Nekton Autonomous Under-Ice Vehicle

Ice Breakers

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Submitted

3.15.24

Table of Contents

Executive Summary

Following the success of *Icefin*, an under-ice vehicle that provided unprecedented images of the Antarctic Ocean, Dr. West and his research teams are working on building *Nekton*, a newer vehicle that's smaller in size and more adaptable based on mission requirements, that will contribute to scientific discovery. This design exhibits unique challenge due to its requirement to operate underwater at a depth of two kilometers, meaning the vehicle must be sufficiently waterproofed. The current vehicle features a modular design to allow for parts of the vehicle to be removed and replaced if necessary.

This team has specifically been tasked with prototyping the thruster module and completing a previous capstone team's work on the battery module. This will provide a unique opportunity to both implement our own designs and build off existing work. Each prototype will be machined out of aluminum stock rather than 3D printed to ensure a sufficient factor of safety against underwater pressures. This team is requesting $1000 to machine both modules and purchase the necessary electronics to allow the T-200 Blue Robotics thrusters to operate at their maximum power.

The end goal is to demonstrate that the thrusters operate, can achieve full orientation control, and that the battery can provide enough voltage for the thrusters to operate at their maximum power. The physical demonstration will be showing the machined thruster module connected to the tail cone alongside the battery module, and this team aims to show the thrusters will work in controlling the position of the vehicle.

The recommended next steps would be to implement the robotics and controls functions needed for underwater navigation and operation to enable scientific discovery.

Nomenclature

AUV – Autonomous Underwater Vehicle

BMS – Battery Management System

CAD – Computer Aided Design

ESC – Electronic Speed Controller

FEA – Finite Element Analysis

GUI – Graphical User Interface

PCB – Printed Circuit Board

MMM – Montgomery Machining Mall

PWM – Pulse Width Modulation

VIP – Vertically Integrated Project

Nekton Under-Ice Vehicle Battery and Thruster Module Design

1. Introduction

The Nekton Vehicle is a sub-ice vehicle which will be used to explore the icy environments in the polar regions of the Earth. A successor to Icefin, the first of its kind under-ice vehicle developed by a team of scientists and engineers from Georgia Tech and other institutes, Nekton will also follow a modular design. The main motive for building an autonomous under-ice vehicle such as Icefin or Nekton is to explore the environment in the sub-ice polar regions and gain insight into the how the ocean and seafloor interact and the effects of climate change on the structure and chemistry of the glaciers and ice shelves. The data collected will not only help scientists learn about the changes in the Earth but will also be crucial in scaling the project to be used on Jupiter's moon, Europa.

The Nekton vehicle will have new features and improvements from the Icefin vehicle. A major upgrade is making the vehicle autonomous and free to move in the water without controlling it manually. Another major change is the decreased diameter of the Nekton. While the structure of the vehicle might resemble Icefin, Nekton requires new modules for the thrusters, batteries, electronics and controls.

For this project, our group aims to machine the horizontal thruster module, complete the battery module, and provide signals to the thrusters. This document highlights the goals of this project, and what we hope to achieve this semester. We will discuss the requirements for our team and how we plan to solve the design problems posed. The document includes technical details about the design and functionality of the Nekton vehicle, specifically the thruster module and battery module. With these specifications, we will convey how we plan to contribute to building the Nekton AUV.

2. Existing Parts, Prior Art, and Applicable Patents

Nekton is a successor to Icefin, and the documentation on the design process, challenges, and constraints of Icefin is being used for Nekton. Nekton will be used specifically for scientific research, and will not be on the consumer market.

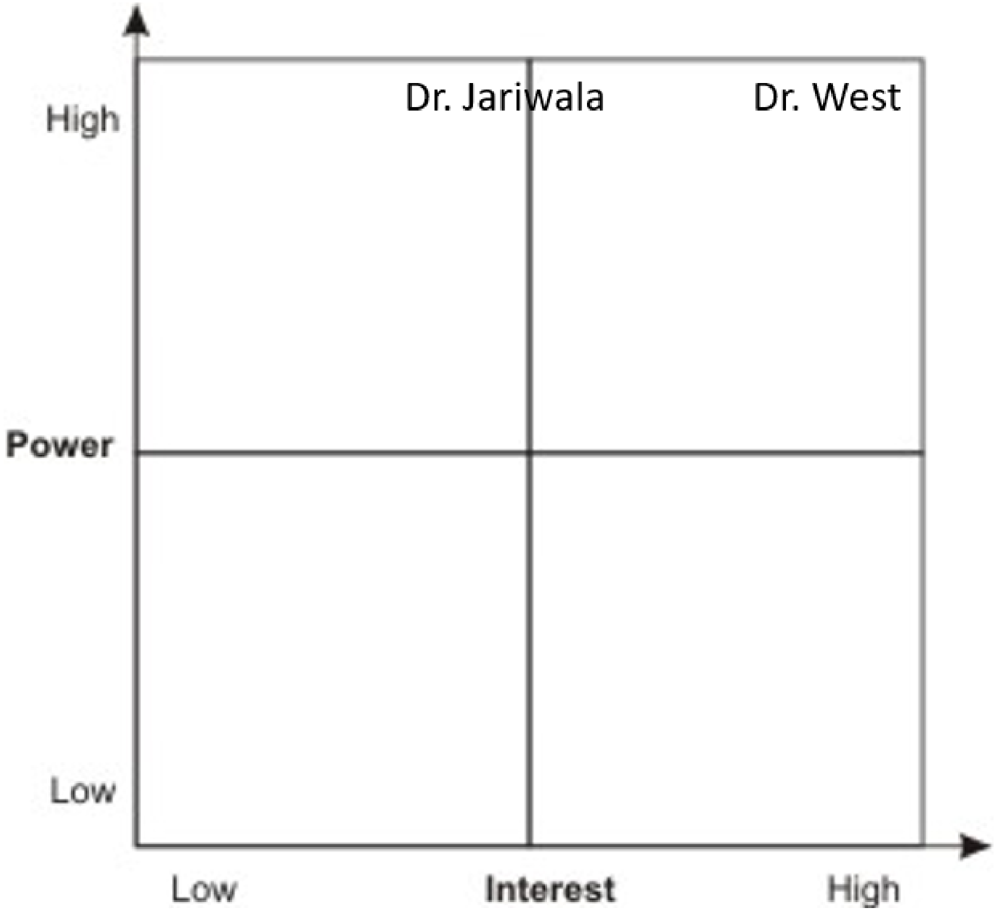
3. Codes and Standards

The Antarctic Treaty signed in 1959 declared that Antarctica will not be used for nuclear testing or radioactive waste disposal and shall only be used for the purpose of scientific discovery. Nekton aligns with the goal of that peace treaty and its characterization of under-ice environments will help scientists all over the world make strides in fighting climate change, specifically in the Antarctic region.

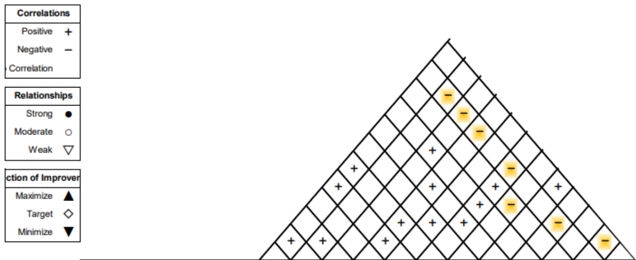
4. Customer Requirements and Engineering Design Specifications

Nekton is an Autonomous Underwater Vehicle (AUV) that will be deployed to explore and research regions such as ice glaciers in Antarctica. The Nekton project is divided amongst two teams for this semester, and our team will be responsible for working on the GUI, electrical interfacing, and design, fabrication, and testing of battery and thruster modules. For the battery module, the current tasks are to reverse engineer a CAD model of the current enclosure to reduce its size, and complete wiring of battery module to end cap. For the thruster module, the team is working on updating the drawings and design to ensure the parts are ready for fabrication.

The main stakeholders for this project are Dr. West and Dr. Jariwala, as shown in the 2x2 Stakeholder Matrix. Dr. West is the customer of this project and provides the team design goals and information for the project. Dr, Jariwala is the professor for the capstone course and will also be our point of contact for any ME capstone related inquiries. Since this is a faculty sponsored project, Dr. West will be more invested and influential over this project.



Customer needs for this project include functioning individual modules of Nekton such as the thruster and battery modules, and preferably a working vehicle ready for testing by the end of the semester. To achieve so, it will require all teams to fully complete the design and fabrication of all relevant parts and modules. Other customer requirements include the ability for modules to withstand subfreezing temperatures in the Arctic depths of at least 2000 m, range of 3 km, remote and eventually autonomous control through integration of navigation modules, and ability to collect and store data once deployed, as shown in the house of quality below that relates the customer and engineering requirements.



Weight	Customer Requirements (Explicit and Implicit) \ Engineering Requirements	Temperature Management	Depth Sensor	CTD Sensor	Manufacturable Thruster Design	Withstand 2000m depth pressure	Range of 3km	Less than 10" diameter	Maneuver Horizontally	Remote System Communications	Buoyancy Control	Sufficient Battery Power	DVL and other components	Row #
	Column #	1	2	3	4	5	6	7	8	9	10	11	12	
	Direction of Improvement	▲	▼	◇										
9	Modular Design	○	●	●	●	▽	▽	●	○	○	○	▽	●	1
9	Portable	▽	▽	▽	○	○	○	●	▽	▽	○	○	○	2
9	Operate in Cold Temperature	●	○	○	▽	▽	▽	▽	▽	▽	▽	○	▽	3
9	Environmentally Friendly	○	○	○	▽	▽	▽	○	○	▽	○	▽	▽	4
9	Minimize Cost	○	○	○	●	○	○	○	○	○	○	●	●	5
9	Deploy Vertically	▽	▽	▽	●	▽	○	●	●	○	●	▽	▽	6
9	Remote Control	○	●	○	▽	▽	●	▽	○	●	○	●	○	7
9	Fit in Drilled Ice Bore Holes	▽	▽	▽	▽	▽	▽	●	○	▽	○	▽	▽	8
9	Utilize Sonar	▽	○	○	▽	▽	●	▽	○	○	▽	○	▽	9
9	navigation module	▽	●	○	▽	▽	●	▽	▽	●	●	○	○	10
9	Navigate Underwater	●	●	○	●	●	●	○	●	●	●	●	○	11
9	Identify Objects	▽	○	○	▽	▽	▽	▽	▽	▽	▽	○	○	12

Since the Nekton vehicle is designed to be modular and will be deployed in freezing conditions, there exist several constraints such as its portability, size, weight, and type of material used in fabrication. Other specific constraints include past design of thruster module that was made for 3D printing prototyping, and as such will need to be redesigned to be suitable for machining. Engineering requirements include reduction of length for the battery module and enclosure (<27.4”), materials suitable for pressure at 2000-meter depth and beyond, space for navigation module and sensors, and 700 Watt-hours of energy form the battery.

The required engineering design specifications and testing methods for each module can be seen in the following tables.

Thruster Module

Specification	Testing Method
Bolted connections and welds must support at least 130 kg weight of vehicle	FEA and bolt formulas
Thrusters must allow for 360 degrees of articulation	Submerging subassembly [detailed Slide 12]
Must be able to provide ideal range of thrust specified in manufacturer's data (11.6-14.8 lbf forward/ 9.0-11.1 lbf backward)	FC22 load cell
Must maintain outer diameter of 180mm	Basic measurement instruments
Must connect with other modules using already fabricated clamps	Assembly pass/fail

Battery Module

Specification	Testing Method
Must consistently output 30 V	Digital Multimeter, first testing individual batteries and then full assembly
Must consistently output current up to 25 A	Digital Multimeter, first testing individual batteries and then full assembly
Must be able to sustain a run time of up to 4 Hours	Run each component until failure to determine maximum runtime
Must consistently output energy density of 105 Wh/kg	Energy analysis using digital multimeter to determine power delivered by batteries; combine with known knowledge of battery weight
Must sustain all of the above in a temperature range of -20° C < T < 60° C	Monitor battery operation at temperature extremes, potentially using a battery test chamber i available

5. Design Details

Battery Module

The design of the battery module consists of four cylindrical battery banks mounted along a rectangular aluminum frame, centered around a central copper bus. The battery banks are then designed to have wired connections to Subconn high power four contacts endcaps on either end of the module, which will facilitate energy transfer to the rest of Nekton.

A great deal of work was previously done on the battery module, which has been built upon this semester to create a more cohesive and promising design. Previous teams machined an aluminum frame which provides structure to the battery module. However, this frame was sized without considering necessary insulation. As such, these rods will be resized to ensure a final size of 0.4 inches on each side once insulation is added; a new rod for this purpose has already been obtained. Five PCBs were previously ordered from JLCPCB, with one part not available from the company (ATTINY) being soldered separately. Three of these PCBs ended up nonfunctional for unknown reasons, and atleast two more PCBs will need to be fabricated.

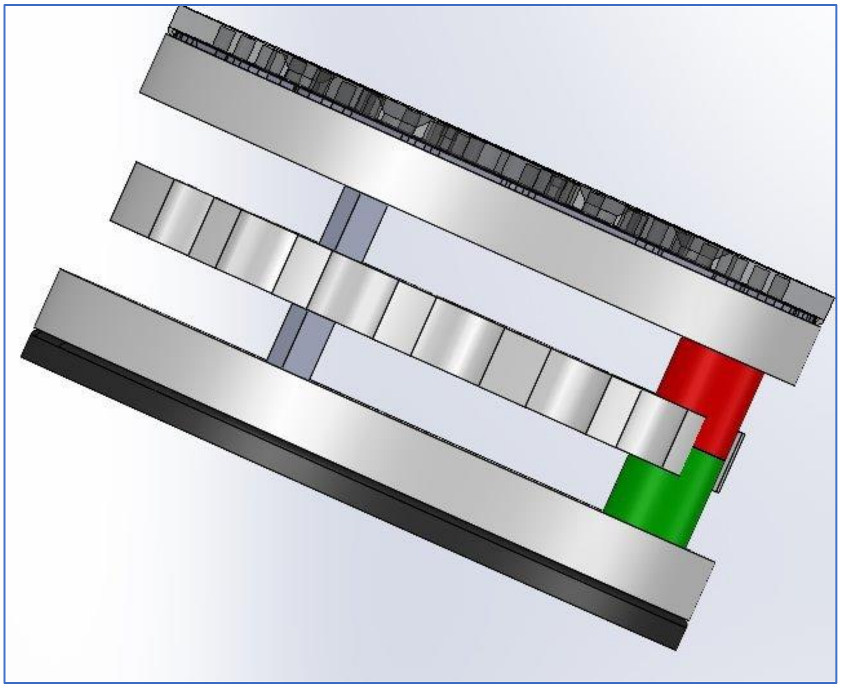


Figure 1: Battery bank with view of rectangular standoff

Previous teams created the design for the battery banks which will slide onto the frame. Several prototypes were created using this design in the past, and the process of doing so revealed multiple issues which will be resolved in a new iteration of the bank design. The new iteration of the bank design avoids previous safety hazards and greatly reduces electrocution risk. It does so by adding rectangular standoffs, which prevent structural screws from shearing the external layers of battery cells while tightening. Additionally, the new design reduces the length of holes which hold battery contacts into place. The holes have been kept at a sufficient length to ensure the contacts can fully screw into the structural portions of the bank, but reduce electrocution risk that was previously present due to the screws having no insulation from the outside of the bank. Finally, both of these sets of holes have been improved from previous iterations through the inclusion of heat set threads, which will create strong threads in the design rather than using threads created from PLA.

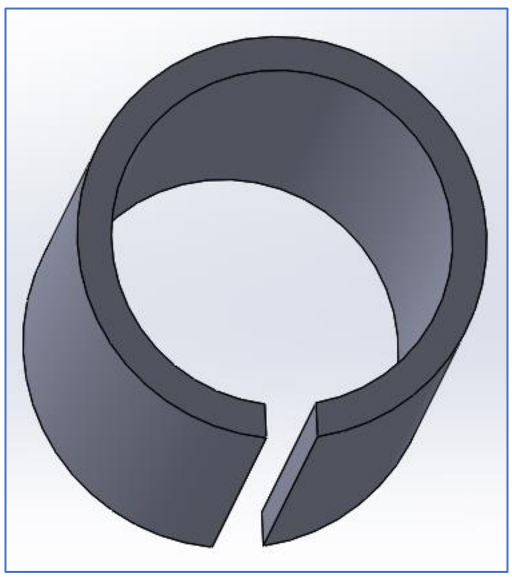


Figure 2: PLA ring to temporarily cover exposed copper bus.

While much of the copper bus in the module is covered with insulation to prevent electrocution, small portions must stay uncovered so banks may contact the buses themselves. This can potentially pose great risk, as all four battery banks must slide along multiple pieces of exposed copper to slide onto the module, which could result in unwanted conduction of electricity. A necessary solution was a temporary cover for these small portions of copper, that could be easily added and removed as needed. The chosen design was a PLA ring, shown in **Figure 2** which can easily clamp on and off the bus. Future testing will be needed in order to determine a potential redesign of shape or size.

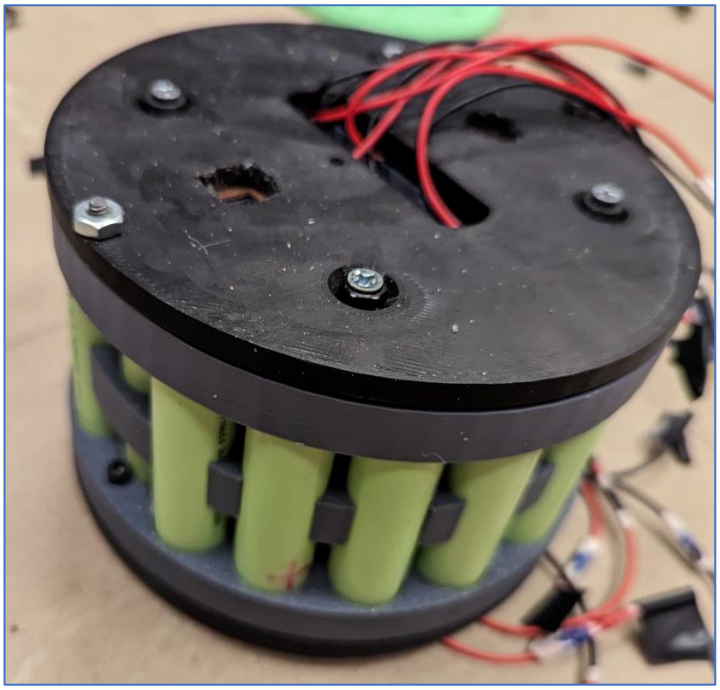


Figure 3: Newly Constructed Battery Bank

Thanks to the alterations made to the battery bank design this semester, Icebreakers were able to efficiently and safely construct a new battery bank which successfully outputted 28.96 V. These changes can be seen in Figure 3 - the screw holes for tabs are no longer through holes, and as such are no longer accessible from outside the bank. This initially provided some difficulties in debugging, as the team could no longer directly access tabs to determine if they were conducting power while the bank was constructed. However, the bank was still easy to debug using color coded wires initially intended to connect to PCBs. Those wires could be used to determine if power flowed across an individual battery or across a copper insert. These debugging tips along with a swath of details regarding the bank construction process were included in a comprehensive battery bank construction guide, which will help to ensure that banks can be constructed safely and efficiently by anyone of any background in the future.

Figure 4: New Tab design with hole installed

Previous teams chose to construct banks using tabs which were affixed into plastic shells as a part of a battery construction kit. During a discussion with Nate Inman, a previous team member, Icebreakers learned that previous teams expressed a degree of frustration regarding these tabs, and requested that Icebreakers find a superior model of tabs to use in the final Nekton bank design. It was requested that a new tab design be cost effective and easily constructed or obtained. The solution Icebreakers came to was constructing new tabs by ordering a set of flat contact and spring contact tabs, installing holes in either end, and using external screws to affix them to the copper inserts. Since many previous tabs remained outside of their plastic shells, there was no need to construct new tabs this semester. As such, new tabs have been obtained, but only one flat contact new tab has been constructed. It is hoped that new teams can use this as a model to create more new tabs if they desire to use them over the old tab design.

Thruster Module

Previous teams utilized 3D printing for prototyping the thruster mount as well as the thruster modules as seen in **Figure 3**. These prototypes allowed for better visualization of the final size of the thruster module while also helping to develop an understanding of parts will with together within the module. While this prototype helped with general understanding, it also demonstrated how this design will not work for the fabrication of aluminum. Primarily, the 3D printing allowable fabrication volume was constrained by the size of the build plate. Since the total length of the chassis was 180mm, the chassis had to be split into two pieces and held together by snap fit. This posed two practical challenges. Primarily, the snap fit connection to hold the two pieces together could not be machined due to its complex geometry. Additionally, the connection would experience elevated stress concentrations when the vehicle experiences tensile loading, making it much more feasible to manufacture the tube as one piece. The main issue surrounding the thruster mount was the curved body that implemented numerous complex splines. This type of curved surface is difficult to machine, and it also creates a very thin, sharp edge that could easily fall victim to chips and bending. The use of prototyping using a relatively cheap option allowed for these flaws in the designs to be found and adjusted before fabricating with aluminum, as a mistake in that process would be more costly.

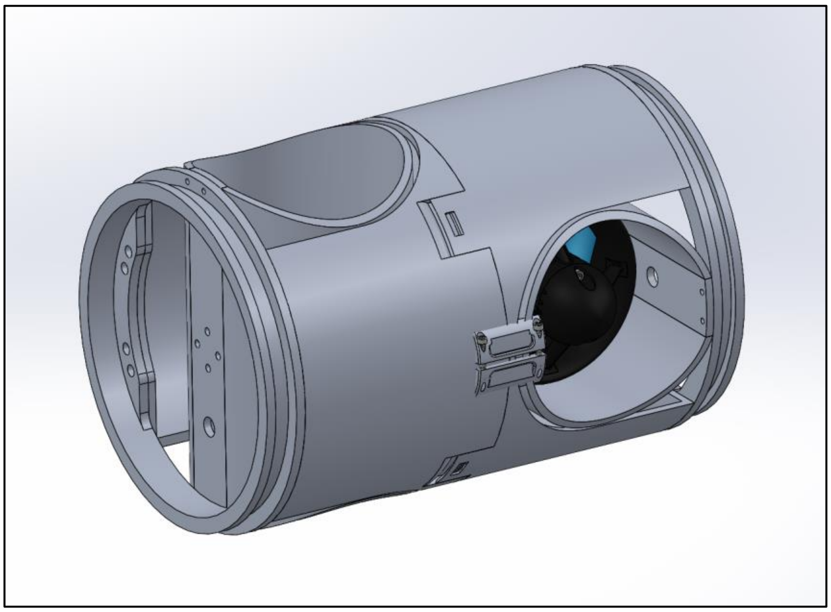


Figure 3: Initial thruster module design for 3D printing.

The final design iteration is shown in **Figure 4.** This design has several features that this team has determined will meet the engineering requirements previously discussed. Primarily, having the chassis made from a single circular tube will make the part easier to machine and will avoid any stress concentrations that arise with connecting mechanisms. Additionally, it can be machined in the Montgomery Machining Mall out of aluminum stock, as complex geometry is avoided.

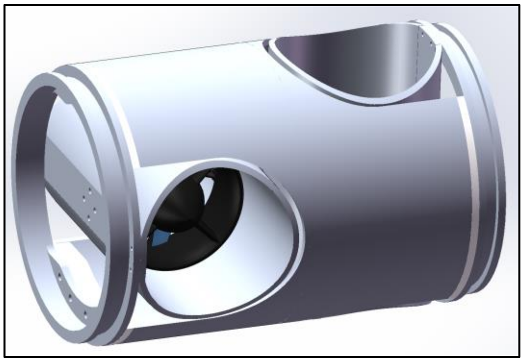


Figure 4: Thruster module designed for modularity and machinability

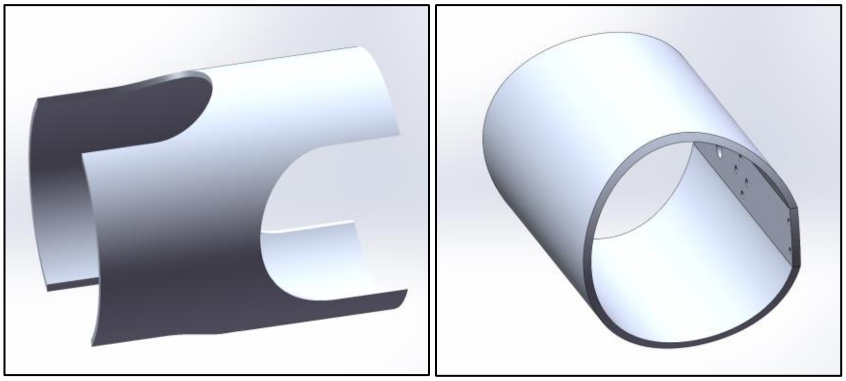


Figure 5a (left), 5b (right): Chassis and thruster housing machined with aluminum stock.

The modular aspect of this design is preserved by the flanges at the end of the thruster module that can interface with the lock-ring clamps shown in **Figure 6**. This feature will allow for greater adaptability if many of these vehicles are to be manufactured in the future or if the thruster module needs to be replaced quickly during the mission.

Figure 6: Two of the above lock rings bolt together to hold modules in place.

6. Prototyping

Coordination with the Montgomery Machining Mall allowed this team to prototype the two thruster modules within 2.5 weeks. The individual fabricated parts are shown below in **Figure 7**.

Figure 7: Individual fabricated components for thruster module.

The housing pieces were cut through wire edm to achieve their flat profile to interface with the T-200 thruster. The individual pieces were assembled to make the thruster assembly pictured below in **Figure 8**.

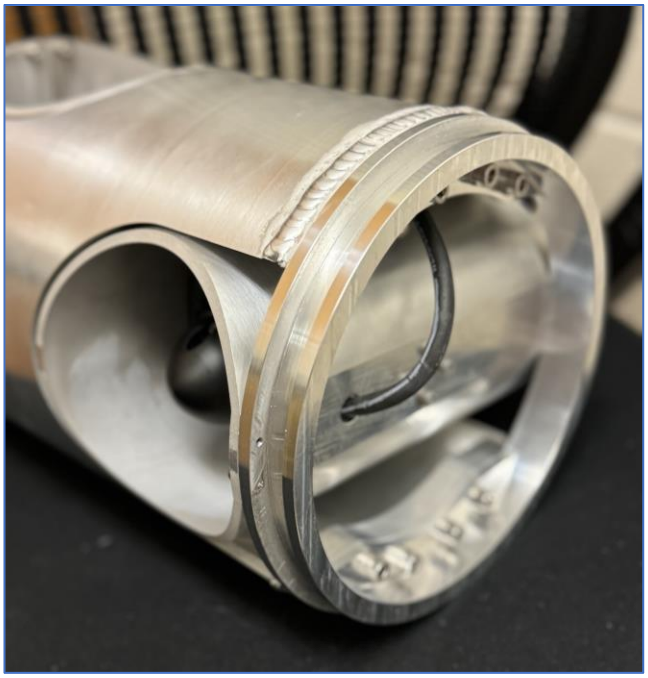


Figure 8: Assembled thruster module.

The tabs were welded onto the chassis, and the ring was bolted into the tabs to allow the thruster module to connect with the rest of the vehicle through lock rings manufactured by a previous team. The thruster housing is screwed into the ring but sanded off to avoid interference with the clamp mechanism between the thruster module ring and the already manufactured lock rings.

7. Testing and Validation

Upon completion of thruster module fabrication, this team will test both the strength of the module and its ability to provide thrust. This will first be done using Finite Element Analysis (FEA) within Solidworks to ensure even at the worst-case scenarios, where the stress concentrations are the highest, the design will not yield to the loads it will experience during underwater operation. Emphasis will be placed on the bolted joints and clamped connections between modules to ensure the thruster module doesn't detach from the rest of the vehicle during operation. This team will carefully analyze the FEA results and compare to the manufacturers provided material properties to ensure a sufficient factor of safety is maintained within the mechanical design.

After the FEA is performed, it is important to ensure the module can provide sufficient thrust to control the orientation of the vehicle. It is already known from the technical specifications [4] that the T-200 Blue Robotics thrusters provide greater thrust in the reverse direction than the forward direction. This makes it imperative to test the modules to ensure orientation control can be achieved in both directions, and which directional orientation best enables that. The testing to achieve that will be performed by submerging the thruster module attached to the tail cone in a water tank and testing the orientation control, as diagrammed below in **Figure 9**.

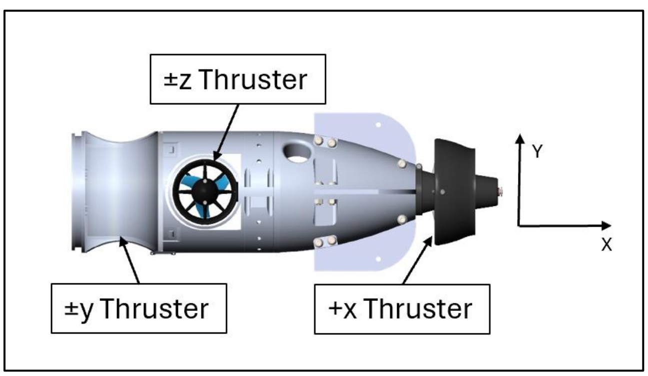


Figure 9: Thruster and tail cone combined assembly for orientation control testing.

Each of the thrusters will be connected to power supply, a Teensy 4.1, and a basic ESC to ensure motor control can be achieved with a varying PWM voltage signal. The acceptance criteria for the electromechanical assembly are outlined below in **Table 4-1**, and are subject to change as new engineering requirements are discovered. Each criterion is pass/fail and will be assigned a weight from 1-5 based on its importance to the vehicle's operation ability.

Table 4-1: Combined thruster and tail cone assembly for thrust control testing.

Criterion	Description	Weight
1	Thrusters turn on and can spin with PWM input	5
2	Tail cone thruster can provide movement in the x axis.	5
3	±z Thruster can provide 360 degrees of articulation about the y axis.	4
4	±y Thruster can provide 360 degrees of articulation about the z axis.	3
5	Thrusters can communicate to move forward while turning and maintaining the same position about the y axis.	4

To test the ability of the thrusters to change speed and spin direction, a subassembly of nekton was created that consisted of the two thruster modules as well as the nose and tail cone as see in **Figure 10.**

Figure 10: Subassembly used to test thrusters and how they respond to different PWM inputs.

Initially, the thrusters were tested using a potentiometer wired to a Teensy that adjusted the PWM input as see in **Figure 11.** This setup would run all thrusters at the same speed and in the same direction with no variations between them.

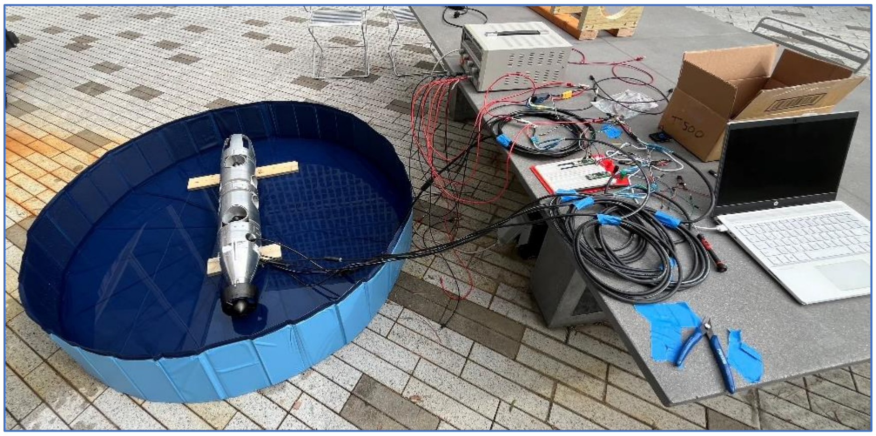


Figure 11: Initial testing set up used for proof of concept and to ensure that all connections worked properly, and thrusters preformed as expected.

To introduce more control to the system using an XBOX controller, an Nvidia Orin was used along with microROS and a Teensy allowing said controller to adjust speed and spin direction of the vertical and horizontal thruster sets individually. This application allows for more variation which in turn would lead to an operator having the ability to orient Nekton however they please. The setup used for this application can be seen in **Figure 12.**

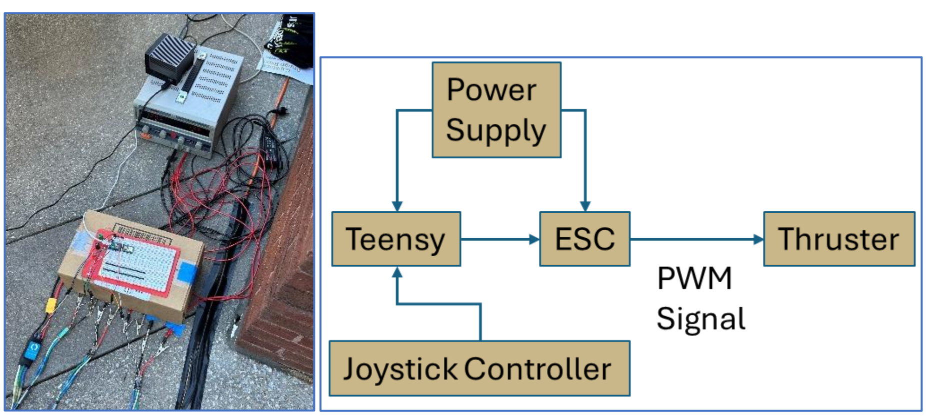


Figure 12: Setup used to control the thrusters allowing for direction and speed adjustments.

The primary aim of this test setup was to mobilize thruster testing. Completion of the battery and electronics module to the point where they can be attached to the already completed modules of the vehicle could take substantial time; however, it is imperative that Dr. West and future Capstone teams are still able to test the thrusters and gather data during this time. This testing rig will allow for the thrusters to be tested without the battery and electronics module being completed. Because the user receives visual feedback on how the thrusters move, this test rig can not only test for basic movements like forward or turning but also more advanced protocols such as autonomous orientation control or obstacle avoidance. The currently hollow nose cone module allows for sensors to be attached as a future application of this testing rig.

After the new battery bank was constructed, it was tested to validate that it was able to consistently output 28.96 V while maintaining an acceptable level of current. Now that this bank has been validated, the other banks will need to be fabricated and then tested, first individually and then inside the enclosure itself. This latter test will allow future teams to ensure that the wiring from the batteries to the endcaps will successfully transfer requisite power from the battery module to other modules of Nekton.

8. Controls Theory

The first step towards designing an adequate motion controller involves acquiring a model of Nekton's assembly. Using Fossen's Handbook of Marine Craft Hydrodynamics and Motion Control [1], the following general model was used to describe Nekton's kinetics:

$$\boldsymbol{M}\dot{\boldsymbol{\nu}}_r + \boldsymbol{C}(\boldsymbol{\nu}_r)\boldsymbol{\nu}_r + \boldsymbol{D}(\boldsymbol{\nu}_r)\boldsymbol{\nu}_r + \boldsymbol{g}(\boldsymbol{\eta}) + \boldsymbol{g}_o = \boldsymbol{\tau} + \boldsymbol{\tau}_{\text{wind}} + \boldsymbol{\tau}_{\text{wave}} \quad (6.4)$$

where

$\boldsymbol{M} = \boldsymbol{M}_{RB} + \boldsymbol{M}_A$ - system inertia matrix (including added mass)
$\boldsymbol{C}(\boldsymbol{\nu}_r) = \boldsymbol{C}_{RB}(\boldsymbol{\nu}_r) + \boldsymbol{C}_A(\boldsymbol{\nu}_r)$ - Coriolis–centripetal matrix (including added mass)
$\boldsymbol{D}(\boldsymbol{\nu}_r)$ - damping matrix
$\boldsymbol{g}(\boldsymbol{\eta})$ - vector of gravitational/buoyancy forces and moments
$\boldsymbol{g}_o$ - vector used for pretrimming (ballast control)
$\boldsymbol{\tau}$ - vector of control inputs
$\boldsymbol{\tau}_{\text{wind}}$ - vector of wind forces
$\boldsymbol{\tau}_{\text{wave}}$ - vector of wave-induced forces

From Equation 6.4, the vector of wind and wave-induced forces were assumed negligible since Nekton will be moving under static water underneath ice. The Coriolis-centripetal matrices are also assumed to be negligible, since the Coriolis forces on an object travelling in the low Reynold's regime are near zero. Hence, Equation 6.4 reduces to:

$$M\dot{\boldsymbol{\nu}}_r + D(\boldsymbol{\nu}_r)\boldsymbol{\nu}_r + g(\eta) = \tau$$

where

$$\boldsymbol{\nu}_r = (\boldsymbol{u}, \boldsymbol{v}, \boldsymbol{w}, \boldsymbol{p}, \boldsymbol{q}, \boldsymbol{r})'$$

$\boldsymbol{\nu}_r$ is the relative velocity of Nekton, with *u*,*v*,*w* representing the linear speeds in the *x*,*y*,*z* directions respectively, and *p*,*q*,*r* representing the pitch, yaw, and roll respectively._This approach to modelling the kinetics of this hydrodynamic system was confirmed by Dr. Alexander Alexeev, a researcher of fluid mechanics at Georgia Tech, and by Dr. Ellen Mazumdar, a researcher in the field of control design at Georgia Tech.

System Inertia Matrix *M* [1]

Nekton's inertia tensor is determined from the CAD model as:

$$I_b = \begin{bmatrix} I_{xx} & I_{xy} & I_{xz} \\ I_{yx} & I_{yy} & I_{yz} \\ I_{zx} & I_{zy} & I_{zz} \end{bmatrix} = \begin{bmatrix} 254.8 & 7.1 & 29.79 \\ 7.1 & 239.06 & 40.05 \\ 29.79 & 40.05 & 60.61 \end{bmatrix} kg * m^2$$

By assuming Nekton is a cylinder and manually calculating the moment of inertia using commonly found formulas for cylinder moments, the inertia tensor above was verified.

The static system inertia matrix M_{RB} is calculated using:

$$M_{RB} = \begin{bmatrix} mI & -mS(r_g) \\ mS(r_g) & I_b \end{bmatrix}$$

where I is the 3x3 identity matrix, and $S(r_g)$ represents the skew symmetric matrix of the location of center of gravity (CG) to the center of rotation (CO). Based on the Nekton assembly CAD model, the mass of Nekton was deemed as 130kg, and the vector $r_g = [0\ 0\ 0]'$. This results in the system inertia matrix of:

```
MRB =

  174.0400         0         0         0         0         0
         0  174.0400         0         0         0         0
         0         0  174.0400         0         0         0
         0         0         0  254.8000    7.1000   29.7900
         0         0         0    7.1000  239.0600   40.0500
         0         0         0   29.7900   40.0500   60.6100
```

Due to hydrodynamic motion, Nekton experiences added mass, which is assumed to be linear and determinable using hydrodynamics derivatives. Using the process outlined in [2], the following added mass matrix was derived:

```
Ma =

    1.2116         0         0         0         0         0
         0    7.4356         0         0         0         0
         0         0    7.4356         0    0.2777         0
         0         0         0         0         0         0
         0         0    0.2777         0   -0.9964         0
         0         0         0         0         0   -0.9964
```

By summing the static system inertia matrix to the added mass matrix, the overall system inertia matrix is determined:

```
M =

  175.2516         0         0         0         0         0
         0  181.4756         0         0         0         0
         0         0  181.4756         0    0.2777         0
         0         0         0  254.8000    7.1000   29.7900
         0         0    0.2777    7.1000  238.0636   40.0500
         0         0         0   29.7900   40.0500   59.6136
```

Damping Matrix $D(\boldsymbol{\nu}_r)$ [1]

A complete drag matrix is a function of the relative velocity of Nekton. However, this is very difficult to precisely calculate, since acquiring hydrodynamic derivatives of velocity which the drag equation is based on is a computationally expensive process, involving a full simulation of Nekton's environment. However, there are empirical estimates of the hydrodynamic derivatives that dictate the drag matrix, as shown in [3].

From these estimates, the following drag equation is calculated:

```
Dv =

         0         0         0         0         0         0
         0    0.0544         0         0         0   -0.0015
         0         0    0.0131         0    0.0016         0
         0    0.0059         0         0         0    0.0004
         0         0    0.0030         0    0.0003         0
         0    0.0070         0         0         0    0.0010
```

Gravitational/Buoyancy Vector [1]

To calculate the buoyancy/gravity restoring forces, the location $\boldsymbol{r_g}$ of the center of gravity (CG) with respect to the center of rotation (CO), and the location $\boldsymbol{r_b}$ of the center of buoyancy (CB) with respect to the CO, are measured:

$$\boldsymbol{r_g} = \boldsymbol{0}, \qquad \boldsymbol{r_v} = \begin{pmatrix} \boldsymbol{0} \\ \boldsymbol{0} \\ \boldsymbol{-0.012954} \end{pmatrix} \boldsymbol{m}$$

For the roll $\boldsymbol{\phi}$, pitch θ, weight W, and buoyancy force B, the gravitational forces are determined as follows:

$$g(\eta) = \begin{bmatrix} (W-B)sin\theta \\ -(W-B)cos\theta sin\phi \\ -(W-B)cos\theta cos\phi \\ -(r_{g,y}W - r_{b,y}B)cos\theta cos\phi + (r_{g,z}W - r_{b,z}B)cos\theta sin\phi \\ (r_{g,z}W - r_{b,z}B)sin\theta + (r_{g,x}W - r_{b,x}B)cos\theta cos\phi \\ -\left(r_{g,x}W - r_{b,x}B\right)cos\theta sin\phi - (r_{g,y}W - r_{b,y}B)sin\theta \end{bmatrix}$$

In the case of Nekton, the buoyancy and weight forces are equal with magnitudes of the mass of Nekton (130kg) times the gravitational constant 9.81 m/s^2, hence the first three values of the gravitational vector are 0.

Note about Theoretical Model

It’s very important to note, however, that while this is a very sophisticated model, it is still purely theoretical, and does not account for any extra effects and errors that are always present in real systems. Further experimental analysis will need to be completed once Nekton is fully assembled to confirm or tweak these values. A simple test of thrust in one direction or one degree of freedom will reveal how accurate each of the terms in each matrix are.

9. Mockup and Prototyping

The team was able to make significant progress in mockup and prototyping of the project, especially regarding the battery module. The battery module team was able to fabricate a functional battery bank that outputs 30V. The battery bank was constructed with new components such as the screw standoffs and new battery connector plates as safety improvements. As the original design calls for more expensive material such as Delrin and aluminum, the team this year opted to go for 3D printed parts instead for a mockup design. Advantages include cost efficiency during testing, and we were able to allocate more of our budget towards the thruster module team as they already had a validated final design ready to be machined.

The main purpose of the battery bank protype was to ensure the battery bank design can still be modified in case of design changes needed. For example, all the battery bank shells were 3D printed, and as such the tolerance can be changed easily and reprinted again if necessary. The decision to use 3D print instead of machining with Delrin was also due to time constraints and inability to change the design once made in Delrin. Now that the prototype has been completed, all the final 3D printed parts turned out well and were able to serve their purpose of improving safety of the battery bank design. The standoffs were able to prevent screws from scratching surface of battery and shorting batteries and was able to hold the weight of the bank when paired with heat set insert threads. The new battery connector plate was able to prevent tabs from coming in direct contact with the users, and although tab installation process was slightly harder due to hole depth sizing, future solutions of adding screws for the tabs can reduce this issue.

10. Team Member Contributions

Gabriel developed the battery module testing plan, battery module design details, and description of future work as seen in this document. He also contributed the bill of materials section.

Colin developed the summary and future work for the thruster, design details for the thruster module, and the overall organization of the report.

Patrick worked on mockup and prototyping section of battery module and added onto other relevant sections of the battery module such as summary & future work.

Ajay worked on the overall organization of the report, design details for the thruster module, and the testing and validation sections.

Rohan worked on the control theory for orientation control and the overall organization of the report.

11. Bill of Materials

Material Ordered	**Module**
6061 Aluminum Round Bar (Width 7.5 Inches, Length 24 Inches) (x1)	Thruster
6061 Aluminum Round Bar (Width 4.5 Inches, Length 36 Inches) (x1)	Thruster
6061 Aluminum Round Bar (Width 4 Inches, Length 6 Inches) (x1)	Thruster
Teensy 4.1 Microcontroller boards and pins (x4)	Thruster
6in/8in ID/OD 3in length Aluminum Tube (x3)	Thruster
Pairs of Electrically Insulative Gloves (x2)	Battery
Battery Contacts (Spring) (x50)	Battery
Battery Contacts (Solid) (x50)	Battery
#6-32 Threaded Heat Set Inserts (2 packs of 50)	Battery
6951 Flat Head Phillips Machine Screw, 6-32 x 1-1/2-Inch, 10-Pack	Battery
#6-32 x 1/4in Flat Head Screw (2 packs of 50)	Battery
0.3" by 0.3" by 6ft 6061 aluminum for support rods	Battery
High-Temperature PUR Subsea Cable, T500 Thruster Cable (3 conductors, 12 AWG), 3 meters in length	Thruster
High-Temperature PUR Subsea Cable, T200 Thruster Cable (3 conductors, 16 AWG), 3 meters in length	Thruster
6061 Aluminum Round tube (length 3 inches, 6/8 in ID/OD)	Thruster
Large rubber bands (100-pack)	Thruster
Collapsable swimming pool	Thruster
Game Controller for demo	Thruster

12. Summary & Future Work

Icebreakers have successfully improved upon the battery module designs set forward by previous semesters, thanks to the guidance of previous teams that worked on the project. A new bank has been constructed and validated to output ~30 V, and the improved standoffs and insert holders have made the process of bank construction far safer and less accident prone. A comprehensive guide on battery bank construction has been created to ensure that future teams will be able to create battery banks with far greater efficiency and far reduced need to collaborate with previous team members. The final design of the battery module requires three more battery banks to be constructed using the new assembly guide; this will either require ordering more battery tabs from the old design, or creating new tabs as detailed in this document. Then, all four battery banks will need to be affixed to PCBs. Our team currently has two working PCBs, meaning at least two more need to be ordered. The aluminum structure will need to be resized to allow the battery banks to slide onto them; the material for this has been obtained and simply needs to be cut and wrapped in electrical tape. The design of the PLA copper bus cover will need to be tested and perfected to ensure the risk of a short circuit during assembly is minimized. Connection will need to be established with the subconn high power four contacts connector, which will allow power to be delivered from the banks to the rest of Nekton. Finally, an aluminum enclosure to hold the battery module will need to be constructed.

Progress on the thruster module has gone smoothly with an easy transition of information between previous teams and Ice Breakers. Designs were discussed and finalized with Dr. West and those who would be fabricating the parts to ensure the design met the proper criteria, and no issues would arise. Fabrication was completed and steps were taken to ensure a high quality product, including sanding excess welds and adding rubber shims between clamping connections. Additionally, the Ice Breakers designed a custom testing rig and successfully integrated MicroROS to allow for xbox joystick controlled pwm testing. We are confident the Ice Breakers work throughout this semester will but future teams in a position for progress and success over the next few semesters.

13. References/Citations

[1] Fossen, T. I. (2011). Handbook of Marine Craft Hydrodynamics and Motion Control. John Wiley & Sons Ltd.

[2] Triantafyllou, M. S. and Amzallag, A. M. (1984). A New Generation Of Underwater Unmanned Tethered Vehicles Carrying Heavy Equipment At Large Depths.

[3] Mai, T. L., Jeon, M., Vo, A. K., Yoon, H. K., Kim, S., & Lee, J. (2023). Establishment of empirical formulae for hydrodynamic derivatives of submarine considering design parameters. International Journal of Naval Architecture and Ocean Engineering, 15(100537). https://doi.org/10.1016/j.ijnaoe.2023.100537