back)
- Can we design so that one control mechanism steers port/starboard & up/down
- Should the controls be fully mechanical, or controlled by electric motors
- What materials are available to us or what will be used
- Will propulsion system size/location interfere with steering system

located on the submarine. When considering the rear situated rudder system, it was noted that the design might be driven by the location and size of the propulsion system, which was unknown at the time. Our initial thought was to use a one-piece pipe that went through the entire rear section of the submarine with rudder sections on the upper and lower portions of the submarine. The pipe would serve as the structure portion for the rudder planes that would be constructed over the pipe using foam, fiberglass and resin. However, this might not be possible due to considerations of the propulsion system which might interfere with this design. It was noted that the top and bottom sections of the rudder system might have to be designed as independent parts of the system, leaving the middle section of the rear portion of the submarine



open for the propulsion system components. Another option would be to use a single rod for the upper and lower rudder, however, design a “c” shaped structure that would be integrated into the rod, while diverting around the drive shaft used for propulsion.

Some of the team members developed a prototype of the steering system using household items to demonstrate a basic design and basic operation. The design included a basic handlebar mechanism with rope attached between the handlebars and the rear situated rudder system. The rope was attached to a lever connected to the pipe structure of the rudder such that when the handlebars were turned it caused the rudder to turn which would control the steering of the submarine.

The team also conducted a field trip by visiting a Kayak shop to research steering/rudder designs used on Kayaks and how this design could be incorporated into the Nautilus submarine. During this field trip the steering team learned about all the moving parts associated with the rudder system on a kayak including the plastic rudder itself, the wire cabling that is connected between the rudder and the steering controls located in the cockpit of the kayak. We learned how the pilot is able to engage and disengage the rudder so that it can be placed in a storage position when not in use, since the rudder is not needed at all times when kayaking. Rudders and steering systems are used in kayaking under certain conditions such as water current conditions, wind and water chops.

The team learned that the kayak rudder and attached mechanical structure is mounted on the external part located at the stern. The team considered the possibility of mounting the rudder on our submarine in a similar fashion which might result in a more simple design in terms of running the cables to the rudder without having to mount most of the steering hardware on the interior of the submarine. However, we also discussed that this external type mounting may increase the drag while the submarine is moving in the water, making it more difficult for the pilot to power.

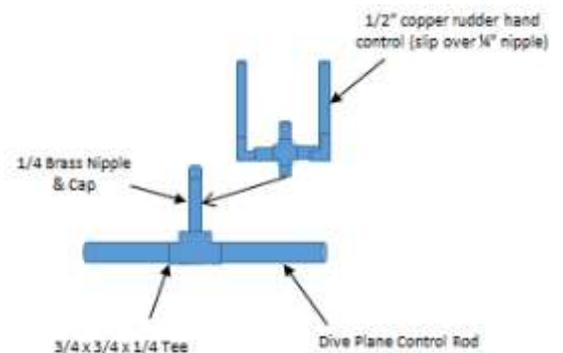
The team learned that some kayaks have a retractable skeg controlled by the pilot. A skeg is a fin like apparatus that extends directly beneath a kayak and is used to improve the directional stability of the kayak. The skeg also helps to keep the kayak moving in a straight forward direction. A skeg on a kayak is not movable in a side to side motion like a rudder and, therefore, is not used to “steer” the kayak. We discussed the possibility of using a skeg on our manned submarine to help maintain straight forward travel through the water, and using our steering system to make minor corrections in the case where the sub may tend to veer off course unexpectedly. We also considered the normal position of the aft rudder that is planned for our submarine, and the normal rudder position could be designed such that it functions like a skeg, but would also be movable by the pilot in the case where steering corrections might become necessary.

The team learned a great deal about the many different hull shapes on kayaks and how each different design serves a specific purpose in maneuvering a kayak and its stability while in the water. We learned that a “rocker” shape hull is used mostly on kayaks that are designed for white water rapids use. The “rocker” shaped hull on a kayak is similar to the shape of a rocking chair base, where the fore and aft ends of the kayak would be situated slightly up and out of the water. This hull shape allows the kayak to be easily maneuvered from side to side while in white water to avoid things like rocks and logs in the water. Other kayaks have keels that are straighter with sometimes a sharp, deep keel toward the fore and aft of the kayak. These shapes are used on kayaks in more calm water and help to keep the kayak moving in a straight forward direction. The hull shape on kayaks helps to control the steering and stability while in the water. The team discussed what we thought the hull shape of our submarine should be to help keep the submarine moving in a straight forward direction. We all agreed that it would make it much easier for the pilot to control the submarine if very little steering was necessary.

Final Design

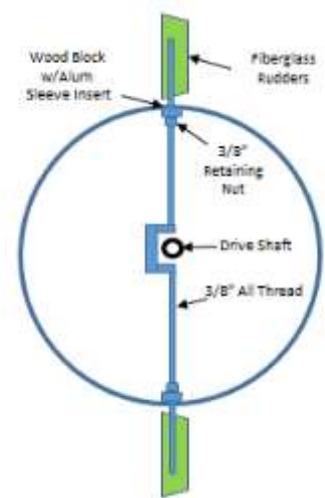
The team decided to stick with the original design concept such that the final design would be completely mechanical in nature and would include port/starboard steering with a rear situated rudder controlled by cables attached to a handlebar like steering mechanism.

The steering control mechanism is designed such that rotating the mechanism counterclockwise (to the left) would cause the rudder to rotate in a clockwise fashion and result in the submarine turning to the port side. The opposite is true when the mechanism is rotated clockwise, causing the submarine to turn to the starboard side. It was decided that designing the steering this way would make it easy for the young pilots to use, because it would be similar to handlebars on a bicycle. In order for the steering to work this way, the cables would need to be connected to a fulcrum attached to the rudder control rod, such that the rudder moves in the opposite direction from the rotation of the rudder control mechanism. See drawing below for an illustration of the steering system components. The steering control mechanism is attached to the dive plane bar so that the pilot will be capable of steering the submarine and controlling the dive planes with one integrated mechanism. Connected to the dive plane control bar is a tee fitting with a 1/4” brass nipple that is situated such that the rudder hand controller fits over the 1/4” nipple in a sliding fashion. The rudder controller is constructed using 1/2” copper pipe and fittings, and secured to the 1/4” nipple using a cap on the nipple. The 1/2” copper slides over the 1/4” nipple and is a snug fit, but just loose enough to allow the rudder controller to rotate on the 1/4” nipple (see drawing).

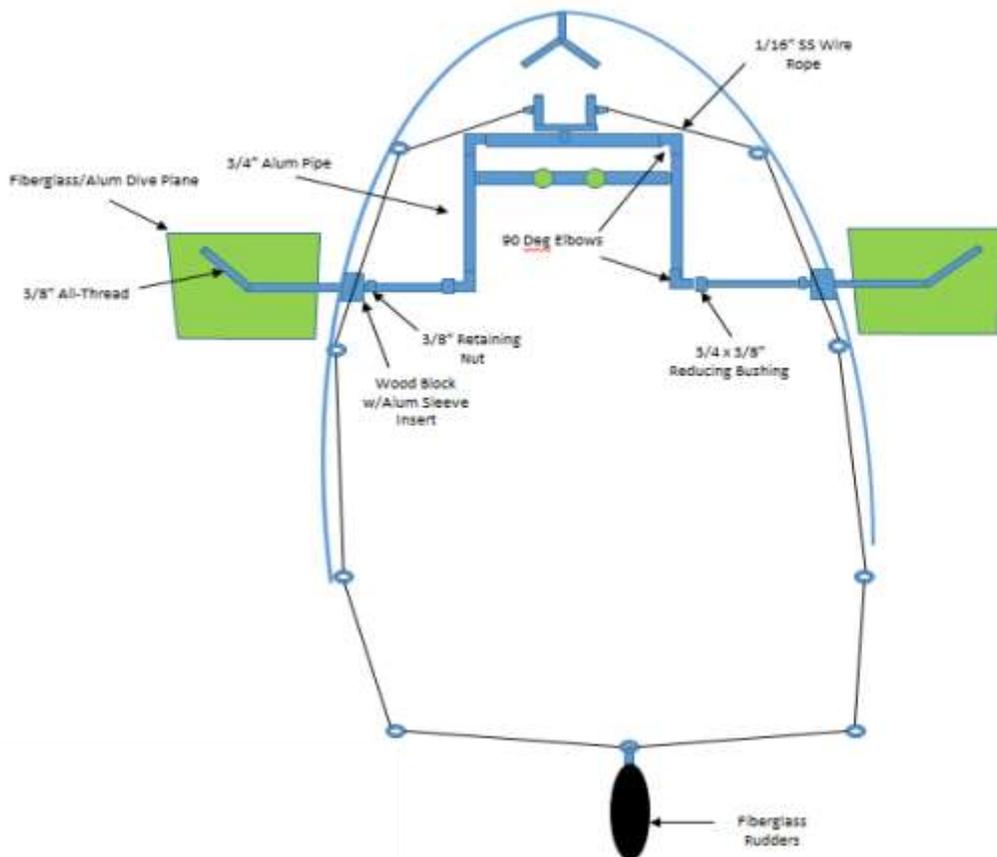


The rudder system includes two separate rudders, one on top of the submarine and one on the bottom located in the aft section of the submarine just fore of the propulsion system. The two rudders operate in unison and are attached to a single 3/8” rudder control rod. Since the rudder control rod is designed to be located in the centerline of the submarine, the control rod needed to be modified such that it wouldn’t interfere with the drive shaft. To accommodate the drive shaft the rudder control rod incorporates a “U” shaped section such that the rudder control rod can rotate almost 90 degrees in either direction for port and starboard steering (see drawing).

Elevation steering will be controlled by a dive plane control bar connected to dive planes for controlling the depth of the submarine while in the water. In order to cause the submarine to dive, the pilot would need to push the dive plane control bar downward, while pulling the dive plane control bar in an upward fashion would cause the submarine to surface. With the help of Mr. John Hollyfield, the manufacturing teacher at North Point High School in Waldorf, Maryland, the dive plane control bar was constructed using $\frac{3}{4}$ " aluminum pipe which was cut to the proper length using a pipe cutter and then threaded on both ends with a pipe threading tool. The pipe sections were then connected together with galvanized fittings to prevent rust. The aluminum pipe was reduced in size with a customized adaptor in order to accommodate $\frac{3}{8}$ " all thread rod which would penetrate the outer hull and also provide the supporting structure for the actual dive planes. The customized reducing adaptor was made using a $\frac{3}{4}$ " galvanized solid threaded plug which was drilled out and tapped with $\frac{3}{8}$ ", 16 threads per inch threads to accommodate the $\frac{3}{8}$ " all thread rod. Where the $\frac{3}{8}$ " all thread rod penetrates the outer hull, wooden blocks were fiberglassed on the interior sides of the hull and included an aluminum sleeve where the inside diameter of the sleeve is slightly larger than $\frac{3}{8}$ ". The wooden blocks provide extra support to reduce the stress on the fiberglass hull from the forces applied by the dive planes.



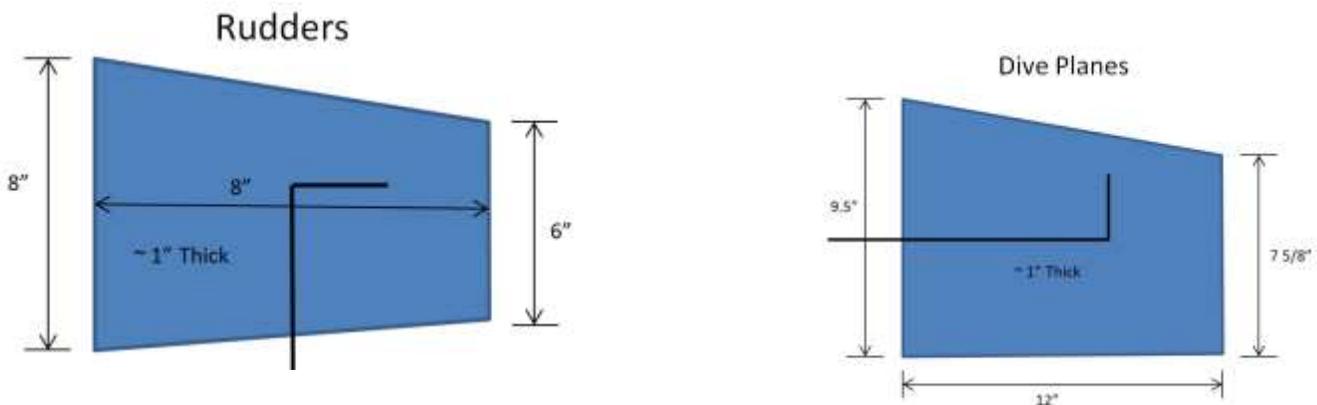
Port/Starboard steering and dive planes will be controlled by one integrated mechanism using the pilot's hands for easy operation. See diagram below for an illustration.



Construction

One of the goals of the steering team was to keep the costs to a minimum and use as many low cost, off the shelf components as possible while also taking advantage of donated items. The team decided to seek help from the local high school manufacturing teacher, Mr. Hollyfield, and the tools available in his high school machine shop to help with building some of the steering system components. Mr. Hollyfield had some extra aluminum pipe that he was willing to let us use for the main components of the dive plane control bar. Pipe cutting tools were used to cut the aluminum pipe sections to the appropriate lengths. Also, since the pipe sections would be connected together with threaded pipe fittings, the pipe sections needed to be threaded using $\frac{3}{4}$ " National Pipe Thread tools which were available in the machine shop.

Fiberglass, foam core and resin will also be used to construct the actual rudder planes and the dive planes based on a NACA symmetrical airfoil design (NACA Airfoil 0012). $\frac{3}{8}$ " all thread rod will provide the structural support for both the dive planes and rudder. The steering team will consult the Hull team for help in constructing the fiberglass parts of the system (dive planes and rudder). The hull team has more expertise in actually using the fiberglass materials and tools. The dive planes and rudder dimensions and shapes are shown below:



The screenshot shows a software interface for a NACA 0012 airfoil. It includes a grid with the airfoil shape, a parameter list, and a control panel. Handwritten notes are present on the left side.

Name = NACA 0012 AIRFOILS
Chord = 241.3mm Radius = 0mm Thickness = 110% Origin = 0% Pitch = 0°

[Open full size plan in new window](#)
[CSV file of coordinates](#)
[Restore defaults](#)

[Open paginated plan in new window for multi page printing](#)
[SVG image as text file](#)

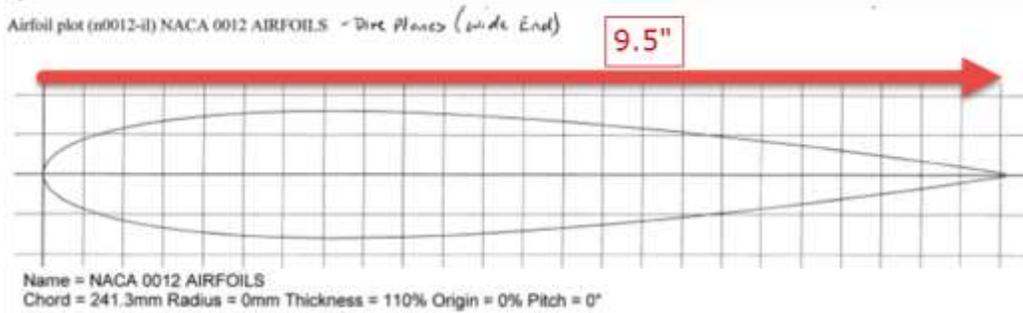
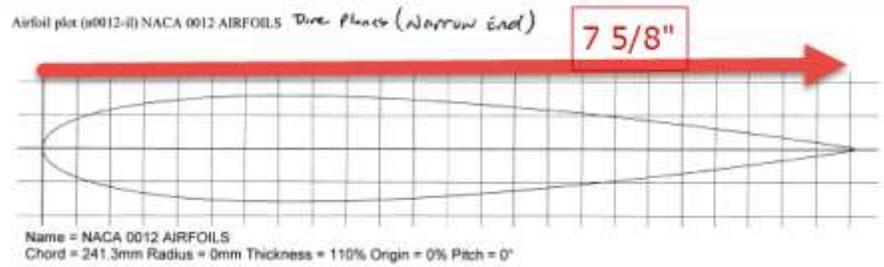
Autofill (n0012-0 - NACA 0012 AIRFOIL)

Chord (mm): 241.3
 Radius (mm): 0
 Thickness (%): 110
 Origin (%): 0
 Pitch (degrees): 0
 Holes (mm): 0
 Reverse:
 Data file:
 Camber line:
 X grid (mm): 10
 Y grid (mm): 10
 Paper width (mm): 280
 Paper height (mm): 210

Print

Dive Planes wide end Printed: 101% Legal Size Landscape

Narrow end Printed: 80% Legal Size Landscape



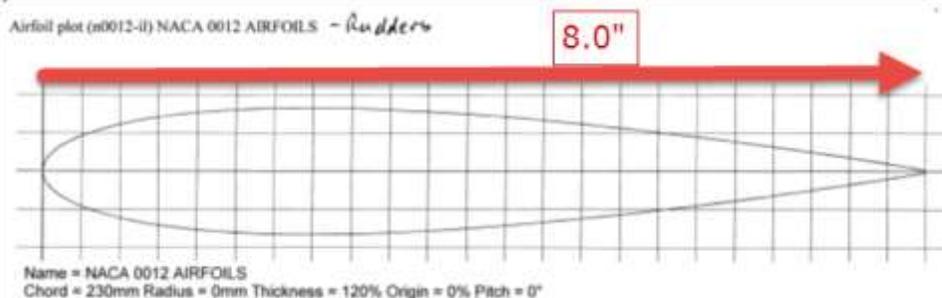
Name = NACA 0012 AIRFOILS
Chord = 230mm Radius = 0mm Thickness = 120% Origin = 0% Pitch = 0°

Open full size plan in new window
CSV file of coordinates
Restore defaults

Open paginated plan in new window for multi page printing
SVG image as text file

*Rudders
Printed: 89%
Legal
Landscape*

Airfoil	n0012-II - NACA 0012 AIRFOIL	Choose from database list or add your own airfoil file
Chord (mm)	230	Chord width in millimetres. (1 inch = 25.40mm)
Radius (mm)	0	Radius of camber in millimetres. Zero for no curve
Thickness (%)	120	Thickness adjustment. 100% is normal thickness. 50% is half, 200% is double.
Origin (%)	0	Adjust the position of the origin e.g. 50% is mid chord
Pitch (degrees)	0	Pitch or angle of attack. 180 flips the plot
Hole (mm)	0	Line parallel to airfoil for wing covering or jig. Negative values are external, positive internal. Plot a mirror image
Reverse	<input type="checkbox"/>	Plot the airfoil data on the image
Data box	<input checked="" type="checkbox"/>	Show camber line on image
Camber line	<input type="checkbox"/>	X grid size in millimetres
X grid (mm)	10	Y grid size in millimetres
Y grid (mm)	10	Used for printing plan. All landscape approx 260mm
Paper width (mm)	260	Used for printing plan. All landscape approx 160mm
Paper height (mm)	216	
Plot		



Buoyancy

Objective

Depth control was designated an important distinct subsystem after the experience of ISR2013, when it was realized that almost all the abortive runs of Il Calamaro were due mostly or entirely to depth control issues. Maintaining more perfect control of depth, and regardless of speed, is the goal of the Buoyancy subsystem. Additionally, providing for static buoyancy trim in design and practice, providing in-water super buoyancy during the hull/propulsion/pilot-fitting stages, and providing for returning Nautilus to the staging area after each race are Buoyancy responsibilities. Finally, the nominally unrelated task of providing power to the Emergency Systems, for two backup beacon lights, is undertaken by Buoyancy Systems because we can easily accommodate the necessary power.

Design Concepts

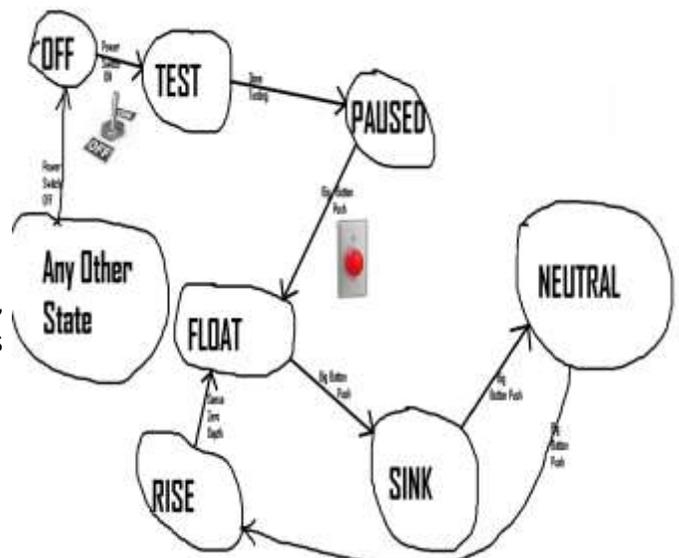
Clearly the pilot is expected to be over-occupied during the race so detasking him/her however possible will allow greater focus on providing power and simple steering. So automated depth control is a specific objective. Depth control at very low speeds, and when stationary, cannot be achieved well or at all merely by dive planes. Control of the actual buoyancy of the craft is necessary. Automatic control of buoyancy (and trim) is the means to maintain a near-constant depth during the race.

It is expected that the submarine with full air tanks will be weighted to be about 10 pounds negatively buoyant. Buoyancy tanks, or rather flexible bladders, will provide for about 20 pounds of adjustable buoyancy. At the start of the race the buoyancy system will have been adjusted to neutralize Nautilus' buoyancy, leaving a control range of about + and - 10 pounds of buoyancy.

Two bladders will be located one each in the bow and stern. Pressure sensors will be located likewise. A computer will read the sensors and make decisions on adjustments to one or both bladder fill levels. A pair of solenoid controlled valves will allow a 6 cu ft pony bottle with 30 psi primary regulator output to fill the bladders. Another pair of solenoid controlled valves will be used as pneumatic deflators to allow for losing buoyancy on the two bladders.

A sealed gel cell will provide power for the entire system, both electronics (low power) and the power components (solenoids and Emergency Systems' beacons).

Waterproofing electronics both by isolating components from water and by making them proof against water (corrosion) is attended to.



Final Design and Construction

Computer

A particular brand of Arduino variant was chosen primarily due to team familiarity with it. PJRC Teensy 3.1 (<https://www.pjrc.com/>) runs off of 3.3 V, has sufficient resources to run the control program anticipated (detailed in subsection, "Program/Algorithm") and has a user base forum with experience with a major and tricky component (the pressure sensor). It measures about 0.7 " x 1.4". All necessary software components (development environment, compiler, downloader, libraries) are readily available open source.

Pressure Sensor

Wireless tire pressure sensors are piezo-resistive, changing resistance as they flex due to pressure changes. These MEMS (Micro-Electro-Mechanical System) devices are available as analog resistive bridges and also pre-integrated with amplifier, digitizer and interface. They do not seem to be available with integrated wireless transmitters; those always seem to be added at the circuit level.

A pressure sensor suitable for truck tires (~100psi, much greater range than needed for ISR) and a digital interface was chosen. Least Significant Bit (LSB), the resolution of the device, is about ½" of water depth. The Intersema MS5541C has an interface which is similar but not identical to SPI (Serial Peripheral Interface). Accommodating its peculiarities involved querying the PJRC project forum.

The sensing element of the MS541C is waterproof but the adjacent electronics are not. Those electronics are potted in RTV and further, the entirety of the sensor is sealed within a waterproof membrane with a small air bubble. The volume of the air bubble will halve at 30' water so by design the air bubble is large enough so that the membrane will not be collapsed at 30', the design depth for ISR. This will allow the pressure sensor to stay dry while reading pressure accurately.

Solenoids

A simple, small, solenoid controlled valve designed for liquids was tried due to its price (< \$10). It seems to perform well with gas instead of liquid. The body is plastic and the slug is totally enclosed within a plastic tube but the coil is not, and it is not guaranteed that the slug will remain dry under water pressure. The maximum working pressure of the valve is about 115 psi but a system high pressure of 30 psi seems to be adequate.

Gas Source

A pony bottle of 6 cu ft is adequate for this application. Both the pony bottle and its regulator will be dedicated to the buoyancy control system and will neither be available nor considered to be part of the pilot air supplies, either main or emergency.

One type of scuba regulator has an adjustable spring-controlled regulation. The buoyancy control regulator is adjusted to provide gas (breathing air) at 30 psi. This supply is "T"ed to feed the solenoid-controlled valves.

Bladders

The first prototype bladder type was chosen to be a boxed-wine bladder for obvious reasons, but also

because the size, the sealing and the bladder durability were all amenable to the task. After initial testing it appears that this will be the final device type. One will reside in the bow and another in the stern.

These bladders have a turn valve have a ¼” spigot ID. The spigot was drilled out and a ¼” OD polyethylene semi-rigid tubing was epoxied into it.

The deflator valve turns out to be the more significant design challenge. A flapper valve built onto a rigid upper surface will, when the deflation system is quiescent, remain closed. Solenoids were investigated for opening the flapper but the actuator movement distance is small and waterproofing is difficult. Instead, a solenoid-controlled valve identical to the fill valve will drive a pneumatic actuator to pull the flapper valve away from the exhaust hole. The actuator will be leaky, so deenergizing the valve will allow the pneumatic actuator to return to its rest position with the help of a return spring.

The bladder will be fixed in place with Velcro. The exhaust hole in the top of the bladder will align with an exhaust hole in the top of the hull. The fill tube inside diameter is 0.170” and the fill pressure is 30 psi above ambient. A full bladder will be at the pressure of its lowest gas element. Since differential pressure is 0.5” per inch of water depth, if the fully inflated bladder is 8” in height the exhaust pressure is 4 psi. Exhausting a 5 liter bladder as expeditiously as it fills involves a larger diameter exhaust hole. The design size is 1” diameter for that hole.

Waterproofing

Various schemes for waterproofing have been considered but the simplest and probably the most reliable method is to enclose all electronics (except the pressure sensors and some electrical connections) within a “dry bag” similar to the type used in water sports. A feedthrough will be provided, allowing air tubing and electrical wiring to pass in/out of the drybag. A few indicators and control buttons will be mounted within the bag.

The pressure rating of the bag should be minimal IF enough air space is provided at surface to allow a halving of the volume at 30’. If this is so then the differential pressure from within to without the bag will be approximately zero. (In practice, if there is 1’ of height of air in the bag, at any depth, the differential pressure of the bottom of the bag will be zero and at the top of the bag it will be $0.5 \text{ psi}/\text{”} \times 12\text{”} = 6 \text{ psi}$.) The height of the bag will be minimized by laying the components side-by-side instead of on top of each other. Sharp features will be avoided and voids between components will be filled to minimize the air volume trapped between features of the electrical components in the bag.

The computer, the voltage regulators, switches, LEDs and other electronics, the questionably waterproof solenoid valves, the battery will all be within this bag. The pushbutton switches will be actuatable regardless of the depth/volume of the bag.

Regular stranded hookup wire insulation allows leakage between the conductors and insulation so the drybag electrical feedthroughs will be magnet wire, which uses a varnish as insulation. Connectors immediately outside the drybag will provide for switching to regular hookup wire.

Electrical Connections

By design the pressure sensors must be located outside of the drybag so connections are necessary. In addition, a USB connection and connections to power various Emergency Systems components must exit the

drybag. The system is being designed largely independently from the hull and other systems so a 'reach' of 10 feet from the electronics dry bag to each bladder/pressure sensor is provided.

Experience has shown that the water of the David Taylor Model Basin is at least moderately corrosive. Electrical connectors have been chosen that both utilize a wiping action on connect and disconnect as well as gold flash on the contact surfaces. Molex C-GRID III components are used. The connector-to-wire crimps are additionally soldered for corrosion resistance. However the Emergency Systems components draw significant current and so the connections should be self-cleaning. Regular Fast-on Quick Disconnects are used for them.

Program/Algorithm

The minimal intelligence of the program roughly involves 1) sampling the current depth of the Nautilus when first triggered, and then 2) adjusting the buoyancy of the two bladders to maintain the average sampled depth until turned off. In addition, the computer must blink the Emergency Systems marker lights periodically regardless of whether buoyancy control is on or off.

This 'mode' station keeping at a constant depth, is only one of several desirable modes possible. For example, maintaining maximum floatation for keeping station at the surface, such as while in queue before a race, is useful. Sinking at a controlled and moderate rate (0.25 feet per second, depending on the sub tenders and their current ear status) also. Sitting at maximum negative buoyancy in a low power mode (decreased computer clock speed, no pressure sensor power draw, decreased marker buoy flash rate) is possible. Surfacing at a controlled and very moderate rate is possible too. In addition a test mode, to exercise all valves and actuators and give readouts of battery voltage, pressure sensor readings and any other diagnostics is useful.

Minimum controls and indicators are planned for. Currently three momentary pushbuttons with differently colored indicator lights are planned. One will control the Emergency System components, one will control the current mode of the buoyancy control system and one is reserved for future use (things we forgot). These will be accessible thru the drybag (which is transparent).

Modes are selected by pressing a button one or a multiple of times. If the current mode is "1" and mode "4" is to be selected then the button is pushed three times. The prospective mode "4" is indicated (four flashes) for a few seconds before being entered. This behavior allows changing modes without actually having the system enter undesired modes.

Power

A 12 Volt Jelled Electrolyte Glass Matt Sealed Lead Acid Battery is used for power. It provides several Amp-Hours of power. The design power cycle of the system is 8 hours between charging with an on-time of 2 hours within that period, meaning the battery should be able to provide the average current draw of the system at 12 volts for two hours and will be able to be recharged only after 8 hours. The continuous power draw of the system is about 0.1 A for the sensors and computer, about 0.2 A for each solenoid (max two of four activated at one time and maximum duty cycle of 50% assuming near-constant inflate/deflate cycles). The Emergency Systems components draw about 1.7 A but it is expected that they will operate one at a time with a maximum duty cycle of 10% for an average of 0.17 A. Maximum average total current draw is thus calculated to be $0.1 + 0.2 + 0.17 = 0.47$ A. The selected 8 amp hour battery should be plenty of power and reserve. This battery will reside within the drybag.

Emergency Systems

Objective

The emergency systems of Nautilus' main purpose is to help keep the three Nautilus pilots safe by making sure that the submarine has the right safety equipment onboard. The main goal of the team is to ensure that the proper emergency equipment is equipped on the submarine to protect the pilots and alert the appropriate personnel when the team needs assistance.

Research & Design

Initially the emergency subsystem reviewed the previous buoy design, and met with the buoyancy team mentor who provided an orientation to the role that the buoy plays and where it can be positioned on the sub. The team then researched various buoy designs, and to provide an update at the following Nautilus team meeting. Once the team presented their design, a prototype was tested in water and the buoy was sealed to prevent water from filling up inside the buoy. During another pool testing meeting, the team tested the buoy in both shallow and deep water to test its acceleration speed once released, a member of team would take the unit to the bottom then release the system, this effort was conducted five times -- twice in eight feet of water and three times in 3 feet of water. The speeds were recorded. At our May 15, 2015 ISR board and team planning meeting, our team met with the Hull team to discuss the placement location of the buoy on the submarine, upon review of the unit, the hull



team lead, requested that we decrease the size of the buoy to make provide more space for the pilot. Our team shortened the buoy by $\frac{1}{4}$ of its original size of 14"x4" to a new dimension of 10.5"x4". After cutting the buoy to its new size, we transferred responsibility of the buoy to the hull team for placement on the submarine. Lastly, we purchased 50 feet of orange marine cord capable of reaching the top of the water when the submarine is at its deepest depth during race week.

The second step that the team began to address was to identify the proper coast guard approved lights and other emergency lighting that is required to be onboard the submarine to comply with the rules. We searched for similar lighting on the internet along with pricing for purchasing a new coast guard approved light. In addition to the SOLAS approved light, the team also purchased a 12 volt LED light strip used in pool applications which will be affixed to the exterior portion of the hull.

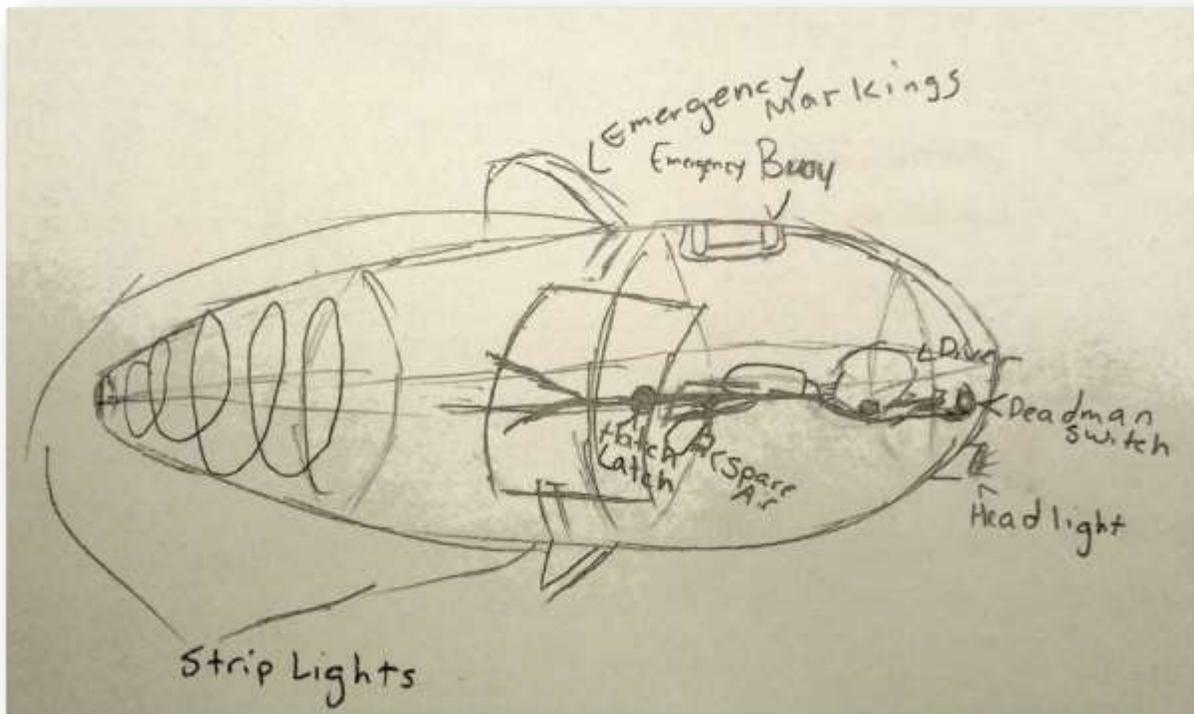


The team began to research and design the hatch latch, however during a meeting with the hull team they decided that since they were in the process of building the

hull and would be creating the cutout and framing for the latch, they would likewise design and purchased the latch. This responsibility is no longer assigned to the emergency sub system and is no longer part of our deliverable. Currently the team has been meeting and discussing the most convenient deadman switch that should be outfitted on the steering. At one of the meetings the steering team presented the design and build of the steering which afforded us an opportunity to see the unit and get a sense of how it would work. After visualizing the steering the team began to discuss the most appropriate switch that would be convenient and easy to be used by the pilot. The Buoyancy sub-system group offered a recommendation and suggested that we explore how a bicycle brake could work as a deadman switch. Team members salvaged parts from an old bicycle, however the team is still exploring using a slip knot connecting the switch to the buoy lock which would release the buoy. We plan to have a final design in place by June 5, 2015 to be tested by the team pilots and turned over to the hull team for installation.



The Emergency system has a few key steps remaining to complete its tasks prior to race week. Our goal is to be completed with all of our deliverables by the third week in June and to participate in the testing phase with the other subsystems. Our key remaining tasks are to meet with the hull team to decide where to place the emergency lighting and the safety markings on the sub, we also will need to paint the buoy orange as recommended by the team. Additionally, we'll be working with the steering team to test and be sure that the deadman switch is placed properly on the steering and is working to their satisfaction.



Cost Breakdown

Subsystem	Component	Quantity	Cost	Source
Steering	Alum. Pipe – 8ft, 1" diameter	1		Donated
	12' lengths of 1/16" stainless steel rudder cables w/3/16" eyelets one end	2	\$ 19.99	topkayaker.com
	16' lengths of 1/4" rudder cable housing (plastic housing)	2	\$ 20.00	topkayaker.com
	4" lengths of shrink tube – for rudder cable connections	4	\$ 12.00	topkayaker.com
	Eyelets for cable runs		\$ 10.00	Home Depot
	Alum Sleeves/Collars for hull support (built into hull)		\$ 10.00	Home Depot
	Dive Planes			Left overs from Hull
	3/8" all thread rod for dive planes/rudder	1	\$ 20.00	Home Depot
	3/4" Galvanized Elbows	4	\$ 20.00	Home Depot
	3/4" x 3/4" x 1/2" Alum tee	1	\$ 12.00	McMaster Carr
	Copper hardware for rudder control		\$ 40.00	Home Depot
	Other misc. hardware for cable connections		\$ 10.00	Home Depot
	Steering Subtotal			\$ 173.99
Propulsion	U-Mold Plastic	3	\$60.00	Radio Shack
	Metal Conduit	3		Donated
	Metal Wire	1		
	Fiberglass			Left overs from hull
	Resin			Left overs from hull
	3D Printed Screw (Prototype)	1		Local School
	3D Printed Screw (Full Scale)	1	\$1,500	John Hopkins University
	Bikes	3		Donated
	Drive Shaft	1		
Bearings	1		McMaster Car	
Propulsion Subtotal			\$1,560.00	
Hull	Fiberglass Supplies		\$ 720.00	US Composites
	Fixtures, tools, foam		\$ 720.00	
	Paint, windows, hardware		\$ 560.00	
Hull Subtotal			\$ 2,000.00	
Emergency Systems	Lights		\$ 100.00	
	Paint		\$ 20.00	
	Buoy Parts		\$ 15.00	
	Spare Bicycle Parts for Deadman Switch		\$ -	
	Tape		\$ 10.00	
Emergency Subtotal			\$ 145.00	
Buoyancy	Electronic Components		\$ 120.00	
	Valves and plumbing supplies		\$ 45.00	
Buoyancy Subtotal			\$ 165.00	
Logistics	Scuba Certification		\$ 3,000.00	
	Scuba Gear		\$ 5,000.00	
	Transport Cart		\$ 100.00	
	Misc. Supplies		\$ 450.00	
Logistics Subtotal			\$ 8,550.00	
Team Nautilus Total			\$ 12,593.99	

Special Thanks to Our Corporate Supporters

