Ocean Well | Reverse Osmosis Membrane Testing and Characterization Rig

A Technical Report for a UCSD Senior Design Project 2023

Engineers: Parker Knopf, Jaden Gilliam, Nikhil Iyengar, Jennifer Hernandez-Mora, Karina Plascencia

Sponsor: Ocean Well

Managers: Michael Porter, Mark Golay, Taylor Wirth

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Abstract

The overarching goal of OceanWell is to provide fresh water to land, while protecting marine ecosystems and ocean health. The long-term goals of this product are to support future-focused climate projects, such as reforestation, aimed at reversing and adapting to the negative impacts of climate change. The scope of this technical report focuses on a small aspect to this larger goal. The intent of this project was to design, manufacture, and empirically test a Reverse-Osmosis membrane (RO membrane) with the intent of finding flow rate and pressure drop across the membrane due to an axial thruster. This testing rig would then be used to test other RO membranes with different filters. To achieve the deliverables of this project, a testing apparatus was developed, integrated with submersible flow and pressure sensors with data then collected and displayed for the user. An understanding of flow dynamics, flow and pressure curves was essential to the characterization and empirical collection of data. Wet testing of the device provided linear relationships between power, pressure drop, and flow rate. Overall the testing apparatus was successful in proving and disproving many hypotheses and sets tremendous groundwork to pursue this inquiry of RO Membrane further.

Executive Summary

This system was built as a test bed to categorize prototype RO membrane filters. The sponsor intends to optimize a filter for their unique deep sea use case. The system has two primary purposes to be accomplished. The first is to create a fluid flow across the membrane and the second is to measure key physical parameters across the membrane. This flow is created via the embedded ROV thruster placed at the tail end of the system. As the thruster sucks water through the membrane, the flow rate of water moving through the filter, as well as the pressure drop across the membrane is measured. The flow rate was attempted to be measured with a custom designed flow probe however an ADV was used in practice.

The flow probe is modeled after a fixed end cantilever. As water flows through the system, this cantilever deflects due to the dynamic pressure experienced on one side. This deflection is then measured and conditioned via two strain gauges placed at the base of the cantilever. Via an empirically calibrated strain to flow rate curve flow rate is measured by this flow stick.

Pressure drop across the membrane is measured by two pressure transducers. Both transducers are placed an equal distance on either side of the membrane within the testing rig tube. These matching transducers are off the shelf components with their own correlation curves relating voltage to pressure. The entire test bed communicates with the user's computer via an Arduino. A custom built application (available on Mac OS, Windows, and Linux) allows the user to control the test bed and view data live both graphed and displayed via read out. After an experiment is complete, the user can save a .CSV file of said data for further study of each test conducted.

The test bed is designed to rely on standard wall power, and is not rated to be submerged to the depth Ocean Well intends on placing their water filtration systems in. However, a few alterations could help this design reach the originally proposed project: some batteries, a bit of waterproofing, an ROV thruster rated to reach the appropriate depth, a water collection tube connected to a Niskin bottle, and onboard memory storage for data collection.

The testing rig is able to collect Power, Pressure Difference, and Flow Rate measurements for any membrane. For the tests conducted so far, a maximum of 7 GPM and around 2 PSI differential was achieved at max thruster power of 1000 W. Overall the project was successful and will allow Ocean Well to continue their research into prototype RO membranes.

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Chapter 1 | Project Description

Background

This project was sponsored by Ocean Well which specializes in innovating saltwater desalination technology through the application of reverse osmosis at depths of 200m-1000m (mesopelagic zone). The reverse osmosis process is made possible with the use of a rolled-up textured membrane layered with filter sheets which leads to a collection tube where fresh water is drawn and the brine exists in separate points. These RO membranes will not be used to produce fresh water in this project but will be used in a testing rig to characterize flow rate through it and the pressure difference across it. Since the RO device is planned to sit at such low depths, we may also add very tiny particles to the system in order to simulate microorganisms that exist in the mesopelagic zone to observe whether or not they get caught in the membrane.

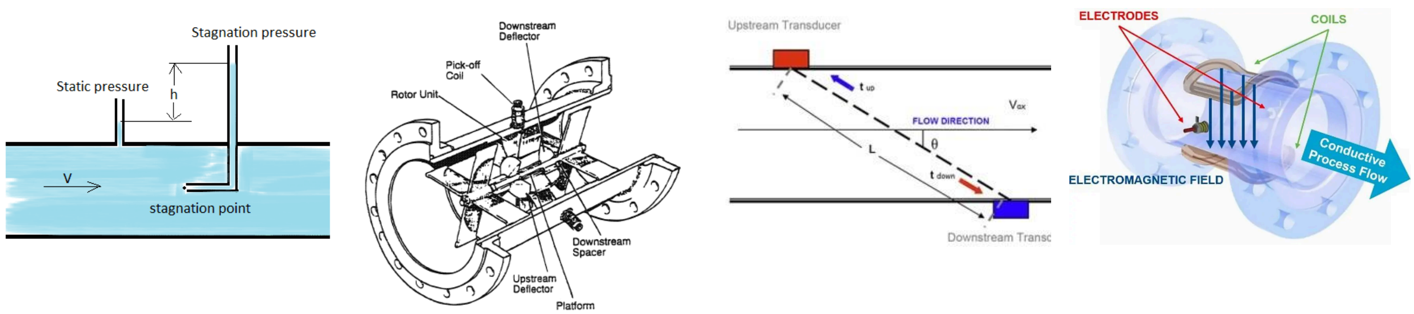
Review of Existing Solutions

Fluid Flow Rate through a Pipe

Idealistic fluid flow through a pipe often produces a predictable velocity profile between the pipe's sidewalls due to the no slip condition applied during this theoretical study. However, due to the large diameter of pipe used in this test bed, and short formfactor from inlet to outlet, along with multiple complex geometries within the system, this idealistic velocity profile is highly unlikely to develop. Thus measuring the velocity at one point of the system in order to predict an average velocity is not only difficult, but likely to lead to inaccuracies in further calculations. Namely, the calculation of volumetric flow rate shown in **Equation 1**,

$$Q = V_{avg} \cdot A \qquad \textbf{Equation 1}$$

which is a major deliverable for this project. Solutions such as combination pitot tubes (static and dynamic), off the shelf flow meters, and industrial level ultrasonic equipment have been explored.



Pitot Tube | **Turbine Flowmeters** | **Ultrasonic Sensors** | **Electromagnetic Flowmeters**

Figure 1: Various types of flow sensors commonly used for fluid flow in pipes

The first option considered was a pitot tube, a device that takes both the static and stagnation pressure at the same location of the pipe, calculating the fluid velocity by the difference in pressures measured. The second sensor considered was a turbine flowmeter, a turbine inserted in series with the pipe that determines flow rate by the rotations counted from the propeller which turns due to fluid flow. Next, an industrial ultrasonic sensor which is considered to be the most reliable, less invasive, but most precise way to industrially measure fluid flow using an upstream and downstream transducer was a third option taken into consideration. Lastly, an electromagnetic flow sensor was considered as it was the main type of sensor recommended by an application engineer. These sensors measure flow rate using Faraday's law and from two electrodes and an electromagnetic coil, the electromotive force, or voltage, of a conductive fluid can be recorded and the average flow velocity is proportional to the magnetic field strength. However, after extensive research, these instruments proved to be costly and would still require calibration. Thus the method adopted was to create a flow sensor for our specific purpose. Ultimately, the goal is to build and calibrate a flow meter by calculating flow induced deflection of a flexing stick with the use of strain gauges. The strain gauges will record a voltage signal when the flow stick deflects and sends as an analog signal to the test bed's processing hardware and software to be transduced into a flow rate.

Static Pressure Drop Across an element

Multiple methods of measurement exist in order to determine the pressure differential. Theoretically, one may use bernulli's equation and some assumptions, perhaps even an energy balance. Empirical data for a pressure differential can also be collected via pressure sensors. The standard for taking a pressure and converting it to an electrical signal is with a transducer. The logic flow of a transducer is shown in **Figure 2** below:

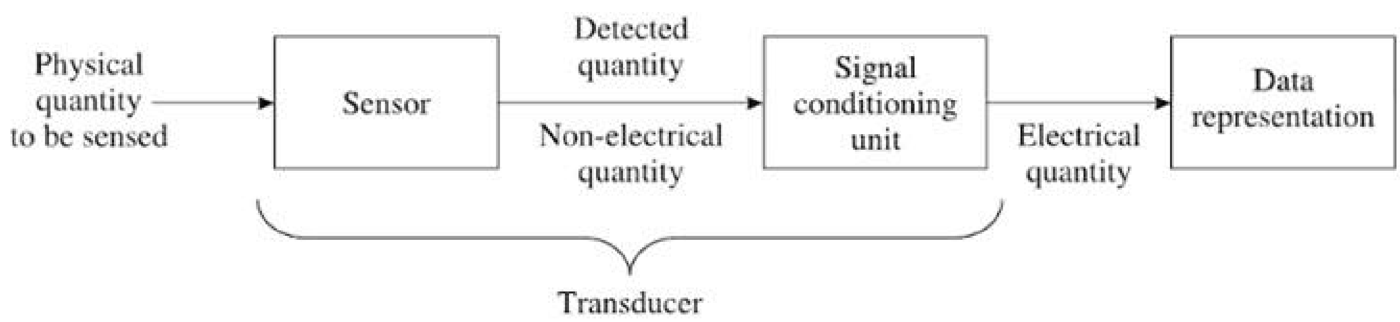


Figure 2: The logic flow of a pressure transducer going from a physical quantity (pressure) to a data signal (electrical voltage)

Opting for a more empirically driven method, transducers have been chosen as the best choice for this testing rig. By placing a transducer on either end of the membrane (inlet and outlet), the pressure differential can be continually monitored.

Statement of Requirements

Project Timeline

The allotted time of completion is one quarter (15 weeks), started March 2nd, and to be completed by June 15th, 2023

Project Budget

The sponsor has allocated a total of $3,600.00 USD to be spent on research and development of the project.

Technical Specifications

- Use a T500 Thruster from Blue Robotics as the pump to the testing rig device
- Limit the pressure head created by the testing rig designed to characterize the reverse osmosis membrane
- Enough power must be supplied and available to the system to last for several hours of testing (4 hours)
- Testing rig must be completely submersible to operate, however can have a tether for electronic and controls components
- Rig must be no longer than 10 ft to fit within a testing tank available (UCSD Scripps)
- Testing rig must remain modular and adaptable for future additions of sensors

Statement of Deliverables

High Priority	Secondary Priority	Low Priority
● Characterize the flow rate through the membrane as a function of power provided to a pump ● Characterize the pressure drop across the membrane that exists due to the pump	● Direct the fluid flow after the thruster to resist rotating to better streamline the fluid dynamics in an effort to increase flow rate ● Use of clear pipes for ease of reduction or elimination of cavitation.	● Integrate a valve to take water samples before and after membrane to later be integrated with a capsule ● Introduce controlled amount of particles to characterize or observe their behavior through the membrane ● Adding ports to the design for future sensors such as a Conductivity Temperature Depth Sensor (CTD). ● Figure a cooling mechanism for the electronics

Chapter 2 | Description of Final Design Solution

High Level Overview

The prototype testing rig developed to characterize a reverse osmosis membrane was developed in three major subsystems as shown in **Figure 3**. There exists two physical modules and an interface that combined, form the entire characterization testing rig. The first module is the testing rig itself to be submerged in the water with the membrane and hold the sensors. The second module is the electronics board that receives all the data from the submerged testing rig while providing power. The third module consists of the software running and recording data for the device the user interacts with. A high level understanding of this system is demonstrated in **Figure 3**:

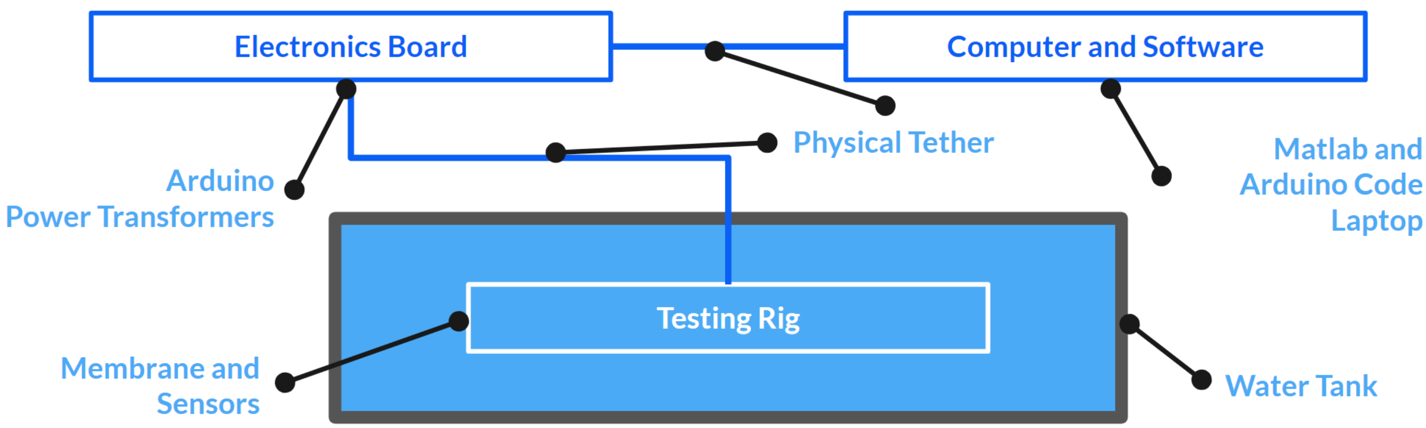


Figure 3: High level overview of System with subsystem modules

System Overview

The entirety of the system can be seen in **Figure 4** :

Figure 4: Physical System Model

For reference, the CAD model can also be seen in **Figure 5** where the major components of the model are color coordinated. The major components to this system are its structure, spreader beam, thruster assembly, sensors, and electronics.

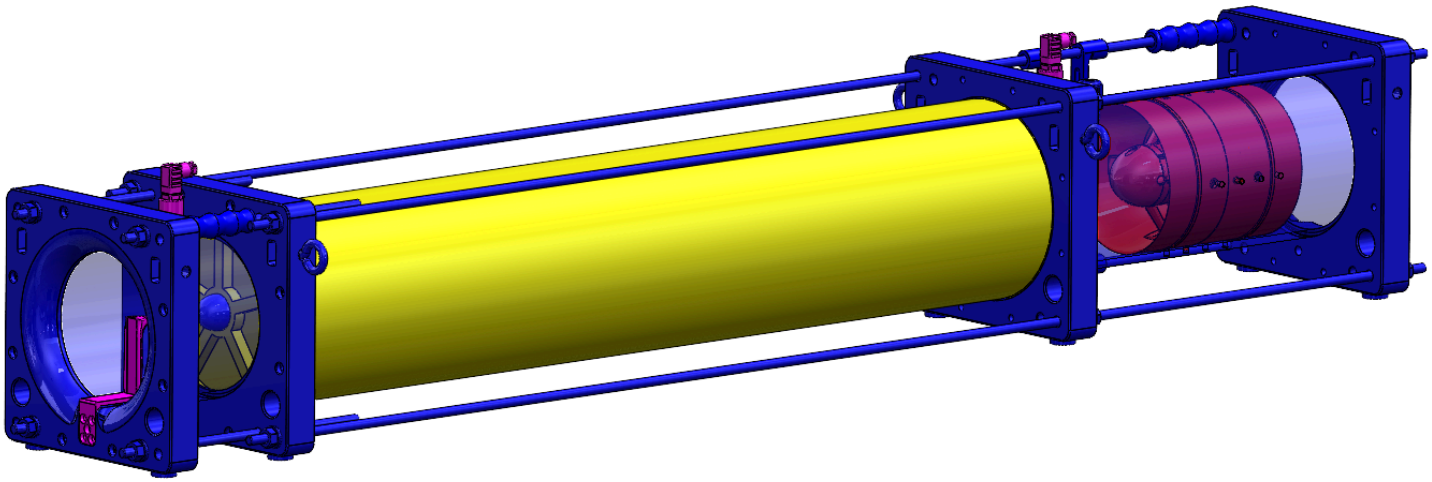


Figure 5: CAD Model of the system with highlighted subcomponents. Structure (blue), Thruster Assembly (red), Sensors (pink), Membrane (yellow)

Operations

A general explanation to the operations of the system will be discussed in this section. The operations of the system will include all actuators, sensors, and general design considerations made. To create fluid flow across the membrane an axial thruster was implemented per request of the sponsor. This axial thruster sucks water into the system and the membrane by creating a low pressure region. The system draws in water from one side and discharges on the other. It was decided water should be drawn into the system rather than discharging to keep the fluid flow as laminar as possible for steady sensor readings.

To record pressure, transducers were implemented along with an innovative empirically characterized flow sensor. These sensors related data through a tether to a dry electronics box stationed outside the water tank. This box supplies power to the rig while also receiving data from the sensors and relaying the data to the software on a computer.

Chapter 3 | Design of Key Components

Structural Testing Rig

The Testing Rig is the structure of the prototype that mounts to the reverse osmosis membrane. The components of this module include the manufactured face plates, tubes, and all hardware and sub supporting components. Different key components to this project are included in larger detail in later sections. This component is the connecting assembly for all components.

Functional Requirements

- Must be modular and adjustable to accommodate different membrane lengths and diameters
    - A membrane will vary only slightly ∓ 2mm
- There must exist locations for both the pressure and flow sensors to be mounted in theoretically determined locations
- The sensors must be waterproofed and rated safe enough for the depth in which it is planned to test the rig as a whole
    - Epoxying the pressure transmitters and their DIN connectors
    - Epoxying strain gauge wiring and coating strain gauge resistor with polyether
- The system must hold a maximum of negative 15 PSI pressure differential from within the system to the surrounding environment
- Designing for a lightweight system is optimal as this prototype will be moved around frequently and with the membrane itself become heavy
- Allow for locations where the flow can be visualized externally by cameras or by the naked eye
- With the primary goal of this system being a prototype testing rig, there must be considerations to allow for changes or add on in design and complexity
    - Extra mounting locations
    - Extra room

Design Iterations and Considerations

Two primary design problems were apparent and considered in the design of this component. One of the most important and pressing issues to be addressed was creating a seal to accommodate the small pressure difference. The other issue to be addressed is the overall structural design for rigidity of the system.

Sealing

Although negligible, standard engineering solutions were considered for practicality and repeatability. Three different ideas were considered to implement a structure that could hold a valid seal. To interface with the membrane and the system to be built a hose clamp, radial, and face O-ring seal were all considered. Each design and their respective pros and cons are tabulated below in **Table 1**:

Table 1: Sealing Designs and Considerations

Version	Description	Pros	Cons
Hose Clamps	Standard plumbing connector used with rubber tubing	• Standard off-the-self • Will hold a pressure	• Not a rigid connection • Poor membrane interface
Radial Seals	O-ring seals on the radial face of the membrane	• Standard seals proven to work • Simple with only one seal	• Membranes may vary slightly radially • Need a radial squeeze to hold
Face Seals	O-ring seals on the axial face of the membrane	• Standard seals proven to work • Structural design can be used to provide squeeze • Simple with only one seal	• Membrane and system must be parallel for a vaid seal

Rigidity

Creating a frame for the system can be accomplished many ways. This open-ended design problem allows for many ideas. Each solution may not be entirely wrong but still have pros and cons that were considered and ultimately decided on. The current standard for reverse osmosis membrane enclosures is an 8" ID pipe. Another design consideration was a wire tensioned pipe end-cap solution. A final design consideration was a face plate threaded rod assembly. These three design considerations are tabulated below in **Table 2**:

Table 2: Structural Rigidity Designs and Considerations for Testing Rig

Version	Description	Pros	Cons
Full Tube Enclosure	An 8" ID tube that entirely contains the membrane	• Simple and standard	• Extremely hard to remove the membrane • Expensive
End-cap Tension Wire	A two part system held to the membrane with tensioners	• Would provide a great seal	• System is in two pieces with loose wire
Threaded Rod Face Plates	A multi-part system with sandwiched tubes and face plates held with long rods	• One structural System • Great sealed connections	• More complex components

Final Design

The decisions on the final design of the prototype regarding both rigidity and sealing were made in conjunction with each other for a simple final design. It became apparent the most simple and effective design for this system would be face plates squeezed together with threaded rods. These face plates directly allowed for both radial and face seals to be implemented simultaneously into the design. The design also allowed for a smaller diameter tube to be implemented that more closely matches the dimensions of the outlet of the reverse osmosis membrane. This tube could also be easily purchased as a clear tube allowing for a better scientific study to be conducted by visually seeing into the system.

The overall design of this testing rig is an axial construction of sandwiched tubes by faceplates all held together with an array of 4 threaded rods. These rods extend across the entire prototype allowing for the faceplates to be held securely by nuts squeezing everything together. The pressure sensors for the system directly connect to the pipe of the system along with the entire thruster assembly mentioned in a following section below. The testing rig prototype can be visualized in **Figure 6**.

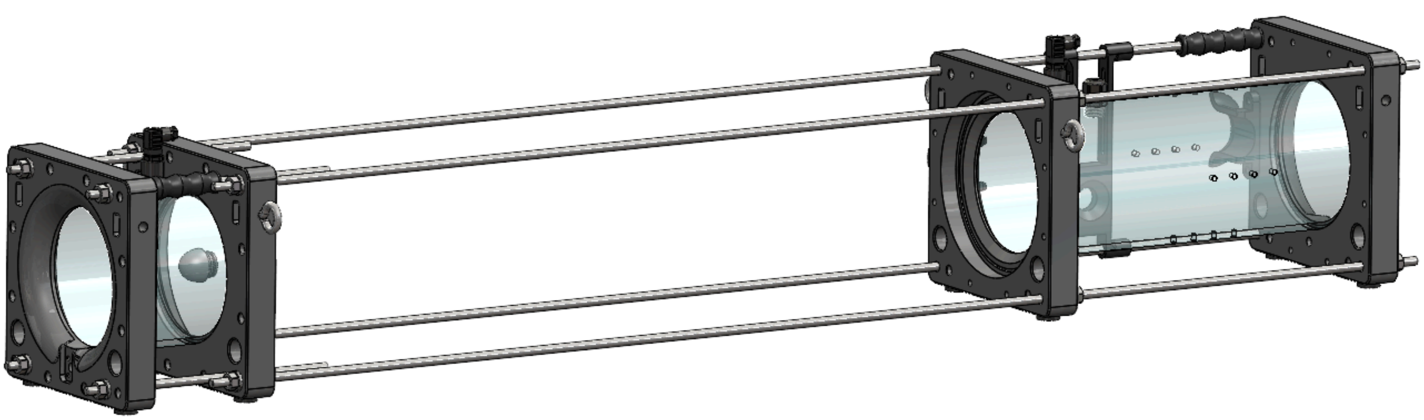


Figure 6: Final Design of testing Rig

Wire Harness

The wire harness of this system is composed of individual wires to every sensor. These wires are 16 gauge. The 1” diameter bores on the lower portion of the plates are intended for wire management. These were used to hold the wires for the pressure and flow sensors. All wires combine together and exit through the tether mount shown in **Figure 7**.

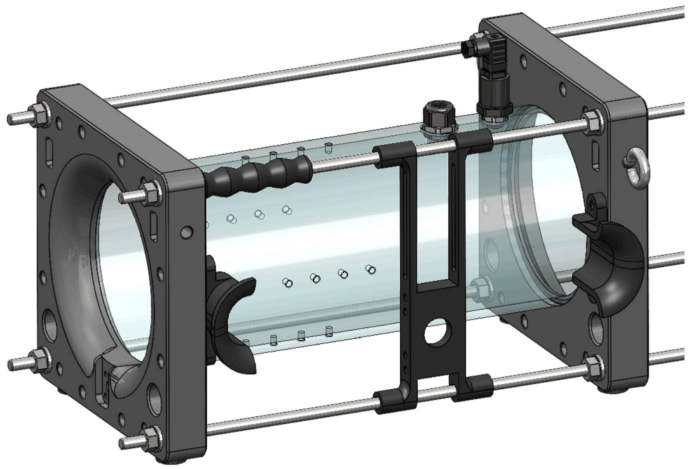


Figure 7: Wire management components on the testing rig of the system

The wires exiting the system combine to form the tether, a bundle of wires, to go to the electronics board. This tether is composed of 4 3-pole signal wires and 1 3-pole power/actuator wire. The signal wires condense to a single vga cable to be plugged into the electronics board. A detailed description of this connection is in the electronics board section of this paper. The power cable ends in a 220V standard outlet to be plugged into the electronics board. The tether can be looped around the side of the system with the components shown in Figure #.

Key Notes:

- Corrosive-resistant wire: 4 individual cables throughout the structure going to sensors
- Tether: A 6ft bundle of cable
- Joint connections between cable types are NOT waterproof

Analysis

This system must meet two major requirements that can be numerically calculated and verified theoretically. The system must hold the entire membrane and itself for transportation, remaining rigid and structurally sound. The system must also hold a negative 15 PSI of pressure.

The weight of the system and the membrane equates to around 100 lbs, when the membrane is saturated with water. With this maximum value, an FEA was performed on the plate components for stress. The following **Figure 8**, illustrates the stress grid of the plate component due to the weight of the membrane when held from the eyebolts.

Assumptions:

- The component is entirely held and fixed to the eyebolt mounts
- The weight of the membrane is a distributed load along the eternity of the inner diameter on the component all in the direction of gravity.

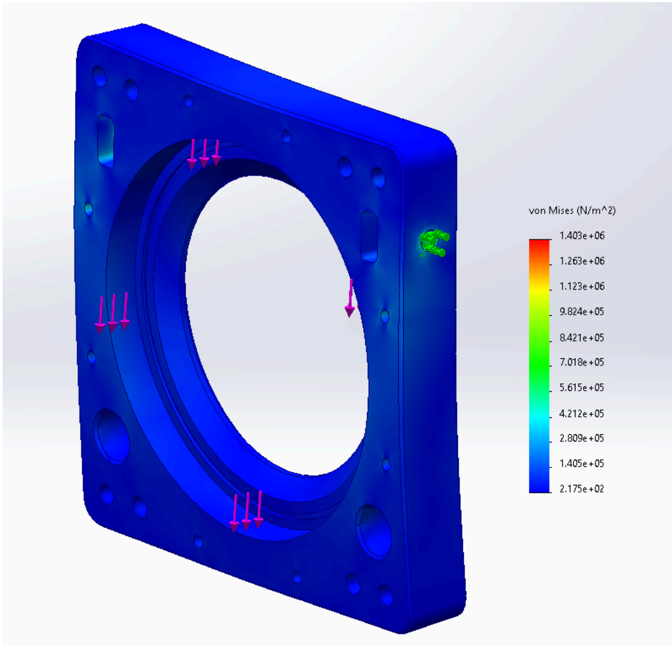


Figure 8: FEA analysis of the plate component illustrating the stress grid due to a distributed load of the membrane on the component. The component is fixed to the eyebolt location mounts.

Fabrication

All components for the testing rig were purchased from McMaster-Carr. The stock material for custom fabricated components were also ordered from McMaster-Carr. All face plates were custom in-house CNC machined to specifications listed in **Appendix C**. The 6” tube of the system was bandsaw cut and hand-drilled for sensors and other mounting locations. Other fabricated components to the testing rig were fabricated with 3D prototyping technology. All 3D components on the system have an infill of 100% to prevent internal leaks due to submersion. These components are not as crucial to the structural integrity of the system.

Assembly

This section will describe step by step instructions to assemble this component of the project. To construct this system a phillips screwdriver, ⅝" wrench, and 3/32" allen wrench was used. To begin this assembly, the thruster assembly must first be completed.

1. Insert the thruster assembly into its respective back tube. Screw in the set screws used to secure the thruster assembly to the tube. When inserting the thruster assembly into the tube make sure to also feed its cord in and out through its respective cord hole outlet.
2. Add O-rings to all plates of the system. There are two different O-rings for both the membrane face and tube faces.
3. Screw the ⅜" nut around 17" from one end of the 5' all-thread rod. Do this for all 4 rods and add a washer for each.
4. Take the first and second plate in the assembly and the front short tube and arrange into place. Insert the 1' all-threaded rods into their respective bores that goes through the first and second plates. Do this for all 4 rods and then add washers and nuts on each end. The excess rod can be toward the membrane.
5. Take the third plate in the assembly and the back long tube with the thruster assembly and arrange into place. Insert the 5' all-threaded rods into their respective bores that go through the third and second plate in that order. Do this for all 4 rods and then add washers and nuts on each end.
6. Add the 4th plate onto the 4 rods to hold the back pipe into place. Add washers and nuts.
7. The membrane can be added by unscrewing the second plate nuts from the 5' rods to remove the front portion of the system to swap membranes. More detail about this step can be found in the user manual.

Spreader Beam

Functional Requirements

- Cheap and simplistic
- Lightweight
- Capable of lifting the entirety of the testing rig system, around 100 lbs, 450 Newtons.

Design Iterations and Considerations

Table 3: Structural Rigidity Designs and Considerations for Spreader Beam

Version	Description	Pros	Cons
Pre-built Spreader Beam	Fully assembled pre-built beam	● No design time	● Extremely expensive
T-Slotted Beam	T-slotted beam with eyebolts	● Standard ● Adjustable	● Not cheap ● Not Strong
I-Beam	An I-beam with welded mounts and chain	● Simple ● Cheap	● Not as adjustable

Final Design

This component of the project has the purpose of transporting the membrane with a crane by distributing the load through the use of straps. The final design was decided on to be an I-beam. This was the most simplistic and cheap option. A visual of the component can be seen in **Figure 9**.

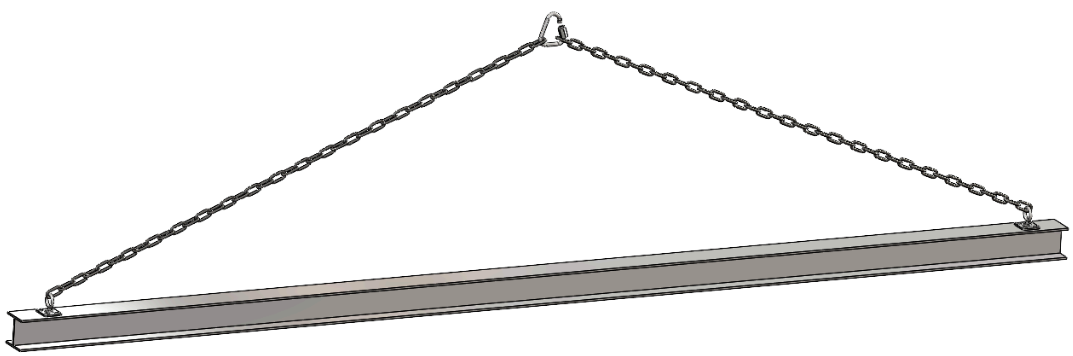


Figure 9: Spreader Beam Assembly

Analysis

This component's sole purpose is to hold the weight of the entire testing-rig. Through several strategically placed straps, an FEA analysis was completed to determine if this design was feasible and worthwhile. **Figure 10** shows the stress grid on the beam.

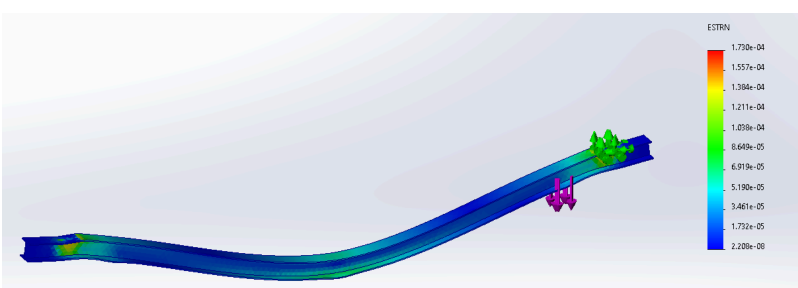


Figure 10: FEA Analysis of the Spreader Beam

In this figure, it can be seen the maximum stress is no larger than 2*10^4 Newtons, which is two magnitudes below the yield strength of the beam. In this figure the deflection is greatly exaggerated, however when analyzed, the max deflection is less than a millimeter.

Fabrication

The simplicity of this component allowed for little to no fabrication. Two swivel eye hooks were attached to a stock I-beam by drilling holes and mounting with flat head screws. The strap pads were 3D printed using an FDM printer.

Assembly

This section will describe step by step instructions to assemble this component of the project. To construct this system a phillips screwdriver was used. To begin this assembly, all fabrication must first be completed.

1. Slide on the strap pads onto the same top side of the I-beam. This side is the one with the holes drilled in fabrication.
2. Mount the swivel eyelets to the I-beam with 4 flat head screws.
3. Attach the chain to the swivel eyelets using the connection links.
4. Hold the assembly up with the chain to find the chain's midpoint. Loop the triangle connection like at this point with the chain double looped through the connection link.

Thruster Assembly

Functional Requirements

- Must incorporate the Blue Robotics ROV 2 Thruster
- Will need to fit inside the 6” tube apart of the testing rig structure
- Necessary to adopt the geometry of the original casing provided with the thruster for fluid flow and pressure differences

Design Iterations and Considerations

Table 4: Structural Rigidity Designs and Considerations for Thruster Assembly

Version	Description	Pros	Cons
Single Funnel System	Only a reduction funnel	• Less room taken in pipe • Possible more attachment locations	• Creates unstable pressure drops • More turbulence
Nozzle Funnel System	A reduction to expansion funnel	• More stable and smooth diameter transitions	• Bigger system and space used
One component (fabrication method between two versions)	A solid funnel instead of multiple 3D printed components	• Solid and structurally sound • Holds better seals	• More expensive • Harder to replace

Final Design

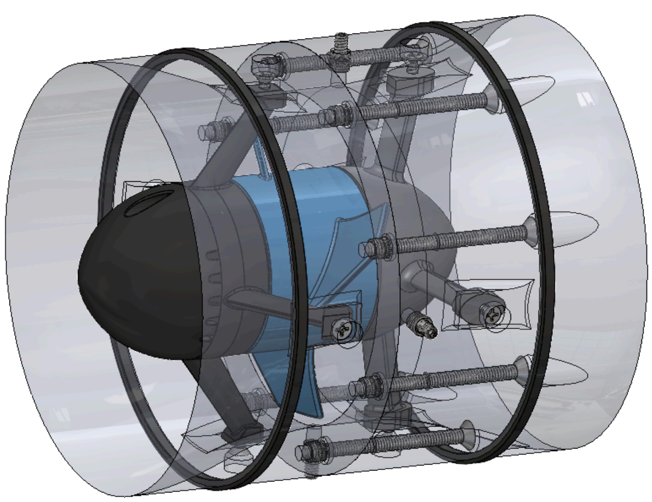


Figure 11: Final Design of Thruster Assembly

Analysis

Based upon fluids knowledge, the implementation of a pipe reduction was expected to produce a negligible pressure difference. With the use of Bernoulli's equation with a diameter of 8 in (the pipe) and that of 6 in (pipe reduction), it was found that there was minimal change in pressure.

$$P_1 + \frac{1}{2} * \rho * V_1^{\ 2} + \rho * g * h_1 = P_2 + \frac{1}{2} * \rho * V_2^{\ 2} + \rho * g * h_2$$

$$V_1 = V_2$$

$$h_1 = 4\ in = .1016m \quad h_2 = 3in = .0762m$$

$$P_2 - P_1 \cong 0$$

Equation 2

P	Pressure
V	Velocity of water through system
ρ	Density of water
h	Height
g	Gravitational Constant

Fabrication

This assembly is a 4 component system excluding hardware. Every custom made component was manufactured using additive manufacturing technology. The major funnel components were fabricated using an inkjet printer. These components were then post-processed by adding heat-set inserts into their respective locations. The thruster tailcone was printed using an SLA printer.

Assembly

This section will describe step by step instructions to assemble this component of the project. To construct this system a phillips screwdriver was used.

1. Take both sections of the funnel and insert and tighten the 8 flat head screws.
2. Insert the thruster into place and attach with 4 flat head screws from the outside of the system.
3. Insert the tail cone and also attach with 4 flat head screws from the outside of the system.
4. Add the square O-rings to their respective locations on the outside of the system.

Flow Sensor

One of the main sensors of the testing rig is the flow sensor that will be custom made to characterize the flow rate and sits at the inlet of the testing rig as it is attached to the inlet plate. It is made up of the flow "stick" and a strain gauge in a quarter bridge setup; one strain gauge to measure in the direction of displacement and a second as a control measurement to account for variations in temperature.

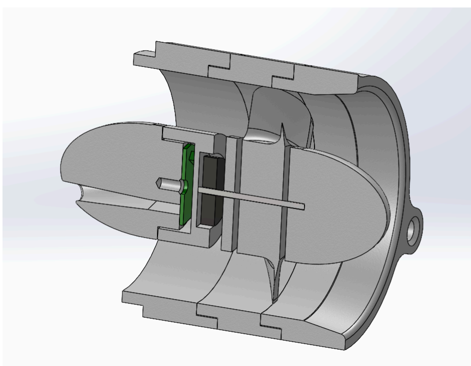
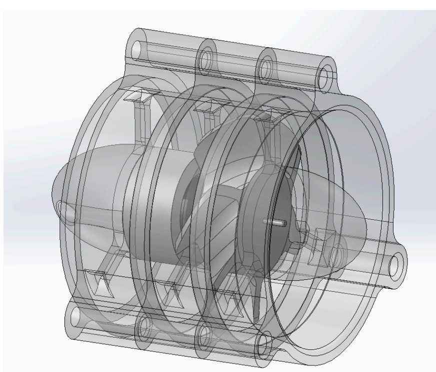
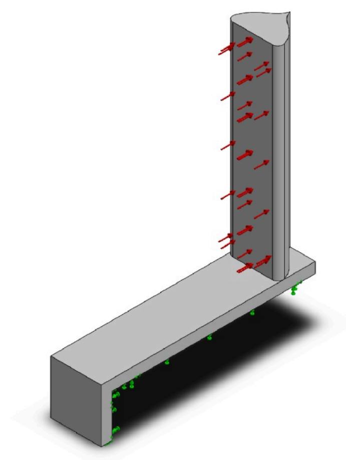
Functional Requirements

Given that the flow probe's strain gauge will be detecting displacement and translation that into a flow measurement, the material selected for the flow stick probe must be stiff enough to withstand drag force but flexible enough to experience strain within the strain gauges' range of sensitivity.

Design Iterations and Considerations

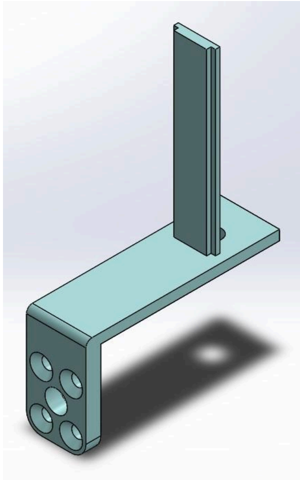
The initial version of the flow sensor to be utilized in this testing rig was a propellor sensor. After further analysis, the flow stick sensor proved to be the best method. Below, in **Table 5**, the differences are outlined.

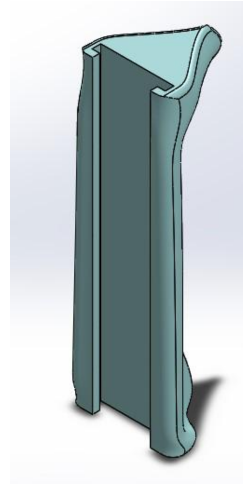
Table 5: The design iterations of the flow sensor during the design process.

Flow Propeller Sensor	Flow Stick Sensor
● Complex to manufacture ● Would sit at the outer edge of the pipe and could be affected by flow profile ● Measures flow rate through magnetic encoder attached to a propeller  	● Easily manufacturable design ● Would be experiencing the force from half of the flow profile, thus negating the need to know the flow profile ● Measures flow rate through strain experienced at the base of the flow stick ● Modeling after cantilever beam 

Final Design

The final design of the flow probe stick is shown in **Figure 12**. The decision to make it into two pieces was made due to the limited availability of strain gauge sensors.





A: Cantilever Mount

B: Fin

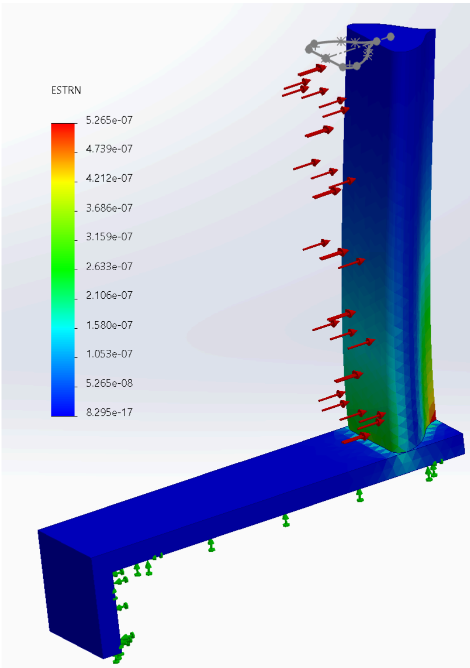
Figure 12: The final design for the flow stick in two parts. a.) The cantilever base that attaches to the inlet plate of the testing rig and is where the strain gauges are adhered to. b.) The detachable fin designed to decrease amount of vortices

The fin was designed to reduce the amount of vortices that are created by the fluid flow around it. In the case that it does not behave how it is expected to, the fin can be redesigned and reprinted without needing to replace the full structure or the strain gauges. This allows for flexibility with the design if more flexibility may be needed.

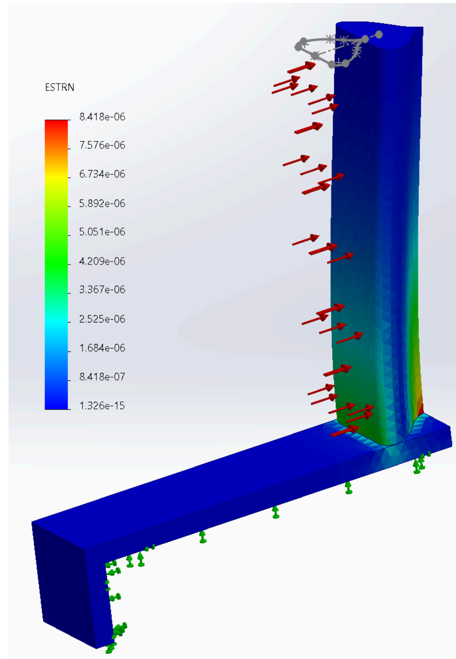
Analysis

The flow probe we designed unfortunately fractured before we could calibrate the strain readings. A strain analysis was conducted for the flow sensor in SolidWorks where the design was modeled as a fixed end cantilever. This helped to narrow the material options by showing expected strain values for each with an expected flow rate of $0.00316\ m^3/s$. The flow sensor must be tested and calibrated empirically before its use in the rig.

After running various solidworks simulations with the first iteration CAD model for the flow sensor, materials such as aluminum and even tin were too stiff for the application and the strain values were out of the range needed in order to be read by a strain gauge properly. When running the simulation using PVC, the strain values were much closer to the desired specifications so it is a good material option. The strain with PVC was also evenly distributed at the base of the stick meaning if the strain gauge were placed there, it could get more accurate data readings. Due to the availability of off-the-shelf strain gauges, we decided to change the material we used from PVC to a Rigid PVC which represented even further desirable strain values during simulation. One concern would be that the material may be too rigid to optically record deflection and therefore our strain gauges must be adhered and soldered well enough to read well. The calibration tests should have provided more information about the need for alternative fins, either verifying our modeled simulation or helping us build upon it. Unfortunately, the flow probe did not survive long enough to be tested, breaking at the base of the fin due to human error.



A 1/10th Max Flow Rate (5 gal/min, 5 PSI)



B Max Flow Rate (50 gal/min, 86 PSI)

Figure 13: Simulated deflection of the flow probe and localized strain illustrating the optimal locations to place the strain gauges, as well as strains to be expected. These simulated strains informed our decision while shopping for strain gauges to be used.

Fabrication

For fabrication of the main flow sensor parts, the two pieces were 3D printed using Stereolithography (SLA) Printers using resin that cures into a rigid PVC. This process uses an ultraviolet (UV) laser to cure the resin into the desired shape. Several iterations of the print were necessary before achieving the final part due to the sensitivity of the resin and material during the washing and curing process. Unfortunately this process made it difficult to add indentations on the cantilever portion for the strain gauges to sit flush with the surface. The indentations could have added ease to the installation process of the strain gauges since it will be difficult to get an even layer of adhesive under them. However, we do not expect this to hinder the fabrication process of the sensor as a whole. We have experienced some difficulties in soldering the strain gauges due to the miniscule size of the leads on them. At the base of the cantilever piece are holes that were countersunk after being printed to allow for easy attachment to the inlet plate and a nice flush surface.

Electronics Box

Functional Requirements

The Electronics Box compactly houses the electronic speed controller (ESC), connected to the thruster, and the Arduino Nano which interprets data from the ESC and all of the sensors. The ESC is expected to run up to 43A for extended durations, but its designers did not anticipate a draw surpassing about 20A for anything more than a few seconds, meaning overheating is a concern, and there must be enough space for cooling mechanisms. It must be affixed to a board with the other electronic components which must be easily portable. All the wires running into the Electronics Box from the thruster and the sensors must be detachable.

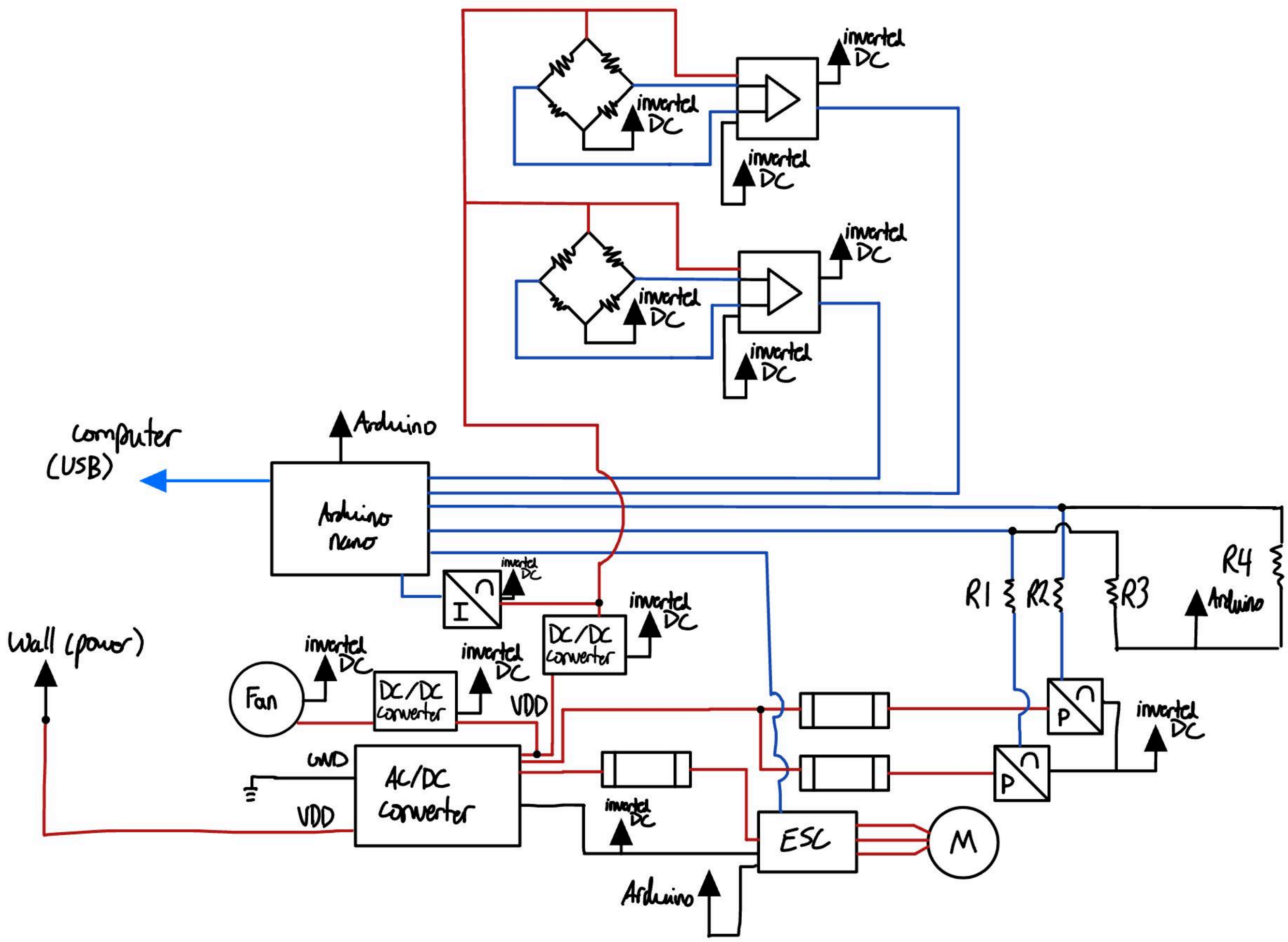


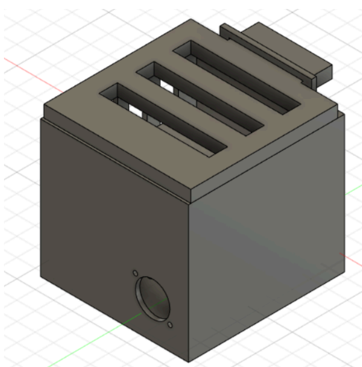
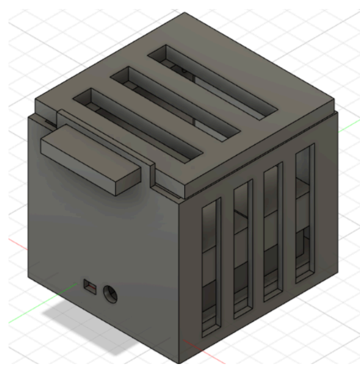
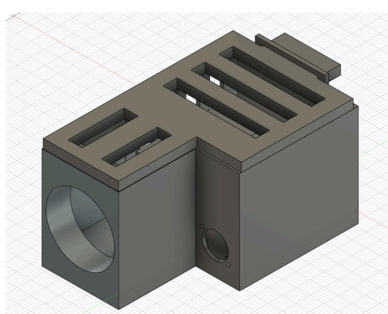
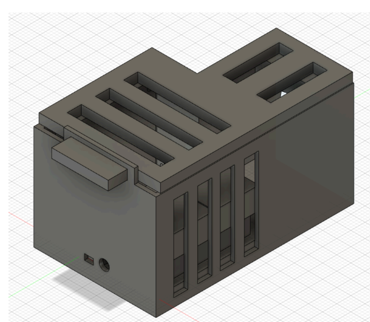
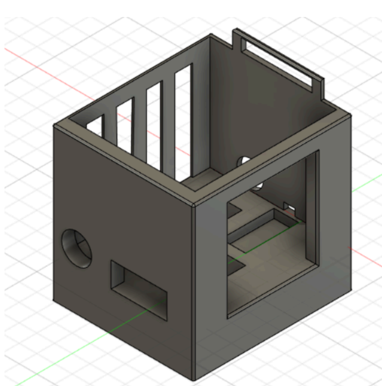
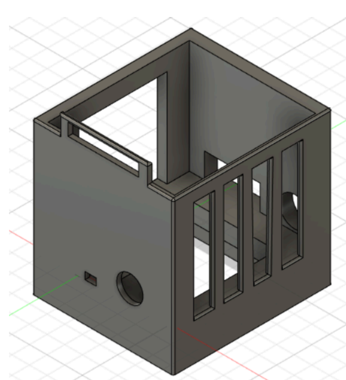
Figure 14: Circuit diagram

Design Iterations and Considerations

In the earliest stages of the project, portability was a major goal so that tests could be conducted in the ocean, and as such, a battery power source was investigated **Appendix F**. The thruster is the primary power strain, requiring a prodigious 24V and 43A for maximum speed, which would need a very large and expensive battery; this and the other mounting costs of portability moved the project to a lab setting where wall power is the most logical option. This necessitated a powerful AC-DC converter, as the thruster and all the sensors use DC current, as opposed to the AC current coming out of the wall. At nearly 10” across, the converter set the minimum length of the electronics board to about a foot. With the 50A kill switch measuring about 5.5”, this left the Electronic Box with about 6” of length maximum if the board was to be a square, compact on all sides.

The first few iterations of the box was a literal box, with tall accessory walls and a lid to hide all the wires away. These had to be scrapped as heat dissipation of the ESC became a major concern. There was also one iteration with a large room meant to house a wall outlet so that a plug could be connected and disconnected from the Electronic Box directly, but this was also scrapped because it was a heavy plug with lots of grip in the socket (as it was rated to carry over a kilowatt) and it would have over time damaged the box.

Table 6: Electronics Board Iterations

Version	Back-view	Front-view	Notes
1			Hole on front-side to feed wires into is too small. No mounting points for fans. Accessory walls. Flimsy slot at top for lid insertion. No hole for ESC–thruster connection. Incorrect hole for Arduino–sensor connection.
2			Big room for a wall outlet to be installed (the large hole is where the socket would be)
3			Removed extra room and installed holes for fans at the bottom and side. Widened hole on front-side to accept more wires. New hole shapes for Box–Membrane connections.

Final Design

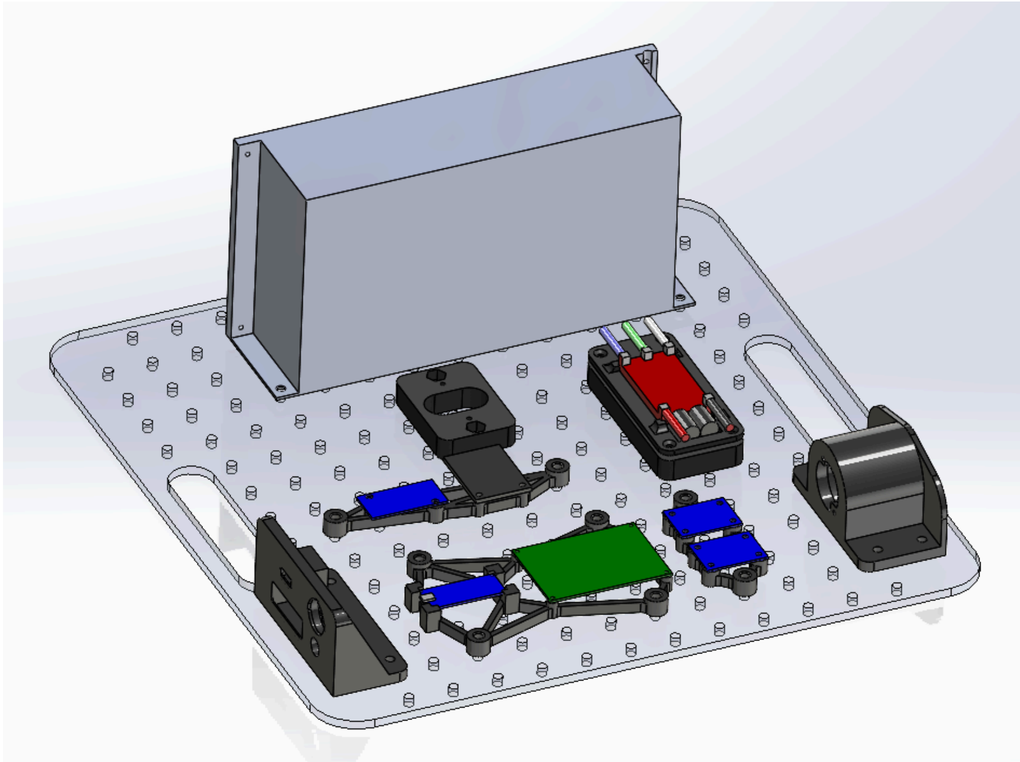


Figure 15: Final Design of the Modular Electronics Board

It was then decided that a modular electronics board would be the best design with so many components, especially as more and more components were added to the design: a large fan with controller chip, a current meter, voltage divider for the incoming pressure signal, amplifiers and Wheatstone Bridges for the flow stick (see below), and a kill switch for the ESC. Each component has a unique 3-D printed mount which can be screwed and unscrewed and moved around the board according to the user's musings.

The ESC, thruster, pressure sensors, and fan are powered by the AC-DC converter. The fan only accepts 12V so there is an intermediary DC-DC 12V 3A converter. The flow stick (including the Wheatstone Bridge and amplifiers) is powered by the Arduino. The AC-DC converter and Arduino are connected to wall outlets for power, and the Arduino is further connected to a computer via a micro-USB.

All the wires running into the Electronics Board from the thruster and the sensors are detachable. The sensors are connected to a male VGA cable, which can be plugged into or plugged out of a VGA breakout mount in the box. The VGA female mount has 15 ports which correspond to the male cable's 15 differently colored wires; their connections are enumerated below. The VGA mount is connected to other components on the Electronics Board via 22AWG wire.

Table 7: VGA port connections

VGA Female Mount Port	VGA Male Cable Wire Color	Component
1	Black	Pressure Sensor 1 Power
2	Brown	Pressure Sensor 2 Power
3	Red	Pressure Sensor 1 GND
4	Orange	Pressure Sensor 2 GND
5	Yellow	Strain Gauge 2 S+
6	Green	--
7	Blue	--
8	Purple	Strain Gauge 1 S+
9	Gray	Strain Gauge 2 S-
10	White	--
11	White/Black stripes	Strain Gauge 1 S-
12	Black/Brown stripes	--
13	Pink	--
14	Turquoise	Pressure Sensor 2 Signal
15	Pale blue	Pressure Sensor 1 Signal

The ESC is connected to a different detachable plug since the connection needs to be able to handle high current flows. So, there are 2 detachable tether connections: one for the sensors, and one for the thruster.

The pressure sensors get power from the AC-DC converter. They run through 0.5A fuses in case of surges, the risk of these may be heightened because the sensors are drawing current from the AC-DC converter in tandem with the ESC, which in turn can pull up to about 150x the amperage. The pressure sensors emit a 10V signal which is sent to the Arduino Nano to be read, but the Arduino can only read up to a 5V signal, so the signals run through a voltage divider circuit. The conversion is described in **Equation 3**. Both the fuses and the voltage dividers are on a PCB board.

$$P_{actual} = \frac{15\ PSI}{10\ volts} \cdot 2 \cdot \frac{10}{2} volts \cdot \frac{signal\ counts}{1024\ counts} \qquad \textbf{Equation 3}$$

The flow stick makes use of 2 strain gauges, one put in tension in response to flow, and the other put in neither tension or compression (so if its resistance changes it is a response to the changing resistance in the wires as they heat up over operation, and this error can be eliminated). Consequently, each strain gauge is put into its own quarter wheatstone bridge and amplifier circuit; the former are on the same PCB board as the 0.5A fuses and voltage divider, and the latter are on their own mount. There is no strain gauge, so this circuit is not wired together (see Wiring Flow Probe for instructions).

A computer fan which doubles as an aluminum heat sink is stuck on top of the ESC. This is controlled by a chip on its own mount which connects back to the Arduino. The fan is powered by the AC-DC converter, but it accepts 12V so it runs through a small DC-DC step down converter which is on the same mount as the amplifiers.

Analysis

The gauge of wires decided upon are: 16AWG for the seawater-resistant cables for the sensors, 18AWG for the regular cables for the sensors, 12AWG for the regular cables for the thruster–ESC–AC-DC-converter circuit, and 22AWG for the rest of the wiring on the electronics board. These wires were chosen based on availability in McMaster-Carr, price, and ampacity. Ampacity is dependent on wire length, ambient temperature, running time, and the quality of the insulation. So for safety reasons, the lower end of expected ampacity for standard conditions was taken.

At first, it was believed the thrusters would pull up to 43A at steady-state, so then 6AWG was going to be used. With an expected length of roughly 15ft, this would correspond to a voltage drop of only 0.63V (a 2.6% drop) according to **Equation 4**.

$$V_d = \frac{2*K*L*I}{A_c} \qquad \textbf{Equation 4}$$

V_d	Voltage drop
K	Resistance of 1 foot of wire per 1 mm diameter (for Copper 12.9)
L	Length of wire
I	Current
A_C	Cross sectional area of conductor

But, it was later noticed that the ESC has 12AWG connectors. The company was sure that, though their thruster is capable of pulling over 110A, it will not pull more than roughly 20A steady-state according to their tests with a 16.8V source. So, cheaper 12AWG was chosen instead, but this confers double the voltage drop along the wire (so the thruster might be seeing a 22.8V source instead of 24V). This should not appreciably reduce maximum attainable speed, nonetheless.

For the sensors, the smallest possible gauge (down to 22AWG) was chosen because collectively they should not be pulling more than an amp (22AWG is rated for roughly an amp). Because of how little amperage is being pulled through any wire, the voltage drop is essentially 0. The smallest regular 3-channel cable that McMaster-Carr offers is 18AWG, and corrosion-resistant cable (to resist seawater should the need ever arise) 16AWG; and 3-channel cable was required because the sensors needed a power, ground, and signal connection. This changed later as the idea of the flow sensor evolved into a strain gauge circuit, because each strain gauge circuit instead needed only 2 wires to be sent to the membrane. On the electronics board, all the sensors are connected solely using 22AWG wire.

Fabrication

The Electronics Board comprises two 3-millimeter sheets of acrylic screwed on top of each other with holes cut out with a laser cutter. The holes fit #10 screws and bolts. Unique mounts for each component on the board were 3-D printed with PLA.

Wiring Flow Probe

The flow probe is designed for two strain gauges to be stuck onto the flow stick, one gauge is placed in tension and the other neither in tension or compression. The strain gauges should be soldered to the provided 16AWG cables, one cable per strain gauge. Each cable is 3-channel, but each strain gauge only runs 2 wires so there will be 1 wire left over in each cable. The strain gauge not put in tension or compression is to eliminate any potential error from the resistance changes in the wire over operation, so it is optional.

Each wheatstone bridge has 3 resistors, the 4th resistor being a strain gauge. So, each bridge on the protoboard has 1 pair of resistors and an unpaired resistor. The two wheatstone bridges for the 2 strain gauges are already wired on the protoboard, and each bridge has two leads. These leads should be stuck into the VGA **Table 7**.

The amplifier has a V_in, S+, S-, and GND port on one side, and a V-, GND, V_out, GND port on the other side. V_in and the top of the wheatstone bridge should be connected to the OUT+ pin on the DC-DC converter which is currently connected to the current meter (a 5V source). On the protoboard, wires have to be soldered onto both of the connections with the resistors and existing yellow VGA leads; these two connections plug into the S+ and S- ports on the amplifier. It does not matter which one is which. All GND ports (except for the GND next to V-, which is not used), as well as the bottom of the wheatstone bridge, should all be connected to the OUT- pin on the DC-DC converter. A separate 5V source can also be used. V_out connects to an analog port on the Arduino. V- is the excess voltage the amplifier did not use, and can be wired to some other component as a negative voltage source if necessary in the future.

Interface

Design Iterations and Considerations

The system's interface was built using Matlab's App Designer Platform. This application is publishable to Mac OS, Windows, and Linux. The app allows the user to interface with the test bed via USB to an Arduino Nano Every using serial communication. In truth, any native or third party arduino like platform can be used to interface between a computer running this application and the test bed, so long as the SBC has the appropriate pins and is capable of serial communication. Originally, this application was meant to drive the nano and serve as the brains of the entire test bed via an Arduino library provided by Matlab. However, after a few iterations it was discovered that serial communication not only simplified the design, but also improved the sampling rate tremendously. This is in part thanks to the parallel computing design where the arduino samples the instruments and calculates trivial arithmetic, which is then passed to the computer in order to be displayed on the far more resource intensive graphical interface. Furthermore, relying on the open source format of the Arduino for all computations grants the user the ability to alter calibration curves, include new data points to be recorded, or even alter the sampling rate.

Introductional User Guide

The user interface is fairly straight forward to use. Once launched, the user is prompted to connect the Arduino by providing the serial communication port to be used. After, a series of buttons become visible; Fill System, Check System, Clear Data, Begin Recording, Export Data, and Thruster. The first few buttons are only used when the test bed is first placed in the water. Fill system runs the ROV at a low power for a set amount of time in order to help the membrane inserted in the test bed to fully saturate before testing. Check system reads the Ardunio's output ensuring the values being presented are sensible for a system without flow; P1 = P2, Power Consumption = 0, Flow = 0. Clear data clears off the graphs as well as flushing the serial port in order to ensure any old data from previous tests does not contaminate the new data set. Begin Recording initiates the live graphing as well as the live recording of data being presented to the interface via the Arduino. Ofcourse, data without flow would be meaningless. That is why included in the right hand side of the interface is a slider running from 100 to -100, along with a switch labeled Thruster which turns on and off the thruster, regardless of the signal selected. For more precision, see below the slider a text box which can also be used to select the signal being sent. Since the thruster has the capability of spinning counter clockwise, or clockwise, 100 correlates to full force forward, while -100 instructs the thruster to spin full force in reverse. Please note these two "full forces" are not equivalent. Finally the Export Data button can be used to being up a save screen UI which allows the user to select what the file name will be as well as where the file should be saved. All data is exported as a .CSV file for ease of use in further calculations. Furthermore, by hovering over each graph, it is possible to download the figure as many different file types. While the graphs are fairly self explanatory, the gauges to their right might not be. Each gauge is updated live according to the latest datapoint interpreted fr0m the Arduino.

It is important to note that even though this interface was built using Matlab's app designer, no subscriptions or other programs are needed in order to run the interface. However, if one desired to alter the interface, a matlab license would be required.

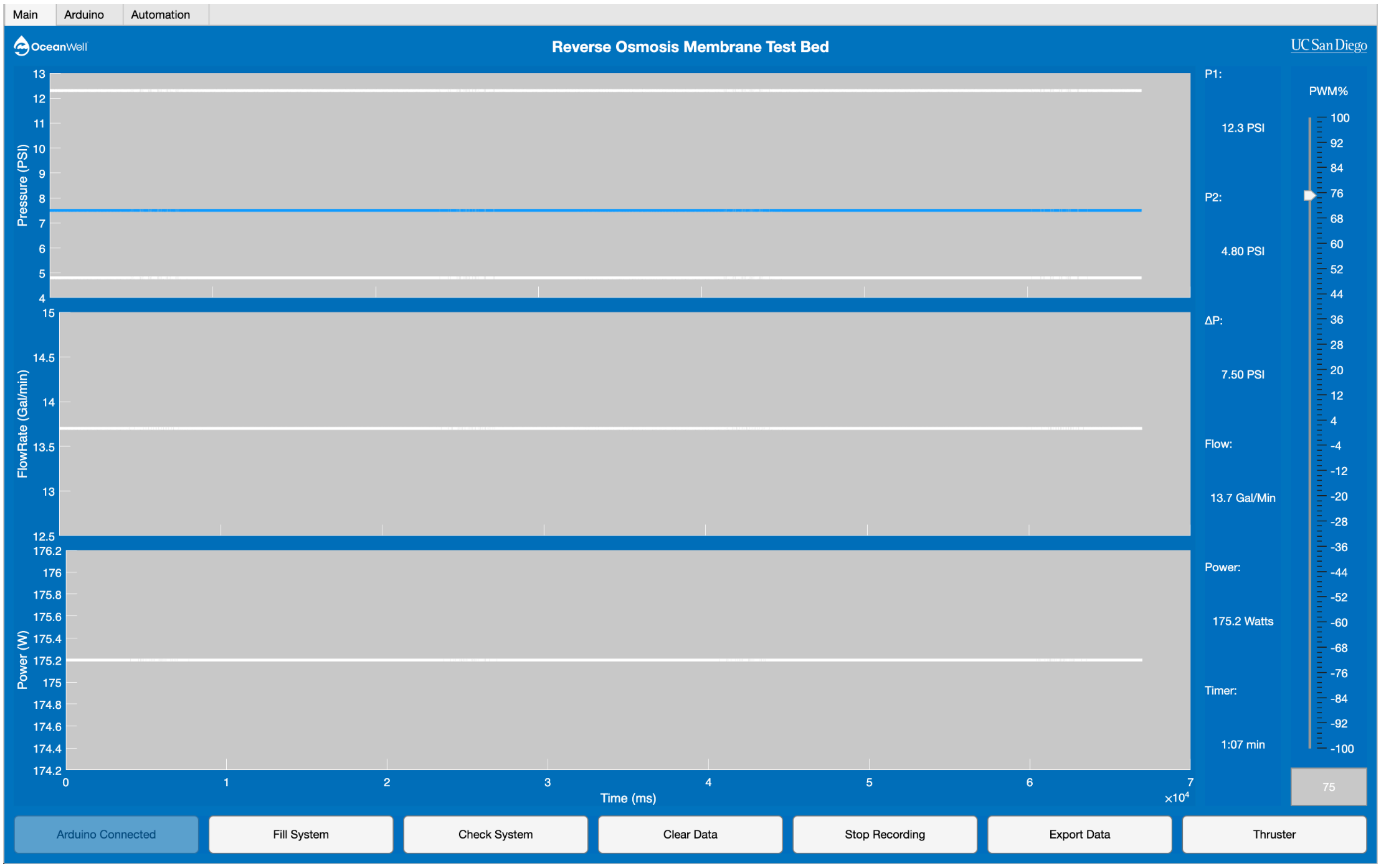


Figure 16: Final Interface Design

Basic Arduino Equations

$$I\,(amps) \;=\; \frac{1\,(A)}{0.04\,(V)}\frac{5\,(V)}{1024\,(cnts)}[analogRead\,(cnts) \;-\; 512(cnts)] \qquad \textbf{Equation 5}$$

Equation 5 is given directly by the manufacturer of the current sensor. Since this sensor can measure current flow in both directions, 0 amps is read as 512cnts, which is the center of the 10 bit 1024 count range. This reading is then correlated to amperage using the sensitivity of 40mV/amp measured.

$$P\,(PSI) \;=\; \frac{15\,PSI}{10V}\,\frac{2V}{1V}\,\frac{5V}{1024cnts}\,[\,analogReading\,(cnts)] \qquad \textbf{Equation 6}$$

Equation 6 simply linearly relates 15 PSI to a 5V output, which is read as 1024 cnts. Physically, the pressure transducer will output 10V at 15PSI. However, the Arduino is only capable of accepting a maximum of 5V logic. Therefore, a voltage divider was utilized to reduce the max pressure voltage from 10V to 5V. Thus the inclusion of 2V/1V in the formula. On the arduino this equation is simply the reading divided by the total possible counts, and multiplied by 15 PSI.

Chapter 4 | Prototype Performance

Theoretical predictions

For the flow meter strain gauge, the following equations were utilized to determine what average pressure would be expected to be experienced.

Bernoulli for stagnation pressure where:

$$P + \frac{1}{2} * \rho * V^{2} + \rho * g * h = P_0 + \rho * g * h_0$$

$$P + \frac{1}{2} * \rho * V^2 + \rho * g * h = P_0 + \rho * g * (h + \frac{1}{2} * v_0)^2$$

$$P + \frac{1}{2} * \rho * V^2 = P_0 \qquad \textbf{Equation 7}$$

P	Pressure
V	Velocity of water through system
ρ	Density of water
h	Height
g	Gravitational Constant

In this case, static pressure is negligible which further leaves us with the following:

$$P_{avg} = \frac{1}{2}(\frac{Q}{A_{pipe}})^2 * \rho = \frac{1}{2}(0.1729m/s)^2 * 1000kg/m^3 = 86.45\,Pa \qquad \textbf{Equation 8}$$

Using some of the known information outlined below, we acquired the average pressure experienced.

$$V = \frac{Q}{A} = \frac{4*q}{D^2*\Pi} = \frac{4*0.003155\,m^3/s}{(0.1524m)^2*\pi} = 0.173\,m/s \textbf{Equation 9}$$

Q	$50\,g/m = 0.00315\,m^3/s$
V	$6\,in = 0.152m$

Observations

This section will detail a small amount of important observations noticed when testing. These observations are not important to results but to design considerations going forward.

- The membrane takes a bit to saturate which can be easily accelerated by turning on the thruster

- The thruster creates a large amount of rotational fluid spin before and after the thruster. On top of creating a negative pressure the fluid inside the tube was largely rotating which can be seen in ("Media") in the project repository
- The testing rig seals did slightly fail when the thruster was operated in reverse. No observation of a broken seal was made when flow was in the correct direction.
- The power source was a limiting factor. The power source would beat up before the ESC.

Test Conditions

The testing bed's experiments were conducted in a small children's pool that held freshwater. The testing rig was completely submerged. All sensors were recorded with an arduino and matlab for different thruster powers. The thruster power was operated using the arduino and interface. A visualization of the testing can be seen in **Figure 17**. Two computers were used. One to control the thruster and monitor the pressure and power, and one to monitor the ADV measurements.

Figure 17: RO Membrane Testing

In place of the originally proposed flow probe, we used an Acoustic Doppler Velocimeter (ADV) pictured in **Figure 18** to create a flow profile to attain the flow rate. The ADV had to be mounted using five metal steel bars, four corner metal steel braces and lastly a 3D SLA printed mounting bracket designed to hold the three prongs of the ADV in place as shown in **Figure 18**. There was also a ruler strategically placed to help us move the ADV prong placement down starting from the center of the pipe and moving vertically down every two centimeters to record the flow across the radius of the pipe. The ADV records about 15 cm away from the prongs and we measured half of the pipe diameter in order to account for a non-uniform flow profile and with the assumption that the profile is symmetrical.

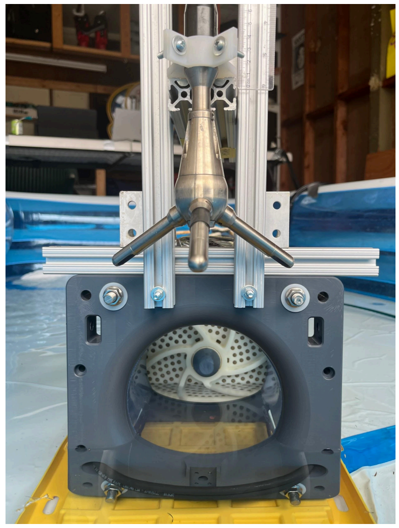


Figure 18: ADV Mount pieces pictured as the pool was filled with water

An example of raw data from the ADV can be seen pictured in **Figure 19**. These testing conditions were not ideal as the testing pool was small relative to the testing rig.

Data Processing

This small pool resulted in noisy readings from the vibrations and turbulence created by the thruster that rebounded back to the front of the testing rig. Although noisy, the data still provided reasonable results that could be read. The data in **Figure 19**, was averaged out giving one scalar value for a particular position of the flow in the tube along the radial axis. It was assumed in this experiment that the flow was symmetric about the radial axis.

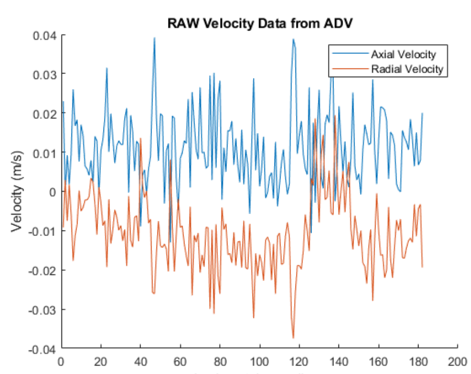


Figure 19: Raw testing data from ADV Instrument measuring velocity (m/s) in two directions at center of the tube at full thruster power

The flow rate of the system was derived by integrating a velocity profile from center to the edge of the tube (0cm,R/2cm). The velocity profile was created using derived normal velocities from the data shown from many figures as shown by the example of **Figure 19**. This velocity profile seen in **Figure 21** is a cubic approximation used because of its best fit with the given data. The math for flow rate was computed using Matlab ("Testing Data/Data.m") which can be found in the project repository. **Equation 10** also illustrates the math conducted to form this measurement.

$$Q = 2\pi \cdot \int_{0}^{R/2} v(r)dr \quad \textbf{Equation 10}$$

Q	Flow rate (m^3/s)
R	Distance from center of pipe (m)
v(r)	Normal flow profile from (0cm,8cm]

Assumptions

- Flow is a steady state
- There exists no spiraling of the flow
- Flow is symmetric about the radial axis

Results

During our pool tests we were able to obtain pressure readings off of the pressure transducers, power from the current meter, as well as a flow rate from the ADV. In **Table 8**, the pressure drop in PSI across the membrane is recorded for 3 different thruster powers. These measurements are then illustrated in **Figure 20**.

Table 8: Differential in Pressure across membrane for Power given to Thruster

Power (W)	282.4637	601.4192	997.6837
Pressure Drop (PSI)	1.1440	1.5950	1.8718

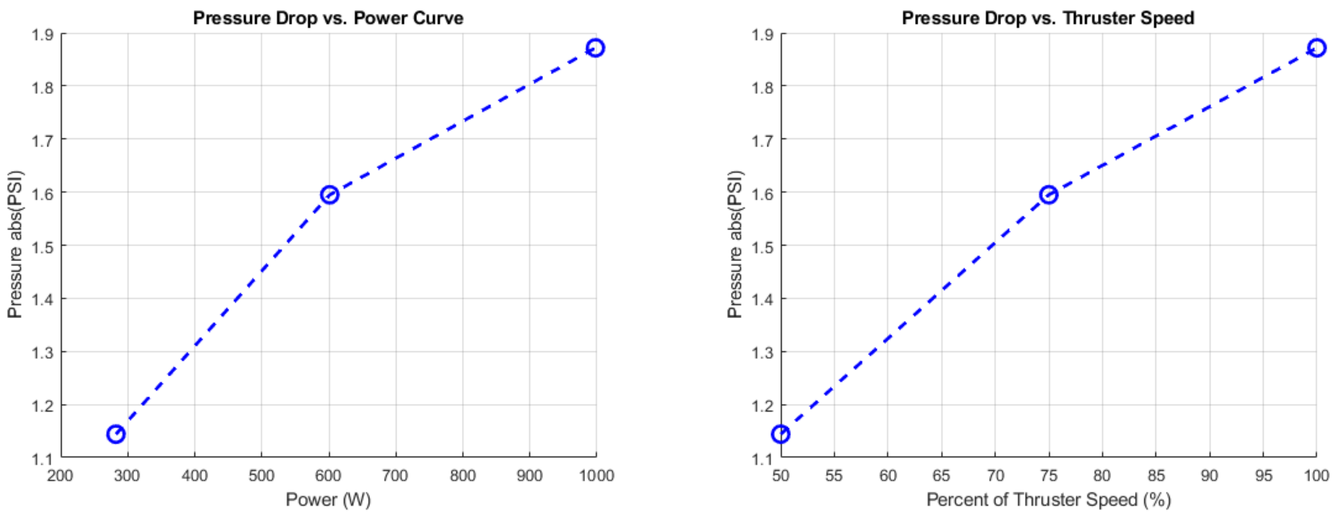


Figure 20: Pressure drop versus Power (left) and the Pressure drop versus Thruster Speed (right)

The pressure drop was relatively small, between 1-2 PSI. These results were slightly lower than the pressure difference expected by our sponsors. Another factor we failed to consider until testing was that the pressure read by the pressure transducers were recording 0-15 psi and did not read a negative pressure which is what would be read due to the vacuum created from the thruster. To produce results with the sensors we had the thruster was run in reverse to get an approximate reading of positive pressure which was assumed to be the same pressure differential that could be achieved in the correct direction of flow.

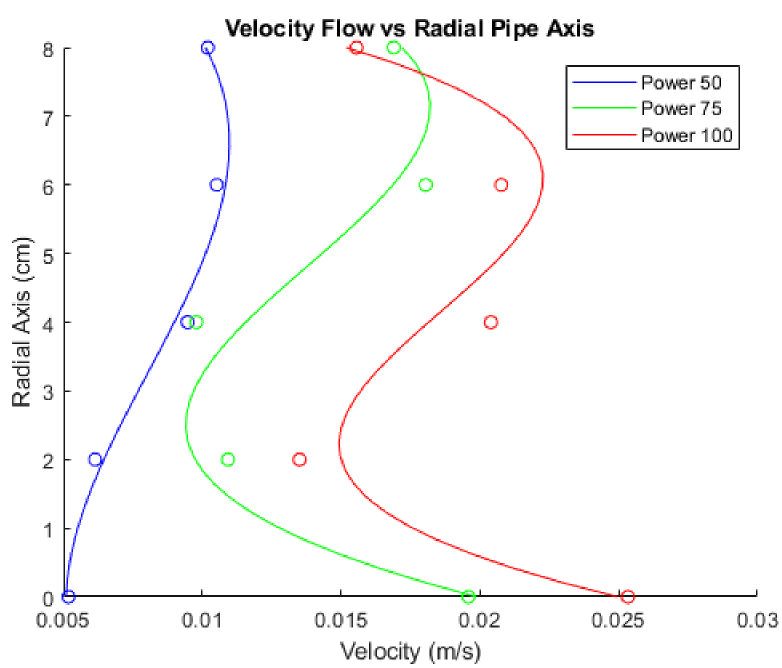
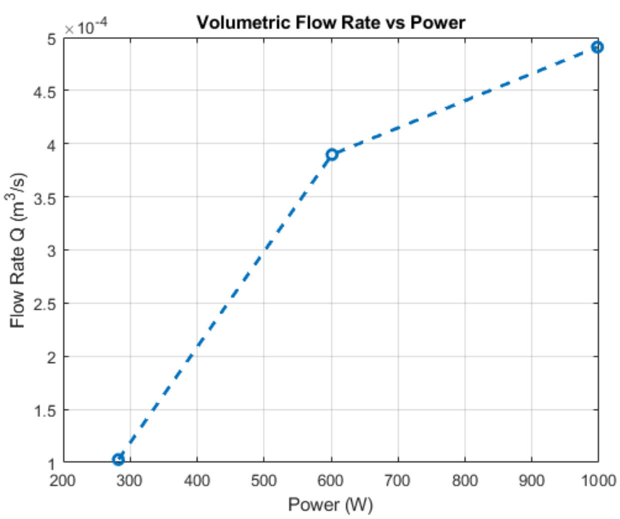


Figure 21: Flow profile recorded at tube edge showing half of the radial axis center from (0cm) to edge (8cm). Flow profile was approximated with a cubic curve for a best fit

The data used to construct the above flow profile was collected with the ADV reading at three different power ratings (50%, 75%, 100%) at 5 different distance points (8cm, 6cm, 4cm, 2cm, 0cm) across the diameter of the 16 cm pipe. **Figure 21** illustrates half of a cross sectional view of the flow profile from the side. It is assumed the flow is radially symmetric so only the center (0cm) to the edge (8cm) of the pipe is shown. In total 15 different sets of data were collected. Initially, there was greater variance in power ratings selected, from 10% to 100% however, it was noted that the numbers at the lower power ratings provided little information as they were essentially insignificant due to noise and thus the latter half of the spectrum was chosen. The flow profiles in the above figures were modeled cubically. It can be seen that there is great variance between the profile at 50% and at 100%. Using **Equation 10** mentioned before, the following tabulated values in **Table 9** were recorded for flow rate and converted to GPM for a better US standard of understanding.

Table 9: Flow rate across membrane for Power given to Thruster

Power (W)	282.4637	601.4192	997.6837
Flow Rate (m^2/s)	1.028*10^-4	3.897*10^-4	4.909*10^-4
Flow Rate (GPM)	1.629	6.176	7.781



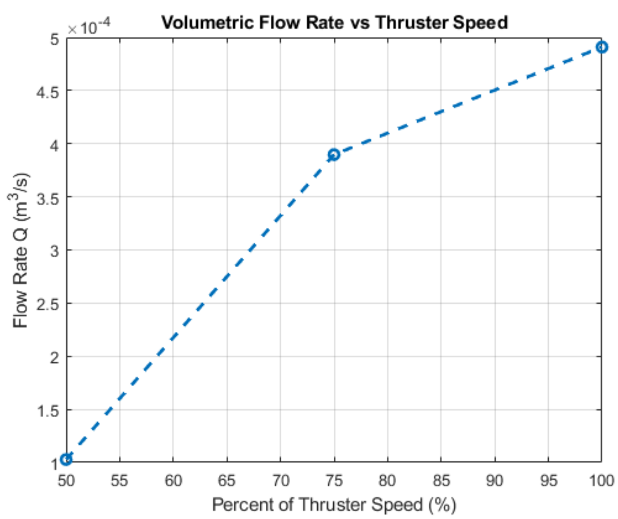


Figure 22: Volumetric Flow Rate across the membrane given power or thruster speed.

The trends shown in the figures above Figure 22 concur with what was to be expected that there'd be a correlation between volumetric flow rate, power, and thruster speed. With a percent increase of thruster speed, there is an increase in the flow rate recorded. Further, the data was recorded with a gradual increment of thruster speeds which correlate with thruster power.

Comparison of results to initial performance requirements

The sponsor had initially mentioned an estimated flow rate of 50 GPM. At our max flow rate, we only reached around 8 GPM. This is significantly lower than anticipated or hoped for. This comparison however is not ideal as the sponsor made this statement regarding a clear tube flow rate, not a tube with a membrane.

Another performance result to compare to is the expected pressure drop across the membrane. The sponsor expected around 4PSI drop where our max pressure drop ended up only being around 2 PSI, half of what was expected.

Chapter 5 | Design Recommendations and Conclusions

Design Recommendations

Overall

Many lessons were learned during the course of this project. Although this project was primarily a success, a few aspects of this project failed and need to be iterated on. The following is an overview of what is to be iterated on, redone, and implemented to better the project.

- The electrical wiring (the tether) is a gauge that is too big and inconvenient. It is recommended to use a 15 pin signal wire (VGA cord) to go all the way down to the testing rig. The tether, although intended to be waterproof, could easily not be. This is a safety hazard and liable to a short circuit
- The tether mount on the testing rig is 3D printed. This mount should be a fixed electrical box for wires with standard cord grips to allow all wires to be brought in neatly and wired securely to a tether that exists through a cord grip.
- The electronics board has open and exposed wires circuits. Although better soldering and wire management should resolve this issue, a PCB board would be a great addition to this device for security and reliability.
- The interface for this system is written in Matlab. To make it more adjustable another interface made with open source software should be developed to interface with the arduino code developed.
- The pressure transducers in this project only measure a positive pressure differential and were not intended to be submersible. This project required a submersible vacuum pressure reading transducer. A great example of one is shown here.
- The flow probe for this project was unsuccessful. A new idea and design will need to be developed. A mounting plate is already in place on the front face plate for any possible flow detection device.

More detail into design recommendations are in the following sections.

Testing Rig

Face Plates

Pipe diameter reduction should be a known angle to improve manufacturing efficiency. Design for a less sided component to increase manufacturing efficiency.

Thruster

The current thruster is not rated for use at depth as the original proposal desired. Providing a more robust thruster would open up the possibility of in the field testing. This component was manufactured using an Inkjet 3D printer. The design ended in a thin wall. This wall was brittle and chips easily. It is recommended to change the design to not end in a thin wall.

Flow Stick

The flow stick was designed and fabricated, with the string gauges also having been attached and wired. However, as the time to test neared our professor, Dr. Pawlak, fractured it during a final hardware review, indefinitely postponing testing and calibration of this flow probe design. After consulting Professor Maziar Ghazinejad, design recommendations were made to change the flow stick design to hold a spherical shape at the tip of the fin to entirely minimize vortices from the fluid flow. He also recommended we change our data reading media from the strain gauges to optically measure deflection of the flow stick using a camera. In order to implement this idea, we would need a different material that is significantly more flexible than the one we have currently fabricated. We did not have enough time to properly execute this new prototype option and therefore used a loaned Acoustic Doppler Velocimeter (ADV) from our professor in order to measure our inlet flow rate instead.

Thruster Assembly

The funnel components were designed to come to a point. This point proved to be very brittle and chips easily. Should design for a flat thicker edge to reduce component damage.

Electronics

Arduino Nano

Assuming the test bed would not need to be expanded upon, replacing the Arduino Nano BLE 33 with a custom circuit board could reduce cost when printed in mass.

Electronics board

Wire management on the board could be improved, specifically strain relief of some of the connections. The amplifiers and wheatstone bridges are not connected to anything, and can be wired according to the Wiring Flow Probe subsection if strain gauges are bought in the future.

ESC

The ESC recommended to drive the ROV is not rated to support the sponsor’s intended use case for long periods of time. While it is possible to build a cooling system in order to retrofit the current ESC into one suited for the task at hand, it would be simpler to provide an off the shelf ESC which is more capable. Given that we came across difficulties with the original ESC we purchased and used, maybe buying a backup option from the beginning would have been useful. The cause of failure of our first device remains unknown and therefore it was a very unexpected delay to need to replace it in such a quick manner.

Wire Harness

The gauge size for most of the wire harness and the tether was too large. Consider significantly reducing this size to signal wire and reducing the tether from 4 individual wires to 1 signal wire. The tether should have a submersible electronics box that mounts to the plates of the device. This electronics box could be accessed with a plate waterproofed with O-ring seals. Cord grips for every sensor should be how each sensor connection reaches the inside of the electronics box. A cord grip should also be how the tether leaves the testing rig to the electronics board.

Spreader Beam

The spreader beam is a relatively simple contraption which has been custom built for use in a specific tank with a specific crane set up. Redesigning this system to be more modular in order to accommodate a variety of cranes makes sense.

Water Collection

In order to test the effectiveness of each prototype membrane, a tube running from the center port of the membrane (where the clean water is produced) should be connected. Capping the other end of this collection area and connecting the aforementioned tube to pump, which outputs into a collection container, would allow for the effectiveness of each prototype membrane. For deep sea testing, this collection area would be a Niskin bottle. It is even possible this bottle would not require a pump when at depth due to the pressure difference between the inside of the container and the deep sea. Of course, the bottle would need to be sealed at atmospheric pressure

Safety Considerations

The ESC-Thruster system will be pulling up to 43A, but it is not rated for anything higher than about 20A for extended periods of time. The manufacturer, BlueRobotics, reported a steady state current draw of about 20A with a 16.8V supply, but should the steady state current draw be much higher than this, then there can be overheating at the ESC, thruster, and the 12AWG wires both units come with (12AWG is rated for about 30A). To remediate this: there is a heat sink attached on top of the ESC which doubles as a fan; and the thruster will be completely submerged in cold water during operation so will be cooled by conduction.

If the cooling mechanisms for the ESC fail and the current draw is sustained at over 20 or 30A, it will overheat, and if the situation is not caught in time, the ESC will stop functioning and may need to be replaced. There is no foreseeable danger if only the ESC is overheating, unless the wires are melting too.

In this scenario, the wires would overheat and: the wires may simple fray and break the circuit and either the wires or the ESC will have to replaced depending on how badly the connectors were damaged; or the wire insulation could melt leaving the wires open to a short circuit with any piece of metal in the Electronics Board (including the ESC). If the latter happens, then the kill switch will activate once it draws over 50A (which will likely happen near instantly once the short is formed), but if in that split second a spark is thrown then there is a risk of a dangerous electrical fire, which could rapidly spread due to its proximity to a high wattage AC-DC converter, a computer, and a wall outlet. This is the worst case scenario and most improbable.

Beyond the Electronics Board, the thruster and ESC are connected entirely by 12AWG wire. On the submersible side, the cold water continually flowing past it during operation should provide ample cooling. The only complication would be if, for whatever reason, a significant portion of the submersible wire is outside the water, and, if current is maintained above 40A is sustained and if this is not corrected for an appreciable amount of time, the insulation may melt causing a 50A livewire in a big pool of splashing water for a split second before the circuit breaker reacts. This is an improbable scenario as, even if a portion of the wire is out of the water, it will still be significantly cooled by conduction via the submerged portion, and cold water will be splashing the unsubmerged portion anyways.

Applicable Standards

The two Pressure Transmitters used to measure pressure an equal distance from either end of the RO membrane are from McMaster-Carr. They provide usage guidelines for their products in the form of specifications for users to follow and for these pressure sensors it is specified that they connect into a fitting with an NPT size ¼ (½”) Threaded end. NPT or National Pipe Thread is an American standard for tapered threads and specifies that there is clearance space between both pieces and should be sealed and leak-free with the use of seal tape or compound both of which would also help prevent corrosion for easy long-term maintenance [Source].

O-rings were also a significant component of the project used that followed strict engineering standards. With O-rings having a critical role in the project, it was important to use engineering standards. The AS568 American standard classification was used for this project. The guidelines and tables provided by major manufacturers supported the O-ring selection and groove geometry these O-rings would sit in for the custom made components for the project. Only static seals were implemented to hold pressure and waterproof components.

Impact on Society

The high level intentions of this project are to positively impact the environment while providing fresh water to communities and projects in need. Implementing this project has the potential to support water-scarce communities and provide resources for environmental projects such as reforestation. These systems proposed by OceanWell will also improve the current standard onshore Reverse Osmosis by increasing power efficiency by a factor of two. Drawing less power is an eco-friendly solution to accomplishing this goal. Another eco-friendly accomplishment to this device is less microorganism entrainment than existing RO systems & reduced physicochemical effect on environment.

Some possible negative effects of this device already exist from reverse osmosis systems today. The by-product of this system is brine, a high salinity solution that is toxic to aquatic life. Entrainment of organisms and the surrounding ecosystem can be negatively affected. Although brine is produced with this technology, it is less harmful then current systems today. A new negative impact to the environment from this system is the introduction of possible ocean junk that could be created if the machine breaks down and is unretrievable at low depths. Another impact of developing a new system at this scale is the carbon footprint from shipment or fabrication of parts.

Professional Responsibility

Building a scalable fresh potable water source at a significantly lower cost, economically and ecologically, compared to typical reverse osmosis facilities in production today is a lofty yet achievable goal. It is the duty of an engineer to use her or his talents in order to further progress the world toward a sustainable and equitable society. Though this test bed will not produce fresh water, it is a large step towards achieving such a reality. As such, it is this team's responsibility to do its best providing an accurate and reliable system. In order to do so, all assumptions made and failure modes anticipated must be thoroughly scrutinized. Any failure to do so would ultimately lead to errors in the next step towards achieving such a reality. Ultimately postponing any potential social, economic, and environmental benefits from being realized worldwide.

Lessons Learned

When working in an environment riddled with particles such as the sea water we eventually intend to filter into potable water, it is important to design systems in such a way that avoids particle build up in critical areas such as measuring devices. Due to this, the original idea of building a flow probe system utilizing a prop and an encoder was scrapped in fear of the sensor providing skewed data due to particle build up. Later on, the flow stick idea was selected due to its simplicity and reliability. This design contains no moving parts to clog while also utilizing a far more precise form of measurement. Best of all, waterproofing a strain gauge is far easier than waterproofing the original idea for a prop centric flow probe.

Since flow rate and pressure reading are highly dependent on the amount of water in the system, it is critical to safe guard against leaks. Though this may seem counterintuitive in a system which is meant to be submerged in water, as designed, any water entering or exiting the system outside of the designated inlet and exhaust ports has the potential to drastically skew an experiment's data. Thus, precautions were taken to ensure every possible leak point is safe guarded against. Most critically, the face plate seal at either end of the membrane was examined since these points experience the highest and lowest pressures. Any leaks here would mean a ruined experiment. A double O-ring technic was utilized in order provide redundant safe guards against such an occurrence. This double O-ring consists of the membrane's original brine seal, which is a radial seal around either end of the membrane, as well a face seal seated between the face plates and membrane faces. While the membrane alone only weighs around 30lbs, in order to ensure the membrane remains properly seated in these face plates while being lifted in and out of the water, a net was slung from the spreader beam under the membrane and back up to the spreader beam. This was done in order to prevent bending along the membrane's central axis – sagging – by evenly distributing a supporting force below it. Additionally, precautions were taken to ensure the tubing's face seals remained seated properly during transportation and hoisting of the test bed. Namely, mounting points connecting each plate to the spreader beam were moved from the outside bottom edge of the system to the top side. By doing so, the potential of allowing the entire system to sag when raised from the water is eliminated, since multiple points along the test bed are supported purely by vertical forces. Finally, ports coming in and out of the system were severely limited in order to introduce as few leak points as possible. All of which were sealed as well.

Acknowledgements

Our team would like to extend our sincere thanks to the following individuals for their advising, and input which propelled the project to come to fruition:

Project Sponsor	Ocean Well Dr. Michael Porter (mporter@oceanwellwater.com) Mark Golay Taylor Wirth Robert Bergstrom
Course Instructor	Dr. Eugene Pawlak
Course Teaching Assistant	Hannah Walker
Engineering Staff	Stephen Roberts

References

McMaster-Carr, https://www.mcmaster.com/. Accessed 5 May 2023.

Blue Robotics - Underwater ROVs, Thrusters, Sonars, and Cameras, https://bluerobotics.com/. Accessed 5 May 2023.

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Appendix A | User Manual

Set-Up

To begin testing there are many prior steps that must be completed and set up in specific orders. For safety, the connections to the wall outlets should be the last connections made. Also, ensure the 50A circuit breaker connected to the ESC is open (that the circuit is broken) before connecting the AC-DC converter to power. Otherwise there may be a voltage spike which could damage the ESC.

All of these have to be disconnected after operation is completed, for safety starting with the connections to the wall outlets.

Exact Steps:

1. At your testing location have a table ready on site for both the electronics board and computer to use and operate the device. This table should be right next to the tank being used.
2. Plug in the tether from the testing rig to the electronics board. Ensure both the VGA control cables and the thruster power cord are securely connected.
3. The testing rig can now be lowered slowly into the water. The membrane will want to float at first and will require weight at first to become saturated completely.
4. Secure all loose cords to prevent tripping. Also move all cords off the ground incase of splashes.
5. Connect a computer into the electronics board via the USB connector.
6. Before plugging into wall power ensure the 50A switch that leads to the ESC is in the off position. Once this is checked, plug in power.
7. Once everything boots up with flashing lights, flip the 50A switch to provide power to the ESC.
8. Run the thruster at some speed for 10 minutes to suck out all the air in the membrane. This step is completed once there is no more air that can be seen spinning inside the tube.

Handling

When moving the testing rig around, always disconnect the tether for safety of high Amps and water. The rig is sturdy enough that it can be carried by the threaded rods on the corners of the face plates. Always carry with two people and use appropriate lifting techniques. When lowering into a tank or open water, use the provided spreader beam. Straps and anchor points on the testing rig can be attached to the spreader beam. It is important to use the spreader bar when operating the system because the membrane will retain water and therefore weight when lifted out of the tank or open ocean.

When moving the electronic board around, lift by the handles provided. Ensure the board is generously away from water as it is not splash proof. Do not plug the board into power until everything is placed in position and ready for testing.

Interface

The user interface is fairly straightforward to use. Once launched, the user is prompted to connect the Arduino by providing the serial communication port to be used. After, a series of buttons become visible; Fill System, Check System, Clear Data, Begin Recording, Export Data, and Thruster.

- Fill system: runs the ROV at a low power for a set amount of time in order to help the membrane fully saturate before testing.
- Check system: reads the Ardunio’s output, ensuring the values being presented are sensible for a system without flow; P1 = P2, Power Consumption = 0, Flow = 0.
- Clear Data: clears off the graphs as well as flushing the serial port in order to ensure any old data from previous tests does not contaminate the new data set.
- Begin Recording: initiates the live graphing as well as the live recording of data being presented to the interface via the Arduino.
- The Slider: running from 100 to -100, along with a switch labeled “Thruster” turns on and off the thruster, regardless of the signal selected. For more precision, see below the slider a text box which can also be used to select the signal being sent. Since the thruster has the capability of spinning counter clockwise, or clockwise, 100 correlates to full force forward, while -100 instructs the thruster to spin full force in reverse. Please note these two “full forces” are not equivalent.
- Export Data: button can be used to bring up a save screen UI which allows the user to input a file name and select a save location. All data is exported as a .CSV file for ease of use in further calculations.
- Hovering over each graph, it is possible to download the figure as many different file types.
- Gauges to the right of the graphs update live according to the latest datapoint interpreted from the Arduino.

Appendix B | Component List and Details

BOM

The Bill of Materials sheet utilized by our team can be found at the following link. It encompasses the details, prices, quantities, suppliers, statuses, order date placed, order date received, and a total sum of all expenses made. Due to the length of the sheet, a link was the best method for sharing this information.

Table 10: Bill of Materials

Component	Supplier	Cost	Quantity	Total Cost
ROV Thruster	Blue Robotics	$861.28	1	$861.28
ROV Controller	Blue Robotics	$0.00	1	$0.00
Pressure Transmitter	McMaster	$163.70	2	$327.40
Cord Grip	McMaster	$3.65	2	$7.30
1/4 NPT Nut	McMaster	$0.89	2	$1.78
1/2 NPT Nut	McMaster	$0.87	1	$0.87
Encoder	Amazon	$15.63	1	$15.63
Amplifier	Amazon	$11.99	1	$11.99
Strain Gauges	McMaster	$76.92	1	$76.92
Resistors	Digikey	$1.10	6	$12.10
Syringes		$3.44	1	$3.71
Loctite Fast Curing Marine Sealant		$12.18	1	$12.69
PIFE Tape		$0.98	1	$1.49
3 wire Strain Gauge	McMaster	$34.65	0	$0.00
Arduino Nano	Arduino	$16.95	1	$16.95
Step-down converter	YIPIN HEXHA	$16.99	1	$16.99
Power transformer	DIGISHUO	$97.86	1	$97.86
Power cord (transformer)	Bergen Industries	$7.37	1	$7.37
Fuse holder	Yetaida	$6.99	1	$6.99
0.5A Fuse	BOJACK	$5.99	1	$5.99
50A Fuse	Welugnal	$12.50	1	$12.50
12AWG Cable	McMaster-Carr	$60.62	1	$60.62
6AWG cable	McMaster-Carr	$50.80	0	$0.00

18AWG cable	McMaster-Carr	$37.25	1	$37.25
22AWG wire	McMaster-Carr	$3.58	1	$3.58
Plugs	Amazon	$13.72	1	$13.72
Plug	Wadoy	$22.99	0	$0.00
Outlet	RVMATE	$9.99	0	$0.00
VGA female mount	Twinkle Bay	$9.79	1	$9.79
VGA male cable	ANMBEST	$17.99	0	$0.00
VGA male cable (2)	Amazon	$10.99	1	$10.99
Noctua Cooling	NOCTUA	$54.95	1	$54.95
Heatsink	LUOQIUFA	$6.99	0	$0.00
USB Adapter	UGREEN			
Thermal tape	Amazon	$9.99	0	$0.00
Cable	McMaster-Carr	$62.25	1	$62.25
		$134.90	1	$134.90
		$28.02	1	$28.02
		$7.53	1	$7.53
		$17.78	2	$35.56
Cord Grip	McMaster-Carr	$4.79	1	$4.79
6" Pipe	McMaster	$135.14	1	$135.14
Stock PVC	McMaster	$275.77	1	$275.77
O-ring -168	McMaster	$12.53	1	$12.53
Threaded Rods	McMaster	$39.24	4	$156.96
Nuts	McMaster	$6.85	2	$13.70
Eye-bolts	McMaster	$6.20	4	$24.80
O-ring -164	McMaster	$10.19	1	$10.19
Rubber Feet	McMaster	$8.60	8	$68.80
Heat-set Threads	McMaster	$9.98	2	$19.96
Screws	McMaster	$8.31	1	$8.31
Set Screws	McMaster	$4.86	1	$4.86
Washers	McMaster	$11.38	1	$11.38
Stock PVC	McMaster	$116.64	1	$116.64
O-rings-256	McMaster	$12.39	1	$12.39
O-rings-020	McMaster	$14.97	1	$14.97
Screws	McMaster	$8.68	1	$8.68
I Beam	McMaster	$61.08	1	$61.08
Weld on Tie Downs	McMaster	$8.56	0	$0.00
Chain	McMaster	$16.00	1	$16.00
Links	McMaster	$1.81	2	$3.62
Triangle Link	McMaster	$16.47	1	$16.47
Screws 10-24	McMaster	$17.48	1	$17.48

Nuts 10-24	McMaster	$2.21	1	$2.21
Acrylic Sheet	McMaster	$10.09	1	$10.09
Swivel Tie Downs	McMaster	$5.31	2	$10.62
#8-32 Nuts	McMaster	$1.92	1	$1.92
#8-32 Bolts	McMaster	$5.94	1	$5.94
#10-32	McMaster	$4.48	1	$4.48
3/8 Threaded Rod 12"	McMaster	$7.56	4	$30.24
Ratchet Straps	Amazon Basics	$29.02	1	$29.02
Inkjet Printer	UCSD	$100.00	1	$100.00
Brine Seal		$30.57	1	$30.57
Epoxy resin	AeroMarine Products	$80.48	1	$80.48
Homedepot Order	Home Depot	$46.58	1	$46.58
Pressure Gauge	Home Depot	$4.48	1	$4.48

Detailed Drawings

Plate | Membrane

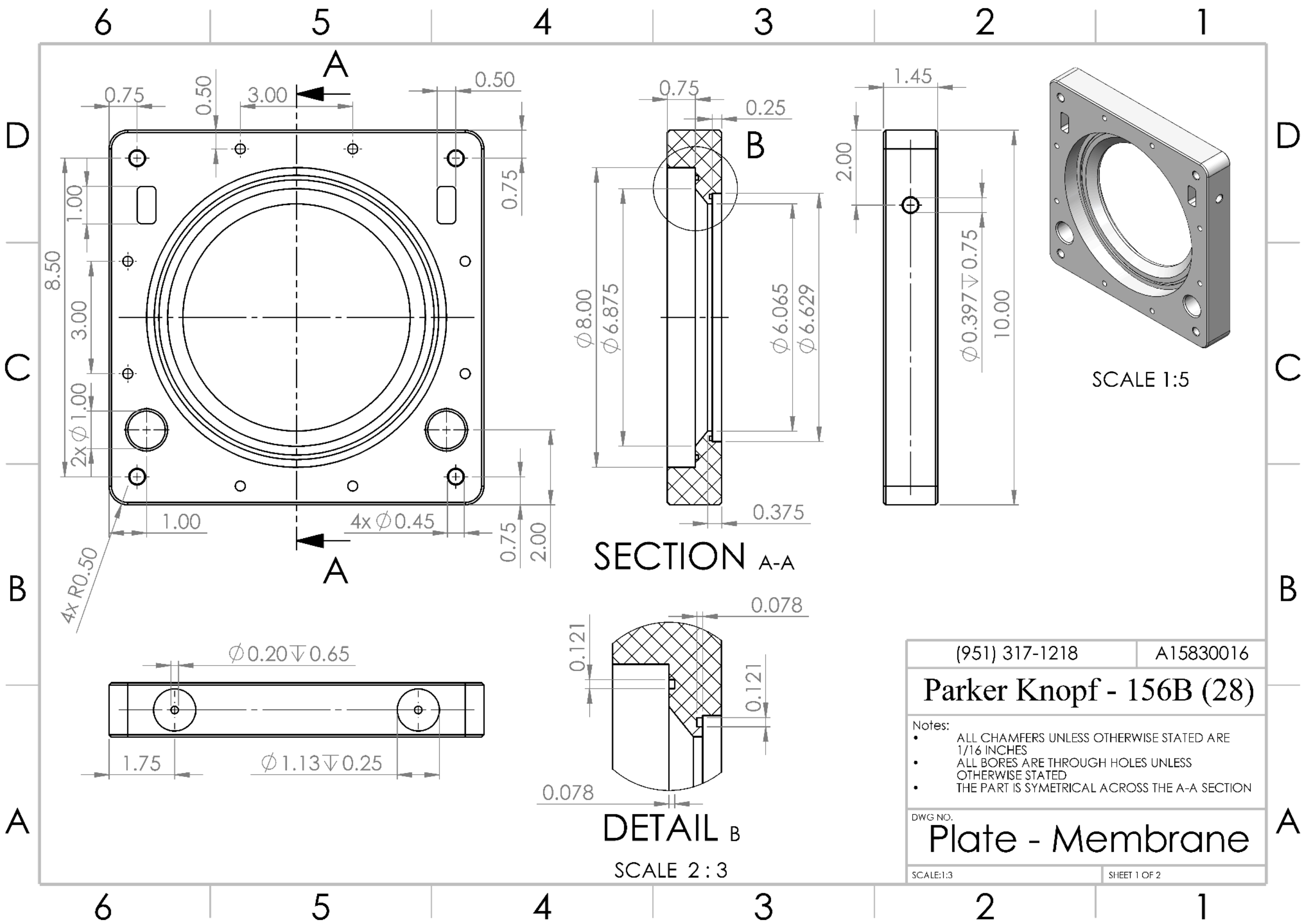
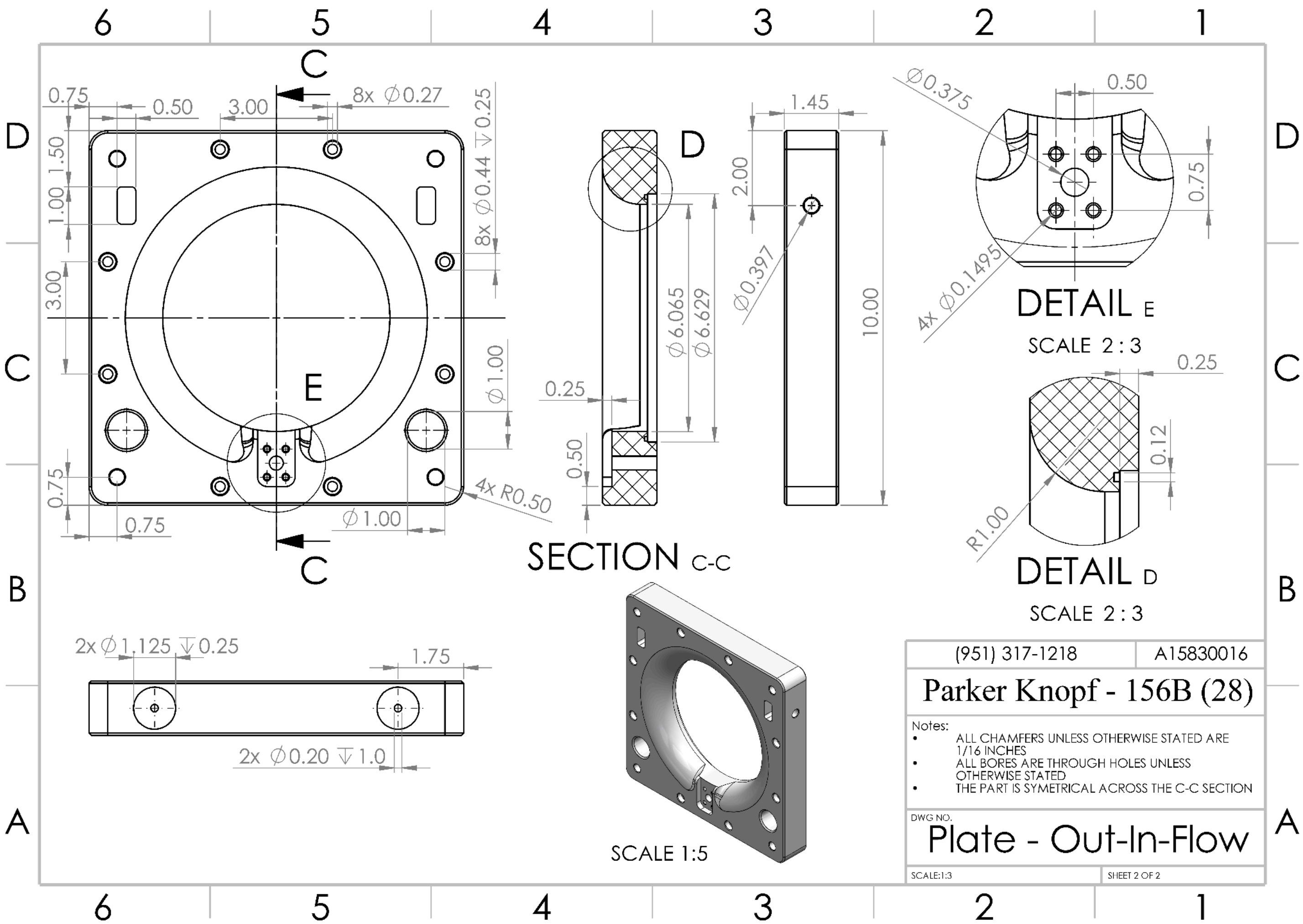


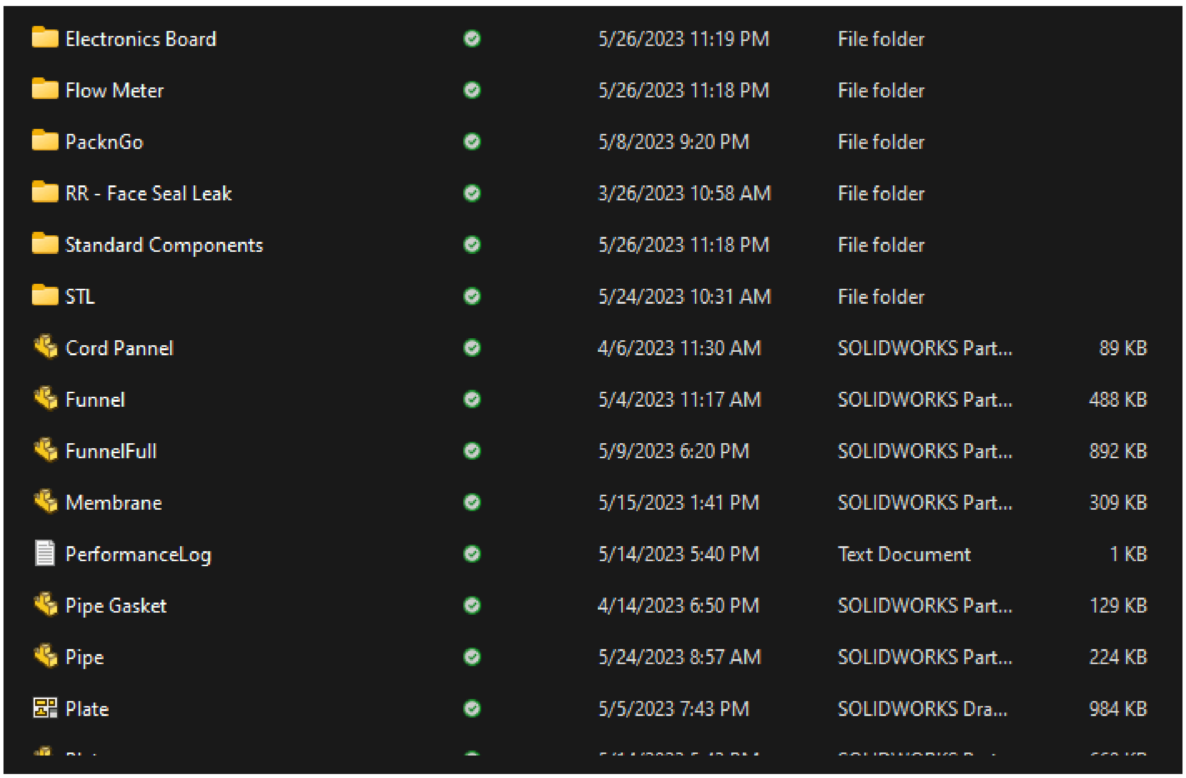
Plate | Out-In-flow



Appendix C | Fabrication

CAD

The source code to the CAD of this project can be found here. This project was designed using Solidworks. All components were designed in imperial units and to use US standard hardware. These standard hardware components used in the project are in the Standard Components in the directory of files. **Figure 23** shows the directory of the CAD for the project.



Electronics Board	5/26/2023 11:19 PM	File folder	
Flow Meter	5/26/2023 11:18 PM	File folder	
PacknGo	5/8/2023 9:20 PM	File folder	
RR - Face Seal Leak	3/26/2023 10:58 AM	File folder	
Standard Components	5/26/2023 11:18 PM	File folder	
STL	5/24/2023 10:31 AM	File folder	
Cord Pannel	4/6/2023 11:30 AM	SOLIDWORKS Part...	89 KB
Funnel	5/4/2023 11:17 AM	SOLIDWORKS Part...	488 KB
FunnelFull	5/9/2023 6:20 PM	SOLIDWORKS Part...	892 KB
Membrane	5/15/2023 1:41 PM	SOLIDWORKS Part...	309 KB
PerformanceLog	5/14/2023 5:40 PM	Text Document	1 KB
Pipe Gasket	4/14/2023 6:50 PM	SOLIDWORKS Part...	129 KB
Pipe	5/24/2023 8:57 AM	SOLIDWORKS Part...	224 KB
Plate	5/5/2023 7:43 PM	SOLIDWORKS Dra...	984 KB

Figure 23: Directory of CAD components and files

Software

Programmed with matlab. Exported as exe and mac files. Software is located in the project repository.

Appendix D | Project Logistics

Team Members

Parker Knopf

Structural Design and Documentation Lead
Phone: (951) 317-1218
Email: parker.knopf@gmail.com

Responsibilities:

- Pressure Transducer Research
- CAD Design, Fabrication, and Assembly of Testing Rig
- CAD Design, Fabrication, and Assembly of Thruster Assembly
- CAD Design, Fabrication, and Assembly of Spreader Beam
- Design, and Fabrication of Electronics Board
- Operational dry and wet testing of RO membrane rig
- Post processing of data to develop results and figures
- Documentation and presentation standards and logistics
- Aided in website development

Jaden Gilliam

Electrical Integration and Interface Lead
Phone: (213) - 369 - 3130
Email: gilliam.jangel@gmail.com

Responsibilities:

- Integrate multiple electronics in conjunction with a SBC
- Built a multiplatform parallel computing system utilizing a SBC as well as the user's computer (Windows, MacOS, Linux)
- Design, simulated, and fabricated Flow Probe
- Aided in electronic board's fabrication

Karina Plascencia

Sensor and Safety Lead
Phone: (661) 874-7447

Nikhil Iyengar

Circuits and Electronics Lead
Phone: (206) 304-2897

Email: kplascen@ucsd.edu

Responsibilities:

- Sensor research and selection
- Fabrication of flow probe; strain gauge.
- Design of ADV Mount for testing and CAD part
- Waterproofing of sensors; pressure sensor epoxying
- Design of 3D printed epoxy mold for pressure transducer 2
- Analysis of acquired pressure data

Email: nikhil.s.iyengar@gmail.com

Responsibilities:

- Design of Circuit Diagram, including Power Sources and Strain Gauge Circuit
- Wiring of Electronics Board
- Design and implementation of a wheatstone bridge and Amplifier circuit

Jennifer Hernandez-Mora

Fluids Analysis Lead and Fiscal Manager
Phone: (805) 623-2823
Email: j7hernan@ucsd.edu

- Flow Calculations and Analysis
- Calculations and Analysis for strain gauge selection and probe feasibility
- Design of test for flow probe calibration and flow profile calculations

Webpage

At this moment the webpage is up to date and live. An overview of the project with videos and other media are pictured.

Task Management

Tasks in this project were largely broken down into major project components. Every individual of the team was largely responsible for completing each respective component of the project. Every submodule of the project involved many tasks. Tasks for the project were recorded and documented in the team task-sheet.

Project Timeline

The project timeline had a strict deadline of 14 weeks, ending on June 9th, 2023. To accomplish this deadline a Gantt chart was implemented for the team to follow.

Risk Reduction Efforts

Face Seal

A ¼ scale model was created to test the feasibility of a face seal to hold a small amount of pressure. The following image in **Figure 24**, show the model used to conduct the test.

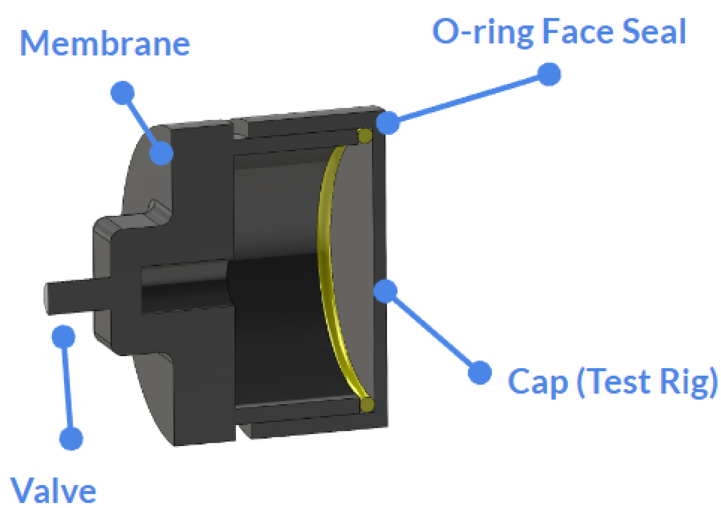


Figure 24: CAD Model of the ¼ scale test between the membrane and testing rig to be constructed

The test performed was to hold a gauge pressure of 15 PSI for an extended period of time. The test would prove successful if no air bubbles were observed and if several hours later the pressure remained constant inside the capsule. The following images in **Figure 25**, show the risk reduction testing model in the tank.

Figure 25: Risk reduction testing rigs for face seal feasibility between the membrane and a face plate

The results of the test were visually recorded with no observations of any bubbles and only a slight decrease in pressure, suspected to be due to the measurement made itself.

Membrane Characteristic Test

Per professor recommendation, a membrane test was performed in order to calculate needed weight values. The recorded dry weight of the membrane was about 6.05kg, however it is suspected this was not an accurate reading so it remains to be repeated. The membrane was then submerged and held down in saltwater for about 15 minutes and the semi-saturated weight after this amount of time was about 22kg. It was observed that it was probably not fully saturated after being submerged for this amount of time. It is planned to be reweighed after saturating it with the ROV thruster turned on to get as much water as possible into the membrane. It was also observed to be very buoyant and we expect to need weights in order to maintain the testing rig as a whole under the surface of the water for testing and data collection.

Figure 26: Membrane held in testing tank of saltwater

Appendix E | Researched Topics

O-rings

A detailed analysis on the current industrial standards for using O-rings for face and radial seals dealing with pressure and vacuum vessels in aquatic environments and applications.

Micro Controller Documentation

A dive into the capabilities and drawbacks of the Arduino Nano BLE 33. Though ultimately the base model Arduino Nano will be used, all other features are the same except for the lack of wireless capability.

Fluid Analysis

A detailed report on the analysis of flow utilizing numerical analysis as well as computational fluid dynamics through the use of computer programs.

Sensor Research

An analysis of existing commercially available flow sensors to narrow down which options would be optimal for this application. Concluded that while mag-meters and large diameter would allow for simpler integration, cost was too high for the budget and the cost-efficient route would be a mechanical flow meter.

Power Sources

A report on battery power sources, early on in the project we were invested in a portable setup. Since then the project has focused on utilizing on shore power instead thanks in part to its lower cost, simplicity, and increased reliability.