Pneumatic Thruster for Marine Applications

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Abstract

The purpose of this project was to optimize the design of a pneumatic (compressed air) thruster for use on boats and investigate whether this type of thruster would be suitable for use in a Solar Splash competition. A thrust measuring test tank was designed and constructed to compare the thrust output of various compressed air thrusters to find the optimal design. 60 unique 3D printed thrusters were tested in a total of 420 total configurations. From this group, 4 configurations produced a higher thrust than the baseline. The best thruster of those 4 produced 6% more thrust than a plain air nozzle holding all other variables constant. This improvement is meaningful, but not enough to make compressed air a viable option for Solar Splash due to the overall efficiency, energy density of compressed air, and the complexity of converting to this system. This project was successful in optimizing the thruster design and proving it can improve efficiency. While there is not a viable use case in Solar Splash, a pneumatic thruster can still be useful. Applications such as long-term storage safety boats, docking bow thrusters, and short distance water taxis/ferries could all benefit from using a pneumatic thruster.

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1.0 Introduction

The purpose of this project is to optimize a pneumatic (compressed air) thruster to see if it could be useful in Solar Splash or other marine applications. Air jets are typically inefficient in terms of thrust and energy density, so they are traditionally a bad choice for propulsion. It is hypothesized that using compressed air to generate a vacuum through a venturi pump style shroud underwater will increase the efficiency of an air jet and make it a viable option for propulsion. This vacuum would pull water through the thruster thereby increasing the mass flow rate and consequently the thrust output.

This project originated while developing drivetrain systems for the USI Solar Splash Team. Initially, this idea was a way to capitalize on a rule in the Solar Splash rules see appendix E that states teams may utilize alternative energy storage devices such as capacitors and flywheels. The premise is that the battery capacity is limited by weight to 100lbs of lead-acid batteries to keep costs and speeds lower. That rule allows for alternative methods to propel the boat which would allow air tanks. The pneumatic storage would be additional energy on top of the battery limit. The goal of this senior design optimization problem was not to expressly design a thruster for the USI Solar Splash Team, but to determine optimal thruster parameters and whether a thruster is a viable option for future use by Solar Splash.

1.1 Background

Solar Splash is an international electric boat racing competition focused on highlighting solar technology. The event has been around since 1994 [1]. The event location has changed several times from Milwaukee Wisconsin, New Orleans, Buffalo NY, Fayetteville Arkansas, Cedar Falls Iowa, and finally to Dayton Ohio shown in (figure 1). In addition to highlighting solar technology, the competition is a way for students to practice teamwork and interdisciplinary skills. The boats are expected to cost less than $10,000. Teams compete against each other in three events: sprint, slalom, and endurance. The podium for the competition is decided by the points earned in these events along with points from the technical report and video submissions. They also give out awards for innovation in hull design, drivetrain design, electrical design, and solar design.

USI has competed in Solar Splash competitions on and off since 2015. The team did not attend in 2022 because most of the previous year's team graduated, and the boat was not ready for competition. In 2023 the team brought a completely new boat and placed 3rd overall and won several awards (Figure 1). The team returned with a revised version of the same boat in 2024 only to place 8th due to a litany of issues which are outside of the scope of this report. In 2025 the team built another new hull in a trimaran configuration and placed 2nd overall in that year's event. They plan to reuse that hull for 2026 along with upgrading the existing systems.

Figure 1 Solar Splash pits 2023

1.2 Statement of Problem

The goal of this project is to find the shape of pneumatic thruster that maximizes thrust. For any application where a pneumatic thruster would be useful, it would need to be as efficient as possible to increase its usefulness. This thruster could be useful for Solar Splash, but it is impossible to calculate the predicted range and speed of the boat without knowing the performance of the thruster. Section 7.2 discusses other applications for a pneumatic thruster where these results might be useful. The difficulty in answering, “what are the dimensions of the best thruster?”, is that there are many configurations for how to shape a pneumatic thruster. Section 3.1 explains the method chosen for solving this problem.

1.3 Review of existing solutions

I have designed each of the Solar Splash drivetrains since 2022, so I have a deep understanding of the problems associated with designing, building, maintaining, and using traditional drivetrains. My experiences with these old drivetrains are a major motivation for exploring the idea of using a pneumatic thruster that could eliminate most of the issues associated with traditional drivetrains. This section documents the previous outboards used in competition along with their pros and cons.

2023 1960’s Outboard conversion

For the 2023 competition, the team was rushing to finish the boat in time and elected to convert an existing gas outboard motor to avoid building a new unit from scratch(see Figure 2). The team purchased a seized outboard motor from a local seller, then removed the motor and cut accessories to save weight. To adapt the lower unit, the team built an adjustable mount for a pair of Lynch LEM 200 electric motors. The major downside of this drive train was its age. It was over 60 years old and used “shear pin” prop mounting. Shear pins are an old standard for propeller mounting which has been replaced by splined shafts. The name comes from a pin that held the propeller to the shaft which would intentionally break if the propeller hit something underwater to protect the internal gears (figure 3). This means the team’s propeller selection was limited, and there was a lot of internal friction from old bearings. To circumvent the propeller issue, the team machined an adapter to mount modern high pitch props and increase top speed.

In competition, the outboard motor worked reliably and helped the team secure 3rd place. However, it was holding the team back with its weight and propeller mounting limitations.

Figure 2 2023 USI Solar Splash Drivetrain

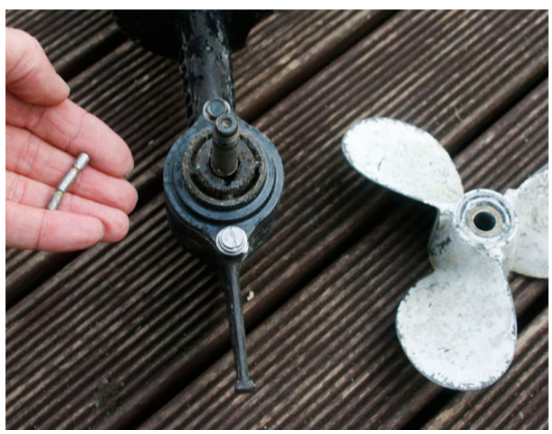

Figure 3 Shear pin style shaft

2024 Chain Drive Outboard

The team took the lessons learned from 2023 and started working on a new drivetrain (figure 4).

The key factors the team was trying to improve were weight, propeller standardization, and swappable gear ratios. The drivetrain the team ended up creating had all these features, but the design was too ambitious and complicated. During the first practice at competition, the team used its largest sprocket, and the torque on the outboard clamp caused it to slide off and throw the chain into the water. To fix this the team bolted the drivetrain directly through the transom so this would not happen again. During the first endurance race the skipper told the team he was hearing concerning sounds coming from the drivetrain. The team had the skipper continue the race because it was almost over. When the skipper reduced the throttle coming into the pits, the chain flew off again. The chain tensioner had seized and was cut in half by the chain. The team replaced it with a new idler wheel and found a brass bushing to reduce flat spots for the rest of the competition. Ultimately, the idea of having swappable sprocket ratios was successful. However, in practice the design was too weak and unreliable. With more development, testing time, and higher quality parts it would have been far more successful.

Figure 4 2024 USI Solar Splash Drivetrain

2025 Lynch Motor's Bluefin II Semi-prebuilt

Figure 5 Bluefin II next to short shaft modification

Figure 6 Completed 2025 drivetrain

After having so many issues converting outboard motors to electric, the team searched more extensively for an off-the-shelf option. The team found that Lynch Motors, who make the LEM 200 electric motor, also sells outboard conversion kits. The team purchased the Lynch Motors Bluefin II outboard (Figure 5) to save on development time and give the team a reliable, light, and high-performance upgrade.

This purchase was ultimately a bad decision. The Lynch Motors website listed the outboard as weighing 18kg in the specification sheet. When the team received the Bluefin II, it weighed 32kg. That much weight is unacceptable for a small boat. Lynch Motors was gracious enough to send the shorter version of the driveshaft to lighten the drivetrain.

With the replacement parts and extensive machining, the team was able to reduce the weight to 25kg including the motor and adding an electric trim plate (figure 6).

2.0 Conceptual Design of Pneumatic Thruster

The basic operating principle of a pneumatic thruster is to use compressed air through a venturi style shroud which creates vacuum on the surrounding water entraining it into the airflow (Figure 7). This type of technology is already used in air amplifiers, which reduces the cost of air cooling in manufacturing settings [2] [3] [4]. With the correct geometry and air pressure settings, the technology should be adaptable to marine applications. Preliminary testing conducted during the Spring 2024 semester yielded promising results. This testing involved designing and printing thrusters to see if the general shape would create a vacuum and accelerate water through it. One of these thrusters is (figure 8) which proved the concept could work.

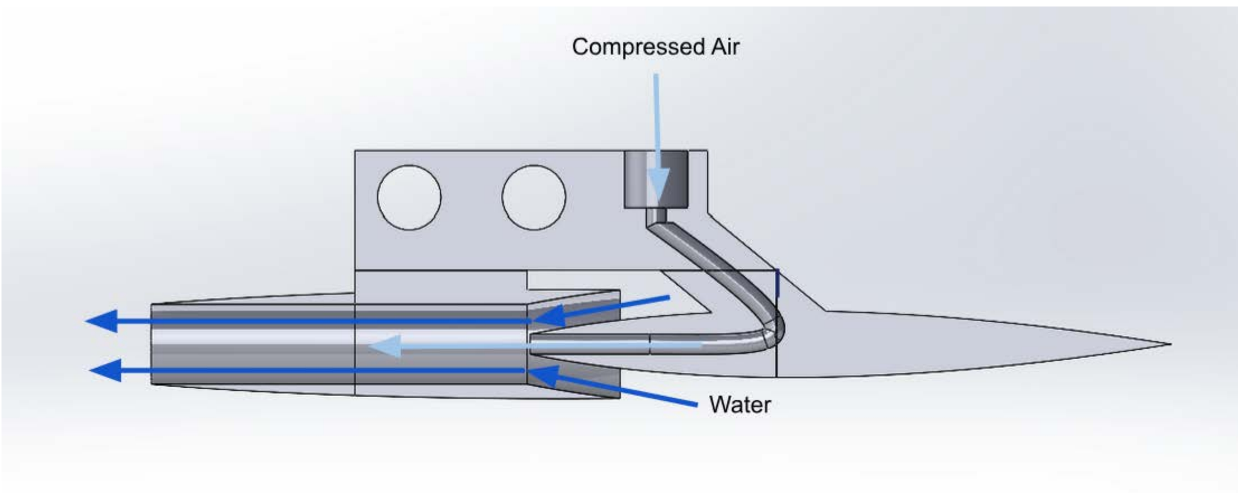

Figure 7 Early pneumatic thruster diagram

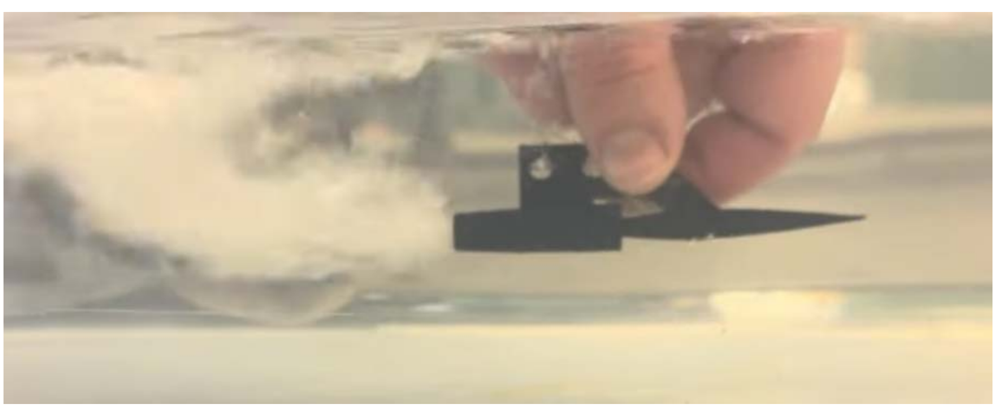

Figure 8 Proof of concept thruster design test

The force sensing tank described in section 3.2, improved the ability to test thrust in order to find an optimal thruster geometry.

2.1 System Hierarchy

The configurations in this section are a hypothetical concept of how a full-size pneumatic thruster system would function if installed as main propulsion for a boat. This project does not go to this stage of development, but it is important to think ahead about how the thruster could be implemented.

Configuration 1: ***Pre-charged tank only***

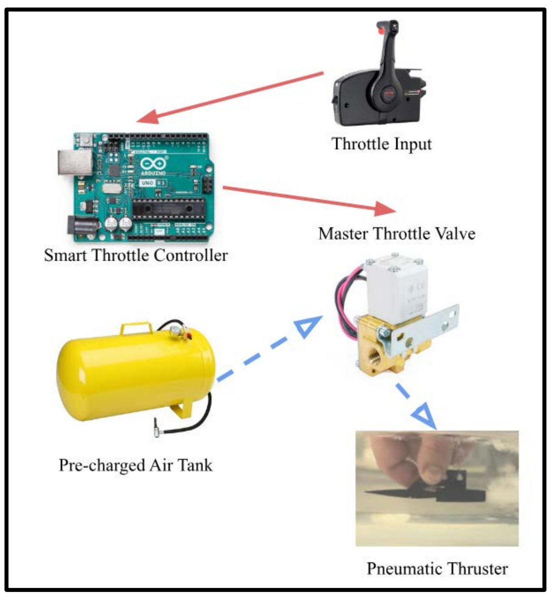

Figure 9 System Configuration 1 tank only

The configuration in (figure 9) shows the boat without an air compressor on board. This configuration would require the boat to use an onshore refilling station to recharge the tank. This configuration is the simplest and lightest version which would be most applicable for a ferry or barge type of boat doing short trips. This is the configuration that should be used for testing a full-size version of the thruster because it is the most cost effective for proof of concept. Speed is directly controlled by the amount of air being released by the throttle valve. This could be a manual valve or electronic. Electronic would be the safer option to keep the operator away from high pressure lines. Another benefit of using an electronic valve is the ability to add cruise control.

Configuration 2: Tank and Compressor Combination

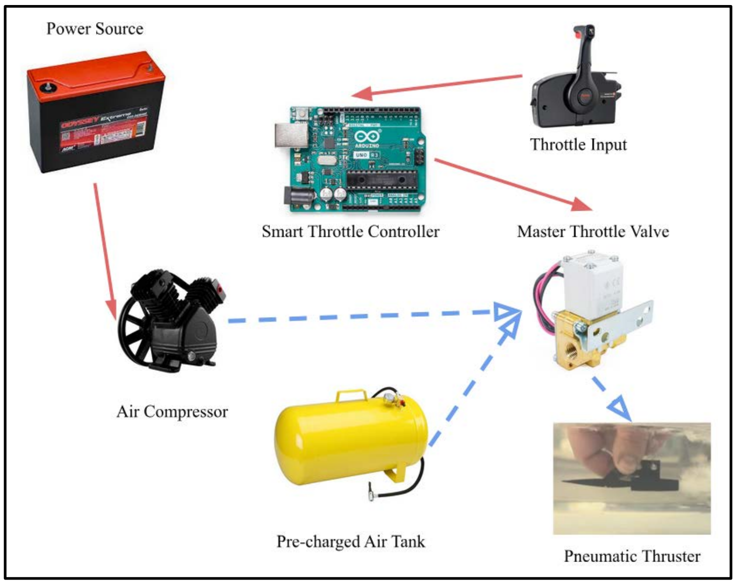

Figure 10 System Configuration 2 tank and compressor

The configuration in (figure 10) shows the boat with both the tank and compressor removing the need for an onshore refill station. In this setup, compressor could be powered with any type of source. Operators could use gas, diesel, propane, or electric compressor to fill the tank as it makes no impact on the pneumatic thruster. Running on tank pressure can be done solely through control of the tank and master valve without using the motor. The compressor functions as a range extender but in no way is necessary for the system to function.

2.2 Requirement Specifications

The main requirements for this project come from the “Rules of Solar Splash 2025”. This contains all design and safety constraints for all systems in Solar Splash [11]. Safety constraints are the most important of these because if the thruster does not pass technical inspection, it cannot be used. In technical inspection all the other requirements will also be checked. All applicable rules from the Solar Splash Rules Handbook are in appendix E.

Apart from the Solar Splash Rules, the drivetrain system must fit within the size and weight constraints of the existing USI Solar Splash hull.

2.3 Design Framework and Evaluation Criteria

This section is a hypothetical of what criteria would be used for a full-size thruster. The project focuses on the tank design and testing of thrusters.

The pneumatic thruster’s evaluation criteria will mainly be based on metrics from existing gas outboards because they are the current standard solution for marine propulsion. If the pneumatic thruster is not an improvement on traditional designs in areas where it should be stronger like, strength and weight. Then, the pneumatic thruster will not be a viable option when it comes to its drawbacks like the potential for inefficiency. For these reasons, it is imperative to make sure the pneumatic thruster is meeting the evaluation criteria listed in Figure 11 or it will not be a successful design.

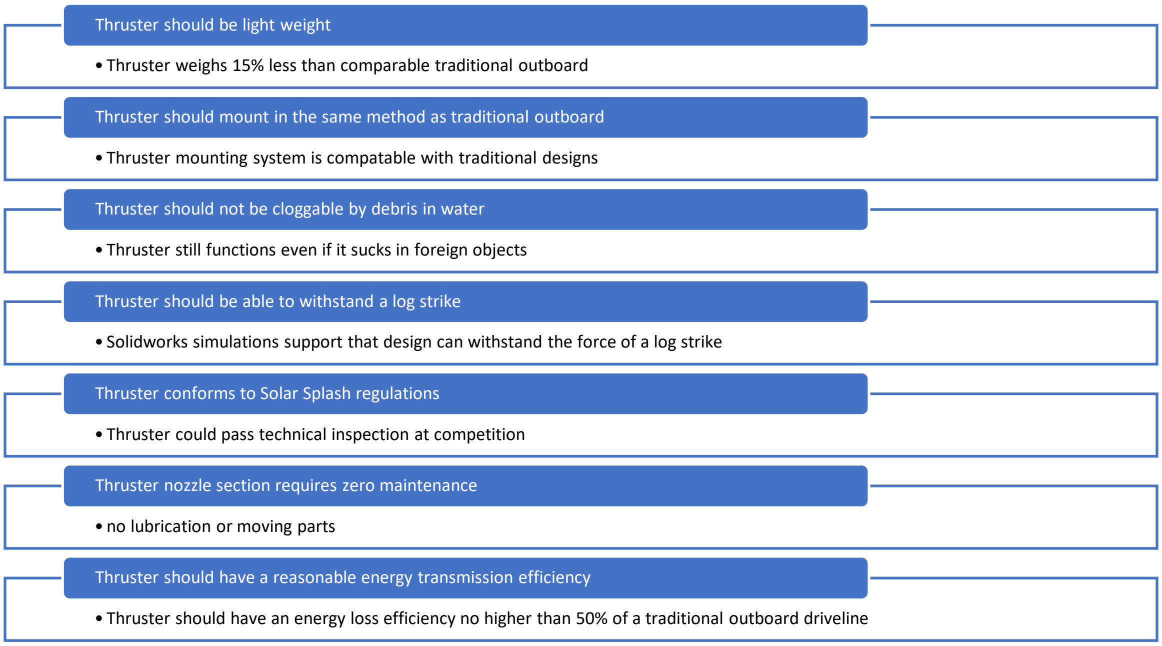

Figure 11 Evaluation Criteria

2.4 Evaluation of Alternatives

The pneumatic thruster is designed as an alternative method for marine propulsion compared to using a traditional propeller or inboard jet drive. The most standard type of marine drive is the outboard motor, which the Honda 20hp is a perfect example of (figure 12).

Figure 12 Equivalent Outboard Motor

Through decades of development, outboard drives like these have become reliable workhorses able to withstand major abuse and long hours. The main benefit of these motors is efficiency and standardization. They have been steadily improved over time, improving fuel efficiency and propeller design. Especially for a wide range of speeds, a traditional outboard will not be beat in terms of efficiency. This traditional style does still have major drawbacks that cannot be overcome. The propeller will always be a point of danger for the driver, swimmers, and Sealife. It is a big spinning blade underwater that will cut anything it encounters. The propeller is also susceptible to damage itself through hitting riverbeds and floating debris. Propellers can be bent and broken leaving boaters stranded. Traditional outboards also require lots of maintenance. Internal combustion motors require oil changes and freshwater flushes to prevent corrosion. The gearbox also requires oil changes. The cooling system for the motor is driven by a rubber impeller which is a common failure point for most outboards, especially as they age. Using a traditional outboard also comes with the weight of a 4-stroke motor hanging off the back of the transom. Maintenance on the motor, like spark plug changes, can be difficult because the motor is packed into a tight cowling and hanging over the water.

The pneumatic drivetrain reduces the complexity and danger that traditional outboards bring. The pneumatic drivetrain does not have moving parts exposed to the water which removes any danger of prop strikes to swimmers or Sealife. The maintenance of a gearbox with moving parts will also be eliminated by a solid pneumatic thruster and air lines. The weight distribution will also be improved because the compressor is connected to the pneumatic thruster by air lines, so the compressor can be mounted anywhere in the boat for optimal weight distribution.

3.0 Conceptual Design of Test Tank

This section of the report details the decision process for choosing a testing method. The process chosen is a test tank which is a commonly used tool in ship design. Also included in this section is the design development for the test tank.

3.1 Evaluation of Testing Methods

A major challenge of this project was finding a reliable way to measure thrust to compare hundreds of different thruster geometries. There are limited options when it comes to testing how fluids will react to different geometries. The most accurate way is to make a full-scale prototype and gather data directly from it. For most projects, including this one, a full-scale prototype is not feasible due to cost and time constraints. There are two options to choose from when moving down from full-scale prototypes. The first option is to make scale models, test them, and scale up the data to find how the full-size version should perform [7]. Option two is CFD (Computational Fluid Dynamics) model which allows simulated full-scale testing and no data scaling.

This project is unique because it evaluates a thruster using air and water in the same space. The interaction between the air nozzle and the water around the shroud is unique and would be difficult to accurately represent in a simulation. Traditionally CFD tests one type of fluid at a time. Some normal use case examples would be simulating a wing profile in air, or a boat propeller in water. The issue of two interacting fluid types eliminates most of the simpler CFD available from being useful in this project. There are more advanced CFD that exist, but they are expensive and require specialist knowledge beyond the scope of this project.

Even if there was a simple to use CFD with an affordable license capable of simulating a pneumatic thruster, it would still make more sense to do scale model tests. The reason for this is that CFD is built from and validated using test tank data. Ultimately, tests done in a tank or on a computer should give results that are similar. CFD however, leaves room for inaccurate results if conditions for the simulation are improperly configured. For unique cases like a pneumatic thruster, CFD might not be able to calculate the results accurately. The CFD that seemed to have best chance of succeeding is OpenFoam (seen in figure 13). However, it does not have its own graphical output and requires more computing power than was available [9]. This software might be a good resource for future senior design groups doing anything fluids related that want more in-depth results than SolidWorks flow simulations can offer but ultimately was not the best choice for this project.

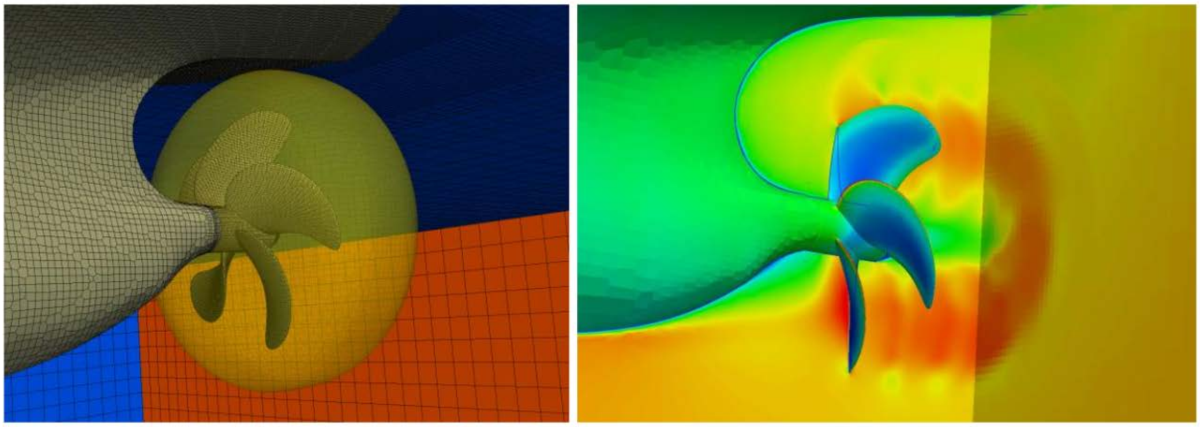

Figure 13 OpenFOAM CFD

Scale testing is usually the correct answer when trying to optimize motor parameters in the marine world because it is more accurate than a CFD model. Computer models can be particularly inaccurate for unique boats and propellers when cavitation and ventilation begin to occur [8]. This is important to consider because of how the pneumatic thruster interacts with the water. This makes the choice to do scale testing the correct solution for this project.

Since test tanks are a reliable method of testing, a mini test tank was constructed using a 40-gallon fish tank. Due to the small size of the model thrusters, this large tank is enough for turbulence not to affect the thrust output in a meaningful way. At this scale it was feasible to 3D print most of the parts which makes construction simple.

3.2 Test Tank Design

The first step in designing the test tank was determining the requirements of the tank. The most important requirement for the tank is to be able to obtain accurate and repeatable measurements. A secondary goal is that the tank should be easy to set up and use.

The second step was sourcing parts that fit the requirements of the design. To accommodate the accuracy requirement, a high-end force sensor was purchased to improve accuracy and repeatability. The exact list of components and prices can be found in appendix B. This sensor was the correct choice because it was easy to mount, highly accurate, and had the capability to send readings directly to my computer. The ability to send readings was an important feature because swapping shrouds can drip water. If this feature was not available, I would have needed to dry my hands after each test to enter the data. The other important feature of this sensor is that it is capable of reading push and pull. Most force sensors are configured as hanging scales where the force is pulling the sensor apart. For this design it was better to have the thruster pushing into the sensor so that it wasn't necessary to protect the sensor from water splashing behind the thruster. Additionally, all push sensors are pull sensors, but not all pull sensors are push sensors. The flexibility to use the sensor in either configuration opened the possibility of using it as a pull sensor if there was a problem with the initial push sensor design. This is also useful if the test tank would later be converted to test something other than a pneumatic thruster.

The next most important part of the test setup is the guide rails for mounting the pneumatic thrusters. With durability, reliability, and repeatability in mind linear ball bearing rails were selected. They are commonly used as an upgrade for 3D printers because they hold tighter tolerances and are more durable than polyurethan V-bearings.

The tank used as the base was a 40gal fish tank. The volume allows for the turbulence created by the thruster to settle and not affect the readings. This tank size was used to help give consistent readings. Sourcing this part was challenging because there are very few stores that will ship a glass tank. To circumvent this issue, the tank was obtained in-person from a pet supply store.

The compressor choice is also an important factor in the design of the tank. An undersized compressor may not supply a high enough flow rate or be able to maintain pressure long enough for a test. One standard test that ensures manufacturer's claims on compressors are accurate is ISO 1217.2009. I exclusively looked at compressors with this standard to ensure what I chose would perform properly. I chose a 6-gallon air compressor so that it had enough reserve to maintain pressure in the small test nozzles. A Dewalt branded compressor was chosen because it had a higher flow rating than others of the same size, which would ensure that the compressor was not a limiting factor during testing.

The next step for designing the test tank was to create a computer model to reference while building (figure 14). SolidWorks was used to model the individual parts of the tank and to create an assembly representing the entire test tank system.

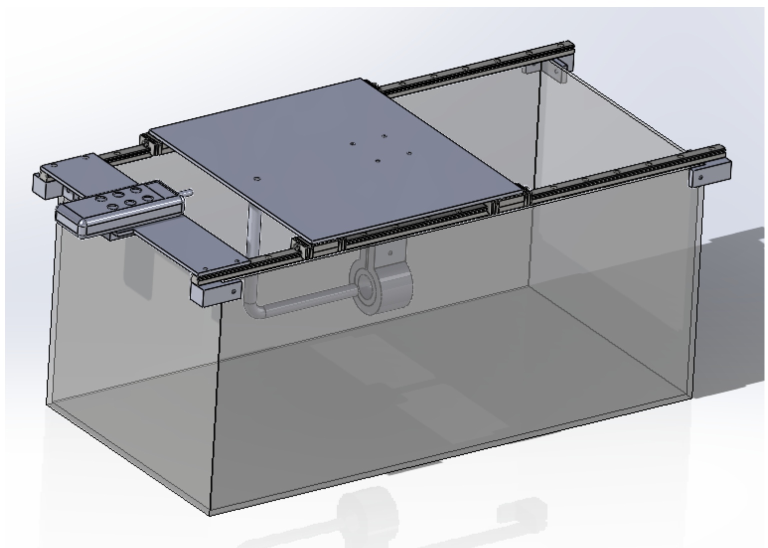

Figure 14 Pre-Senior Test Tank Design

The force gauge came with a dimensioned mounting drawing which made modeling easy. Once all the components were in the assembly, they were constrained to the approximate locations they would occupy in the actual tank. Once the general design had been completed, the mounting brackets were 3D printed.

The next step was designing the moving gantry along with a mount for the shrouds and a nozzle. These components work together, so they must be designed with consideration for where each piece fits into the whole. The first step was deciding on the nozzle and shroud dimensions to use so in order to build the gantry and mount around those parts. The selected nozzle diameter was 2.5mm, because in my experience, that is the smallest hole that a 3D printer can accurately make. Sizes of 2mm and smaller tend to swell closed due to limitations of fused deposition modeling printers. This size is also small enough to not expel more air than the air compressor tank could supply during the test. The rest of the shroud was designed around the 2.5mm nozzle. In figure 15 the driving dimensions of the shroud are shown. The inlet can be 40mm, 30mm, 20mm, and 15mm. The throat can be 30mm, 20mm, 15mm, and 10mm. The length can be 30mm, 40mm, and 50mm. Using design tables in SolidWorks, it was possible to make each shroud configuration in one model and export them for 3D printing. The external diameter of the shrouds are all 50mm to fit in the same standard mount.

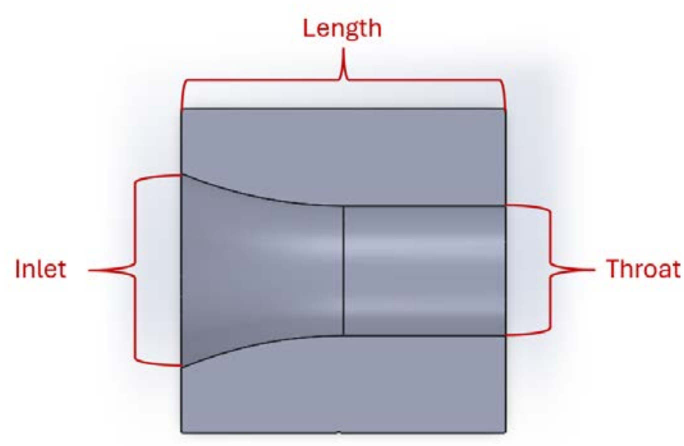

Figure 15 Shroud dimensions

It quickly became apparent that it would be difficult to easily distinguish between each of the 3D printed shrouds because many of them look similar. To avoid this issue, a feature was added to the design table that engraved the file name into the external face of the shroud (figure 16). The file names followed the format: SYM40_30_30, where SYM stands for symmetrical shroud, and its counterpart STR indicates a straight exit. The first number is the inlet diameter, the second number is the throat diameter, and the last number is the length of the shroud. Including this feature was simple, yet it helped me avoid confusion and saved significant time. This feature did not add any additional cost or take more time to print.

Figure 16 Shroud file and part number example

Working from the nozzle diameter and the standard shroud diameter, the next parts to be modeled were full nozzle, shroud mount, and the gantry plate (figure 17). The nozzle and shroud mount are long enough to allow for testing at different depths in the tank by raising or lowering the water level. The air nozzle is mounted using M3 stainless bolts and heat set inserts to make it removable. Those inserts are used in the shroud mount, allowing it to be repeatedly moved without damaging the threads. The same inserts are used on the shroud holder ring so that a bolt can be tightened into the removable shroud to hold it for testing. The mounting plate has just one location for the air nozzle to mount, but the shroud mount has a slot with indented bolt holes. This allows the shrouds to be tested at different distances and for it to reliably be mounted in the same location. The shroud mount can be placed at -10mm from the tip of the nozzle to 30mm from the tip in 10mm increments. The front of the gantry has a flat section for the force sensor to contact. There are small drain holes added to any enclosed section that could hold water. There are six larger holes in a triangular pattern that are for mounting V bearing wheels in. The outermost hole is for a V bearing in an eccentric shaft so that the tension on the aluminum extrusion can be finely tuned to remove slop.

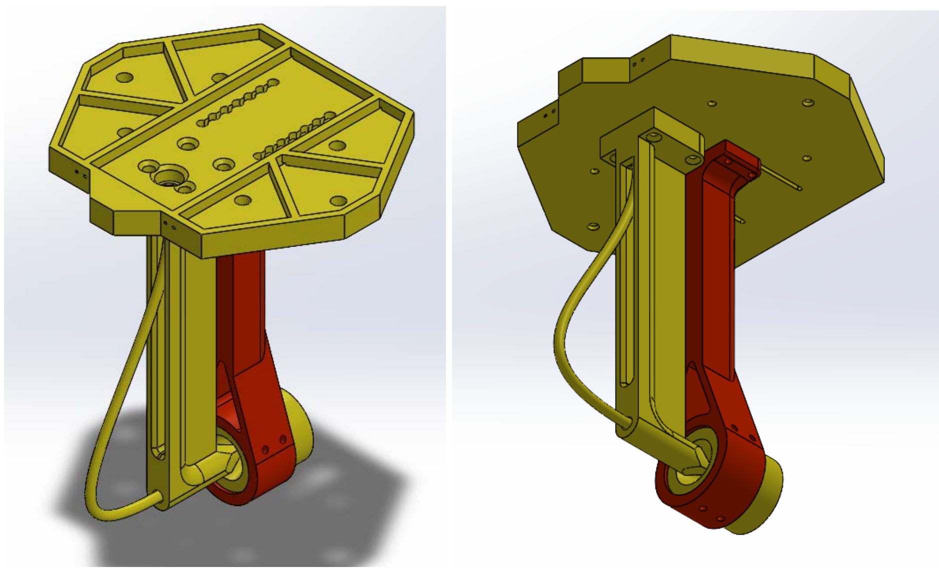

Figure 17 Full gantry assembly – final design

Each model was printed in yellow PLA (Polylactic Acid) because yellow is the most visible color underwater. This is the same color commonly used in full size test tanks where the idea for this whole tank comes from (figure 18) [8].

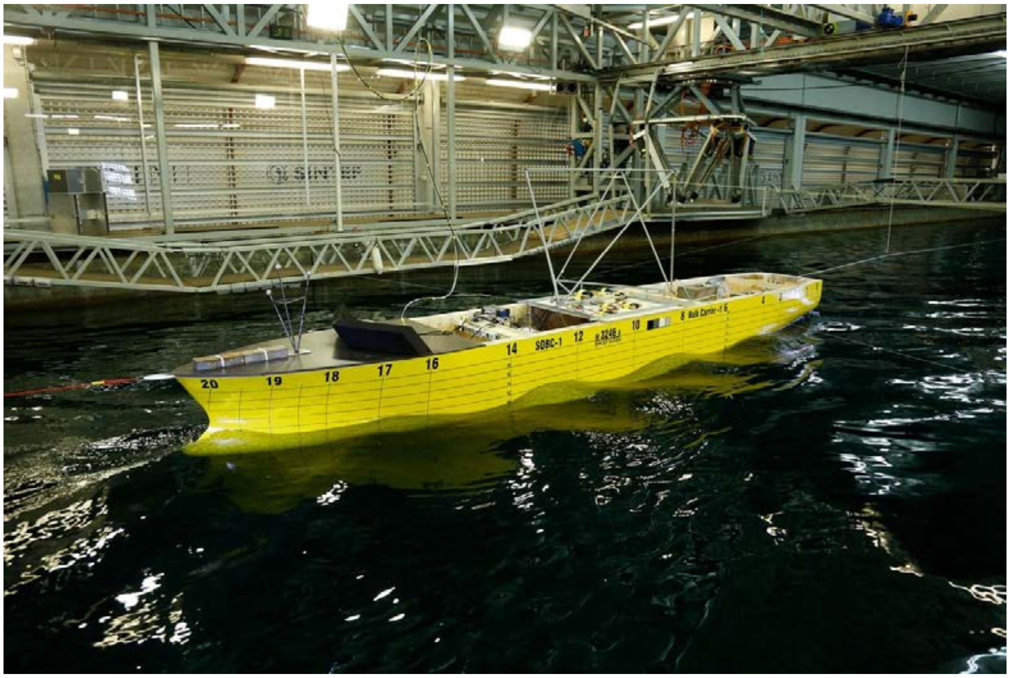

Figure 18 SINTEF towing test tank facility

4.0 Test Tank System Implementation

Due to pre-senior being in the fall, there was time during the summer of 2025 to prepare the test tank design. Much of the 3D printing of the shrouds and mounting parts took place before the fall 2025 semester. When the parts were opened in the fall and I began mocking them up on the tank, there were a couple of issues.

The linear rails chosen for the tank were doubling as the frame to mount the gantry and the force sensor. However, they came with a stiff preload out of the box (figure 19). The rails for the test tank must have extremely low resistance for the force readings to be accurate. It was necessary to abandon the idea of using linear rails, and with that scrap the initial design and mounting prints.

In response to this issue, the rails were changed to 20x20 aluminum extrusion rails and urethane V-bearing wheels for the gantry. This style of rail is much lighter duty than a linear ball bearing rail and has lower weight ratings. The thruster does not produce enough force, and the rollers do not move enough for them to wear out. Both V-bearings and linear bearings are used in 3D printers with great success. Linear ball bearings are the better option for that because they are more durable and accurate, but for light duty applications a V-bearing setup is completely fine.

Figure 19 Test tank before assembly

Swapping the rail system required a new mounting design and CAD model (figure 20). The revised design using extrusions and V-bearings ended up being far better than the original design. The extrusion style frame is built so that it can be removed as one piece. It also allows for more alignment adjustment to ensure smooth bearing operation. Another benefit is the modularity and compatibility with 3D printing. If future teams wanted to use this tank to measure thrust or drag for a different situation, it would be simple to modify the tank and add more sensors. I would recommend aluminum extrusion structures for any kind of similar light duty project. There are tons of resources online for 3D printable parts and hardware that is compatible with aluminum extrusions. The parts are also cheap because they are standard 3D printer parts.

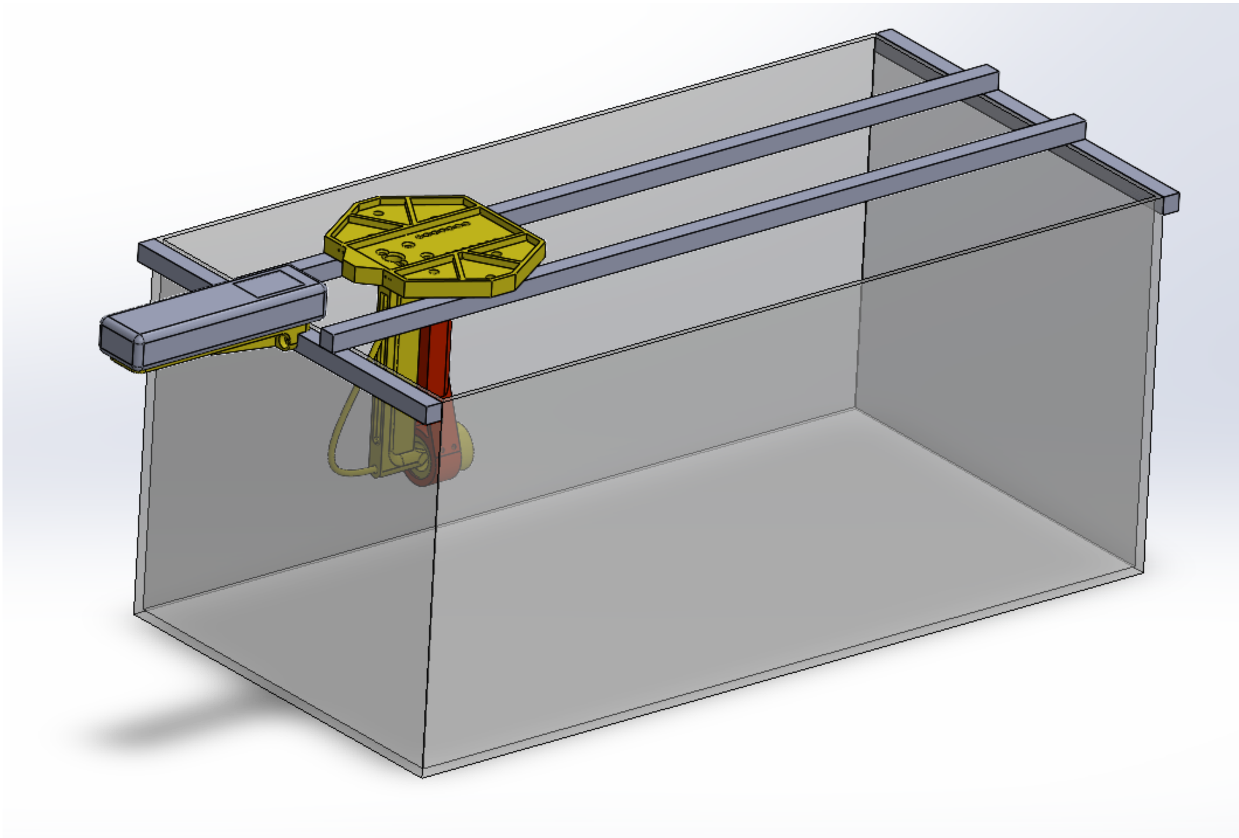

Figure 20 Aluminum extrusion-based test tank CAD model

4.1 Test Tank System Evaluation

The most important feature of the test tank is that it must always provide repeatable results across testing sessions so that data taken one day can be compared to another. It does not necessarily need to be accurate at predicting the force output for a full-scale version of the thrusters but should be consistent across trials of the scale models in order to find the optimal combination of thruster parameters.

The force sensor is the most important piece of the test tank and for that reason, a large portion of the budget was spent on buying a quality one. The force sensor that was purchased is linked in the budget appendix B. This sensor came with a calibration certificate in appendix G which is important for verifying its accuracy. The sensor was also tested against known weights to double-check the results of the manufacturer. Then before each testing session, a calibration check was performed, running the baseline nozzle at 100psi which gave a result of 0.50lbf each time. This shows that the force sensor maintained calibration throughout all testing sessions and the force results can be compared to each other with confidence in their accuracy.

The other condition to maintain between tests is air pressure. The Dewalt air compressor in appendix B came with its own regulator. That regulator was cross-checked with another pressure gauge on the output line. The regulator on the air compressor is easy to move and not a precise dial, so having another way of measuring pressure was important (figure 21).

Figure 21 Air pressure regulator

5.0 Thruster Testing

This section of the report outlines the testing process, data collection, and results. The test tank is easy to use, but to maintain it and consistently gather reliable data, the steps below should be followed exactly.

5.1 Test Tank Operation

Due to ease of use being a top priority in the test tanks design, the testing process was simple. To ensure operator's safety, safety glasses were worn during testing, and another person was always present as compressed air can be dangerous if mishandled. The procedure for testing each thruster was as follows:

1. Start the air compressor and set the regulator to 100psi
2. Check the water level in the tank and fill if needed
3. Screw the nozzle into the gantry plate
4. Set the distance to test on the shroud mount
5. Connect the air nozzle hose to the compressor
6. Zero the force sensor
7. Without a shroud in the holder, open the air valve and note the force. For my testing with a 2.5mm nozzle the baseline was 0.50lbf
8. Install the shroud and start testing

When testing was completed, the last shroud was removed from the holder. 3D prints are not usually watertight, and it is best to take the shroud out quickly so that it does not leak in storage. Then pressure was released from the tank and cleaning filter was turned on to finish the session.

5.2 Testing Process and Configurations

The pneumatic thruster consists of two parts, the nozzle and the shroud, which is explained in greater detail in the thruster conceptual design section. In actual use, the thruster would be a single solid part. In the test tank, the nozzle is a separate part from the shroud so that the shroud can be printed as a small component and be swapped quickly for a different geometry to make a new configuration. As explained in section 3.2.1, each of these shrouds had part names based on their inlet, throat, length, and exit dimensions. Each trial had the following independent variables: shroud type, nozzle diameter, shroud distance, water level, air pressure. The shroud types were grouped by throat diameter because it is the easiest visual identifier of which shroud is being used. It also happens to be the most impactful dimension on thrust output. The nozzle diameter for each test was 2.5mm because that was a reasonable size given the scale of testing and the accuracy of the 3D printer. The shroud distance was set by moving the shroud mount on the gantry to preset 10mm increments. The water level also has impact on the performance of the thrusters, so the level was held constant for all testing. The pressure was also a constant 100psi set using a regulator on the air compressor. Each of these variables were documented for each testing configuration that can be seen an excel table in the appendix F.

Due to the number of configurations possible with that many variables, blindly testing configurations would take too long. To improve testing efficiency, shroud configurations at the minimums and maximums were tested first to identify and trends in the thrust performance. There are three lengths of thrusters, 30mm, 40mm, and 50mm. All the 30mm and 50mm shrouds were tested first because if any trends appeared it could mean that the 40mm would not be worth testing. The same idea was applied to the shroud distance from the nozzle. The closest distance was tested first (-10mm) before moving away from the nozzle because I suspected worse performance farther from the nozzle. This helped eliminate unnecessary testing. The empty cells in the table seen in appendix (letter) are tests that were not performed because the trends observed rendered unnecessary. In total 420 tests were performed.

5.3 Testing Results

From all the thruster configurations I evaluated, only four of them are improvements over the baseline thrust of .5 lbf (figure 22).

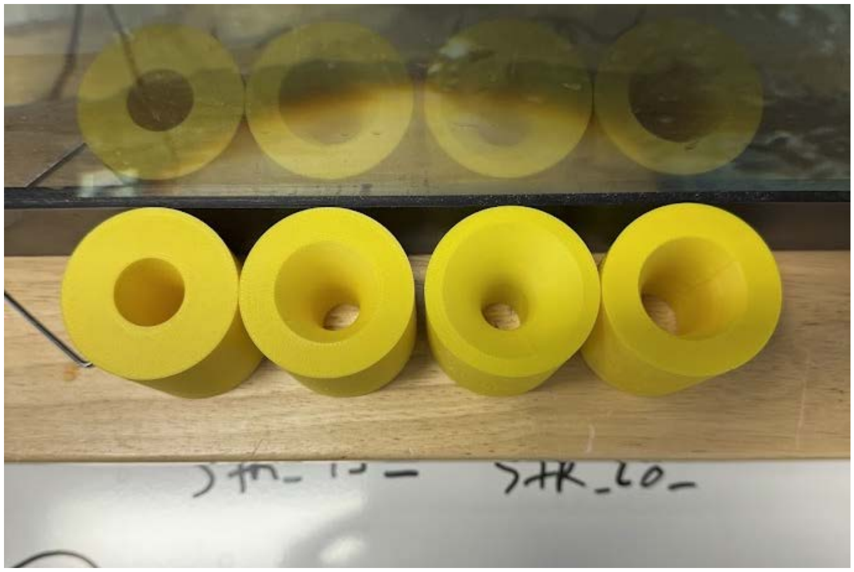

Figure 22 Successful nozzles

The features that these shrouds have in common is the throat diameter and the length. The inlet has some effect on the performance but not as much as the throat size. This makes sense because the air expands into the throat, making that ratio important. When looking at the resulting force data in appendix F, sizes above and below the 15mm and 20mm throat diameter perform worse. Moving to shorter lengths also hurts performance. Since the only over performing shrouds are in the 50mm length configuration, it might be helpful to test longer shrouds at some later date to see if more improvement is possible.

Between the straight exit shrouds and the symmetrical shrouds it is clear that the straight exit shrouds outperform the symmetrical shrouds across all sizes.

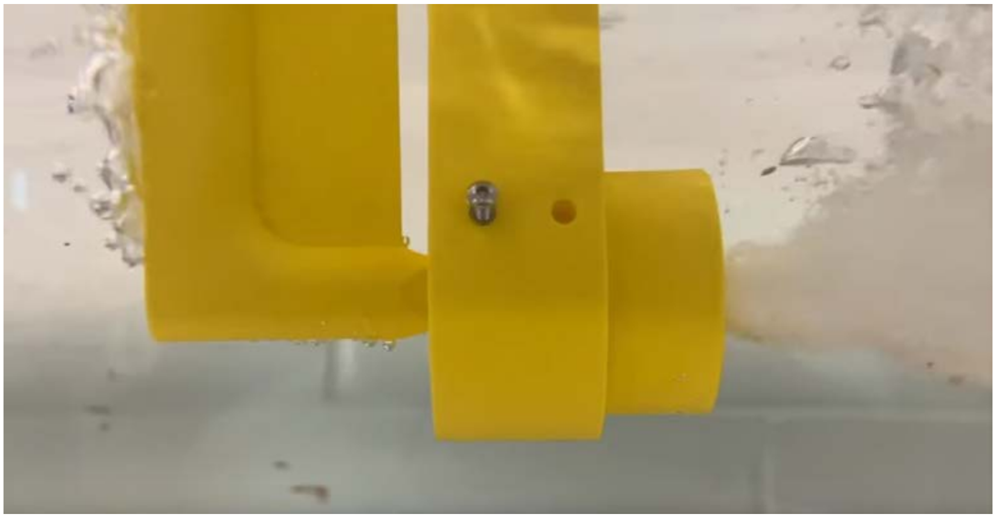

Figure 23 Test tank running

6.0 Conclusion

The objective to find the optimal thruster parameters was a success. This project identified 4 configurations that improved the thrust output without changing anything other than the shroud location and geometry. The best configuration improved thrust from a baseline of .50lbf to .53lbf, a 6% increase. This improvement is in small scale testing, so there is a potential for larger gains using a larger thruster with higher pressures.

In an event like Solar Splash, where efficiency is key to winning. Despite the slight gain in thrust, I do not recommend using a pneumatic thruster due to the poor energy density of air tanks and the inefficiency of air compressors. However, there are applications for a pneumatic thruster as outlined in section 7.0. Optimizing this design makes it even more useful for those cases.

7.0 Recommendations

This section contains recommendations based on the results of completed testing and work done in this project.

7.1 Continued Testing

While this project has identified four thrusters that improve thrust, there could easily be another design that outperforms those. It would be a good idea to continue using this force measuring test tank for similar projects in the future. This project only tested designs where the air nozzle is in the middle of the thruster, but it might also be possible to have the compressed air in a ring similar to a Dyson bladeless fan.

Even though this type of thruster would not make sense for Solar Splash, one of the previous hulls would make an excellent test bed for proving out alternative applications for a pneumatic thruster. It is beyond the scope of this project, but it would be worthwhile to scale up the geometry of the most successful designs with consideration for fluid densities and test at full-scale.

I also recommend using the test tank for propeller design testing. Many of the successful Solar Splash teams machine their own propellers. USI has never done this, and it could be a major improvement in boat performance. The thrust measuring test tank could be modified to hold a small electric motor underwater to test scaled down propeller designs to measure thrust vs current draw. The force sensor and tank are completely capable of this application.

7.2 Pneumatic thruster Applications

As I stated in the conclusion, a pneumatic thruster is not suited well for an endurance competition like Solar Splash. That does not mean that a pneumatic thruster is without a good use case. Four applications have been identified that fit the strengths of a pneumatic thruster while minimizing it’s weaknesses.

Application 1: Safety Boats

One of the benefits of a pneumatic thruster system is that it requires virtually no maintenance. It is like a fire extinguisher in the idea it can be left alone in storage for years with just annual pressure checks. This makes a pneumatic thruster excellent for long term storage emergency boats. In the event of a large ship sinking, there is a danger of being sucked down with the ship even in an emergency boat if too close. The other danger is if the ship is on fire, the emergency boat needs to get far away. The common SOLAS emergency boats have diesel engines with 24hrs of power. This is used to steer the boat into waves for sea keeping, to gather other survivors, and reach shipping lanes. Since this style of safety boat uses diesel, it is susceptible to many types of diesel fouling. This requires weekly checks on the diesel, battery, and other parts of the safety boat. A pneumatic thruster and air tank combination would eliminate many of the parts that could break and simplify the safety boat operation. The range would likely be reduced compared to a diesel safety boat, but an air tank has plenty of energy to get away from a sinking ship and collect survivors.

Figure 24 Example enclosed diesel free-fall lifeboat

Application 2: Bow Thruster

Large ships usually have a part called a bow thruster. The function of these is to move the boat horizontally for docking. The simple idea is to cut a hole through the bow horizontally and then place an electric motor with propeller inside the hole to provide thrust to port and starboard. The downside of these systems is that they require a sealed electric motor and propeller to constantly be in corrosive salt water. An alternative version could be designed using a pneumatic thruster made from composite materials that would remove the maintenance associated with traditional bow thrusters. This is an excellent application for a pneumatic thruster because it is only used while docking, so range is not a concern.

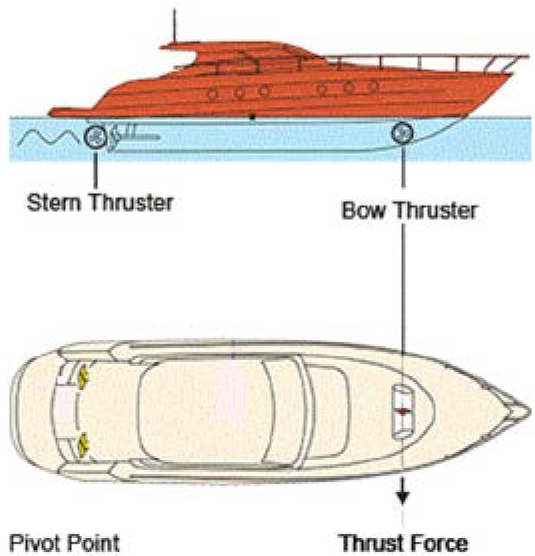

Figure 25 Bow thruster diagram

Application 3: Ferries and Water Taxis

With range being a concern when using a pneumatic thruster, an ideal application is short range trips. Ferries are a perfect example; river crossings and trips of just a few miles work perfectly. They could be set up with a large efficient air compressor and storage tank at the dock which would be used to instantly fill the ferry's tank. Then they could complete their route and refill. This would simplify the systems on the ferry and reduce maintenance costs. River taxis [fig] are particularly applicable because they do not go as fast as large car ferries on open water.

Figure 26 Example water taxi vessel

Application 4: Gas Turbine Ships

The navy has a class of ships called the Littoral Class. These are ships built to quickly intercept threats around coastlines and can reach speeds above 40 knots. They use gas turbines instead of diesel engines for power, which are connected to water jets to provide thrust. I see these as a good application for a pneumatic thruster because the byproduct of gas turbines is hot exhaust gases. A pneumatic thruster could be modified to work with a gas turbine functioning as a compressor. This would be ideal because all the gases would be expelled under water through the thruster. The pneumatic thruster would not be susceptible to clogging or breakage like a propeller or water jet. In this application the reliability would be greatly increased with no reduction to range or performance.

Figure 27 Littoral Class trimaran

8.0 References

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9.0 Appendices

Appendix A: Project Schedule

This schedule was created during pre-senior design in spring 2025.

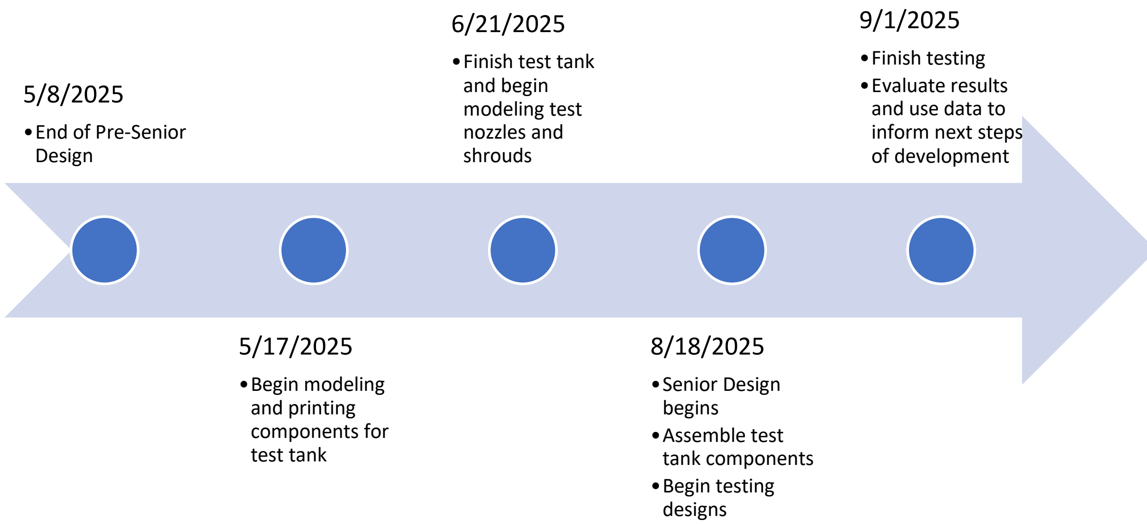

Figure 28 Timeline

Appendix B: Budget

The budget decided during pre-senior was to stay under $600 for the complete test tank. The initial materials purchased achieved this, but the issues with the rails during the Fall semester caused a slight budget overrun. If I had planned to use 2020 aluminum extrusion construction from the start, the project would have stayed under the target budget. If there was a straightforward way to return the expensive linear bearing rails that could recover the overrun. In hindsight, I could have chosen a cheaper compressor tank, but it was so important that the regulator hold a constant 100 psi that it made sense to buy a brand name product.

Appendix C: Bill of Materials

	Item	Price	Count	Link
1	Glass Tank (40gal)	$129.99	1	https://www.petsmart.com/fish/tanks-aquariums-and-

				nets/aquariums/marineland-open-glass-aquarium-86933.html
2	Force Gauge	$165.00	1	https://www.amazon.com/gp/product/B08YKDGTQJ/ref=ox_sc_act_title_3?smid=AG2VN7SZOVHTA&psc=1
3	1000mm Linear Rail	$59.02	1	https://www.amazon.com/gp/product/B099WT1B4Y/ref=ox_sc_act_title_19?smid=AEQA183W2UTEO&psc=1
4	6gal Air Compressor	$169.00	1	https://www.amazon.com/gp/product/B00K34UZBW/ref=sw_img_1?smid=ATVPDKIKX0DER&th=1
5	1/4" NPT push to connect fittings	$9.99	1	https://www.amazon.com/gp/product/B07XBHYP3B/ref=ox_sc_act_title_1?smid=AHFECNLX97BDC&psc=1
6	Regulator	$18.99	1	https://www.amazon.com/gp/product/B0C2TX6N43/ref=ox_sc_act_title_2?smid=A3UWGAZTVSFUQQ&psc=1
7	Airline	$14.99	1	https://www.amazon.com/gp/product/B08B86ZR8W/ref=ox_sc_act_title_3?smid=A37DFQ476WZ5XM&psc=1

Total Cost Order 1: $566.98

	Item	Cost	Count	Link
1	2020 Aluminum extrusions	$38.99	1	https://www.amazon.com/Aluminum-Extrusion-European-Standard-Anodized/dp/B0CLGYBHHN/ref=sr_1_3?crid=22HXOOF5912KX&dib=eyJ2IjoiMSJ9.l_weCcbUgtvHqqVv33sl-rTn3yMjy2fMc9HH0mpEe8p_HxNqYO5-oxpepe0MMfzzkjvE567yV2SIN19IgLPzwQGXm2_HDkczH0EMuZ1UD4c1ghVW4_-OR8roNzntPlqfv0FSHtASG9WwpivqYxAUjafbjkVUJUf-cnL4rA0GmMLA_lKg8A3K0gqgyUpGMGaaS9Z_o3G2X-KQXswUZHingJyYhNgi68GMe3cU96tfe4w.h9a-zMW2GWOwL3UhzwE0DblgK1ENGsJSurvATmcOom0&dib_tag=se&keywords=2020%2Baluminum%2Bextrusion%2B1000mm&qid=1756146004&sprefix=2020%2Baluminum%2Bextrusion%2B1000mm%2Caps%2C146&sr=8-3&th=1
2	2020 V-Slot Gantry Plate	$11.89	1	https://www.amazon.com/gp/product/B0DXKVNRKD/ref=ewc_pr_img_2?smid=A2DGLVBBDAJTOF&psc=1
3	2020 M5 Hardware Kit	$9.99	1	https://www.amazon.com/2020-Aluminum-Extrusion-Accessories-Connectors/dp/B0C4JTL1MP/ref=sr_1_5?crid=245QQIGON8B3U&dib=eyJ2IjoiMSJ9.cLp91dFnitS3JVjuKRScuZy5BHO_YzcKwrq3Lli_vy0j71Mv9Kka2_iwUhWt-UUIXvePxRfUckilYo7tRFn1mHxaKlHUUCfBNEpWSTENej4cMWK5D_rLqQFhDVS1E6Cd6T4OqNHjZOswakUkBncuVrpeVY__T3WJYNinKsrUIfRFgwQrkkCGLNBjTJqFjD4WjwA22gybMzaTTR2nrV5oicz-hv2T8V29PRpTSZLSjf_glaF1E3M7obRmLtqh8PVY3eIKTRPdG_dZJTvdDE_7u9_i_d-UPyVat97nSDEtfsM.FDUZFoQ78cQMNB5NO3eysYOL3_rurCh3mmJleLBASEM&dib_tag=se&keywords=2020%2Baluminum%2Bextr

				usion%2Bwith%2Bhardware&qid=1756146438&s=industrial&sprefix=2020%2Baluminum%2Bextrusion%2Bwith%2Bhardware%2Cindustrial%2C94&sr=1-5&th=1

Total Cost Order 2: $60.87

	Item	Cost	Count	Link
1	Tank Filter	$39.99	1	https://www.amazon.com/gp/product/B0DR2LT2KD/ref=sw_img_1?smid=A1ZOV9XVDG66CE&th=1

Total Cost Order 3: $39.99

Appendix D: FMEA for Chosen Alternative

This failure mode evaluation and analysis is for the conceptual full size thruster if it were to be tested or produced.

Part	Failure Mode	Effect	Cause	Severity	Likelihood of Occurrence	Undetectability
Thruster nozzle Part breaks	Loss of control / loss of thrust	Boat cannot move	Crashing the thruster into something large underwater	10	1	0
Airline breaks	Loss of thrust	Boat cannot move	Airline wore through / Fittings installed improperly / Airline dry rotted	8	1	0
Compressor breaks	Compressor loses rpm / vibrates / makes sound	Compressor loses efficiency / should be turned off	Compressor ran out of oil / failure of user to maintain the only moving part	9	2	9 (no warning until damage is done)

Figure 29 Failure mode analysis of conceptual full-size thruster

Appendix E: Applicable Rules From the Solar Splash Rules Handbook:

7.14 Propeller Safety - The propeller may not be attached to the shaft except when the boat is in the Restricted Area or on the water. The motor electrical system must be deactivated using the Dead-man's Switch and the Motor Switch prior to installing or removing the propeller. The motor may not be run with the propeller attached when the boat is on land.

7.13.10 Covers and Shields - The boat's revolving parts must be suitably covered to prevent accidental contact. All steering linkage must be shielded from contact with the skipper. If a flywheel is used, an NHRA approved scatter shield must cover it

7.3.6 Energy Storage Devices - In addition to the storage of solar energy in batteries, energy may be stored using other devices such as capacitors or flywheels. Storage of energy may begin upon entering the Restricted Area.

7.3.5 "Source Voltage" - May not exceed 36 VDC nominal value (usually 3 batteries). A maximum open circuit voltage of 52 VDC for the photovoltaic charging devices is allowed.

7.2 Materials - Teams are encouraged to be creative in the selection of materials. The only restrictions are 1) flexible materials are not allowed to create a sail, 2) any materials that would pollute the water are not allowed.

Appendix F: Test Tank Data

The straight and symmetrical data represent the two types of shrouds used in testing. The straight exit shrouds have exit diameters that match the throat diameter. The symmetrical shrouds have the same inlet and exit diameter and are therefore symmetrical front to back. Section 5.2 explains how this data was collected and why there are empty cells in the sheet. Also in that section is an explanation for how the file name convention works and how the shrouds were organized into families.

Straight Exit Data

								2.5mm nozzle	2.5mm nozzle	2.5mm nozzle	2.5mm nozzle	2.5mm nozzle
	File Name	Inlet	Throat	Length	Difference	Modeled?	Printed	Peak Thrust (lb/f) -10mm	Peak Thrust (lb/f) 0mm	Peak Thrust (lb/f) 10mm	Peak Thrust (lb/f) 20mm	Peak Thrust (lb/f) 30mm
1	STR40_30_30	40	30	30	10	YES	YES	0.47	0.49	0.44		
2	STR40_20_30	40	20	30	20	YES	YES	0.49	0.5	0.49		
3	STR30_20_30	30	20	30	10	YES	YES	0.49	0.475	0.46		
4	STR40_15_30	40	15	30	25	YES	YES	0.49	0.48	0.46		
5	STR30_15_30	30	15	30	15	YES	YES	0.5	0.485	0.46		
6	STR20_15_30	20	15	30	5	YES	YES	0.48	0.49			
7	STR40_10_30	40	10	30	30	YES	YES	0.5	0.435			
8	STR30_10_30	30	10	30	20	YES	YES	0.49	0.42			
9	STR20_10_30	20	10	30	10	YES	YES	0.46	0.455			
10	STR15_10_30	15	10	30	5	YES	YES	dim	0.45			
11	STR40_30_40	40	30	40	10	YES	YES					
12	STR40_20_40	40	20	40	20	YES	YES					
13	STR30_20_40	30	20	40	10	YES	YES					
14	STR40_15_40	40	15	40	25	YES	YES					
15	STR30_15_40	30	15	40	15	YES	YES					
16	STR20_15_40	20	15	40	5	YES	YES					
17	STR40_10_40	40	10	40	30	YES	YES					
18	STR30_10_40	30	10	40	20	YES	YES					
19	STR20_10_40	20	10	40	10	YES	YES					
20	STR15_10_40	15	10	40	5	YES	YES					
21	STR40_30_50	40	30	50	10	YES	YES	0.49	0.5	0.5		
22	STR40_20_50	40	20	50	20	YES	YES	0.51	0.485	0.47		
23	STR30_20_50	30	20	50	10	YES	YES	0.53	0.47	0.47		
24	STR40_15_50	40	15	50	25	YES	YES	0.52	0.45	0.44		
25	STR30_15_50	30	15	50	15	YES	YES	0.53	0.44	0.41		
26	STR20_15_50	20	15	50	5	YES	YES	0.46	0.43			
27	STR40_10_50	40	10	50	30	YES	YES	0.47	0.36			
28	STR30_10_50	30	10	50	20	YES	YES	0.45	0.4			
29	STR20_10_50	20	10	50	10	YES	YES	0.44	0.37			
30	STR15_10_50	15	10	50	5	YES	YES	dim	0.37			

Figure 30 Straight shroud exit data

Symmetrical Exit Data

								2mm nozzle	2mm nozzle	2mm nozzle	2mm nozzle	2mm nozzle
	File Name	Inlet	Throat	Length	Difference	Modeled?	Printed	Peak Thrust (lb/f) -10mm	Peak Thrust (lb/f) 0mm	Peak Thrust (lb/f) 10mm	Peak Thrust (lb/f) 20mm	Peak Thrust (lb/f) 30mm
1	SYM40_30_30	40	30	30	10	YES	YES	0.49		0.45		
2	SYM40_20_30	40	20	30	20	YES	YES	0.48				
3	SYM30_20_30	30	20	30	10	YES	YES	0.47				
4	SYM40_15_30	40	15	30	25	YES	YES	0.45				
5	SYM30_15_30	30	15	30	15	YES	YES	0.45				
6	SYM20_15_30	20	15	30	5	YES	YES	0.46				
7	SYM40_10_30	40	10	30	30	YES	YES	0.44				
8	SYM30_10_30	30	10	30	20	YES	YES	0.46				
9	SYM20_10_30	20	10	30	10	YES	YES	0.46				
10	SYM15_10_30	15	10	30	5	YES	YES	dim				
11	SYM40_30_40	40	30	40	10	YES	YES					
12	SYM40_20_40	40	20	40	20	YES	YES					
13	SYM30_20_40	30	20	40	10	YES	YES					
14	SYM40_15_40	40	15	40	25	YES	YES					
15	SYM30_15_40	30	15	40	15	YES	YES					
16	SYM20_15_40	20	15	40	5	YES	YES					
17	SYM40_10_40	40	10	40	30	YES	YES					
18	SYM30_10_40	30	10	40	20	YES	YES					
19	SYM20_10_40	20	10	40	10	YES	YES					
20	SYM15_10_40	15	10	40	5	YES	YES					
21	SYM40_30_50	40	30	50	10	YES	YES	0.47	0.46			
22	SYM40_20_50	40	20	50	20	YES	YES	0.48	0.44			
23	SYM30_20_50	30	20	50	10	YES	YES	0.45	0.445			
24	SYM40_15_50	40	15	50	25	YES	YES	0.47	0.4			
25	SYM30_15_50	30	15	50	15	YES	YES	0.46	0.43			
26	SYM20_15_50	20	15	50	5	YES	YES	0.45	0.44			
27	SYM40_10_50	40	10	50	30	YES	YES	0.44	0.37			
28	SYM30_10_50	30	10	50	20	YES	YES	0.44	0.35			
29	SYM20_10_50	20	10	50	10	YES	YES	0.43	0.36			
30	SYM15_10_50	15	10	50	5	YES	YES	dim	0.37			

Figure 31 Symmetrical exit shroud data

Appendix G: Force Sensor Calibration

CALIBRATION CERTIFICATE

DIGITAL FORCE GAUGE

Model: HP-500

Serial No.: H5002409820

Calibrated: 23th Sep., 2024

Operation Standard: Q/HPI002-2005

Calibrated by: Q.C. 005 PASSED

Load	Pressure		Tension	
(N)	Course	Backhaul	Course	Backhaul
0	0.0	0.0	0.0	0.0
100	100.0	100.0	100.0	100.0
200	200.0	199.8	200.0	199.8
300	299.8	300.0	299.8	300.0
400	399.7	400.0	399.7	400.0
500	500.0	499.8	499.8	500.0

Figure 32 Force sensor manufacturer calibration certificate

Appendix H: ABET Outcome 2, Design Factor Considerations

ABET Outcome 2 states "An ability to apply engineering design to produce solutions that meet specified needs with consideration of public health safety, and welfare, as well as global, cultural, social, environmental, and economic factors." ABET also requires that design projects reference appropriate professional standards, such as IEEE, ATSM, etc.

Design Factors Considered:

Public health safety, and welfare: In regard to the design of the pneumatic thruster, safety is one of the major benefits over a traditional outboard. I mention in the background section how removing the propeller from the drivetrain and other moving parts greatly increases the safety of boating.

Relating to safety of the test tank, I state in section 5.1 Operating the test tank, that safety glasses must be worn and another person must be in the room because compressed air can be dangerous if mishandled.

Global: Global impact is not a consideration of this project because of the niche application of the technology involved.

Cultural: This project does not have any cultural impact.

Social: There are no social design factors to consider for this project.

Environmental: This project does have environmental impact because of the improved safety associated with a pneumatic thruster. In the background section I discuss the cons of a traditional outboard, one of them being marine life prop strikes.

Economic: There are no economic factors to consider with this project.

Ethical & Professional: There is no relation to Ethical or Professional design factors in this project.

Reference for Standards: I cited the ISO 1217.2009 standard test for air compressors. This test ensures that air compressors are meeting their listed performance numbers in air flow.