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Diver Propulsion Wearable

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Diver Propulsion Wearable

The goal of this project was to create a device that allows a diver to maneuver underwater while leaving their hands free to perform other tasks. The project was proposed by Jin Hwan An, a student at the Olin Business School who has an interest in diving and has experience with other diver propulsion vehicles. After a brief interview with the customer, several important requirements were identified: the device must be extremely safe, the battery must last for an appropriate duration, the user must be able to operate the device hands-free, and the device must protect the user (a possible novice diver) from the bends by taking ascent speed into account. A very rudimentary mockup was created to help us visualize the end-product and several different concepts were explored. The selected concept was a tank-mounted device with a single propeller that is controlled by a corded control interface strapped to the diver’s wrist. An important safety feature in this concept was the ability to completely remove the device in a short period of time. Before beginning construction, several parts of this design had to be tested. Proofs-of-concept were created for the release mechanism, the tank holding system, and the motor control wiring. Based on these proofs of concepts, several changes were made to the design and the first prototype was constructed.

The performance goals decided on for this initial prototype were: varying speed control, a maximum ascent speed, and a maximum time of removal of 7 seconds. The first prototype addressed these by using a dial and button to precisely control speed, an accelerometer to measure the ascent angle and limit the motor speed accordingly, and a pin-and-hinge mechanism for quick removal of the device. All three goals were passed, including a removal time of 3.91 seconds. This design was then refined to be better manufacturable and accessible. The wrist control device was altered to be easier to waterproof and usable with large gloves, and a propeller housing was added to make the device safer. The main task going forward is to fully waterproof the device to be able to test it in a pool.
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1 Introduction

This project was proposed by Jin Hwan (Josh) An, a current undergraduate student in the Olin Business School at Washington University in St Louis. Given his interest in diving and his experience with current diver propulsion vehicles, Josh has challenged us to design a hands-free diver propulsion wearable (DPW). While Josh has left the project rather open-ended for the engineers, the main challenge is to create a design that can propel the diver using a hands-free control system. Having a hands-free controller will allow the user to engage in other tasks while gliding underwater. Ideally, this design would be useful for both leisure and military scuba divers, with leisure scuba divers being the main focus. As such, the design must be compatible with a scuba tank. While diver propulsion technology already exists, most of the current designs either require the system to be controlled with both hands or are well outside the price range for a leisure diver. While the design priorities are safety and hands-free control, additional goals are to ensure a long battery life, allow precise speed control, and have a design compatible with a variety of different sized oxygen tanks.

2 Problem Understanding

2.1 Existing Devices

There are several different diver propulsion systems currently available across the military and commercial sectors. We have been able to examine each of these concepts to identify how different components can be modified to fit the requirements of this project.

2.1.1 Existing Device #1: x2 Sport Underwater Jetpack

![x2 Sport Underwater Jetpack](http://www.supermarinovation.com)

**Link:** [http://www.supermarinovation.com](http://www.supermarinovation.com)

**Description:** Offering the ability to “unleash your inner superhero,” the X2 underwater jetpack features two, 1.8 kW (2.4 horsepower) waterproof brushless motors attached to the user’s forearms with an attached backpack containing an integrated control system and the batteries. By using an analog trigger located on the handheld throttle, the X2 enables the user to fly through water at a range of speeds (up to 6 mph) in whatever direction they can point. However, while the X2 invites the opportunity to glide underwater like Aquaman, the substantial price of about $2500, the lack of an included oxygen tank, and a max depth of 30 feet limits its applications for divers. [1]
2.1.2 Existing Device #2: Cuda Underwater Jetpack

![Figure 2: Cuda, the 3D printed underwater jetpack](image)

Link: [https://www.cudajet.com/](https://www.cudajet.com/)

Description: The Cuda underwater jetpack was designed as a low-cost alternative to underwater scooters, the current standard for consumer diver propulsion vehicles. Notably, the Cuda features 45 3D printed parts including a metal-turned driveshaft and a CNC-milled heatsink. Despite having a non-trivial amount of components, the Cuda boasts an estimated assembly time of only 10 minutes. The 3D printed jetpack’s speed is controlled by a hand-held remote, and direction for the back-mounted jetpack is determined by where the user’s shoulders are pointing. Similar to other underwater jetpack designs, the Cuda offers the capability to effortlessly glide underwater. But the Cuda is limited to shallower waters since an oxygen tank is not included for deeper diving. [2]
2.1.3 Existing Device #3: P3M Jetboots

Figure 3: P3M Jetboots

Link: http://www.patriot3.com/maritimeproducts/p3m_jetboots/

Description: Advertised primarily for military use and backed by the US Department of Defense, the P3M Jetboots enable quick aquatic movement while remaining hands-free in case of a combat situation. The rugged design made of waterproof aluminum features two thrusters powered by waterproof brushless motors strapped to the user’s thighs and a control box located at the hip. Featuring batteries that are hot-swappable underwater and rated for ocean depths of 300 ft and altitudes of 37,000 feet, the P3M Jetboots are made for almost any environment. However, coming in at a steep price of $34,000 and not featuring an included oxygen tank, the P3M Jetboots are more reserved for the Navy SEALs than the typical consumer. [3]
2.2 Patents

2.2.1 Underwater personal propulsion device
(US20110174209A1)

This device is designed to allow a diver to work underwater completely hands-free. It attaches primarily to the legs through a brace or pad that connects at about knee level. The primary point of contact with the diver is through a pair of footrests. It also attaches through cables or bungee cords connected to the diver’s waist belt. The propulsion is delivered through a “shrouded impeller.” The motor is “preferably” electric and a battery would also be encased in the housing. The motor is controlled by the diver either through a foot control on the footrest or a controller on the belt. The inventor is open to other propulsion methods such as compressed air or a pump. [4]

Figure 4: Image of diver using personal propulsion device to work hands-free
2.2.2 Personal Dive Device with Electronic Speed Control (US20090249991A1)

This device has a body that includes a power source, a rotary device, and a controller. A propeller assembly is attached to a brushless motor, which will engage when prompted by the controller, which in turn is activated by a trigger mechanism. The power source is stated to be equal to about 37 volts. The propeller will be a fixed-pitch prop that is better for reducing vibrations and increasing durability. This device is designed to be operable with a single hand. The inventor states that though other handle arrangements are possible, it is preferable to use handle arrangements that are conducive to single-hand operation. This is an example of the conventional underwater scooter that will be improved by our design. [5]
Figure 6: Side view of personal dive device with electronic speed control showing housing and propeller case.

Figure 7: Detail view of rigid propeller and electric motor of personal dive device with electronic speed controller.
2.3 Codes & Standards

2.3.1 U.S. Department of the Interior Bureau of Reclamation 10-1.4

This standard specifically addresses weight belts and harnesses for divers. It states that this type of equipment should be capable of quick-release. Weights that are integrated into the diver’s suit are also discouraged. The spirit of this standard is understood as an emphasis on being able to quickly release weight that might be keeping the diver from surfacing. This standard applies to this design because the batteries powering the device will be heavy, and may even partially replace diving weights. The alteration dictated by this standard is the inclusion of a battery pack that can easily be detached with a simple action taken by the diver. However, care must be taken to ensure that the battery never detaches accidentally. [6]

2.3.2 Hazards of Rotating Propeller and Helicopter Rotor Blades (AC 91-42D)

This standard by US DoT Federal Aviation Administration is a briefing on the statistics of propeller-related injuries and fatalities. The standard highlights that moving propellers are dangerous in and of themselves due to the large amount of force generated from the motor even at slow speeds. More significantly, the standard notes that the risk is significantly higher amongst the “nonprofessional public.” Even though this standard is primarily intended for aircraft, it is relevant to our project as our design is aimed at leisurely divers who will be keeping this device in their home. While safety is always the most important aspect to an engineering design, this standard specifically makes us focus on designing our product to ensure that the propeller is safely covered from any potential interaction with the user. [7]

2.4 User Needs

Josh An, a business student at Washington University in St. Louis, had the idea for this project. He was inspired after watching the movie Aquaman. He is also on track to become a professional diver and has a good amount of experience in the sport. His goals for the project are eventually to manufacture and sell the device.

2.4.1 Customer Interview

Location: Louderman 458, Washington University in St. Louis, Danforth Campus
Date: September 6th, 2019
Setting: Josh An arrived in the lecture hall. Three total groups were present in the first two rows. Josh gave a short presentation that included his background, current products, and his goals for the product. After the presentation, clarifying questions were asked and the answers were both transcribed and recorded. The whole interview was conducted in the lecture hall, and took ~40 min.

When not in the water, do you have any requirements about weight or portability?
- The lighter, the better. But keep in mind that once in the water, it’s a zero gravity situation.

Should we expect a single tank or double?
- I’m not very concerned about double tanks. One is the standard. One tank lasts about 45 minutes to an hour.
What is the maximum depth you would want to bring this?
- I’m primarily focused on leisure divers, so 40 meters.

Are there buoyancy compensator compatibility issues? Should it be integrated?
- Completely up to you, but I don’t think you need it. I want to just be able to take it off. The more modular it is, the better.

How long should the battery last?
- Yeah, about 1 hour and a half, two hours. People have extra power just in case.

What safety considerations should be taken into account?
- Traveling on an X-Y plane, its perfectly fine. But going up and down is a little tricky. When coming up, there’s a speed limit. I’m pretty sure its about 5 meters per minute. Its for safety... ...If you come up fast, it will pop your artery. This is also a problem in leisure diving. It hurts. It’s very serious and can kill you.

Is there a top speed for this that you want?
- I forgot what the spec was for the other DPW, but I wouldn’t put any limit on it. It’s to increase the range, so faster than we can swim hopefully. The swimming speed on top of water and under water is completely different.

Do you have any preference for noise?
- Less noise the better. I don’t know the spec for the actual DPV stuff, but let’s not annoy the natives and fish.

What do you not like about similar products?
- I’ve used a DPV before. Its fun when you don’t think about it, but sometimes it gets boring and I don’t want to hold on to this for an hour.

How far out can this device extend from the diver?
- I think smaller is better, but I was thinking about more the size of [my very large backpack]. If it has a wing, that’s a little tricky because the weight shifts and it can get caught in a weird current.

Would you prefer it be attached to the back, or some other place?
- Please explore other avenues too. The only stuff that I know is on the back. I got inspired by Aquaman, so I think that if stuff were in the back that would be pretty cool.

Would you want this to be able to push you forward only, or would also want this device to be able to turn?
- I was thinking that twisting your body should be able to turn you. If you make a turn, it should make a turn. *Later conversation decided that your body should control the direction of movement if you are just pushing forward.

To what extent should this device be hands-free?
- I wish to be hands free, but if you need a controller it should be similar to the computer on the wrist that all divers have. It says how deep you are, your speed traveling up and down, and if you are going too fast it’s red. Software is somewhere else, not you guys.
If it weren’t integrated into the computer on your wrist but instead you had a separate wristband, would that be fine?

– Why not?

Is there any budget or price ceiling you have in mind?

– I wouldn’t be too concerned with a budget for now, but if you make something and I can look at it, I would like to see if there are any areas where I can cut the budget down a little bit. That will be my exercise as a project manager.

Would it be fine for this to attach to the tank?

– [paraphrased] This would be fine, because I am only worried about the single tank situation. I had in mind something that would actually connect underneath the oxygen tank.

2.4.2 Interpreted User Needs

After interviewing the customer and discussing the primary goals for the project, the following table was created. It lists the many user needs for the design as well as quantifies each need’s importance. The most important needs have a score of five, while the less important have a score of one. The relative scores were decided based on the customer’s recommendations as well as the codes and standards for propeller and diving safety.

Table 1: Interpreted Customer Needs

<table>
<thead>
<tr>
<th>Need Number</th>
<th>Need</th>
<th>Importance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Caged and highly visible propeller</td>
<td>5</td>
</tr>
<tr>
<td>2</td>
<td>Battery must last for 1.5 hours</td>
<td>4</td>
</tr>
<tr>
<td>3</td>
<td>The DPW must be hands free</td>
<td>5</td>
</tr>
<tr>
<td>4</td>
<td>Different travel and ascent speeds</td>
<td>4</td>
</tr>
<tr>
<td>5</td>
<td>Maintain small size</td>
<td>2</td>
</tr>
<tr>
<td>6</td>
<td>Low noise level</td>
<td>1</td>
</tr>
<tr>
<td>7</td>
<td>The DPW must be compatible with an oxygen tank</td>
<td>4</td>
</tr>
<tr>
<td>8</td>
<td>The DPW must be faster than a swimmer</td>
<td>3</td>
</tr>
<tr>
<td>9</td>
<td>Batteries and other heavy weights can be removed quickly</td>
<td>4</td>
</tr>
<tr>
<td>10</td>
<td>DPV must be able to sustain pressures up to 40m underwater</td>
<td>2</td>
</tr>
</tbody>
</table>
2.5 Design Metrics

Based on the interpreted user needs we identified, we compiled a table with specific design metrics to meet the needs. We attempted to quantify the acceptable and ideal specifications for each associated need.

<table>
<thead>
<tr>
<th>Metric Number</th>
<th>Associated Needs</th>
<th>Metric</th>
<th>Units</th>
<th>Acceptable</th>
<th>Ideal</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>Opening size in propeller cage, Standard 2.5.2</td>
<td>cm</td>
<td>&lt; 3</td>
<td>&lt; 2</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>Total time at optimal thrust</td>
<td>hr</td>
<td>&gt; 1</td>
<td>&gt; 1.5</td>
</tr>
<tr>
<td>3</td>
<td>8</td>
<td>Power when traveling on flat plane</td>
<td>Watts</td>
<td>&gt; 500</td>
<td>&gt; 1000</td>
</tr>
<tr>
<td>4</td>
<td>5</td>
<td>Width of device</td>
<td>cm</td>
<td>&lt; 50</td>
<td>&lt; 33</td>
</tr>
<tr>
<td>5</td>
<td>9</td>
<td>Time to release batteries, Standard 2.5.1</td>
<td>Seconds</td>
<td>&lt; 5</td>
<td>&lt; 1</td>
</tr>
<tr>
<td>6</td>
<td>6</td>
<td>Motor noise as measured from diver’s ear</td>
<td>dB</td>
<td>&lt; 70</td>
<td>&lt; 40</td>
</tr>
<tr>
<td>7</td>
<td>4</td>
<td>Assent power to remain below 9 m/min</td>
<td>Watts</td>
<td>&lt; 300</td>
<td>&lt; 300</td>
</tr>
<tr>
<td>8</td>
<td>10</td>
<td>Depth achievable</td>
<td>m</td>
<td>&gt; 40</td>
<td>&gt; 50</td>
</tr>
</tbody>
</table>

2.6 Project Management

The Gantt chart in Figure 8 gives an overview of the project schedule.
<table>
<thead>
<tr>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
</tr>
</thead>
<tbody>
<tr>
<td>26</td>
<td>2</td>
<td>9</td>
<td>16</td>
<td>23</td>
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<tr>
<td></td>
<td>30</td>
<td>7</td>
<td>14</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td>28</td>
<td>4</td>
<td>11</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Design Report**

Problem Understanding

Concept Generation

Concept Selection

Concept Embodiment

Design Refinement

Peer Report Grading

**Prototypes**

Mockup

Proofs of Concept

Initial Prototype

Initial Prototype Demo

Final Prototype

Final Prototype Demo

Prototype Expo

**Presentations**

Critical Design Review

Final Presentation

Figure 8: Gantt chart for design project
3 Concept Generation

3.1 Mockup Prototype

The DPW mockup was created using cardboard, tape, string, two bolts, and a wingnut. The mockup made us more aware of several key design choices. Most importantly, we realized that interfacing with a round surface of a tank would be very difficult. This is an aspect that will take more planning than we intended, and we solved this in the mockup by creating a box with one side rounded so that it contours to the tank. The clear flaw with this design is that we can only fit a tank with a certain diameter. Another aspect of the design that we had to reconsider is how to connect the batteries. Initially, we just thought that they would replace weights in the BCD or the weight belt, but we quickly noticed that the wires (strings in the mockup) needed to make the connections would be cumbersome. A final note that we took from this experience was that we would have to put more thought into the exact buttons or dial configuration used to operate the motor. In discussions, we had different ideas of how to go about this and we settled on a dial and button for the mockup, but we found that we should explore areas like a joystick, spring-loaded dial, and slider.

Figure 9: View of wrist-mounted motor controller and 'wired' connection to DPW mockup
Figure 10: View of propeller and propeller housing located near the bottom of the DPW mockup

Figure 11: View of DPW mockup showing roughly how and where the DPW will be attached to the diver, as well as where the battery will be located.
3.2 Functional Decomposition

The DPW was analyzed and the main function was determined to be "to propel a scuba diver forward at varying speeds". This was then broken down into several sub-functions that could each be achieved with a single part or system. The actual propulsion of the user had many possible parts or systems that could achieve the function, so it was split up into categories of solutions.

```
Propel scuba diver forward at varying speed
  └── Interfaces with diver
      ├── Interface with control system
      │    └── Motor control interface
      │          └── Detach weight from diver
      │                  └── Monitor direction
      │                              └── Supports batteries
      └── Propels User
          └── Propulsion method
              └── Propulsion location
```

Figure 13: Function Tree for Diver Propulsion Wearable
3.3 Morphological Chart

A certain device, system, or arrangement was found to address each of the lowest levels of the function tree. The solutions are illustrated in Fig. 14.

Figure 14: Morphological Chart for Diver Propulsion Wearable
3.4 Alternative Design Concepts

Based on the above functional decomposition and morphological chart, several different designs were created that uniquely addressed each of the required functions and took advantage of various solutions on the morphological chart. For each concept, the first image shows preliminary sketches used to brainstorm and the second image contains the final sketch of the concept.

3.4.1 Ejectable, Self-contained Tank Attachment

Figure 15: Preliminary sketches of Ejectable, Self-contained Tank Attachment concept
Figure 16: Final sketches Ejectable, Self-contained Tank Attachment

Solutions from morph chart:

1. DPW is attached with straps
2. Interface with motor control is on wrist
3. Interface involves a dial and a button
4. Detaches from body with a Y bracket
5. Direction is monitored with an accelerometer
6. Batteries are placed on top of the tank
7. The DPW is propelled by a single propeller
8. The propeller is located on top of the tank

Description:
The DPW attaches to the back of the tank with a form-fitted connection piece. This piece has holes on the side to accommodate straps that will secure the entire DPV to the tank. A second piece is the propeller mount, which holds the propeller and houses the electronics. The batteries will also be stored inside the propeller mount. Two pins will hold these two main body pieces together. When a cord is pulled by the diver in an emergency situation, the two pins will be removed and the two pieces will be free to separate.
The diver will control the DPW through a device worn on the wrist. This device will have a dial to control the velocity, but a button must be pressed and held down for the motor to operate. This is done so that the motor cannot be left on by accident. The angle of the DPW will be monitored by an accelerometer, and in the case when the diver is pointed upward, the speed of the motor will automatically slow. The motor mount will be a sealed container with the exception of a door on the top that grants access to the electronics.

3.4.2 Velcro-Attached Diver Propulsion Wearable Device

Figure 17: Preliminary sketches of Diver Propulsion velcro concept

Figure 18: Final sketches of Diver Propulsion velcro concept
Solutions from morph chart:

1. DPW is attached with velcro
2. Interface with motor control is on belt
3. Interface involves a dial and button
4. Detaches from body with velcro
5. Direction is monitored with a GPS
6. Battery is placed on top of tank
7. The DPW is propelled with 2 propellers
8. The propellers are located on the sides of the tank

Description:
The DPW attaches to the back of the tank via velcro strips. A single battery is attached to the top of the tank. The two propellers, attached to the sides of the tank, are controlled by button and dial control system that is attached via belt to the diver. This allows for a completely hands-free operation. Direction can be monitored with a GPS system that will be located inside the DPW along with the electronics (arduino). Finally, the system can be detached from the diver by velcro as well to make for a simple, safe detachment option.
3.4.3 Rail-mounted, Diver Propulsion Wearable Backpack

Figure 19: Preliminary sketches of Rail-mounted, Diver Propulsion Wearable Backpack
Figure 20: Final sketches of Rail-mounted, Diver Propulsion Wearable Backpack

- Sensors in pinky and thumb initiate motor movement based on contact and how hard they are pressed together.

- Rail-mounting system

- Oxygen tank will lock in using a torsional spring system inside those rails

- Propeller DPW latch lock (operated by pushing/pulling)

- Battery latch lock (operated by grabbing and pulling away from body)

- Rail-mounted oxygen tank

- Dual, rail-mounted, motorized propeller DPW

- Detachable, waterproof batteries

- Battery release latches

- DPW release latch

- Wires from motor controller to hand

- Diver watch (from customer interview)

- Force sensor leads on thumb and pinky

- System mounting straps

- Whole system (“Backpack”) made of flexible nylon material and plastic rails (sewn or epoxied) into nylon
Solutions from morph chart:

1. DPW is rail-mounted
2. DPW is controlled through the hand
3. The motor is controlled through sensors on the hand (not listed on morph chart)
4. The weight detaches from diver using latches and levers to lock components in on rail system
5. A GPS would be used and integrated into the backpack
6. The battery is mounted at the back of the backpack
7. Two propellers used
8. Propellers are mounted on either side of the oxygen tank

Description:

This dual propeller DPW system with batteries and an oxygen tank will all be contained on the same backpack with six straps that meet at a harness on the diver’s chest. Each component will be rail-mounted (3-D printed plastic) and attached to the flexible nylon backpack material via sewing or epoxy. Two propellers controlled by waterproof, brushless motors were chosen to greatly increase the speed of the diver. Pressing the thumb and pinky fingers together to control speed is a relatively easy motion, allows the diver to still use both hands for lifting objects, and is also unlikely to be done accidentally. A GPS tracker will also be located on the backpack to provide real-time altitude data to be relayed to the diver’s watch in order to ensure the diver is not moving to the surface too quickly.

The weight detach system for the battery relies on latches with a curved profile to a lower flange that will push the battery out when the latch is pulled. Likewise, a latch will be located over the diver’s right shoulder that when pulled down will rotate a shaft that will push up blocks to lock the motorized propellers in the rail. When the latch is pushed up, these blocks will be pulled down to allow the blocks to be released.
3.4.4 Rail-Mounted, Dual-Propeller Diver Propulsion Wearable

Figure 21: Preliminary sketches of dual propeller DPW model
Figure 22: Final sketch of dual propeller model
Solutions from morph chart:

1. DPW is attached with a rail system
2. Interface with motor control is on wrist
3. Interface involves a dial
4. Detaches from body with velcro
5. Altitude and direction is monitored with a GPS
6. Battery is placed on both sides of tank
7. The DPW is propelled with 2 propellers
8. The propellers are located on the sides of the tank

Description:
The bottom or "mounting" piece of the diver propulsion wearable (DPW) is attached by Velcro to the tank, while the mounting pieced is attached to the other piece of the wearable by a rail system. The top piece contains the electronics and motor needed to rotate the dual propellers on both sides of the DPW. The batteries, which are to large to fit inside the top piece of the DPW, are placed on the sides of the DPW. The propellers are controlled by a single dial worn on the wrist of the user. The dial controls whether the propellers are on an off as well as their speed.
4 Concept Selection

4.1 Selection Criteria

Below is the Analytic Hierarchy Process (AHP) table we used to generate our criteria weights. Safety was decided as the most important criteria. The remaining criteria were ranked from greatest to least weight in this order: removable weight, hands-free control, cost, user friendly, and bulk. An important note is that the "hands-free control" and "removable weight" criteria are not the same as the required design features; each proposed DPW design will be compared with respect to how well a user will be able to multitask while using the DPW and how easily the device will be able to release, respectively.

<table>
<thead>
<tr>
<th></th>
<th>Bulk</th>
<th>User Friendly</th>
<th>Cost</th>
<th>Hands Free Control</th>
<th>Removable Weight</th>
<th>Safety</th>
<th>Row Total</th>
<th>Weight Value</th>
<th>Weight (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulk</td>
<td>1</td>
<td>0.50</td>
<td>0.33</td>
<td>0.25</td>
<td>0.20</td>
<td>0.17</td>
<td>2.45</td>
<td>0.05</td>
<td>4.63%</td>
</tr>
<tr>
<td>User Friendly</td>
<td>2</td>
<td>1</td>
<td>0.67</td>
<td>1.00</td>
<td>0.33</td>
<td>0.33</td>
<td>5.33</td>
<td>0.10</td>
<td>10.07%</td>
</tr>
<tr>
<td>Cost</td>
<td>3</td>
<td>1.5</td>
<td>1</td>
<td>1.00</td>
<td>0.50</td>
<td>0.33</td>
<td>7.33</td>
<td>0.14</td>
<td>13.85%</td>
</tr>
<tr>
<td>Hands Free Control</td>
<td>4</td>
<td>1</td>
<td>1</td>
<td>1.00</td>
<td>0.67</td>
<td>0.50</td>
<td>8.17</td>
<td>0.15</td>
<td>15.42%</td>
</tr>
<tr>
<td>Removable Weight</td>
<td>5</td>
<td>3</td>
<td>2</td>
<td>1.5</td>
<td>1</td>
<td>0.67</td>
<td>13.17</td>
<td>0.25</td>
<td>24.87%</td>
</tr>
<tr>
<td>Safety</td>
<td>6</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>1.5</td>
<td>1</td>
<td>16.50</td>
<td>0.31</td>
<td>31.16%</td>
</tr>
</tbody>
</table>

Figure 23: Analytic Hierarchy Process (AHP) to determine scoring matrix weights
4.2 Concept Evaluation

Each design was evaluated on a scale of 1 to 5 based on the selected criteria. The score for each criteria was then multiplied by the calculated weight from the AHP table and summed into one score. The design we would continue with for our prototype had the highest score. This design was the Ejectable, Self-contained Tank Attachment design.

Figure 24: Weighted Scoring Matrix (WSM) for choosing between alternative concepts

4.3 Evaluation Results

After analyzing the Weighted Scoring Matrix, we have decided to use the Ejectable, Self-contained Tank Attachment design, which was also our reference. Most notably, we deemed this design as the safest design of the four due to the accelerometer being used to track ascent speed. Since safety was the most heavily weighted criteria, the Ejectable, Self-contained Tank Attachment predictably had the highest final score. This design, however, did not perform the best in the "removable weight" category; the second highest weighted category. To solve this problem a new, simpler weight-removal system was designed and tested in the proof of concept stage of prototyping.

The Ejectable, Self-contained Tank Attachment had a relatively poor score in hands-free control because two hands are required to operate the DPW. A modification we have made to the design to improve the hands free control aspect was to modify the wrist control to only control the speed and then have a dead man’s switch on the same hand as the watch. This eliminates the need for a second hand to control the speed and allows for an extra safety factor in an emergency where the power needs to be killed immediately. The design scored relatively low in the user-friendly category due to the difficulty in mounting the device after ejecting the weight. The Dual Propeller DPW model performed better in this category because it used Velcro instead, which would have been difficult to remove but much easier to explain and replace.

This design did quite well in the cost category because there was only one motor, compared with two in the other designs. Being that power was not one of the selection criteria, the drawbacks of one motor did not count against the Ejectable, Self-contained Tank Attachment. It also had a smaller battery and the components were relatively simple and made of plastic. The single propeller as well as the self-contained battery design helped this design score well in the "bulk" category, especially when compared to designs that had the batteries stored separately from the main body of the DPW.
4.4 Engineering Models/Relationships

There were several engineering models used to quantify various design choices of the DPW. They gave us insight to how these choices will play out without having to construct a unique prototype for the purpose of testing these decisions.

4.4.1 Drag in water

The following equation shows how the force of drag in a fluid is calculated [8].

\[
F = \frac{1}{2} \rho C_d A v^2
\]  

(1)

In Equation 1, \( F \) represents the force of the fluid on the object [N], \( C_d \) represents the drag coefficient unique to the shape of the object, \( A \) represents the cross sectional area of the object moving through the fluid \([m^2]\), and \( \rho \) is the density of the fluid \([kg/m^3]\).

This equation applies to the DPW because it yields the projected top speed of the diver when a motor of a certain size is used. While speed seemed to be a relatively low priority for the customer, Josh did indicate that the DPW should be about as fast or faster than a person can swim. If the top speed is found to be too small, a larger motor would be chosen. This equation is also useful in that it indicates that a smaller cross sectional area and a lower drag coefficient will result in a higher velocity. These factors will be taken into account when designing the housing for the battery and electronics. It will be made both as small as possible and with a shape that has a lower drag coefficient, such as a bullet or cone shape.

4.4.2 Velocity calculation

The following image shows the relationship between a measured acceleration and the components of a velocity with respect to an angle [9].

![Figure 25: Engineering model for relating an accelerometer value to the appropriate speed of the DPW](image)

In Fig. 25, \( V \) is a velocity \([m/s]\), \( g \) is the acceleration of gravity \([m/s^2]\), \( a_{sig} \) is the signal from an accelerometer \([m/s^2]\), and \( \theta \) is the angle with respect to the horizontal [radians].
This model relates to the DPW because the customer explicitly stated that ascent speed must be closely monitored while scuba diving. The maximum ascent rate was found to be 9 meters per minute [10]. An accelerometer will constantly be measuring the angle $\theta$ by measuring the proportion of gravity that acts on the x-y plane. It is assumed that the forward velocity $V$ is known from the thrust given by the motor specifications. The relationship between velocity and thrust is described in the previous section. Using the angle and the forward velocity, the ascent speed can be monitored and if it is greater than 9 meters per minute, the power to the motor can be reduced to reduce the thrust by an appropriate amount.

4.4.3 Battery life

The following equation shows the relationship between the battery capacity and the amount of time that a device will be able to run [11].

$$T = \frac{C_{batt}}{\sum(I \times V)}$$ (2)

In Equation 2, $C_{batt}$ represents the battery capacity [Wh], $I$ represents current [A], $V$ represents the voltage of the battery [V], and $T$ represents the amount of time the device can run [hours]. The summation is necessary because each component in a device will draw a certain current at a certain voltage, and all these contributions must be summed.

This relates to the DPW because the customer specifically requested that the device last for about the same amount of time that a typical tank will last. Josh stated that time to be 45 minutes to an hour. The DPW will have a motor that will be the primary source of battery drain, drawing up to 20 amps at a voltage equal to that of the battery. The battery will likely be a 4 cell, 14.8V battery. There will also be an Arduino on the device that will draw up to 1 amp at 5 volts. The capacity of the battery divided by the draw of these two components will give the time that the battery in the DPW will last. Alternatively, given the power requirements of the motor and Arduino, a proper battery can be selected that would give the necessary duration.

5 Concept Embodiment

5.1 CAD

The DPW was modeled in Solidworks 2019. The overall assembly was split into different components to make the assembly easier to understand. The battery housing, wrist control, and the tank connection assembly are each shown in separate drawings. Three drawings were created for each of the main assemblies: A three-view and isometric, an isometric view with a bill of materials, and an exploded view with bubble callouts that reference the bill of materials. These drawings are shown in Figs. 26 through 37.
Figure 26: Projected views of full assembly with overall dimensions

MEMS 411 GROUP F

Title: Full Assembly

Scale: 1:8

Sheet 2 of 3
<table>
<thead>
<tr>
<th>ITEM NO.</th>
<th>PART</th>
<th>QTY.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Tank Connector Assembly</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>Battery Housing Assembly</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>Electronics Housing Cover</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>1/4-20 x 1.5, McMaster #: 92620A546</td>
<td>6</td>
</tr>
<tr>
<td>5</td>
<td>1/4 x 20 Hex Nut, McMaster #: 94819A043</td>
<td>2</td>
</tr>
<tr>
<td>6</td>
<td>M3 X 0.5mm, Length 1&quot;, McMaster #: 91772A115</td>
<td>4</td>
</tr>
<tr>
<td>7</td>
<td>BlueRobotics T-200 Thruster</td>
<td>1</td>
</tr>
<tr>
<td>8</td>
<td>Control Assembly</td>
<td>1</td>
</tr>
<tr>
<td>9</td>
<td>Control Cable, McMaster #: 9936K13</td>
<td>1</td>
</tr>
</tbody>
</table>

Figure 27: Assembled isometric view of full assembly with bill of materials (BOM)
Figure 28: Exploded view of full assembly with callout to BOM
Figure 29: Projected views of battery housing with overall dimensions

MEMS 411 GROUP F
Battery Housing Assembly

SIZE: A
DWG. NO.: 3 VIEW
REV.

SCALE: 1:5
WEIGHT:
SHEET 2 OF 3
<table>
<thead>
<tr>
<th>ITEM NO.</th>
<th>PART</th>
<th>QTY.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Electronics Housing</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>Arduino Leonardo</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>Sparkfun Accelerometer</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>Arduino Screw-Down Shield</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>2 Pole Washdown Toggle switch, McMaster#: 7172K211</td>
<td>1</td>
</tr>
<tr>
<td>6</td>
<td>Breadboard</td>
<td>1</td>
</tr>
<tr>
<td>7</td>
<td>1/4 x 20 Hex Nut, McMaster #: 94819A043</td>
<td>4</td>
</tr>
<tr>
<td>8</td>
<td>M3 X 0.5mm, Length 1&quot;, McMaster #: 91772A115</td>
<td>5</td>
</tr>
<tr>
<td>9</td>
<td>3 Pole Washdown Toggle Switch, McMaster #: 7347K11</td>
<td>1</td>
</tr>
<tr>
<td>10</td>
<td>Turnigy 4S 20 Ah Battery</td>
<td>1</td>
</tr>
</tbody>
</table>

Figure 30: Assembled isometric view of battery housing with bill of materials (BOM)
Figure 32: Projected views of control assembly with overall dimensions.
### Bill of Materials (BOM)

<table>
<thead>
<tr>
<th>ITEM NO.</th>
<th>PART</th>
<th>QTY.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Control Housing Base</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>Control Breadboard</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>4-40 x 1 Bolt, McMaster #: 91735A117</td>
<td>2</td>
</tr>
<tr>
<td>4</td>
<td>Control Housing Cover</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>4-40 Nut, McMaster #: 90242A166</td>
<td>2</td>
</tr>
</tbody>
</table>

---

**Figure 33:** Assembled isometric view of control assembly with bill of materials (BOM)

---

**MEMS 411 GROUP F**

**TITLE:** Control Assembly

**SIZE** A | **DWG. NO.** BOM | **REV**

**SCALE:** 1:4 | **WEIGHT:**

**SHEET 3 OF 3**
MEMS 411 GROUP F

Control Assembly

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
FRACTIONAL:
ANGULAR-MACH:
TWO PLACE DECIMAL:
THREE PLACE DECIMAL:

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL

Q.A.

COMMENTS:

CHECKED
ENG APPR.
MFG APPR.

Q.A.

COMMENTS:
Figure 35: Projected views of tank connector assembly with overall dimensions.
Figure 36: Assembled isometric view of tank connector assembly with bill of materials (BOM)
Figure 37: Exploded view of tank connector assembly with callout to BOM
5.1.1 Parts List

Table 3 shows each component that was used to construct the initial DPW prototype. The table shows that we successfully stayed below the $400 limit for this prototype. It should be noted that the link for the individual parts is no longer functional in this document, but a link is provided in the appendix that leads to the google sheet where the initial parts list was created.

Table 3: Full materials list for diver propulsion wearable prototype

<table>
<thead>
<tr>
<th>Part</th>
<th>Source Link</th>
<th>Supplier Part Number</th>
<th>Color, TPI, other part IDs</th>
<th>Unit Price/</th>
<th>Quantity</th>
<th>Total Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Thruster RobotShop</td>
<td>BESC30-R1</td>
<td>T-200 Thruster With BlueESC</td>
<td>$194.00</td>
<td>1</td>
<td>$194.00</td>
<td></td>
</tr>
<tr>
<td>2 Arduino Shield Adafruit</td>
<td>196</td>
<td>Screw-Down Shield, 0.1&quot; Grid</td>
<td>$14.95</td>
<td>1</td>
<td>$14.95</td>
<td></td>
</tr>
<tr>
<td>3 Arduino sparkfun</td>
<td>DEV-13975</td>
<td>Pins in R3 Format</td>
<td>$19.95</td>
<td>1</td>
<td>$19.95</td>
<td></td>
</tr>
<tr>
<td>4 Accelerometer sparkfun</td>
<td>ADXL335</td>
<td>Triple Axis</td>
<td>$14.95</td>
<td>1</td>
<td>$14.95</td>
<td></td>
</tr>
<tr>
<td>5 Battery HobbyKing</td>
<td></td>
<td>5.2 Amp, 4S, 30C</td>
<td>$44.05</td>
<td>1</td>
<td>$44.05</td>
<td></td>
</tr>
<tr>
<td>6 OP/TECH Wrist Straps</td>
<td>amazon</td>
<td>1301432 Black</td>
<td>$5.95</td>
<td>1</td>
<td>$5.95</td>
<td></td>
</tr>
<tr>
<td>7 Washdown toggle switch</td>
<td>mcmaster</td>
<td>7172R21 Two position, rounded</td>
<td>$11.48</td>
<td>1</td>
<td>$11.48</td>
<td></td>
</tr>
<tr>
<td>8 D-ring yoga straps</td>
<td>amazon</td>
<td>Multicolor</td>
<td>$9.99</td>
<td>1</td>
<td>$9.99</td>
<td></td>
</tr>
<tr>
<td>9 1/4 -20 bolts mcmaster</td>
<td>92620A546</td>
<td>Grade 8 Steel, 1/4&quot;-20 Thread Size, 1-1/2&quot; Long, Fully Threaded</td>
<td>$7.15</td>
<td>1</td>
<td>$7.15</td>
<td></td>
</tr>
<tr>
<td>10 1/4 20 nuts mcmaster</td>
<td>94819A043</td>
<td>316 Stainless Steel</td>
<td>$4.08</td>
<td>1</td>
<td>$4.08</td>
<td></td>
</tr>
<tr>
<td>11 m3 bolts mcmaster</td>
<td>92000A130</td>
<td>18-8 stainless steel, 25mm</td>
<td>$7.32</td>
<td>1</td>
<td>$7.32</td>
<td></td>
</tr>
<tr>
<td>12 m3 nuts mcmaster</td>
<td>94150A325</td>
<td>316 stainless steel, hex nut</td>
<td>$3.08</td>
<td>1</td>
<td>$3.08</td>
<td></td>
</tr>
<tr>
<td>13 4-40 bolts mcmaster</td>
<td>91772A115</td>
<td>18-8 stainless steel, 1 inch</td>
<td>$5.29</td>
<td>1</td>
<td>$5.29</td>
<td></td>
</tr>
<tr>
<td>14 4-40 nuts mcmaster</td>
<td>90242A166</td>
<td>Black-Oxide 316 Stainless Steel</td>
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<td>1</td>
<td>$5.56</td>
<td></td>
</tr>
<tr>
<td>15 1/4-20 Wing nuts mcmaster</td>
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<td>316 Stainless Steel</td>
<td>$6.37</td>
<td>1</td>
<td>$6.37</td>
<td></td>
</tr>
<tr>
<td>16 Control Cable mcmaster</td>
<td>9936K13</td>
<td>Seven 20 gauge wires, 10ft</td>
<td>$15.60</td>
<td>1</td>
<td>$15.60</td>
<td></td>
</tr>
</tbody>
</table>

Total: $369.77

5.2 Design Rationale

Throughout the designing process, many decisions needed to be made involving the design of the 3D printed components and the purchasing of several parts. The rational for each decision involved uses engineering concepts and models from previous classwork and outside sources. These models were first introduced in Section 4.4, and are expanded upon below with values specific to this project.

5.2.1 Battery Choice

When considering what battery should be used for the DPW, the goal was to maximize the amount of time the battery could be used on a single charge while keeping the cost of the battery reasonable. The motor used requires 25 amps of power. The battery being considered had the specifications of 14.8 V and 20 Ah. The equation shown below provides the rationale for the battery we chose.

\[
T = \frac{C_{batt}}{\sum (I \times V)}
\]

In Equation 3, \(C_{batt}\) represents the battery capacity [Wh], \(I\) represents current [A], \(V\) represents the voltage of the battery [V], and \(T\) represents the amount of time the device can run [hours]. Using the specifications described above, the run time can be calculated. The power draw of the
Arduino was neglected in this calculation because in this prototype, the Arduino had a separate battery that is projected to outlast the motor battery.

\[
T = \frac{C_{batt}}{\sum (I \times V)} = \frac{20Ah \times 14.8V}{25A \times 14.8V} = 0.8 \text{ hours} = 48 \text{ minutes} \tag{4}
\]

Equation 4 shows that the motor can run on full power for 48 minutes if this battery is selected. In normal use, the motor would often not be running or not running on full power for an entire scuba session. This suggests that, for normal use, the device can be used for a scuba trip over 1 hour and that the selected battery is appropriate for this application.

5.2.2 Motor Selection

Along with battery choice, ensuring the DPW can surpass the average swimming speed of 1.86 mph was important for establishing the market need for our product [12]. Rearranging the equation for the drag coefficient to solve for velocity:

\[
v = \sqrt{\frac{2 \times F_{\text{thrust}}}{\rho \times A_c \times C_d}} = \sqrt{\frac{2 \times 4.635 \text{ kgf thrust} \times 9.81 \text{ m/s}^2}{1029 \text{ kg/m}^3 \times 0.1066 \text{ m}^2 \times 0.4}} = 1.44 \text{ m/s} = 3.22 \text{ mph} \tag{5}
\]

where \(\rho\) represents the density of seawater was used, \(A_c\) represents area value was found from measuring the cross-sectional area of a group member’s head and shoulders, \(C_d\) represents the coefficient of drag for a scuba diver was determined from research [13], and the thrust force value \(F_{\text{thrust}}\) was determined from a linear interpolation of thrust values between 12 and 16 volts from the thruster specification sheet for an operating voltage of 14.8 volts [14]. From the result of Equation 5, it was decided that the T-200 thruster was an appropriate choice and that the DPW will be able to propel its user at speeds faster than the average swimmer.

5.2.3 Battery Housing Shape

The battery housing was designed with a focus on both aerodynamics and manufacturability. Angles of 60° in the front and 15° in the rear were decided based on drag values found by Dr. Sighard Hoerner [15] and researchers investigating truck trailer ends [16] respectively. In terms of manufacturability, the battery housing was designed without filleted edges and with a flat base to ensure the highest quality 3-D print.

5.2.4 Accelerometer Angle

A key safety component mentioned by the customer specified that the maximum ascent rate of the diver should be 9 meters per minute. This max value is achieved by putting an accelerometer in the device and making the thrust of the motor dependent on the accelerometer reading. The engineering model for this relationship is shown by Fig. 25. The information obtained from this model will show how the accelerometer reading translates to a motor speed.

The following equation was used in the Arduino code to find the angle of the diver with respect to horizontal.

\[
\theta = 90 - \cos^{-1}\left(\frac{\text{servoReading}() \times 180}{\pi}\right) \tag{6}
\]
A call to ServoReading() returned a value between zero and one that corresponded to the acceleration in a certain plane (corresponding to $\frac{a_{x}}{g}$ in Fig. 25). The maximum speed attainable by the motor was achieved when a signal of 2000 was sent to it, and stationary was achieved with a signal of 1500.

The maximum speed of the DPW was approximated to 2 miles per hour for this calculation, which equals about 53.6 meters/minute. Assuming this speed corresponds to maximum throttle and that speed varies proportionally to the throttle, the throttle associated with the maximum speed is equal to $\frac{9}{53.6} \times 500 = 83$. The following equation relates the maximum speed to the tilt.

$$\text{maxSpeed} = \frac{83}{\sin\left(\frac{\theta \times \pi}{180}\right)} + 1500$$

(7)

The only further modification made in the arduino code in the DPW is that the maxSpeed value was passed through an if statement: if the maxSpeed was greater than the throttle (as decided by the potentiometer), the output would be the unadjusted throttle. If the maxSpeed value was less than the throttle, the throttle would be set to the maxSpeed and this new value would be output to the motor.

5.3 Prototype Performance Goals

5.3.1 Time to Remove Wearable is Less than 7 Seconds

Our first performance goal was to remove the DPW is less than 7 seconds. This goal is purely safety-oriented and the benchmark was decided through conversation between team members and course instructors. This performance goal was tested by having the subject pretend to be using the DPW and having a third party say "go" so the subject was not prepared (simulating an emergency). The removal process includes disconnecting the wrist strap and then pulling the release pin off the DPW.

5.3.2 Motor Speed Adjustment Based on Ascent Angle

Another performance goal was to adjust the speed of the DPW according to the ascent angle. This was tested by having a test subject lay on a table and start the DPW in the prone position. The subject then leaned upwards to create a greater angle with respect to the horizontal. The motor appropriately reduced speed and reached a minimum speed when the DPW was oriented vertically. At this point, the motor speed was limited to the maximum safe ascent speed.

5.3.3 Control Input can Vary Speed Between 0 and 100 Percent Capacity

The final performance goal consisted of adjusting the speed of the propeller from stationary to maximum capacity without releasing the kill switch. This allows the user to adjust speed without have to come to a stop, providing a smoother and safer ride. This was tested by having a subject slowly increase the speed from minimum to maximum without the propeller turning off.
5.4 Proofs of Concept

For the diver to be able to remove the weight quickly, a release mechanism was invented. In Fig. 38, the initial concept of a release pin was tested. It was found that it did function, but the pin took a significant amount of force to pull out. It was decided that this concept would need further refinement.

Figure 38: Proof of concept for release mechanism
After the motor was received from the manufacturer, we first tested to see if the motor could be controlled with a potentiometer. A solder-less breadboard and an Arduino were used to wire the potentiometer and monitor the output on the screen. Figure 39 shows the setup to test the motor. This test was a success, and this wiring was the setup for the final wiring of the wrist control.

Figure 39: Proof of concept for motor control
We were initially unsure of how the strap would fit in the tank mounts and how they would fare when the straps were fully tightened. The design was fully printed and a strap was inserted through the parts. A strap inserted into two tank mounts is shown in Fig. 40. This device was then tested by tightening the straps around a "tank" (a wide piece of PVC) and it was found that they performed quite well.

Figure 40: Proof of concept for attachment straps
5.5 Changes from Selected Concept

The following sections outline the main changes that were made as we developed the DPW prototype from the selected concept.

5.5.1 Arm Modifications

While the arm design was generally acceptable, we increased the width where the piece attaches to the tank connector. The rationale of this adjustment was to limit the movement of the piece. Figure 40 shows the original concept with a significant gap between the arm and connector piece in the top left corner of the photo while Fig. 41 below shows the modified connection with a reduced gap.
5.5.2 Release Pin Assembly

The release pin was initially designed to have two horizontal pins connected by a handle. However, this design was non-ergonomic mainly since the diver would have a hard time reaching the pin. Instead, the design was simplified to have one pin at a slight angle down to the diver attached to a string. Figure 38 shows the original two-rod design while Fig. 42 below shows the angled, one-pin design.

Figure 42: Angled Pin Assembly

5.5.3 Reduced Release Gap

Initially, we designed the gap between the arm and tank connector to both be rectangular in shape with a relatively large tolerance. However, we noticed a large amount to movement when the pieces were attached together. We modified the tank connector to have an angled gap which allowed for a smoother attachment and limited movement.

5.5.4 Hex Indent in Tank Mounting Piece

We added a recessed hexagonal indent designed to fit our 1/4-20 hex bolts into the four tank mounting pieces. This was done to ensure the bolt would not slip or loosen while the DPW is in
5.5.5 Used Wing Nuts for Connector Piece

We initially used hex nuts to tighten the tank mounting pieces to the tank connector. However, as our DPW is designed to be adjustable for different sized scuba tanks, we decided to switch to wing nuts for user convenience. This allows a user to adjust the connector based on tank size without needing a wrench on hand.

5.5.6 Battery Housing Internal Structure

The internal structure of the battery housing was not fully accounted for in early designs. However, as shown in Fig. 43 for the initial prototype, design decisions were made to properly protect and organize the electrical components of the DPW. These design decisions include a ridge that mostly spans the length of the inner housing to separate the battery from the more fragile electrical parts, an internal cut-out for the battery, and supports for the accelerometer.

Figure 43: Battery Housing Internal Structure
6 Working Prototypes

6.1 Overview

In this section, we will explain the results of our performance goal tests and the design changes from the initial prototype to the final prototype.

6.2 Initial Prototype

We used the three performance goals as benchmarks of our progress for the initial prototype. The first prototype met all of our performance goals, ensuring the viability of our design.

6.2.1 Performance Goal One: Changing Speed

The first goal was that the user must be able to change the speed of the motor without needing to turn the motor off and back on. To do this, we designed a wrist controller, which is shown being used in figure 44. The user was able to change the speed at will without needing to turn the motor off and back on.

![Figure 44: Speed Control Performance Goal Test](image)

6.2.2 Performance Goal Two: Ascent Speed Regulation

The second goal was to prevent the diver from ascending too quickly. To achieve this, we put an accelerometer in our DPW. When the angle of the DPW with respect to horizontal was too high, the maximum speed of the motor was decreased and a red light came on the wrist controller turned on. In figure 45, the user increased his angle and the speed of the motor decreased accordingly and the red light on the wrist control turned on.
6.2.3 Performance Goal Three: Device Removal

The final goal was that the diver must be able to remove the device in case of emergency in under 7 seconds. This was achieved by a quick release pin model where the diver simply needed to pull on a string to remove a pin. The drag force from the water, gravity, or motion of the diver would then pull the DPW off the tank. This was done in 3.91 seconds, and is shown in figure 46.

6.3 Final Prototype

There were several changes made between the initial and final prototypes. The biggest change made was the updated wrist controller. The newest version is shown in Fig. 47.
In the new design, the controller has been simplified and made more user-friendly. The green button increases the motor speed and the red button decreases the motor speed. This wrist controller can now be used with diving gloves and in low-light conditions. This design is also much easier to waterproof. Since the user no longer has to hold a button to move forward, the new design is much more hands-free than the old one.

Figure 48 shows the wrist controller without the top cover. Here it is apparent that the cables are no longer exposed, and a bead of hot glue was applied to the control cable immediately inside the housing. This glue bead ensures that an axial force on the cable no longer disconnects the individual cables and instead pulls on the hot glue.
Figure 48: Updated wrist control without top cover

Figure 49 shows several changes that were made to the lid. First, the material was changed from wood to acrylic. The wood was originally used because the battery housing was printed with slightly off-square corners. The battery housing was then re-printed and this second print was perfectly rectangular. A 1/4" red acrylic lid was then laser-cut to fit. The tolerance between the lid and housing was tight enough that waterproofing could be pursued.
To begin waterproofing, we used waterproof grommets typically used for boat GPS cables to waterproof the control and motor cables. These are visible in Fig. 49. We also added rubber washers to each of the bolts and switches to waterproof these holes. The wood spacer block was moved from underneath the lid to above to reduce the shear on the motor cable. This change also had the effect of making the heads of the m3 bolts that secure the motor interface with acrylic as opposed to wood, forming a much tighter seal (with rubber washers as well).

Figure 50 shows the rubber liner that was added to the battery housing to waterproof the opening. Waterproof grease was also added.
Figure 50 also shows the battery housing submerged up to the switches in water. It was held here for several seconds and no water entered. We then attached the lid and decided to fully submerge the DPW. After removing the lid, there was a small pool of water in the device. While this could have been due to errors in our waterproofing, we suspect a large crack in the battery housing may be partially to blame.

A final change that was made was the addition of the propeller housing. The propeller cage both protects user from injury and protects the propeller from debris in the water while diving. The propeller cage was successfully printed, and is shown in Fig. 51.

Figure 51: Image of propeller cage.
7 Design Refinement

7.1 FEM Stress/Deflection Analysis

7.1.1 FEA Analysis for a diver falling backwards out of the boat

For analyzing the diver falling out of the boat and impacting the water with the cross-sectional area of their upper-body, it was determined that all of the detachable DPW components (motor housing, battery housing, and release arm) would experience the most significant stress and deflection. For this analysis, the remainder of the DPW that attaches to the oxygen tank was omitted from the analysis since it adds unnecessary complexity to the FEA simulation and can be simplified to a rigid wall due to the rigidity of the oxygen tank. As such, the release arm was fixed in this analysis along its lower faces since it mounts to the oxygen tank attachment system at these areas. The control cable that connects the Arduino to the wrist controller was also omitted from this analysis due to the flexibility of the cable and the cable coating that would prevent any static failure. A load of 1154 N was distributed over the top-most face of the battery and motor housing. This load was determined from rearranging the equation for the drag force which serves as a relevant approximation for the desired impact load.

\[ F = \rho \cdot A_c \cdot C_d \cdot 2 \cdot g \cdot h = 1029 \, kg/m^3 \cdot 0.25 \, m^2 \cdot 1 \cdot 9.81 \, m/s^2 \cdot 0.4572 \, m = 1154 \, N \quad (8) \]

The diver’s velocity when impacting the water was determined from an energy balance of the diver’s gravitational potential energy converted to kinetic energy when falling 1.5 ft (0.4572 m). The upper body measurements for an average person were found online and the cross sectional area was determined to be 0.25 m² [17] [18]. Since saltwater has a greater density than freshwater, the density of saltwater was assumed to test the worst possible case. Additionally, a drag coefficient of 1 was assumed to be conservative since the actual drag coefficient would be difficult to determine. For the mesh, a fine mesh with 4 Jacobian points was chosen to ensure the simulation was as close to reality without requiring excessive computing time.

In general, FEA results should not be used as doctrine when experimental results or simple hand calculations are possible. However, given the lack of data and the complex DPW geometry, this simulation is appropriate as an approximation for the impact load seen by the diver when falling backwards out of a boat.
Figures 52 through 54 outline the direction of the 1154 N applied force (orange arrows) with the mesh and fixed boundary condition (green arrows) applied to the release arm as well as the color-coded von Mises (Distortion Energy Theory) stress plot in units of pascals ($N/m^2$) and the displacement plot in millimeters. Note that the stress and displacement plots use the non-deformed result since the deformation scale of the deformed result produced misleading images that exaggerated the deformation of the analyzed system.

Figure 52: Forces, boundary conditions, and mesh for an average diver’s impact load when falling backwards out of a boat to enter the water on their back (1154 N).
Figure 53: Von Mises predicted stress from an average diver’s impact load when falling backwards out of a boat (1154 N).

From Fig. 53, the components as a whole survived the applied load of 1154 N. The von Mises stress plot in Fig. 53 does show small red regions on the motor housing that reach stresses \((1.121 \times 10^7 \text{ Pa})\) near the yield strength of the PLA material used to print the housing \((4.95 \times 10^7 \text{ Pa})\) \cite{19}. However, since the PLA yield stress was not met, the analyzed detachable components can survive a diver falling backwards into saltwater. This corresponding safety factor is:
Safety Factor \[ = \frac{\sigma_{\text{yield}}}{\sigma_{\text{max}}} = \frac{4.95 \times 10^7 \text{ Pa}}{1.121 \times 10^7 \text{ Pa}} = 4.42 \] (9)

Then, from Fig. 54, the maximum displacement was found to be 3.469 mm (0.137 in) at the top of the motor housing. The distance between the motor and the inner face of the motor housing is 13.865 mm (0.546 in), so this maximum displacement is not enough to interfere in the operation of the DPW. Though the maximum stress did not surpass the yield strength and the maximum displacement was not large enough to inhibit the motor, both of these conditions occurred at the motor housing. As such, the motor housing wall thickness will be increased for safety.

7.1.2 FEA Analysis for a diver jumping out of the boat

In testing another form of diver entry into water, the same fixed boundary condition was applied to the release arm. The mesh was similar to the backwards fall simulation except that the motor housing mesh was slightly more coarse to decrease computing time while maintaining a similar simulation quality. For this diver entry method, a load of 137 N was calculated and distributed over the faces of the detachable components that would impact the water first.

\[ F = \rho \cdot A_c \cdot C_d \cdot 2 \cdot g \cdot h = 1029 \text{ kg/m}^3 \cdot 0.0296 \text{ m}^2 \cdot 1 \cdot 9.81 \text{ m/s}^2 \cdot 0.4572 \text{ m} = 137 \text{ N} \] (10)

The same conditions as the first simulation were assumed except that the cross sectional area used was only the detachable components of the DPW (0.0296\(m^2\)). This assumption was made since the diver and the other DPW components would not directly affect the drag force experienced by the detachable components. Unlike the first simulation when the diver’s larger upper body cross sectional area would add to the drag force from falling backwards, there is no other component in the line of action of the analyzed components for this vertical diver entry method.
Similar to the first FEA simulation, figures 55 through 57 outline the direction of the 137 N applied force (orange arrows) with the mesh and fixed boundary condition (green arrows) applied to the release arm as well as the color-coded von Mises stress plot in units of pascals ($\text{N/m}^2$) and the displacement plot in millimeters. Note that the stress and displacement plots use the non-deformed result since the deformation scale of the deformed result produced misleading images that exaggerated deformation of the analyzed system.

Figure 55: Forces, boundary conditions, and mesh for an average diver’s impact load when jumping out of a boat to enter the water vertically (137 N).
From Fig. 56, the components survived the applied load of 137 N. The von Mises stress plot in Fig. 56 does show small red regions on the circular plate of the motor housing that reach stresses \(2.857 \times 10^7 \text{ Pa}\) near the yield strength of the PLA material used to print the housing \(4.95 \times 10^7 \text{ Pa}\) \([19]\). However, since yield stress for PLA was not met, the analyzed detachable components can survive a diver jumping into saltwater. This corresponding safety factor is:

\[
\text{Safety Factor} = \frac{\sigma_{\text{yield}}}{\sigma_{\text{max}}} = \frac{4.95 \times 10^7 \text{ Pa}}{2.857 \times 10^7 \text{ Pa}} = 1.73
\]  

(11)
Then, from Fig. 57, the maximum displacement was found to be 8.41 mm (0.331 in) at the top of the motor housing’s circular plate. The distance between the motor and the inner face of the circular plate is 39.185 mm (1.543 in), so this maximum displacement is not enough to interfere in the operation of the DPW. Though the maximum stress did not surpass the PLA yield strength and the maximum displacement was not large enough to inhibit the motor, both of these conditions occurred at the motor housing circular plate and were more severe than the first simulation. As such, the motor housing circular plate wall thickness will be increased for safety and this load case will serve as a test for future DPW iterations.

7.2 Design for Safety

7.2.1 Risk #1: Unprotected Propeller Blades

**Description:** When the motor is running, the propeller blades move very quickly and if the user (or anyone else) were to accidentally put their fingers in the propeller when it is running the finger could be severely injured.

**Severity:** The severity would depend on the speed of the motor. At a low speed, assuming the user removes their finger quickly, it is possible the finger would only sustain minor damage. If, however, the speed of the motor was relatively high, the finger could be badly cut, broken, or bent by the propeller.

**Probability:** As of now, if someone is not paying attention, it is very possible that someone’s finger would get caught in the motor if the device was turned on while on land. If being used under water however, this problem becomes much less likely as it would be difficult if not impossible for the user to put their finger in the motor while the DPW is on their back.

**Mitigating Steps:** A cage-like propeller housing that will prevent anyone from putting their fingers in the motor is currently being implemented. Once the housing is installed, the problem should be eliminated.

7.2.2 Risk #2: Strangulation

**Description:** There is a risk of strangulation from the cord that connects the DPW to the wrist control interface. While this risk is nearly impossible while the diver is not operating the DPW, the risk increases as the user operates the device. The risk is most prevalent in a scenario where the diver extends the hand with the wrist control attached across his/her body while in motion.

**Severity:** This would cause a critical risk factor as strangulation can cause extreme pain and, in the worst cases, death.

**Probability:** This specific event is unlikely to happen based on the safety measures we have placed.

**Mitigating Steps:** Firstly, the 30-second kill switch in the system means the device shuts off after 30 seconds of inactivity, allowing the user to safely remove the device from his/her neck. In a more immediate risk, the diver can detach the device using the pin release system (see prototype performance goals).

7.2.3 Risk #3: Choking Hazard

**Description:** There is an inherent choking risk with a product that contains small pieces. Specifically, nuts, bolts, and many of the electronics are small enough to provide a choking hazard for small children.
**Severity:** A choking incident poses a catastrophic risk as it could, in the worst scenarios, cause death.

**Probability:** Because the product is designed for certified scuba divers, the risk has been labeled as unlikely as the product will probably not be used by children small enough to present a choking hazard.

**Mitigating Steps:** Regardless, there is a possibility that a child may interact with the product while in a household scenario. To prevent this, warnings will be printed on all user manuals, informing users of the risks of choking.

### 7.2.4 Risk #4: Rapid Ascent

**Description:** There is a term well-known in the diving community called ”the bends.” This is a condition that causes numbness, dizziness, and potentially loss of consciousness if a diver ascends too quickly in the ocean.

**Severity:** The bends can cause catastrophic health problems.

**Probability:** Unlikely

**Mitigating Steps:** To ensure that the user will not ascend too quickly while operating the DPW, an accelerometer has been placed in the device. The accelerometer automatically regulates the divers ascent speed. Thus, if the diver is angled upwards, the accelerometer will slow the propeller speed enough to ensure a safe ascent. The only way the diver can ascend too quickly while operating the device is if the accelerometer malfunctions which has been deemed as an unlikely scenario.

### 7.2.5 Risk #5: Electrocution

**Description:** The DPW contains a large amount of electronics, primarily in the battery housing and the wrist controller. If used unsafely, these electronics could be dangerous. Problems from the electronics could stem from the circuit failing or shorting, which could lead to sparks, heat, and smoke. Also, if water leaks into the system, the current from the battery could also electrocute the user.

**Severity:** The electronics shorting could lead to burns to the user that could vary in severity. If water leaked into the equipment, however, the possible electrocution could lead to severe injury for the user.

**Probability:** If the device were to be put in the water now, water would undoubtedly leak into the electronics, so the probability of some injury happening would be very significant. The electronics in the wrist control would be most likely to cause any problems because those are mere inches away from the users hand, while the electronics stored in the housing are much farther away from the user. The electronics also have shorted multiple times, so the probability of that leading to a problem are relatively high.

**Mitigating Steps:** The layout of the electronics is being redesigned to prevent any future shorts. Additionally, work had began on waterproofing the entire DPW, and the device will be thoroughly tested to make sure each component of it is waterproof.

### 7.2.6 Conclusion

As it stands, strangulation and electrocution are the most dangerous risks with our product. While the probability of strangulation is unlikely, the catastrophic nature of the risk requires consideration in the design process. Alongside the other mitigating steps previously mentioned, we have
purchased a neon yellow rope to replace our string. We believe, because the rope is bright colored, this will lower the probability of the risk. The probability and severity of electrocution show that it is imperative that the design is waterproofed, and every effort is being made to accomplish this goal, including using wax, flex seal, and a redesigned wrist controller. While all other risks fall in the yellow and green areas of the heat map, we have made design changes since our initial prototype to ensure the safety of the user. Specifically, we are adding a cage to the propeller to protect the user from having a body part lodge into the running propeller.

Below in Fig. 58 is the risk heat map:

<table>
<thead>
<tr>
<th>Category</th>
<th>Frequent</th>
<th>Likely</th>
<th>Occasional</th>
<th>Seldom</th>
<th>Unlikely</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Likely to occur immediately or in a short period of time; expected to occur frequently</td>
<td>Quite likely to occur in time</td>
<td>May occur in time</td>
<td>Not likely to occur but possible</td>
<td>Unlikely to occur</td>
</tr>
<tr>
<td>Catastrophic</td>
<td>Electrocution</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Critical</td>
<td>Strangulation</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Marginal</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Negligible</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 58: Risk Heat Map
7.3 Design for Manufacturing

Two different parts were analyzed in Solidworks for their potential to be manufactured with various techniques. The release arm was selected first (call-out 3 in the Tank Mounting Assembly CAD drawing). As a simpler part that would not experience a significant amount of stress, the possibility of injection molding was explored. An important part of an injection-molded part is the draft angle of the sides of the part. Figure 59 shows both the initial draft analysis and the final part after modifications.

![Before and after images of the release arm using solidworks draft analysis.](image)

Figure 59 shows several changes that were made to the part easier to manufacture. The sides of the part were drafted either inwards or outwards to make removing the mold easier. An additional change was the design of the hinge that holds the bar on the tank mounting plate. This piece would be impossible to injection mold as it was designed. Figure 59 shows how the single channel was made to alternate halves such that the channel is not a full semicircle at any point. Now, the inside surface of the channel is visible from the top or bottom of the part, indicating it can be injection molded with a single draw.
Next, the Tank Connector Plate (call-out 1 in the Tank Mounting Assembly CAD drawing) was analyzed in Solidworks DFMXpress tool to explore the potential of different manufacturing techniques. Figure 60 shows the results when the part was tested for injection molding.

As shown in Fig. 60, the part passed the test for minimum wall thickness but in many instances, the walls were shown to be too thick for this manufacturing technique as shown. In the example in Fig. 60, the distance from the top of the plate to the bottom is too large. This would be a difficult criteria to satisfy for this part and would require a complete redesign (changing the design of the channels), meaning that this part cannot realistically be injection molded. Figure 61 shows the results when tested for fabrication on a mill.
Milling the connector plate failed many tests as well, but many of these failures could be fixed easily. The problem of sharp internal corners could be remedied with fillets. Hole depth and standard hole size failures could be fixed with a slight resizing of the holes. Fillets on outside edges could simply be removed. One of the failures was because the axis for the pin hold is not perpendicular to the surface of the part. This could be remedied by angling the front surface. The most difficult failure to address would be the "hole intersects cavity" rule, as shown in Fig. 61. This is brought on by the pin hole intersecting the location where the arm head rests. The release mechanism would need a minor redesign to allow the pin hole to be a through-hole, but aside from that, milling and drilling could be a potential manufacturing method for this part.

7.4 Design for Usability

7.4.1 Vision

The wrist control system is the only use interface that involves vision. The now redesigned control system is very simple as it contains one green button that increases the speed of the motor and one red button which decreases the speed. Additionally, the two buttons are labeled with a plus and minus sign so a colorblind user that cannot see the difference in color of the buttons can still understand the functionality of each button. These plus and minus signs also are etched into the controller, so theoretically even a blinded user would be able to feel which button is which. The controller layout is shown in figure 62.

![Figure 62: layout of controls](image)

7.4.2 Physical

While many individuals with severe physical impairment cannot scuba dive safely, scuba diving is actually utilized as a program for those with moderate physical impairments. This is possible because of the weightlessness one feels in the water, and this device would actually be able to aid those who have trouble moving themselves in the water. By simplifying out controller design as described in the section above, we have made the DPW more accessible. Assuming the user is cleared to scuba dive safely, the two requirements the diver must have to use the device is to be
able to hit the buttons on the controller and to be able steer themselves (which is already necessary for normal scuba diving). Putting the device on the tank could also provide a physical challenge for some, but not compared to properly installing the rest of the scuba equipment, and another person could help the user put the DPW on.

7.4.3 Hearing

The only way a lack of hearing could theoretically affect the usability of the DPW concerns the speed of the motor. This is because the easiest way to tell the relative speed of the motor is to listen to it because as the speed of the motor increases the motor gets much louder. This potential problem for a user with hearing issues is rectified by having a light on out wrist control. When the motor is not running, the light will be solid. When it is on the lowest speed it will blink in series of one. When it is on its second to lowest speed, it will blink of series of two, etc.

7.4.4 Control

It is necessary to mention in this section that any loss of control by a diver in any scuba diving environment can prove to be dangerous, and it is imperative that any scuba diver focus on the diving. That being said, the DPW itself will add little danger to the scuba diving environment. One possible danger the user could have faced with a propulsion unit is ascent speed, as ascending too quickly could lead to a large change in pressure which in turn can cause averse health affects for the user. To rectify this, a fail safe was put in that regulated the speed of ascent by reducing the speed of the motor if the measured angle of ascent is too high. All in all, the only possible danger that is currently present from loss of control would be the user hitting an object underwater. But there are designed fail-safes in place that allow the user to quickly turn the motor off if at all necessary. Primarily, the user can simply hold down the red button for a short period of time to turn the motor off.

8 Discussion

8.1 Project Development and Evolution

Does the final project result align with its initial project description?

- For the most part, the results of out project matched the initial project description. Primarily, the project can work as described: it is wearable and the diver can use it completely hands free except when changing speeds. The housing is defined to fit a battery that can run the motor at full speed for 48 minutes, which is plenty of charge for a single scuba diving trip. When considering safety, we were able to regulate ascent speed (reducing the possibility of the bends) and designed an emergency removal system.

Yet, one thing the was not done was waterproofing the entire device. Towards the end, we made several alterations to the DPW to make it as waterproof as possible, but after testing we concluded that it is not completely waterproof. This is the main result that did not meet the initial project description. Lastly, we did not address the potential pressure the device would be under when relatively deep underwater.

Was the project more or less difficult than expected?
Most of the project was about as difficult as we had expected, but there were certain parts that gave as some trouble. The electronics assembled pretty easily, but after a brief short in the battery, it took about a week to figure out what had gone wrong and in that time nearly all of the components were replaced. The redesigned wrist controller was also very difficult to design; the increased size of the buttons gave less room on the breadboard for wires and resistors.

The other main unexpected challenge we encountered was in waterproofing the device. As we began the planning, we kept noticing more ways water could enter we hadn’t noticed before. After addressing every possible inlet we could think of, water had still found its way in.

On which part(s) of the design process should your group have spent more time? Which parts required less time?

The primary thing in which our group should have spent more time on in the design phase is designing more manufacturing friendly parts. When designing in SolidWorks, we rarely considered the possible ways our parts could be designed, and ended up 3D printing almost everything. While these parts fit together well for the most part, the material is weaker compared to a part that could be manufactured with metal, especially when considering waterproofing. We could have spent time on our initial prints, as they took up time and resources and were barely used (compared to the prints for the next iteration of design). Lastly, while the proof of concepts were important in the design process, too much time was spent refining them and making sure they worked well while we could have been moving to the next phase of designing.

Was there a component of the prototype that was significantly easier or harder to make/assemble than expected?

One component that was harder to make than we expected was the electronics housing. After researching the required battery dimensions, we found that the part would have to be much larger than we anticipated. We still decided to 3D print it. This caused several flaws in the part: the bottom of the part had a "pillowy" appearance due to sitting on the heated bed for so long, the holes were slightly undersized, it didn’t print square (the first time we printed it) and it also had cracks that may have allowed water into the part. If given the opportunity to re-design the part from scratch, we may have gone with glued laser-cut pieces or injection molding.

In hindsight, was there another design concept that might have been more successful than the chosen concept?

In hindsight, using two propellers rather than one would have improved our design in two ways. Firstly, it would have allowed for more power and thus a much faster maximum speed for the user. Secondly, it would have brought the motor closer to the users back, thus reducing the moment from the propulsion force. It is important to note that using two motors would have made us over budget, but in future iterations of this project, using a two motor design could lead to many improvements. Secondly, the current design does not efficiently connect our DPW to our tank. While it connects well, there is a lot of wasted space, again leading to the motor being farther away from the user’s back than it should be. Redesigning this connection to reduce wasted space would help solve this problem.
8.2 Design Resources

How did your group decide which codes and standards were most relevant? Did they influence your design concepts?

– Since diving can be a dangerous sport, we focused on finding codes and standards that focused on the safety of the diver. Specifically, we considered unsafe situations that the diver could find themselves in while wearing the DPW, such as a malfunctioning jetpack or accidentally placing their hands near the motor blades, and then found codes and standards to address these situations. These codes and standards then influenced our design concepts through the quick release pin mechanism and the motor housing covers.

Was your group missing any critical information when it generated and evaluated concepts?

– We did not consider operating this jetpack at a depth of 40 m or the diver entry modes such as falling backwards out of the boat when generating and evaluating concepts. Understanding these load cases might have changed the material and the structure of the selected DPW concept to focus on withstanding these conditions in addition to the safety, removable weight, hands-free control, cost, user friendly, and bulk criteria used for the selection process.

Were there additional engineering analyses that could have helped guide your design?

– An additional analysis that would have been very helpful and would have helped us achieve one of our initial customer goals was to analyze the effect of pressure on the device. With the lid and bottom of the battery housing providing a relatively large unsupported span, it’s most likely that these spots would not hold up to an FEA that can simulate the pressures at a depth of 40m. With this engineering analysis, we may have been prompted to create an additional support structure inside the battery housing.

If you were able to redo the course, what would you have done differently the second time around?

– While we concluded that we would likely have chosen to stick with a design similar to the one we ended up using this semester, we would have liked to experiment more with other manufacturing-friendly techniques for certain parts such as the electronics housing component. This would have several benefits including improved waterproofing capability as well as making the product more market-capable. As it stands, we have four unique 3d printed objects, which is not suitable for mass production.

Given more time and money, what upgrades could be made to the working prototype?

– Budget constraints were most apparent with the decision to use one propeller on the top of the device. We are aware that the current design may produce torque on the user while operating. With a larger budget, we would have explored the possibility of using two propellers on either side of the device, providing increased thrust and reducing the torque on the diver.

In terms of time constraint, we would have looked to improve the waterproofing ability of the device. This would have been done by either using a higher quality 3d print with larger wall thickness and greater infill or by looking at alternative materials to eliminate the need for 3d printing all together.
8.3 Team Organization

Were team members’ skills complementary? Are there additional skills that would have benefited this project?

- Considering that all team members are senior mechanical engineering students from the same university, we concluded that we were each able to provide specific skills that helped benefit the project. Specifically, Lucca was able to bring his knowledge of electronics and coding to help with the actual running of the device. Nico was able to use extensive CAD skills for a large portion of the design. Andrew Beukelman was able to use his knowledge of FEM and manufacturing for stress analyses, the acrylic top, and sunken bolt-holes. Andrew Kessler was able to provide a business background in terms of satisfying the customer’s needs and viewing the device from the users’ perspective. While Lucca was able to construct the electronics setup, it may have been nice to have a computer science student to help with the coding and provide additional features we did not think of. Additionally, a more knowledgeable engineer to help with the waterproofing ability would have been helpful to advise us early on in the design process. Waterproofing was our last step and many design decisions were made in the earlier stages that did not take waterproofing into consideration.

Does this design experience inspire your group to attempt other design projects? If so, what type of projects?

- Making the DPW definitely inspired us to attempt other design projects. Specifically, we found that projects that require a wide range of skills or that have an inherent challenge to them, such as waterproofing, interest us the most. Additionally, projects that enable people to glide faster than the average swimmer without any exertion, or do what is normally impossible alone, are what we want to continue pursuing.
Bibliography


## A Parts List

The following link leads to the google sheet that contains the original parts list: [https://docs.google.com/spreadsheets/d/1FkjrjK93L0IPG-aQoGJPVgZkEgAFN7IMnPBPXj1bgh4/edit?usp=sharing](https://docs.google.com/spreadsheets/d/1FkjrjK93L0IPG-aQoGJPVgZkEgAFN7IMnPBPXj1bgh4/edit?usp=sharing). Table 63 is an image of this spreadsheet.

<table>
<thead>
<tr>
<th>Part</th>
<th>Source</th>
<th>Supplier Part</th>
<th>Color, TPI, other part IDs</th>
<th>Unit Price/Price per</th>
<th>Quantity</th>
<th>Total Price</th>
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<tbody>
<tr>
<td>1 Thruster</td>
<td>RobotShy</td>
<td>BESC30-R1</td>
<td>T-200 Thruster With BlueE</td>
<td>$194.00</td>
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<td>2 Arduino Shield</td>
<td>Adafruit</td>
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<td>Screw-Down Shield, 0.1&quot; G</td>
<td>$14.95</td>
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<td>3 Arduino</td>
<td>sparkfun</td>
<td>DEV-13975</td>
<td>Pins in R3 Format</td>
<td>$19.95</td>
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<td>ADXL335</td>
<td>Triple Axis</td>
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<tr>
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<td>5.2 Amp, 4S, 30C</td>
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<td>Black</td>
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<td>7 Washdown toggle switch</td>
<td>mcmaster</td>
<td>7172K21</td>
<td>Two position, rounded</td>
<td>$11.48</td>
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<td>Multicolor</td>
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<td>Grade 8 Steel, 1/4&quot;-20 Thread Size, 1-1/2&quot; Long, Fully Threaded</td>
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Total: $369.77

Figure 63: Parts List from Google Sheets