Electric/Solar Powered Jet Ski

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Abstract

The overall goal of our MQP project is to convert a gas-powered jet ski into a fully electric vehicle with custom battery housing, motor mount, and electrical system. Our purpose for this project is to contribute to the green energy initiative by realizing vehicle designs that reduce carbon emissions, particularly personal watercrafts (PWCs). The goal of our work was to develop a fully functional prototype demonstrating benchmark performance with respect to existing academic and commercial designs.

Table of Contents

Table of Figures

Authorship

Michael Hartwick is responsible for the research, design, fabrication, analysis, and written sections of the motor mounting system.

Mason Kolb is responsible for the research for the environmental impact, jet ski history, overall jet ski design, finite elements analysis for the battery box and driveshaft, writing parts of the conclusion and FEA on the battery box.

Jack-Duffy Protentis is responsible for conceptualizing the electric jet ski and proposed this MQP. Jack is responsible for the research, design, fabrication, analysis, and written specifications of the battery box.

Daniel Luis Soltren is responsible for research, design, and implementation of electrical system components for this project.

Leo Quick is responsible for research, design, overseeing manufacture and assembly of driveshaft assembly, and relative written sections.

1. Introduction

Following its invention in the late-1700s, the internal combustion engine "has been the dominant prime mover in our society… gasoline and diesel engines have a prominent position since they are, by far, the largest produced engines in the world; as such, their influence on social and economic life is of paramount importance" (1).

The most prominent application of these engines is its utilization as a power source for the majority of both land and water operated vehicles. For more than 75 years, gas powered engines have been the leader in transportation technology with little to no alternative or competition. This was until the emergence of electric motors began to not only challenge the use of these gas engines but expose some of the problems that they bring to the society they influence so greatly.

Although a strong source of power generation for vehicles, gas engines have drawbacks. Among the most notable and seemingly obvious is the emission of toxic chemicals into the atmosphere resulting from the use of gas power. Apart from vehicles, this issue has become increasingly apparent over recent years seeing as though "approximately 75% of the power generated in the United States comes from the burning of fossil fuels" (2) which has the potential to develop into a major concern for the planet's well-being if something is not done to change it. With respect to gas-powered watercrafts, engines are also dumping toxins into the waters of oceans, rivers, lakes and streams in addition to the pollution going into the air from the likes of land vehicles. Furthermore, fossil fuel is nonrenewable and includes gas and oil that are of depleting quantity and will completely run out if changes are not implemented, which creates a need for sustainable electric vehicle design.

Companies have already made large strides into widening the market and advancing the progress and efficiency of electric vehicles. However, in the current market there is little to no commercial production for electric powered watercrafts, which is where our project hopes to advance that progress by converting a gas-powered jet ski to one that is fully electric.

2. Background

In the early 1900's, the electric car accounted for more than one-third of all vehicles on the road. However, the evolution of the Model T and Henry Ford's efficient assembly lines led to a rapid decline in electric vehicles (3). Cheap crude oil from Texas also contributed to the disappearance of the electric car. Although there were small periods of creativity and attempts at improving electric vehicles, it was not until the mid-1990's that, due to changes in federal and state regulations, there began a renewed interest in improving and refining the electric car.

2.1 Solving a Global Crisis

Most recently, the international attention on the global climate crisis and the immediate need to create and formulate innovative solutions to improve our ecosystem have forced us to begin to think creatively and differently as to how we use fossil fuels. It has become apparent and an immediate crisis that we need to create, grow, and enhance any and all possible options that would result in environmentally friendly solutions to problems such as pollution, radioactive waste, and carbon emissions. Knowing the impact fossil fuels have in our waterways and personal watercrafts (PWCs) are worthy of scrutiny and further development of which there has been very little work done.

It is a significant environmental crisis that motorized watercraft engines dump toxins into the environment that compromise rivers, streams, and lakes (4). These toxins also create significant damage and harm to the wildlife in our waters whose survival is critical for the long-term stability of our ecosystem. We need to look beyond just a standard motorized boat, but we also need to look at jet skis that dump excessive amounts of pollutants directly into the waters through which they travel (4). Based on its gasoline use and potential for oil spills, the jet ski is an example of a vehicle that must evolve to satisfy the requirements for a sustainable environment.

2.2 History of Jet Ski Design

Introduced by Kawaski in 1972, the jet ski was first developed as a stand-up personal watercraft as a motorcycle for the sea (5). Popular amongst thrill seekers, the jet ski offered both waterpower and performance. At the time, the engine was a modified 400 cubic centimeter, 2-stroke twin cylinder engine, however, in 2011, the Environmental Protection Agency created restrictions on two stroke engines because they are inherently dirtier, leaving un-combusted oil and gas exiting the exhaust. As of current state, we have jet skis on the market that are 1400 cubic centimeters and are supercharged that are designed to be extremely high powered. However, there is a direct relationship between greater power and greater waste entering the atmosphere and water.

A jet ski's main form of propulsion is a water jet, as the name suggests. The jet propulsion is accomplished by sucking water in through an intake gate at the bottom of the craft and pushing the water out a smaller diameter hole called a nozzle. This sucking is created by a set of spinning blades in a confined tube that makes up an impeller. The impeller is the name for a propeller that has been encased in a tube which is what the jet ski has was previously stated. The impeller is powered by the engine of the jet ski which allows for the small PWC to have the great acceleration and the directional control it is so well known for.

The directional controls of the jet ski are fairly simple, consisting of a set of handlebars that when turned adjust the direction of the nozzle, which controls the direction of the jet. This changes the direction of the force out and, because all forces have an equal and opposite reaction, causes the jet ski to turn as it reacts to the force of the jet of water.

The jet ski does however have some drawbacks that should be noted. Due to its relatively small hull width, the jet ski's handling at slow speeds leaves much to be desired. It is not uncommon for a jet ski to roll while taking a relatively shallow turn at slow speeds. Also, any significant shifting of weight by the driver and/or passengers while at slow speeds can cause the jet ski to roll as well or dump the passengers into the water. Overall, the jet ski needs to have a powerful jet in order to be the nimble PWC that is expected of it.

As a response to this environmental and global crisis, our team proposes to utilize natural resources that will effectively and systematically help reduce motor vehicle pollution. Our team's work is to develop an alternate, environmentally friendly design for power watercrafts. To accomplish this task, our team has proposed to design and develop a battery powered solution to power a fully electric jet ski. Applying alternative power to fossil fuel to provide energy and drive the performance of our jet ski will demonstrate a reasonably affordable and environmentally acceptable method to enjoy the benefits of watercraft technology without the associated environmental costs.

What we currently know is that due to environmental concerns, some bodies of water already do not allow motorized watercrafts on them (6). As the global climate crisis and research developed continues to demonstrate the negative impact fossil fuel has on the environment from air quality to wildlife to drinking, there has been a significant shift in looking to reduce the impact of these fuels on the environment. As a result, we believe that this industry could be dramatically improved by looking at methods to reduce the environmental impact of fossil fuel powered watercraft. The significance of our project is evident and we believe that the jet ski, and in particular, our MQP, could have the potential to reduce the carbon footprint.

2.3 Electric Jet Ski Progress

Even though there has not been much innovation in the market for an electric jet ski, there has been some progress made in the area. One example comes from the University of Western Australia (UWA). In 2016, A project team from UWA developed a fully functional electric powered jet ski with modifications to a stock 2008 Seadoo 4-TEC (7). In partnership with Submersible Motor Engineering, the team designed a jet ski that had the capability of operating at a speed of 25 mph for roughly 30 minutes. One of the most important design criteria for our project is to analyze this initiative by achieving both an improved top speed and battery life while remaining cost effective.

Another example of an electric powered jet ski comes from Nikola Motors, an electric trucking company based in Scottsdale, Arizona. In April of 2019, the company announced "an all-electric sit-down personal watercraft called the Wav… a wild looking jet-ski style vehicle that Nikola Motors CEO Trevor Milton called the "future of watercraft" (8) which is planned to be released sometime in 2020. However, price details and performance specifications have not been released at the time of the conclusion of this project. We believe that our project could provide various reference points as to specifications necessary to have an ideal vehicle regarding motor and battery requirements.

As of current state, there are no well-designed, well-tested electric powered jet ski models on the market. As referenced above, there have been very few attempts that have resulted in limited success. An example of one of these models that has been experimented with is one that uses a traditional body jet ski that utilizes a hydrofoil design. However, both models that have been recently tested on the market, lack the performance in comparison to gas-powered jet skis. Therefore, while their jet ski is fully electric, it is not a competitive solution and will not perform well on the market.

We know that there is an opportunity in the marketplace for quality, battery powered jet skis that deliver the performance and price range that consumers are looking for. In addition to its positive impact our solution will have on the environment, there are many rural and remote parts of the world that have access to large waterways without access to gasoline (9). Our proposed project, once complete, will in theory provide a working model to enable affordable transportation and commerce for communities across the globe.

2.4 Work Plan

Our work will involve us in taking a standard jet ski, removing all of the gas engine components. We will also remove the impeller and old drive shaft. This is to verify the integrity of the impeller and clear out the workspace. We will then prepare the hull for the new parts by leveling out sections with fiberglass, fiberglassing over the exhaust hole, and removing the old motor mounts. Once the hull is prepared the battery banks will be mounted first. They will be eveningly distributed along the sides of the inner hall and have a grouping in the front. The base plate for each battery box will be inserted first, then the boxes themselves to check fit. The mounting blocks for the motor will be inserted next. These will be screwed into the fiberglass hull and be set a specified distance in based off of the drive shaft size and motor fitting. The motor mount will be attached to the motor next and will be lowered into the hull. At this point the motor mount will be attached to the mounting block. This will conclude the motor mounting process. The batteries now have to be attached to the motor and the motor controller system. This will be installed and properly mounted inside the hull. The throttle control will also be set up in this step. The final step for the jet ski is to secure the drive shaft onto the motor and reinstall the impeller, taking care to make sure it too is secured to the drive shaft.

3. Methodology

The purpose of this project is to successfully convert a gas-powered personal watercraft into a fully electric-powered system that matches or exceeds the capability of the original design. Our research focuses on the following question: what specifications, parts, and mounting are required to satisfy our performance criteria? To address this question, we developed a series of objectives: Research, Design, and Build/Test.

3.1 Research

In the initial development of our project, the team needed to conduct preliminary research in order to understand what we needed to accomplish, how it was going to be done, and what has been done previously from which we can learn and apply to our work. Some of the first things we looked into were previous work with electric jet skis so that we could determine where we to begin with our re-design. We learned a lot from the electric jet ski project done by the University of Western Australia, as stated in the background, by analyzing their report and understanding the specific steps they took for their design and details with their motor and electrical system. Additionally, the team looked into calculations to figure out the specifications for an ideal motor to power the jet ski, fit the physical hull constraints, align with the electrical configurations, and remain within an allotted budget.

Furthermore, the team researched different battery configurations that would be applicable to our prototype, while remaining cost effective and space efficient for a battery box design, as well as a complete electrical configuration including a motor controller. Finally, we wanted to understand more about the environmental impact of certain aspects of our design ideas such as lithium ion batteries and potentially some of the negative impact by some of our hardware.

We spent a great deal of time at the project's outset during Term A researching and learning all we could about any innovation, failed or not, of an electric jet-ski prototype. In order to generate a detailed plan for our design, we needed to look more deeply at the evolution of this personal watercraft as well as any best-practices that have evolved in the industry as it relates to environmentally-friendly jet-skis. We used that information as the foundation for the development of our plan for the prototype.

3.2 Mechanical Design

3.2.1 Motor Mount

The design of the motor mount system relied on a majority of the preliminary research that was done, having to consider weight, material, and most importantly which motor was ultimately going to be used. One of the initial aspects of the design was making sure that the mount was able to conform to the inner hull of the jet ski itself, being able to mount to the holes on either side of the interior. Along with this, the mount (shown later in Figure 10) would have to fixture the motor while resisting forces in 3 different configurations: the acceleration of the jet ski forward, the force of the jet ski landing on the water, and finally the actual torque that the motor would apply to it. Furthermore, the mount would have to keep the motor securely fastened so that it cannot become displaced or succumb to any sort of vibration.

On the material side, only a few were initially considered seeing as though we knew what application we were going to use it for. The material of the mount had to be light enough so that it does not hinder our weight limit, strong enough to resist the forces mentioned previously, and finally cost effective to remain within a specific budget while being easily obtainable. The mounting system was initially designed utilizing the SolidWorks CAD software, moved to

3D-printed prototypes, and finally would be coded through ESPRIT to be machined on a MiniMill.

3.2.2 Battery Housing

After research as it relates to the design of the battery box, we realized that we would need to have the battery box (shown later in Figures 14 through 16) able to withstand the forces of a jet ski bouncing on the surface of the water while having three Nissan Leaf battery cells safely contained and watertight. Each battery box fit three cells but we needed 27 cells. The most constricting aspect was fitting the battery box in between the motor and the wall of the jet ski all while fitting under the seat and still being easily accessible and removable. The battery box is still needed to be able to fit throughout the hull as well. Along with the size restrictions, the mounting of the batteries to the hull required a mounting plate. This plate needed to be durable enough to keep the batteries in place during use but also be able to allow easy removable and replacement when wanting to replace with a fully charged battery box.

When considering the material, there were multiple factors at play that persuaded our decisions. The first consideration was strength versus weight of the battery box material. We knew that some type of plastic would be ideal material for the battery because of its strength to weight ratio. We then looked into lead-acid batteries. We discovered that there are few other batteries that deliver bulk power as cheaply as lead acid which makes the battery cost-effective for automobiles, golf cars, and marine power supply. The grid structurer of the battery is made from lead alloy (10). Unfortunately, this method needs an injection molding manufacturing project which we do not have access to. .

3.2.3 Drive Shaft

The drive shaft is the shaft that connects the motor to the impeller seen in Figure 14 and 15 in section 4.1.3. The original SeaDoo shaft is a long and thin stainless steel rod with splined gearing on both ends. The driveshaft has to be aligned properly and a proper fit, or detrimental vibration can cause it to fail. The shaft is made out of 316 stainless which is commonly used for marine applications. The shaft has rubber bumpers on each end. One end presses directly into the impeller. The shaft runs through the hull, there is an assembly of a boot and carbon seal to prevent water getting in the hull. The shaft's axial tolerances are sloppy, illustrated by the rubber bumpers, and the ability to perform while slightly contracted under high torque.

3.3 Electrical Design

For this project, there are several considerations, as well as numerous approaches, toward achieving the objectives stated above with respect to electrical design. Since the overall performance of our jet ski depends primarily on the output power provided by the motor, the battery configuration, motor controller design, as well as selection of other electrical components are all dependent on the type and specifications of the selected motor. In order to satisfy our performance goal of a linear speed of 50mph, given a max. load weight (including jet ski, two passengers, and 22lbs of luggage) of 786lbs, our selected motor must produce approximately 78.3kW output power. Based on this information, we initially selected an AC induction motor (AC-51 motor, 144V/500A) capable of producing 88HP and 108ft-lbs of torque with a peak KW output of 65.99KW. Unfortunately, due to current financial constraints, we settled with a series DC motor (ME1002 motor, 144V/300A) capable of producing 66.5ft-lbs of torque with a peak power output of 60KW. With respect to the electrical part of our project, we selected a Nissan Leaf lithium ion battery configuration for a power source with a commercial off the shelf (COTS) battery management system. The motor controller, throttle control, and user display are custom design blocks.

To provide a general description, a trigger on the handle-bar controls the throttle, which allow the operator to accelerate by sending analog information to the encoder which functions as an analog-to-digital converter (ADC), converting the analog signal to a digital signal that can be read by a microcontroller, which is usually part of a motor controller. The battery configuration is connected to a motor driver (also part of the motor controller) that uses a larger chip or discrete MOSFETs which can handle large amounts of current and voltage relative to the microcontroller. The microcontroller functions as the "brain" of the device, indirectly instructing the motor to operate based on input received from the encoder. By regulating the amount of current the motor has access to, it controls the output power and torque of the motor. The torque force generated by the motor is related to the angular velocity (RPM) of the motor shaft which is connected to a drive shaft. This drive shaft turns the impeller which “converts” the angular velocity to linear speed by sucking in the water received from an intake grate located at the bottom of the hull and pushing it out of the tail-end of the jet ski.

It is also imperative that the operator have access to certain information about the jet ski in order to make informed decisions regarding jet ski operation and maintenance. With that being said, the overall jet ski system design is as shown in Figure 1 below.

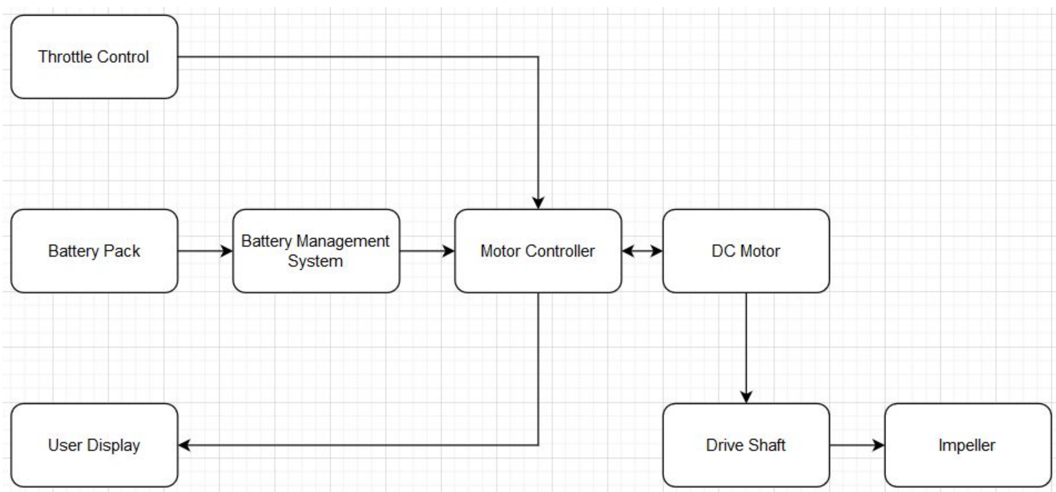

Figure 1: Overall Electrical Design Chart

The electrical system is composed of five design blocks: voltage source, battery management system (BMS), throttle control, user display and motor controller. For a power source we used Nissan Leaf Battery G2 Modules. For the BMS, we decided that it was best to purchase an off the shelf item. We purchased a Dilithium Design BMS Controller which is ideally suited for electric vehicle applications and capable of measuring up to 24 cells. Our user display is meant to convey critical information such as voltage levels and speed in Miles per hour and RPMs. The throttle control consists of a half twist throttle grip and a rotary encoder to convert the angular position of the throttle grip into a digital signal that can be fed into an Arduino UNO for processing.

In our design of the motor controller we used the Microchip Curiosity Nano evaluation kit. Supported by MP LAB X IDE, features an on-board debugger and used to evaluate the PIC18F47Q10 microcontroller. The microcontroller itself is inexpensive and has core independent peripherals such as complementary waveform generator and configurable logic cell, which is ideal for the application of the ripple counting technique which is used to determine the motor speed and position based on the current drawn from the motor. In case there were any issues with our motor controller design, we purchased an on the shelf motor controller as a backup. The motor controller is not complete and we were not able to move forward with the user display design. With the preliminary work achieved this year, a future MQP team could successfully complete those portions.

3.3.1 Battery Pack

There are no ideal contenders for the electric vehicle conversions, and lithium-ion remains a good choice. Out of the battery chemistries shown in Figure 2, Li-nickel-manganese-cobalt (NMC), Li-phosphate and Li-manganese stand out as being superior. The popular Li-cobalt (not listed) used in consumer products was believed to be not robust enough; nevertheless, this high energy dense “computer battery” powers the Tesla Roadster and Smart Fortwo ED.

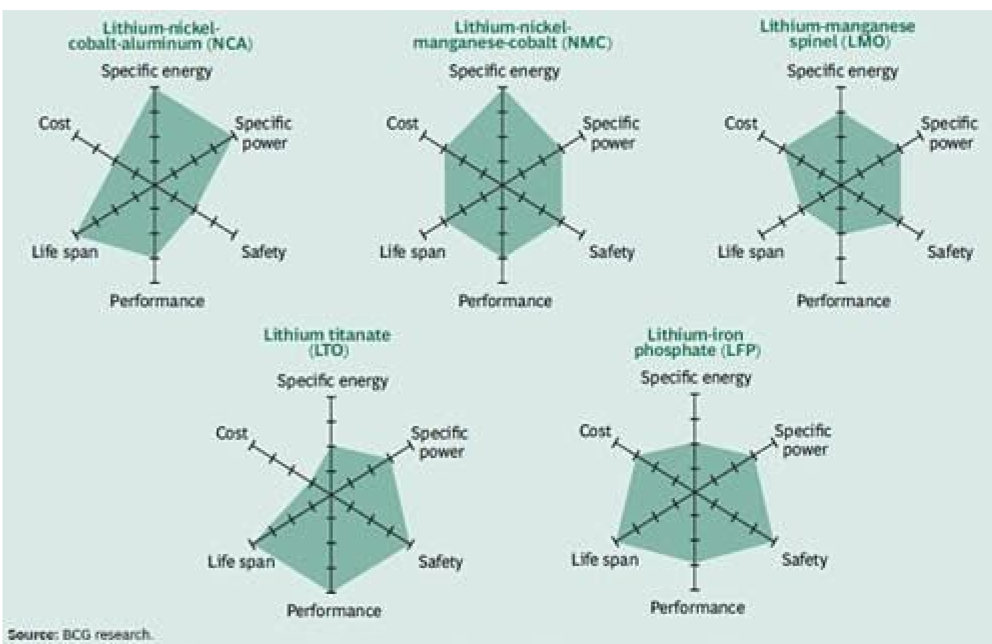

Figure 2: Battery Analysis for Electric Cars (Boston Consulting Group (BCG))
https://batteryuniversity.com/learn/archive/is_li_ion_the_solution_for_the_electric_vehicle

The above table compares batteries in terms of *safety; specific energy,* also known as energy density or capacity; *specific power,* or the ability to deliver high current on demand; *performance,* the ability to function at hot and cold temperatures; *life span,* which includes the number of cycles delivered as well as calendar life; and finally *cost.* The figure does not mention charge times. All batteries offered for EV powertrains can be charged reasonably fast if a suitable electrical power outlet is available. A charge time of a few hours is acceptable for most users, and super-fast charging is the exception. Nor does the table reveal self-discharge, another battery characteristic that needs scrutiny. In general, Li-ion batteries have low self-discharge, and this parameter can mostly be ignored when the battery is new. However, aging when exposed to heat pockets can increase the self-discharge of the affected cells and cause management problems. Among the EV battery candidates, Li-phosphate exhibits a higher self-discharge than the other systems.

None of the five battery chemistries in Figure 2 show a significant advantage over others, and the size of the spider fields are similar in volume, although different in shape. Focusing on one strong attribute inevitably discounts another. NCA, for example, has a high capacity but presents a safety challenge, whereas Li-phosphate is a safer system but has lower capacity. In the absence of a clear winner, car manufacturers include peripherals to compensate for the deficiencies. Battery manufacturers in turn assist by custom-designing the cell to strengthen the important characteristics needed for the application. Here is a brief summary of the most important characteristics of a battery for the electric powertrain:

a. **Safety** is one of the most important aspects when choosing a battery for the EV. A single incident blown out of proportion by the media could turn the public against such a vehicle. Similar concerns occurred 100 years ago when steam engines exploded and gasoline tanks caught fire. The main concern is a thermal runaway of the battery. Carefully designed safety circuits with robust enclosures should virtually eliminate this, but the possibility of a serious accident exists. A battery must also be safe when exposed to misuse and advancing age.

b. **Life Span** reflects *cycle count* and *longevity.* Most EV batteries are guaranteed for 8–10 years or 160,000 km (100,000 miles). Capacity loss through aging is a challenge, especially in hot climates. Auto manufacturers lack information as to how batteries age under different user conditions and climates. To compensate for capacity loss, EV manufacturers increase the size of the batteries to allow for some degradation within the guaranteed service life.
c. **Performance** reflects the condition of the battery when driving the EV in blistering summer heat and freezing temperatures. Unlike an IC engine that works over a large temperature range, batteries are sensitive to cold and heat and require some climate control. In vehicles powered solely by a battery, the energy to moderate the battery temperature, as well as heat and cool the cabin, comes from the battery.
d. **Specific energy** demonstrates how much energy a battery can hold in weight, which reflects the driving range. It is sobering to realize that in terms of output per weight, a battery generates only one percent the energy of fossil fuel. One liter of gasoline (1kg) produces roughly 12kW of energy, whereas a 1kg battery delivers about 120 watts. We must keep in mind that the electric motor is better than 90 percent efficient while the IC engine comes in at only about 30 percent. In spite of this difference, the energy storage capability of a battery will need to double and quadruple before it can compete head-to-head with the IC engine.
e. **Specific power** demonstrates acceleration, and most EV batteries respond well. An electric motor with the same horsepower has a better torque ratio than an IC engine.
f. **Cost** presents a major drawback. There is no assurance that the battery's target price of $250–400 per kWh, which BCG predicts, can be met. The mandated protection circuits for safety, battery managements for status, climate control for longevity and the 8–10-year warranty add to this challenge. The price of the battery alone amounts to the value of a vehicle with an IC engine, essentially doubling the price of the EV.

After conducting research, it was concluded that Nissan Leaf Lithium Ion batteries are most suitable for our application. Lithium-ion batteries are used in most consumer electronics and electric vehicles due to their high-energy per unit mass relative to other electrical energy storage systems. Some of their benefits include: high-energy efficiency, better-than-average high temperature performance, low self-discharge, and high power-to-weight ratio. Lithium-ion batteries are also the most expensive of battery types. For the average electric vehicle, a lithium-ion battery configuration can range anywhere between $7k and $20k, by far the most-costly component of the vehicle.

3.3.2 Throttle control

The throttle is the physical connection between the operator and the performance of the jet ski. In marine jet propulsion systems, throttle control is applied to control the operation of the electric motor of the watercraft. The encoder detects the change (in degrees) of the turning of the handle grip or lever and sends a corresponding digital signal to the microcontroller for use in regulating the motor. For our design the throttle control will consist of the following:

- Half-twist throttle grip

Figure 3: Throttle Grip

- Rotary encoder

Figure 4: Rotary Encoder

- Arduino UNO Microcontroller

Figure 5: Arduino UNO Microcontroller

With a rotary encoder, we have two square wave outputs (A and B) which are 90 degrees out of phase with each other. The number of pulses or steps generated per complete turn varies. The diagram below shows how the phases A and B relate to each other when the encoder is turned clockwise or counter-clockwise.

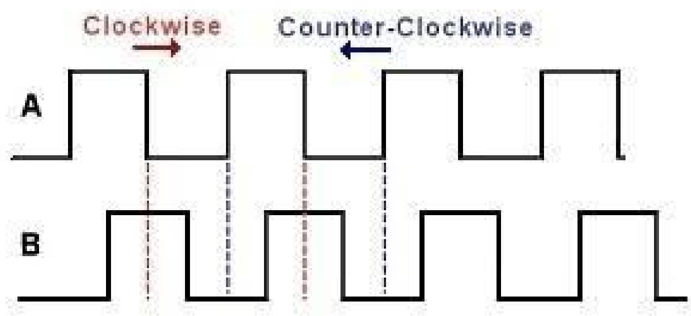

Figure 6: Rotary Encoder Square Wave Outputs

Every time the A signal pulse goes from positive to zero, we read the value of the B pulse. We see that when the encoder is turned clockwise the B pulse is always positive. When the encoder is turned counterclockwise the B pulse is negative. By testing both outputs with a microcontroller we can determine the direction of turn and by counting the number of A pulses how far it has turned. Indeed, we could go one stage further and count the frequency of the pulses to determine how fast it is being turned. We can see that the rotary encoder has a lot of advantages over a potentiometer.

Each time our timer code triggers, we compare the value of our A pulse with its previous value. If it has gone from positive to zero, we then check the value of the B pulse to see if it is positive or zero. Depending on the outcome we can increment or decrement a counter. We then can feed this signal into a microcontroller to generate a pulse width modulated (PWM) signal to control the motor.

The microcontroller will be powered by a separate battery configuration then that of the motor and connected to the motor driver in order to direct the motor driver with respect to encoder input.

3.3.3 Battery Management System (BMS)

There are three main objectives common to all Battery Management Systems:

- Protect the cells or the battery from damage
- Prolong the life of the battery

- Maintain the battery in a state in which it can fulfil the functional requirements of the application for which it was specified.

To achieve these objectives the BMS may incorporate one or more of the following functions:

a. **Cell Protection:** Protecting the battery from out of tolerance operating conditions is fundamental to all BMS applications. In practice, the BMS must provide full cell protection to cover almost any eventuality. Operating a battery outside of its specified design limits will inevitably lead to failure of the battery. Apart from the inconvenience, the cost of replacing the battery can be prohibitive. This is particularly true for high voltage and high power automotive batteries which must operate in hostile environments and which at the same time are subject to abuse by the user.
b. **Charge control:** This is an essential feature of BMS. More batteries are damaged by inappropriate charging than by any other cause.
c. **Demand Management:** While not directly related to the operation of the battery itself, demand management refers to the application in which the battery is used. Its objective is to minimise the current drain on the battery by designing power saving techniques into the applications circuitry and thus prolong the time between battery charges.
d. **SOC Determination:** Many applications require a knowledge of the State of Charge (SOC) of the battery or of the individual cells in the battery chain. This may simply be for providing the user with an indication of the capacity left in the battery, or it could be needed in a control circuit to ensure optimum control of the charging process.
e. **SOH Determination:** The State of Health (SOH) is a measure of a battery's capability to deliver its specified output. This is vital for assessing the readiness of emergency power equipment and is an indicator of whether maintenance actions are needed.
f. **Cell Balancing:** In multi-cell battery chains, small differences between cells due to production tolerances or operating conditions tend to be magnified with each charge / discharge cycle. Weaker cells become overstressed during charging causing them to become even weaker, until they eventually fail causing premature failure of the battery.

Cell balancing is a way of compensating for weaker cells by equalising the charge on all the cells in the chain and thus extending battery life.

g. **History - (Log Book Function):** Monitoring and storing the battery's history is another possible function of the BMS. This is needed in order to estimate the State of Health of the battery, but also to determine whether it has been subject to abuse. Parameters such as number of cycles, maximum and minimum voltages and temperatures and maximum charging and discharging currents can be recorded for subsequent evaluation. This can be an important tool in assessing warranty claims.

h. **Authentication and Identification:** The BMS also allows the possibility to record information about the cell such as the manufacturer's type designation and the cell chemistry which can facilitate automatic testing and the batch or serial number and the date of manufacture which enables traceability in case of cell failures.

i. **Communications:** Most BMS systems incorporate some form of communications between the battery and the charger or test equipment. Some have links to other systems interfacing with the battery for monitoring its condition or its history. Communications interfaces are also needed to allow the user access to the battery for modifying the BMS control parameters or for diagnostics and test.

3.3.4 Motor Controller

With respect to motor controller design, brushed DC motors are easier to control since its speed and torque are proportional to the applied voltage and current. The speed of the brushed DC motor is controlled by the voltage applied to the armature, and the torque by the armature current. The flux and the torque can easily be controlled separately. The controller is used to regulate the torque, speed, position or direction of the motor. Control can be implemented either in an open or closed loop and the system can use feedback from optical encoders and limit switches. The ideal features a motor controller should have for brushed DC motor control are:

- Basic I/O: on/off control
- Capture/Compare/PWM: variable speed/torque
- Comparators: overcurrent detection and protection

- Analog-to-Digital Converters: motor voltage or analog control input
- Programmable Gain Amplifiers: current measurement for torque control
- Quadrature Encoder Interface: interface with optical encoders

After conducting research, it was determined that for this design block we would implement a half-bridge circuit controlled by a Microchip microcontroller (see Figure 7). The Microchip website contains useful documentation regarding DC motor control that was intended to be used as a template for the design of our motor controller. Central to this design is the PIC18F47Q10 microcontroller (see Figure 8). The curiosity Nano evaluation kit includes a debugger and useful documentation regarding how to integrate this device into a custom design.

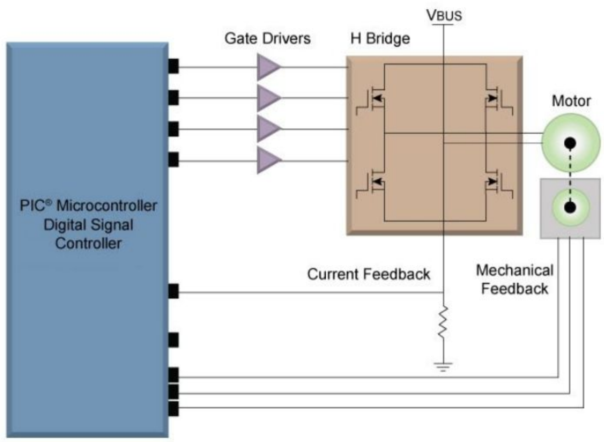

Figure 7: General Motor Controller Diagram
https://www.microchip.com/design-centers/motor-control-and-drive/motor-types/brushed-dc-motor

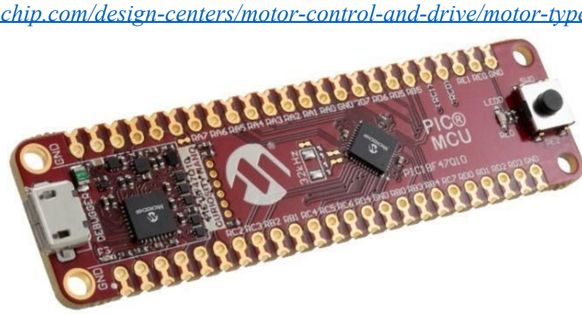

Figure 8: PIC18F47Q10 Curiosity Nano Hardware Platform
https://www.microchip.com/DevelopmentTools/ProductDetails/PartNO/DM182029

There is documentation on the Microchip website that provides information regarding how to control a brushed DC motor using a ripple counting technique. This type of motor control does not rely on sensors to determine the actual motor position or speed. It determines the position of the motor based on electrical parameters such as Back-EMF or motor current feedback, which is present during the motor run-time. Current feedback is used for circuit protection, motor speed estimation or position control. The motor current can be monitored by placing a current sense resistor in a series with the motor. Using a current sense amplifier tapped on the resistor terminals, the current detected is converted to a measurable voltage that acts as a position or speed feedback signal to a closed-loop motor control. In this application, the periodic variations in current feedback, due to BDC motor electro-mechanical construction, are observed. The displacement taken by the motor rotation can be identified by counting the number of those periodic variations during motor operation. Thus, this method is called the "ripple counting" technique.

3.4 Build/Test

In the building of the battery boxes, we realized that the most effective way to 3-D print would be to use a Morse extruder which prints thicker layers and is a more time effective printing method for large prints. For testing, we inserted three Nissan Leaf battery cells into our battery boxes to ensure a good fit and that the battery casing would withstand the forces in real life and not just in simulation. We also tested to make sure all of our tolerances were accurate. Unfortunately, due to COVID-19, we only had one battery case completed without any base plate so we could not finish testing all of our testing and quality assurances. Due to COVID-19 we were never able to mill the motor plate or the mounting blocks for attaching the motor to the jet ski. This made it impossible to test the output of the engine and if our design actually worked.

The progress of the electrical system design was limited due to late access to funding as well as the extent of work to be done in a limited amount of time. A general simulation was run in MATLAB/Simulink, and physical parts were ordered for the battery configuration, BMS, motor controller and throttle control design blocks. The user display design block remains to be developed.

4. Results and Analysis

4.1 Mechanical System

4.1.1 Motor Mount

The preliminary motor mount design for the jet ski was made up of three pieces to fit the ME0913 PMAC motor that was left over to our project from the SAE Baja Vehicle MQP. Some initial considerations were made before beginning the modeling of the mount such as planning for 6061 Aluminum as the material and utilizing an overall part thickness of 0.25 inches. These considerations were made based on research done on the electric jet ski project from the University of Western Australia (UWA) in which a similar mounting system was constructed out of Aluminum alloy at a similar thickness (see Appendix A).

Unlike the UWA motor mounting system which conformed to the hull of the jet ski, we decided to design a mount which more conformed to the motor itself based on the smaller dimensions of the hull and to give as much support to the motor while fastened. The three pieces designed for the mounting system include a bottom bracket, a top bracket, and back plate. Images of the preliminary motor mount design can be seen in Appendix A, including the three individual parts and an assembly of the entire mount together. We have also started the initial fabricating of these parts using the Foisie Innovation Studio at WPI and the makerspace workshop to 3D print each part out of PLA plastic to test the fit and potentially work out necessary alterations. Once the mount design is finalized the parts will be fabricated in Washburn labs preferably out of 6061 aluminum or similar aluminum alloy.

After additional research on the specifications and performance of the ME0913 motor in comparison to potential alternatives, our group decided to move to purchasing the ME1002 motor (Figure 9) in order to come closer to our desired goals for top speed and battery life due to a higher torque and power output. These performance specs can be found in Appendix A.

Figure 9: ME1002 Series Wound DC Motor

The purchase of this motor used the last of our MQP budget but we were able to justify it after being awarded $3,500 through the WPI Tinkerbox program. As a result of our ability to secure a brand new motor, the mounting system would subsequently have to change from the preliminary iterations stated above. In the first part of the term, we began with some initial ideation designs on using Solidworks that were similar to that of the design for the ME0913 motor (see Appendix A). However, after discussion with both the team and Ian Anderson from the machine lab, we came up with the final version of an adaptable mount design for the ME1002 utilizing a front plate and two-side blocks (Figure 10).

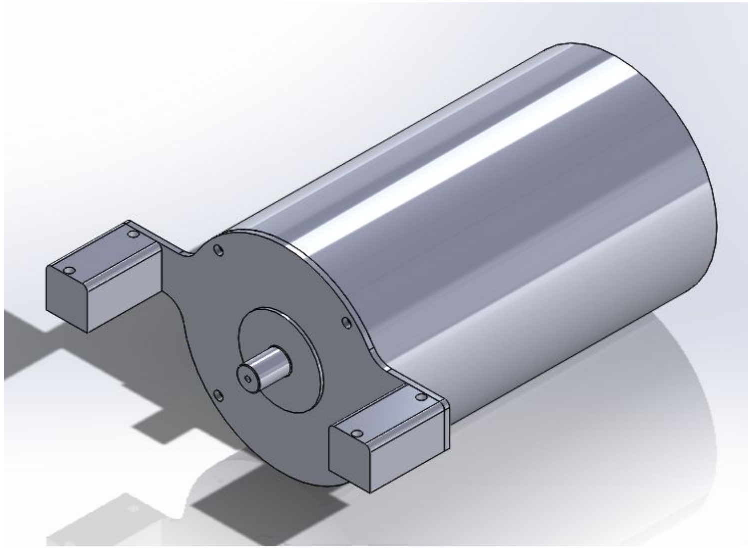

Figure 10: ME1002 Final Mount Design w/ Motor

The current design was a culmination of multiple different considerations brought up through meetings and research. First, in terms of ease of manufacturing, the use of a simple front plate is much easier to fabricate being made from a quarter inch thick aluminum plate that can be machined entirely through one code. Moreover, this plate, when screwed into the motor at the four hole locations will be able to resist the torque that comes when it is running while also holding it in place within the hull. Second, the side blocks will also be manufactured from a 2" x 2" 6061 aluminum block and have four threaded holes on the front side which the front plate will screw into. The blocks themselves will sit up on the side of the hull with two clearance holes which are for bolts that will go through the bracket mounting into threaded holes in the inner hull. Pictures of each individual part for the motor mount can be found in Appendix A.

Overall, the team is confident that this design will be a superior design that will be able to support the motor while also being very space efficient. The only consideration is that we may need to make a motor support bracket that will brace the motor in the rear allowing for better alignment of the motor and prop shaft. We can use the remaining aluminum from the motor mounts to manufacture those support brackets.

Later, the team worked on finalizing the ESPRIT files for each of the mount parts so that the entirety of the system can be machined at the start of D-term. The team met with a lab monitor from Washburn shops several times to go over specifically how the files needed to be created so that there would be no issues with their fabrication on the MiniMill. The front plate consists of a pocketing operation for the center cutout, followed by multiple drilling operations for the 12 total clearance holes, and lastly the outline is machined through a contouring operation. The side blocks needed to be machined using two different codes, one for the top face fillets and clearance holes, and one for the threaded holes on the front.

One positive to the simplicity of this design is that both side blocks can be machined using the same two codes for each, one would just have to be rotated 180 degrees in the MiniMill so the top holes line up correctly. For the first code of the side block, the team needed to create a wireframe milling operation for the filleted edges and then another combination of drilling operations for the clearance holes. The second code consisted of three unique drilling operations, a spot drill, pre-drill, and finally a form tap to actually create the necessary threads. Screenshots of the operations and simulations for each of these ESPRIT files can be found in Appendix A.

To analyze the motor mounting system, the team put the design into Ansys Workbench in order to simulate the multiple forces mentioned earlier that the system would be put under during the motion of the jet ski. For these forces and analyses to be correctly output, certain boundary conditions needed to be set within the setup of the software. First, the underside of the side blocks were grounded to the x-z plane to emulate the blocks being bolted to the inner hull. Also, a contact region was inserted so that the 4 holes on the front of the side blocks were rigidly connected to either set of 4 holes on the sides of the front plate to emulate the plate and side blocks being bolted together. Figures of both of these boundary conditions can be found in Appendix A.

Once the initial boundary conditions were set, the 3 forces mentioned previously in the methodology section were applied to the system which can be seen in Figure 11.

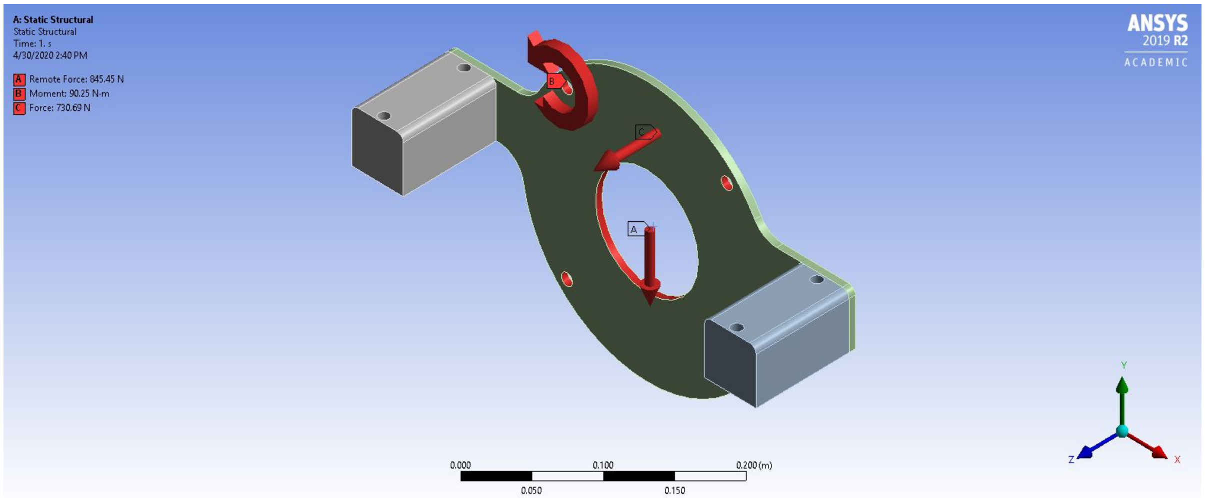

Figure 11: Motor Mount Simulated Forces A, B, and C

Force A was applied directly downward onto the center cutout of the front plate calculated by multiplying the mass of the motor times the acceleration due to gravity:

$$A = 86.18\ kg \times 9.81\ m/s^2 = 845.45\ N$$

Force B was applied as a moment on the 4 holes connecting the front plate to the motor itself with the torque value equal to that of which the maximum that the ME1002 could apply which can be found on the motor's data sheet in Appendix A:

$$B = 90.25\ N * m$$

Force C was applied into the backside of the front plate to emulate the forward acceleration force that the motor would apply to it, calculated by multiplying the mass of the motor times the estimated acceleration of the jet ski forward.

$$C = 86.18\ kg \times 9.83\ m/s^2 = 847.15\ N$$

The estimated value for the acceleration of the jet ski was calculated by dividing the top speed of an average jet ski and dividing it by the average time it would take for it to reach that speed:

$$24.58\ m/s \div 2.5\ s = 9.83\ m/s^2$$

Looking into the force analyses, the two types of results that were simulated were the total deformation and equivalent von-mises shear stress. These two results were the two most important to take into consideration with the aspect of the design in order to understand the stability and rigidity of the material and the structural integrity of the design as a whole. First, looking at the maximum total deformation of the design, the bottom side of the front plate deforms 1.15 mm as shown in Figure 12. Although this is not a negligible amount, it is very minimal and will not affect the longevity of the mount.

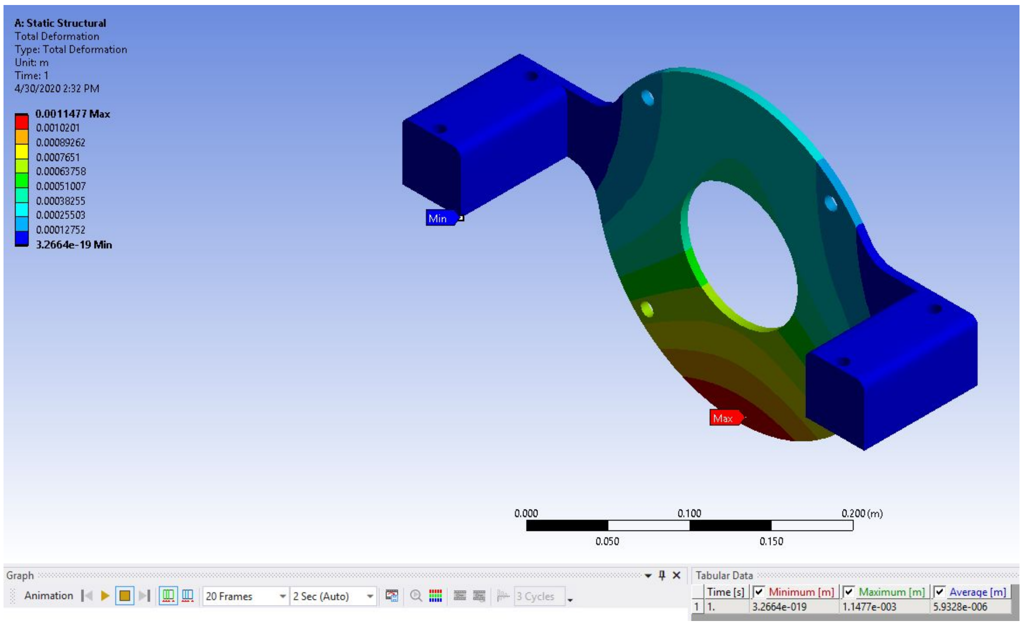

Figure 12: Motor Mount Total Deformation

Moving to the equivalent shear stress, almost the entirety of the mounting system has negligible stress. The only portion of the design that showed stresses that should be taken into account is on the edge of the underside of the front plate protrusions near where they contact the side blocks. At this point the maximum stress is 74.1 megapascals, which when compared to the tensile yield strength of the 6061 aluminum (276 megapascals) (11), is comfortably within a safety factor of 3. The underside of the motor mount showing these shear stresses are shown below in Figure 13.

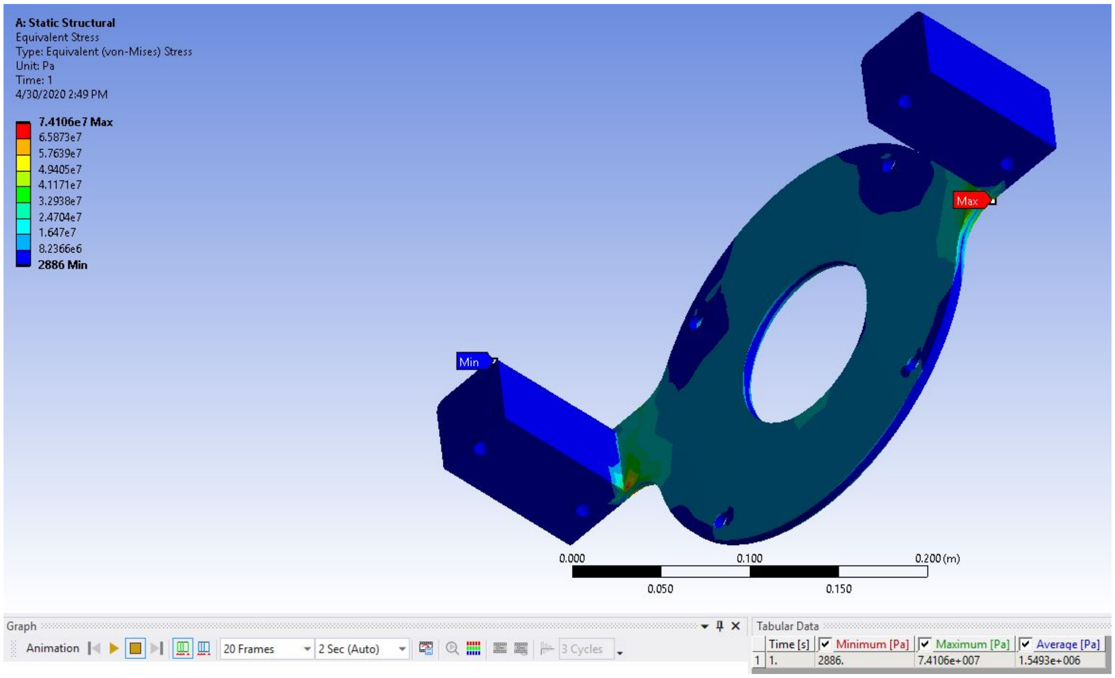

Figure 13: Motor Mount Equivalent Stress

In conclusion, the installation of the mounting system would be fairly simple. Unfortunately, as previously stated due to COVID-19, the team was unable to install any components to the jet ski but this will explain what would be done and how. Going through the necessary hardware to install it, all fasteners that would be needed can be seen in the following table:

Type	Quantity	Description
M10 x 1.25”	4	Fastens front plate to the ME1002 motor
¼-20 x 1”	8	Fastens side blocks to front plate
⅜-16 x 2.5”	4	Fastens side blocks to inner hull

Table 1: Motor Mount Parts List

As far as steps for installation, first, the two support blocks mentioned previously should be epoxied onto the bottom of the inner hull to provide support. Next, the side blocks should be fastened to the inner hull followed by the plate attaching to the blocks. Finally, the motor should be hoisted down onto the support blocks, then slid into the cutout of the front plate and fastened to it from there. This needs to be done making sure the motor connects to the drive shaft correctly and that all parts are secure.

4.1.2 Battery Housing

In the selection of the material for the battery box, the choice was easy. In order to create a water-tight, light-weight, durable box and mount, plastic would be the most suitable material. We decided that the best course of action for prototyping, given the nature of the project and the availability of resources, would be to proceed with 3-D printing the battery boxes by first, modeling them up in Solidworks and then putting them into a slicing software to be 3-D printed.

In the process of designing the waterproof battery casing for the electric jetski, we looked at the two other electric jet skis on the market at the moment. The Nikola Wav (8) is one brand and the other is the Taiga Orca (12). We noticed that their battery range was limited. We were inspired by electric tools to incorporate a replaceable battery box that could be easily swapped out for a fully charged one.

To design this piece, we decided to 3-D print the pieces for the best cost and weight effectiveness. The only disadvantage was that the 3-D printers print size restrictions. As a result, we had our battery box in three different parts.

a. One was the base plate. This would be screwed into the hull and be a permanent fixture that the battery box would be locked in to. Through a tested pattern that was printed, the protrusions on the battery box would allow the battery to slide left and right and then drop into its proper location making it substantially easier to align the battery box in place. To secure the battery box to the base plate, the protrusions would keep it sliding around in the X axis and Y axis direction. To ensure the battery box is stable in the Z axis, you would have to install metal hooks on either side of the base plate and then run a tough rubber strap connecting the two hooks up and over the battery box back down to the base plate keeping the battery secured down to the hull. Additionally, in the base plate we added slotted holes throughout the entire battery box to prevent water from pooling inside of the base plate. There are also channels running in a lattice pattern to allow for easy wiring and to ensure proper drainage of the hull along with making sure there is no standing water.

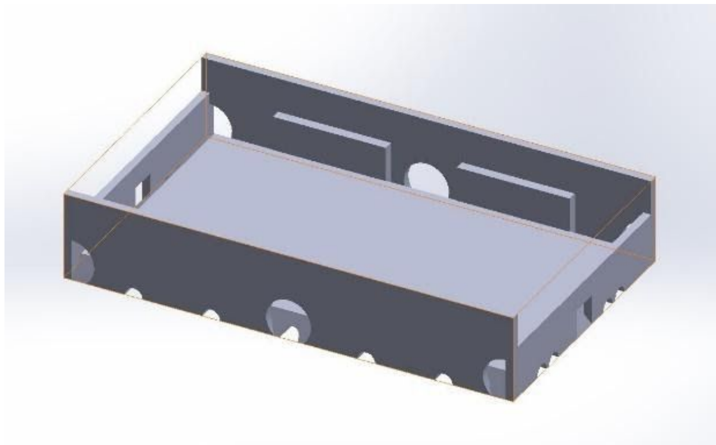

Figure 14: Battery Housing Base Plate

b. The bottom of the battery casing. This would be where the batteries sat in and where also where the battery would lock into the base plate. On the inside of the battery box, there is a small ridge that ensured the battery would not slide around on the inside. We would also run metal rods through all four corners with nuts on both ends to compress the batteries together ensuring they became one unit.

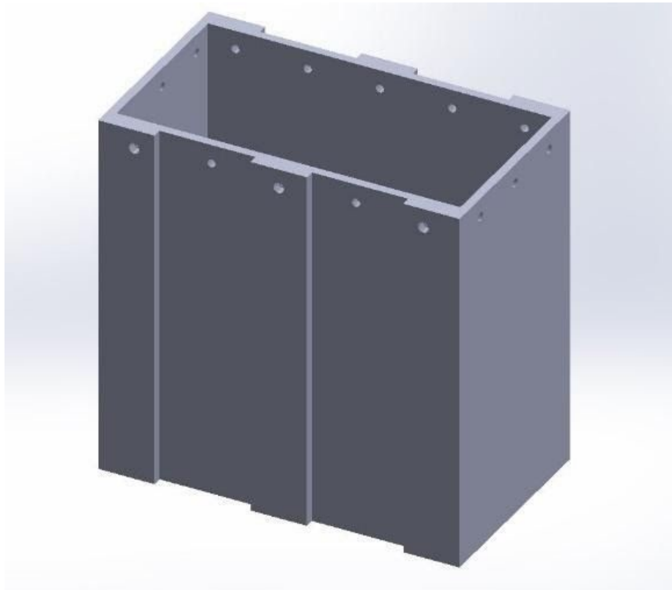

Figure 15: Battery Housing Bottom

c. The top of the casing which would be screwed into the bottom of the casing completing a watertight sealant around the batteries and also where the handle would mount to. To ensure a good connection with the battery management system (BMS), there needed to be a hole on one side that the plugs would protrude out of with a rubber grommet around the wires ensuring a water-tight seal.

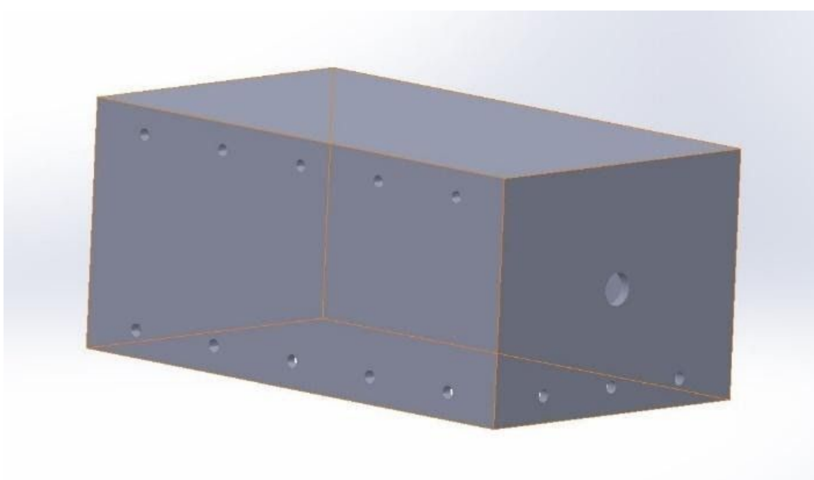

Figure 16: Battery Housing Case Top

d. The handle. This would be made out of aluminium due to the forces that would be applied to it for structural rigidity. We decided that the best way to mount the handle to the battery box and the bottom and top of the battery box to each other to maximize space efficiency would be to use hooked brass-threaded inserts. These inserts are installed by attaching one to a soldering iron inserting it into a specified diameter hole and setting it in to the correct depth by melting the plastic around it via the heat from the soldering iron.

The battery box consists of three major parts; a lid, a body and a mounting plate as seen in the appendix. The purpose of these parts is to have quick and interchangeable batteries made from the battery cells of a Nissan Leaf, hybrid, electric car. Creating the battery box, the restriction was the width of the hull and the motor and the size of the print plate of the 3D printer that we planned on using. We designed the battery box to be the maximum size that we could fit in the hull and the 3D printer's build platform. The battery box is loosely based upon what cordless drills do for their battery systems which is the batteries slide into place making contact with the electrical system transferring power. We also ran simulations to calculate and make sure that the battery box could withstand the forces that it would be subjected to.

One thing that the team tried to accomplish is that the batteries were easy and quick to remove from the hull replacing them with a fully charged battery while maintaining the battery cell's water tightness. For ease of wiring, we have decided to go with a plug-style connector instead of a contact-based connection. It should still be just as easy to remove and replace with a new battery but easier to wire. We have also decided to for material strength use an aluminum handle system instead of a 3-D printed handle.

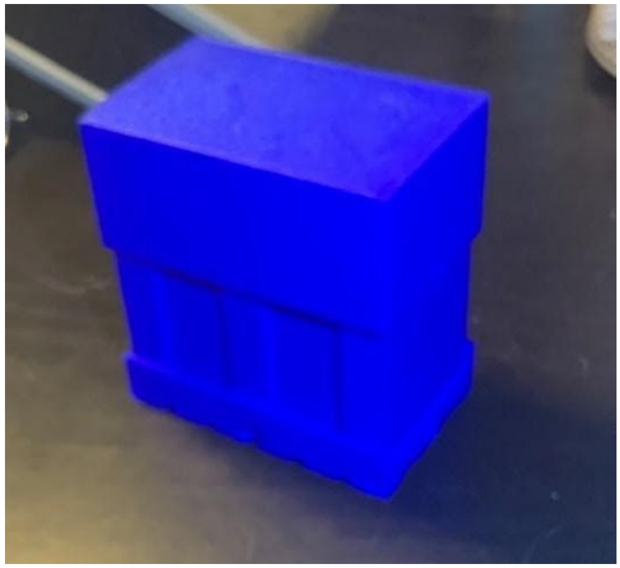

Figure 17: 3/10 Scale Battery Housing

A Finite element analysis (FEA) was done on the battery box with the primary function of making sure that when the box was removed it would not break under the weight of the batteries and itself. In the study the bottom of the box was fixed to simulate the proper force dynamic of the batteries inside. Next the top hole had a load applied to them as if they were bearings. This load is about 9.31 N per hole and is to simulate the force needed to lift the batteries up at a relatively normal rate. A picture of the setup is included below on the left. The yellow arrows represent the force and the blue triangles represent the fixed surf. An up-close hole can be seen to the right of the full box in figure 18.

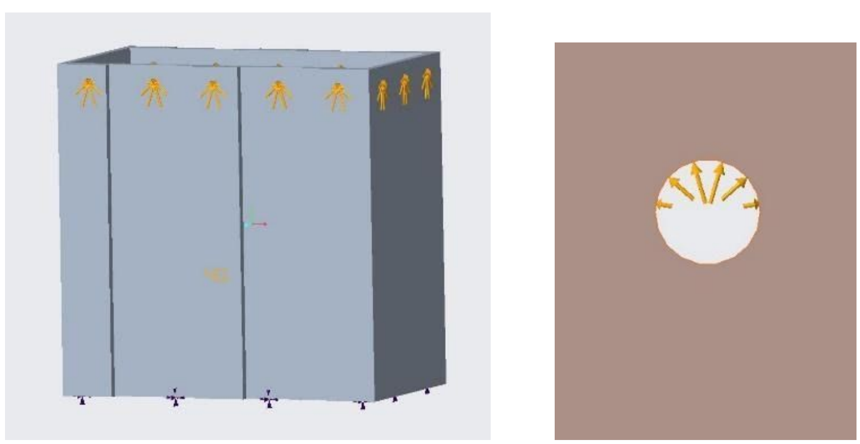

Figure 18: Battery Box Force

The results from this study are below. Figure 19 is the von Mises stress concentration of the whole part.

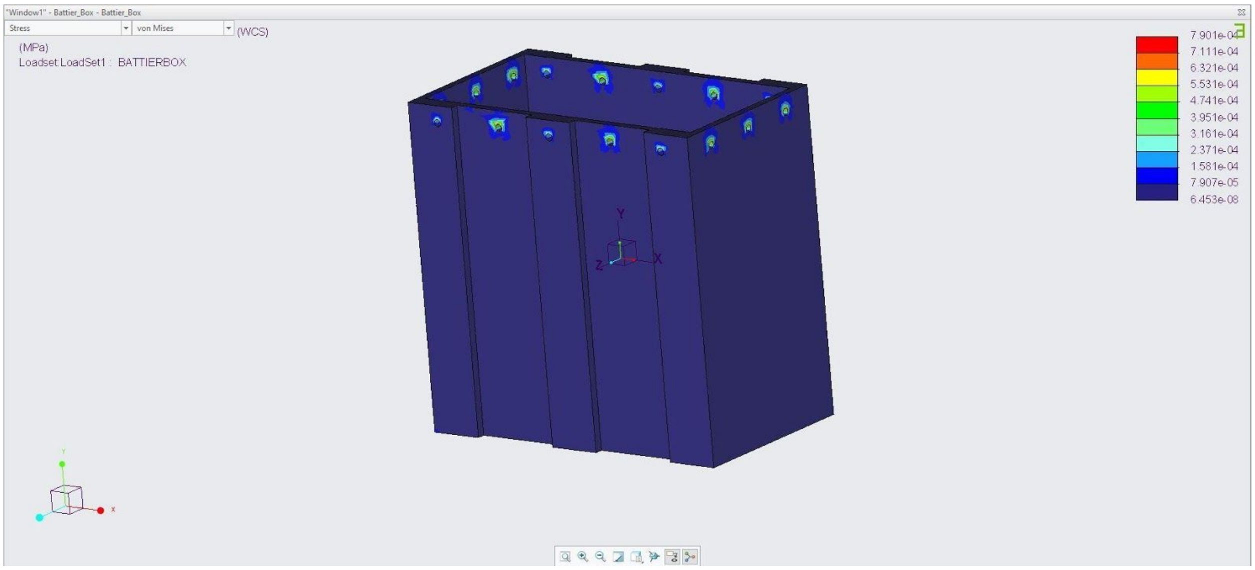

Figure 19: Battery Box Von Mises Stress

As you can see from the overall design, not a single section of the part reaches the high end of the stress principle. The max being 7.9E-4 MPa and the min being 6.45E-8 MPa. With the majority of the holes falling into the range of 1.58E-4 and 6.32E-4. Figure 20 shows a closer representation of the hole and stress ranges. The Young's Modulus of the material being used is 2390 MPa. This is significantly greater than the applied stress in any one region. In conclusion, the part should not fail at the holes or anywhere else on the part according to the simulations. If CoV-19 had not hampered this project, testing of the prototype could have been done to verify the FEA results.

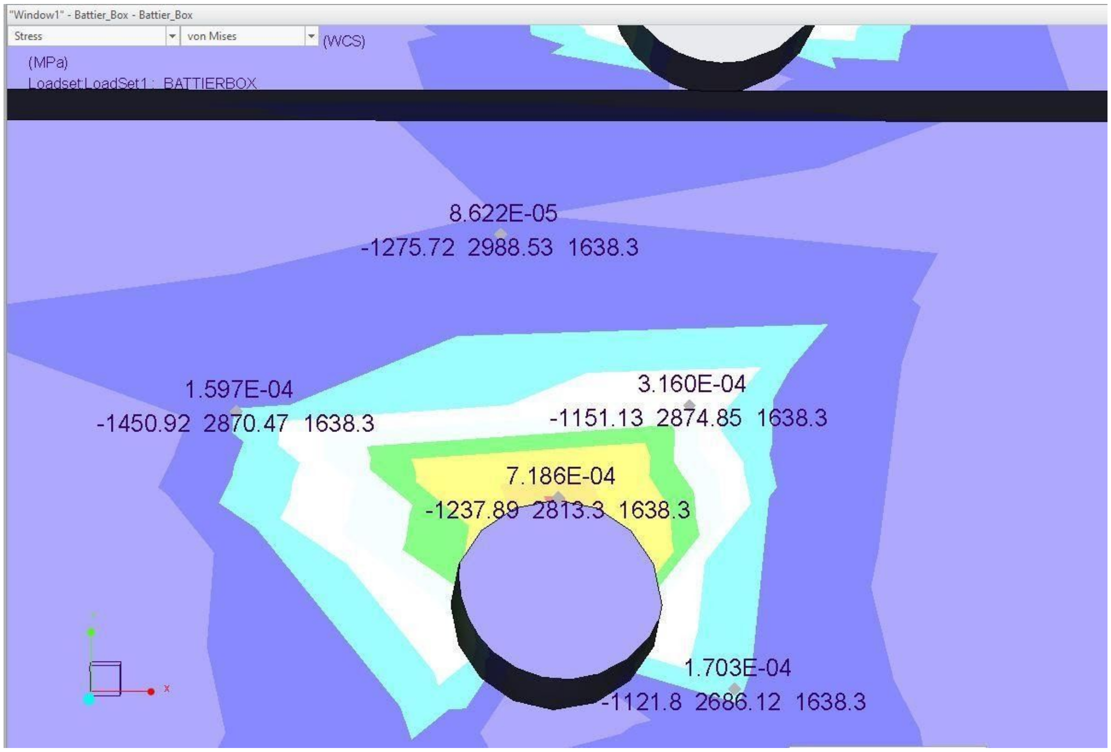

Figure 20: Point stress

4.1.3 Drive Shaft

The driveshaft transfers power from the motor to the impeller. Normally in a Sea Doo jet ski, the splined drive shaft fits into a large flywheel assembly, called the PTO, at the rear of the motor. The drive shaft itself needs a routine rebuild to ensure none of the sealing components have failed. The original shaft had grizzly corrosion, and a used replacement shaft was obtained. The steel the shaft is manufactured from is 316 stainless steel, which has good anti corrosion properties, a high strength, and high hardness (13).

The electric motor that the team selected is different in many aspects from the original combustion engine, so a new drivetrain had to be designed. With the electric motor, the PTO, or power take off, could have been adapted to fit the electric motor shaft. That would allow for the usage of the original driveshaft but would weigh the most for connection options. PTOs are able to protect the engine and shaft from bumps and vibrations.

An internal gear style couple could have also been used. Gear couplings have higher torque ratings than universal joints, which makes a gear coupling a more prudent choice. Gear couplings are also very space efficient, which is an important design factor for the project. The major drawback to using a gear coupling is cost.

The initial plan was using a monolithic cylinder, a large gear with two receiving ends. The first major issue with the singular receiving gear is it is a rigid couple. Rigid couples do not allow for misalignment and are not great in situations where shocks/vibrations in the drive occur. Another issue with the receiving gear is cutting the internal splining, to receive the driveshaft, can be complicated. Also designing the correct spline profile is a difficult process, as had been learned when designing a 3D-printed prototype. The design was abandoned due to the complexity/infeasibility to manufacture the piece.

The final design chosen for the shaft was a two-piece adapter shown in Figure 21.

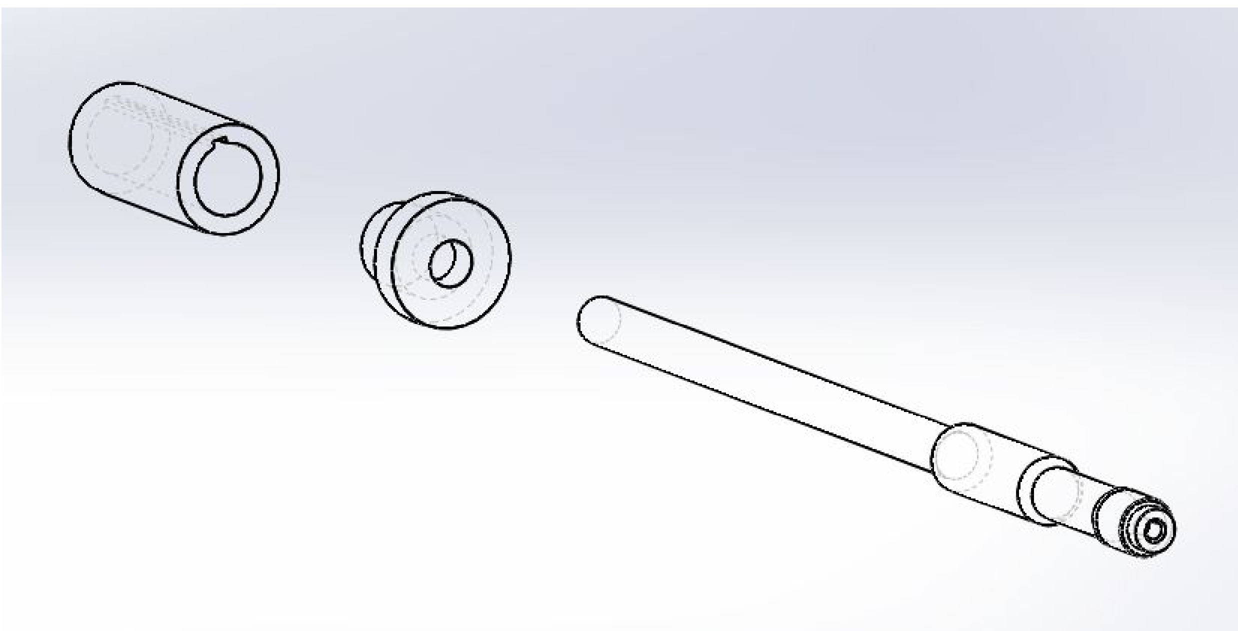

Figure 21: Driveshaft Exploded Assembly View

The sleeve part is a long cylindrical piece of 316 steel bored out to the diameter of the electric motor's shaft with 0.002" for an interference fit. A keyway would have been broached into the sleeve to lock the electric motor shaft to the sleeve (14). Two threaded holes would have been machined perpendicular to the keyway on the sleeve, for installation of securing grub screws. The sleeve was purposely made too long and meant to be lathed down to exact length once the motor and mount were installed. Consideration of the contraction driveshaft assembly, while being twisted, was taken in consideration. A second piece would have been machined to fit in the other end of the sleeve part. To fixture it, a weld would be used. The other end of the piece has a section to allow the drive shaft to be pressed and welded in. The splined end of the driveshaft that connected to the gasoline engine would be machined off, and the end would be lathed smooth, to allow for fitting to the piece.

Figure 22: Impeller Shaft (Driveshaft) and Impeller Connection

Welding can cause metal to lose temper/hardness, but with competent welding the change only occurs in the weld puddle. After welding the alignment is checked in a lathe and adjusted with heat, if needed. The welds would be peened when hot welds, to defuse stress risers and compress the surface of the weld (13).

Analysis for a shaft is tough since it requires incorporating forces translated from the drag of water translated from the impeller to the shaft, at different speeds. The areas next to weld are more prone to failure than welds themselves. A static test shows high stress at necked areas of the shaft, and the section where the shaft is welded to the adapter, under a static test at 100 N*m of torque. The boundary conditions for the test are fixturing of the motor end and a torque of 100N*m at the impeller end. This is illustrated in Figures 24 and 25 below. The maximum lateral displacement would be 0.6 mm at the end near the torque. The Von Mises stress analysis shows no spots approaching the yield strength of 410 MPa of a 316 steel bar. 100 N*m as a torque was used since the maximum possible torque with a 90 Volt DC setup is 90.25 N*m. Since the jet ski would normally be operated well below this output, 100 N*m acts as an extreme for testing.

Voltage Volts DC	Current AMPS	Speed RPM	Torque NM (Ft Lb)	Power KW (HP)	Efficiency %
90	300	2423	90.25 (66.5)	22.9 (30.7)	84.8
	250	2649	70.23 (51.8)	19.48 (26.1)	86.6
	220	2800	59 (43.5)	17.3 (23.2)	87.4
	205	2912	54.11 (39.9)	16.5 (22.1)	89.4
	180	3091	44.8 (33)	14.5 (19.4)	89.5
	170	3200	42.38 (31.3)	14.2 (19)	92.8

Figure 23: ME1002 Motor Technical Data

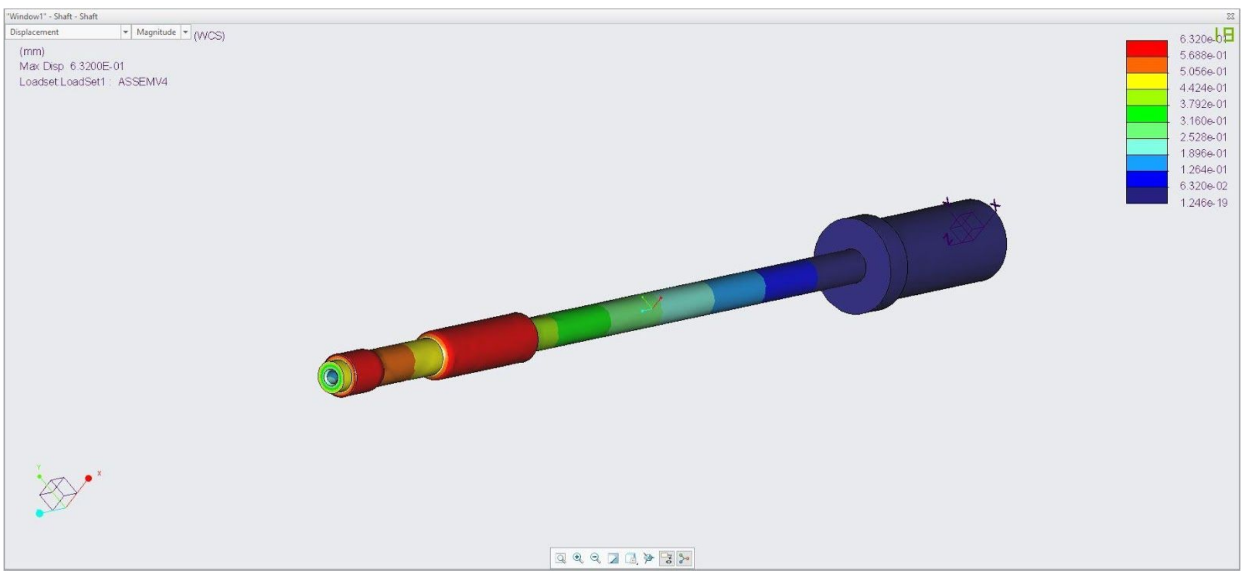

*Figure 24: Displacement under 100 N*m Torque at Impeller End*

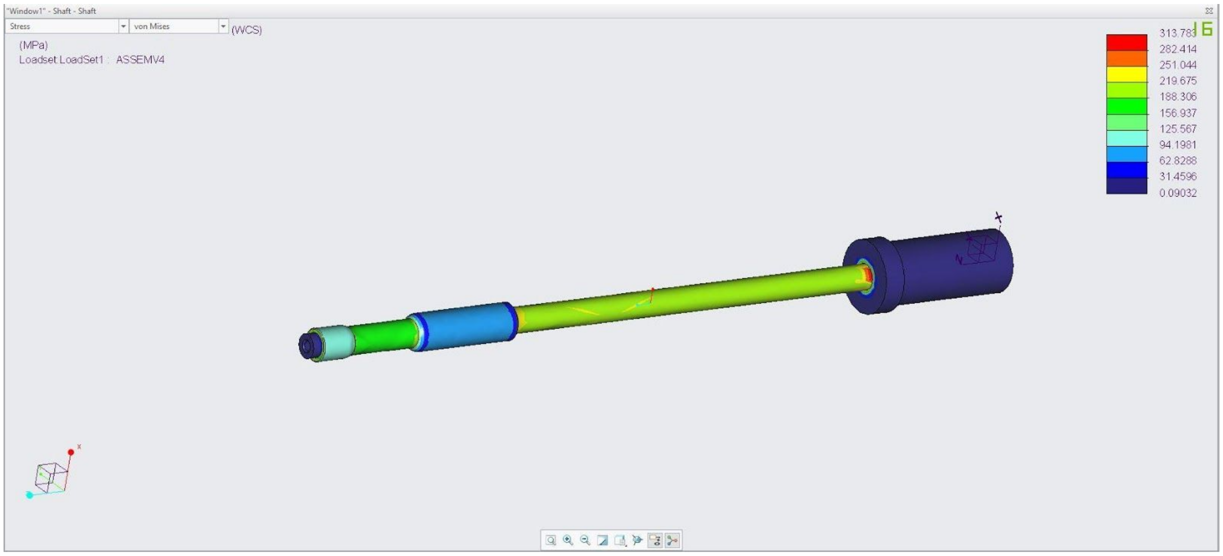

Figure 25: Von Mises Stress Analysis

4.2 Electrical System

4.2.1 MATLAB/Simulink Simulation

For our motor controller, we ran a simulation in MATLAB where we generate a PWM signal which is fed to a half-bridge circuit to control the speed of the motor. By setting the motor parameters to that of our physical motor (based on rated values), we were able to estimate the RPMs and current based on voltage source.

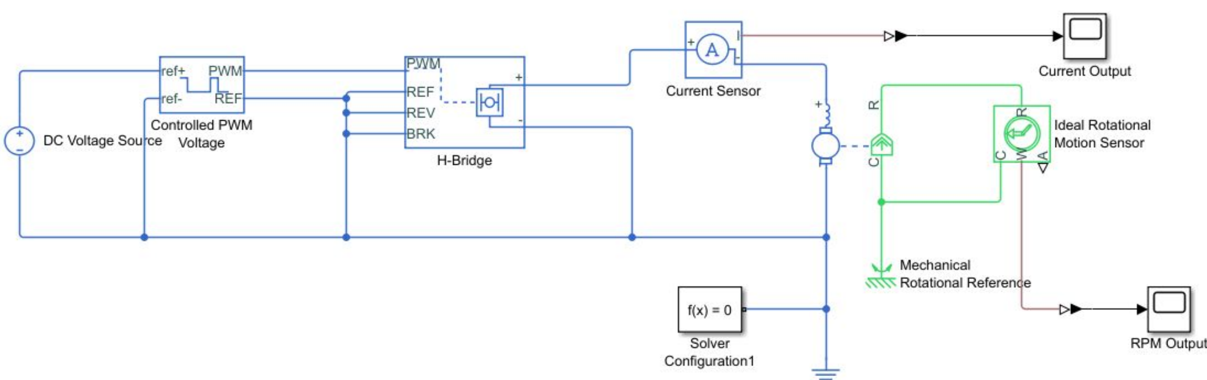

Figure 26: MATLAB/Simulink Simulation

The following figures show the results from running the simulation at different voltage values (in comparison to the ME1002 specification sheet rated values):

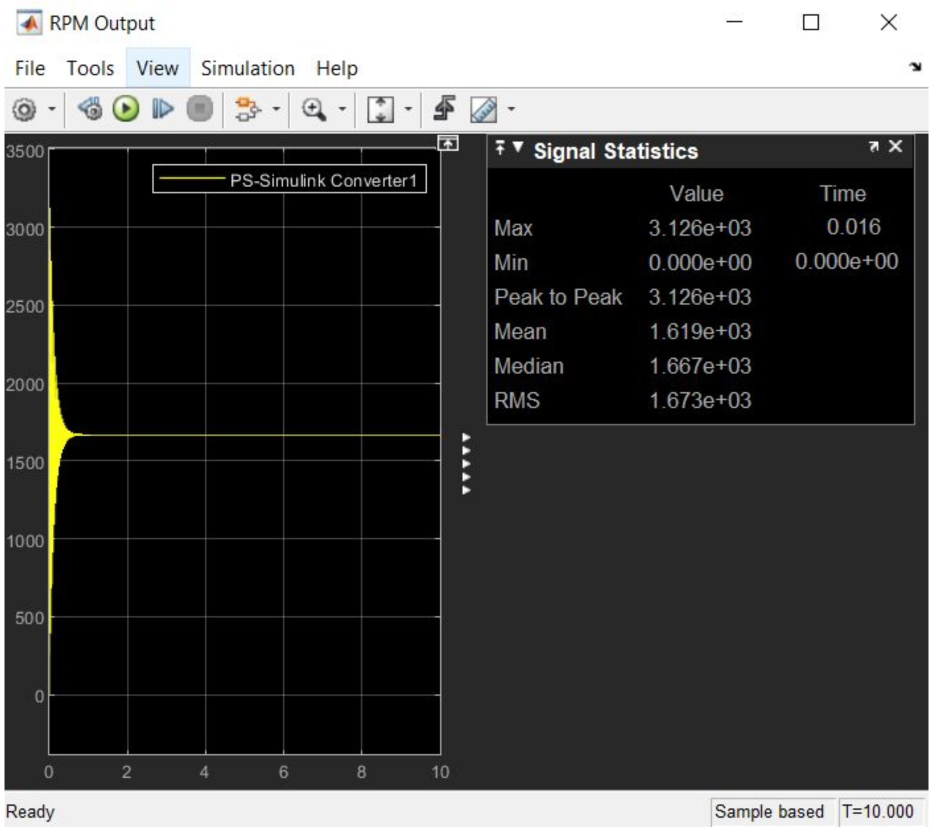

Figure 27:MATLAB/Simulink RPM Output at 48V (RPM (simulation) = 1667rpm; RPM (ME1002 spec. sheet, rated values) = 1700rpm)

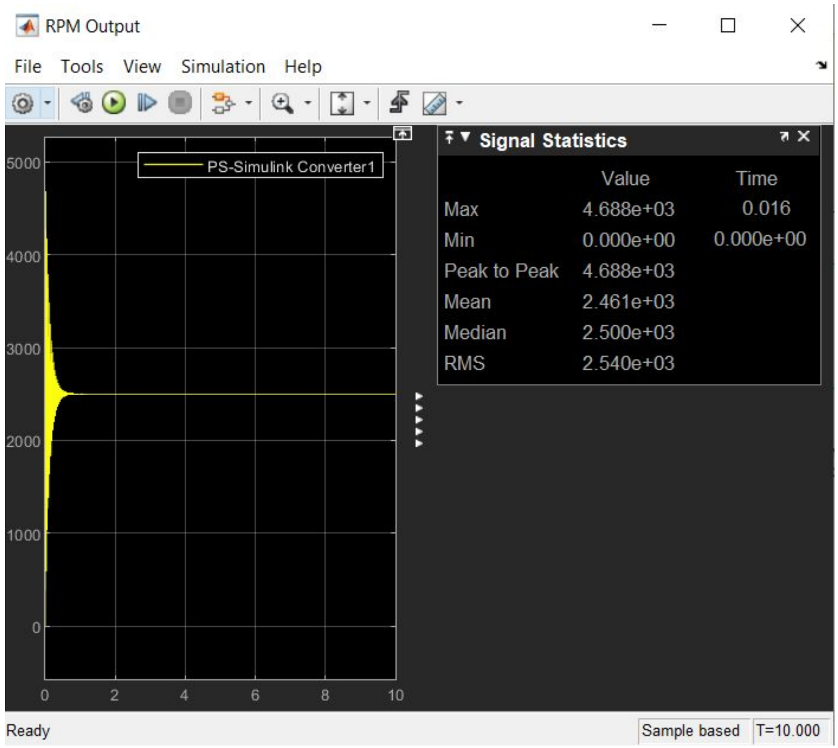

Figure 28:MATLAB/Simulink RPM Output at 72V (RPM (simulation) = 2500rpm; RPM (ME1002 spec. sheet, rated values) = 2329rpm)

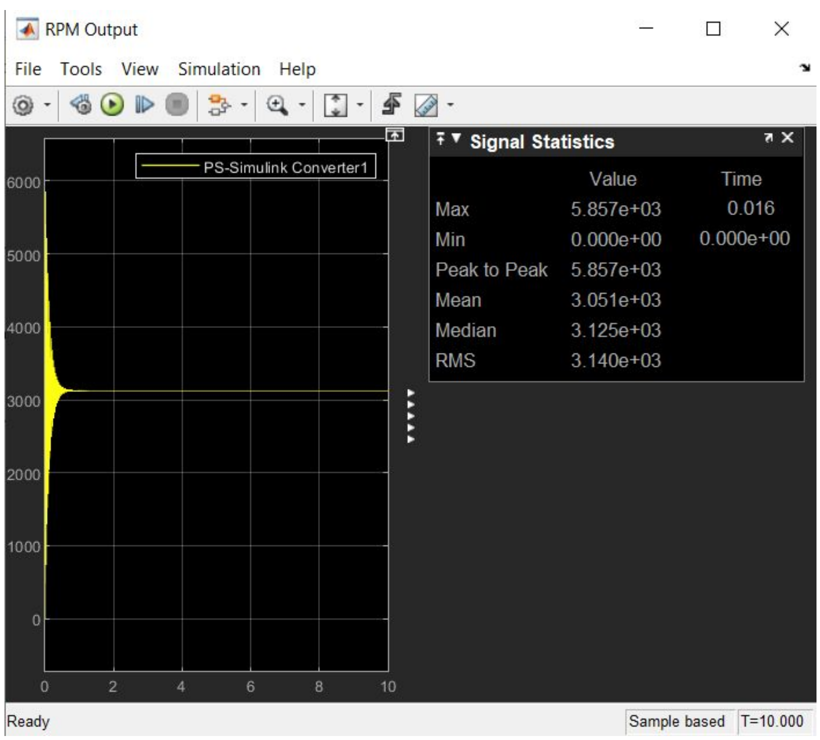

Figure 29:MATLAB/Simulink RPM Output at 90V (RPM (simulation) = 3125rpm; RPM (ME1002 spec. sheet, rated values) = 2912rpm)

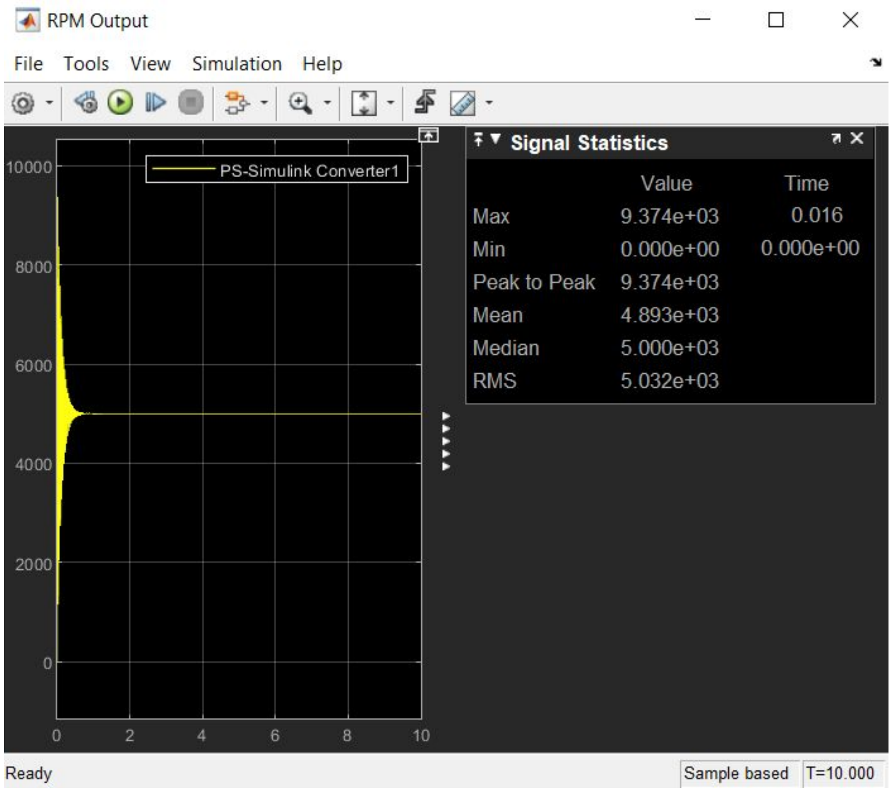

Figure 30:MATLAB/Simulink RPM Output at 144V (RPM (simulation) = 5000rpm; RPM (ME1002 spec. sheet, rated values) = 4659rpm)

4.2.2 Battery Pack

Each Nissan Leaf module is rated at 7.6V, 66A*hrs (for 5 in series we get 37.5V per pack). From our calculations we obtained the following values (given $276 per 5 modules):

To satisfy 144V/300A (packs of 5):

264A*hrs: 4s4p (4 in series, 4 in parallel) - $4800.00

132A*hrs: 4s2p (4 in series, 2 in parallel) - $2400.00

66A*hrs: 4s0p (4 in series, 0 parallel) - $1200.00

To satisfy 96V/300A (packs of 5):

264A*hrs: 3s4p (3 in series, 4 in parallel) - $3600.00

132A*hrs: 4s2p (3 in series, 2 in parallel) - $1800.00

66A*hrs: 4s0p (3 in series, 0 parallel) - $900.00

As stated above, the battery configuration is related to the voltage/current draw of the motor. Our load consists of a 144V/300A motor, therefore, due to financial constraints, we were able to purchase 24 G1 lithium-ion Nissan Leaf Batteries (7.6V, 500W, 66aH each cell). With 12 in series we will obtain 91.2V each pack (6kWh). Therefore, to satisfy our current application, we will use a 12s2p configuration (2 packs of 12 cells in parallel). This battery configuration will be connected to the motor driver which in turn will be controlled by the microcontroller to regulate the motor.

4.2.3 Throttle Control

The throttle grip, rotary encoder and Arduino UNO items were purchased (See Appendix D for price sheet), but due to timing constraints, no further steps were taken for this design block.

4.2.4 Battery Management System (BMS)

Due to the complexity involved with designing a battery management system, it was decided to purchase an off the shelf item to manage our Nissan Leaf battery pack. We purchased the Dilithium Design Battery Management System, which is ideally designed for electric vehicle applications (see Figure 31).

Figure 31: Dilithium Design BMS
https://www.thunderstruck-ev.com/bms-controller.html

The BMS controller consists of the BMS Processor and a measurement board in a single enclosure. The container is roughly 5 3/8" x 3 3/8" and 1 1/8" tall. It is a standalone 24 cell BMS, and up to three BMS Satellites may be added, resulting in 48, 72, and 96 cell systems. The BMS measurement board is optimized for monitoring cells in large lithium packs and designed to minimize power consumption, especially during long-term storage where battery drain is unacceptable. The BMS diagnostics verify proper functioning of measurement circuitry, verify cell wiring, and monitor for communication errors. Statistics captured include high and low cell watermark data which can be used to track cell performance under load, and Standard Deviation, which measures pack balance. The BMS also supports several error conditions. When driving, an alert is generated if any cell drops below the Low Voltage Cutoff (LVC) threshold. When charging, the BMS will generate an alert if any cell rises above the High Voltage Cutoff (HVC) threshold which can be used to stop charging. The BMS also supports a configurable Balance Voltage Cutoff (BVC) threshold, which can be used to communicate with the charger to reduce charge current.

4.2.5 Motor Controller

This part of the design was the most fluid given the uncertainties involved with whether we would actually purchase the motor with the specifications we were looking for. We initially agreed on an AC induction motor given it is the best type of motor for our application. However, we found a brushed DC motor with similar output power for roughly one-third the price of the AC-51 motor. Of course, the motor type has a direct effect on the motor driver/microcontroller system regulating its function. In general, it is usually advised to purchase a motor controller rather than building/designing one because of the potential setbacks due to time, effort, and likelihood of making costly mistakes. This is especially true for AC motor controllers.

We were fortunate to have secured the funding through Tinkerbox and GoFundMe therefore we were able to move forward and purchase a brushed DC motor. We were also able to purchase the majority of parts required to build a motor controller based on the Microchip documentation provided. This guidance allowed the motor controller to be much easier to accomplish. Unfortunately, due to COVID-19 constraints, it was difficult to move forward with the process of building the motor controller, designing a circuit board and ultimately connecting the controller to determine whether it functioned accurately or not. See Appendices for the Bill of Materials for all parts purchased for this design.

4.2.6 User display

The user display was intended to display useful information such as battery life and linear speed. There are numerous options as well as approaches to take, such as whether to use 7-segment displays or an LCD screen in case a “dashboard” approach is taken with respect to displaying information. If the Microchip motor controller solution is pursued, then the user display will need to be connected to the PIC18F47Q10 microcontroller. This design block was neglected primarily due to timing constraints.

5. Conclusions and Recommendations

Our team was very excited about the project as we saw tremendous potential in improving the personal watercraft market. As previously stated, between the environmental impact of the jet ski dumping fossil fuels into waterways and the attempts at creating a fossil-free device, we had proposed what we anticipated to be a good market solution. Working collectively with a diverse team including mechanical engineering majors and an electrical engineering major, we believed that our team would be able to successfully produce a potential prototype for the industry. We began our work with great ambition, a thoughtful and deliberate plan developed with thoughtful background research so we were eager to begin this MQP.

In developing this project, there were a series of unforeseen challenges that were presented to us. The first obstacle was the struggle we faced as it relates to the financial resources that we needed to secure in order to build the prototype. Fortunately, we worked tirelessly and were able, by the middle of Term C, to acquire a majority of the funding. According to our projected calculations, the operation of the jet ski with the resources that we had were adequate verses what we had originally calculated as performance goals pending full funding.

The second, much greater challenge, was a result of the pandemic and the closing of our campus. This translated to our inability to work collaboratively and collectively on campus in order to access and complete our project. We understand that this was challenging for all of us at WPI yet we know that it is of a historic, unprecedented nature.

Our recommendations as it relates to the development of the battery-operated jet ski including the following:

1. Finish the project as we had detailed in our work plan including the assembly, testing, troubleshoot and re-test to ensure the best prototype.
2. Find and purchase more powerful, smaller, and lighter weight batteries
3. Find and purchase a smaller, more lightweight motor.
4. Complete the user display design and motor controller design based on relevant Microchip documentation and software (MP Lab X IDE).

A future research project could look at a solar powered charging dock. As this jet ski's batteries are removable, a system could be constructed to charge the extra batteries when they are not being used. This system could be a power bank that is attached to a solar panel that tracks the sun to maximize the efficiency of the solar panel. This power bank eliminates the need for fossils fuels to power the batteries. You could also have it have its own batteries so that it can quickly charge the ones from the jet ski and extend the overall ride time.

6. References

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7. Appendices

Appendix A: Motor Mount

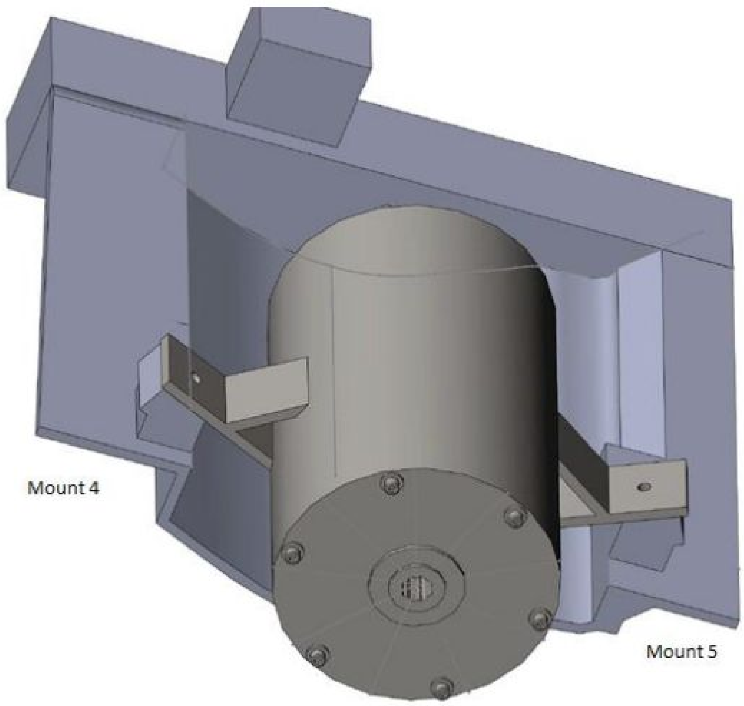

Figure 46 Final design

Figure A1: UWA Final Motor Mount Design

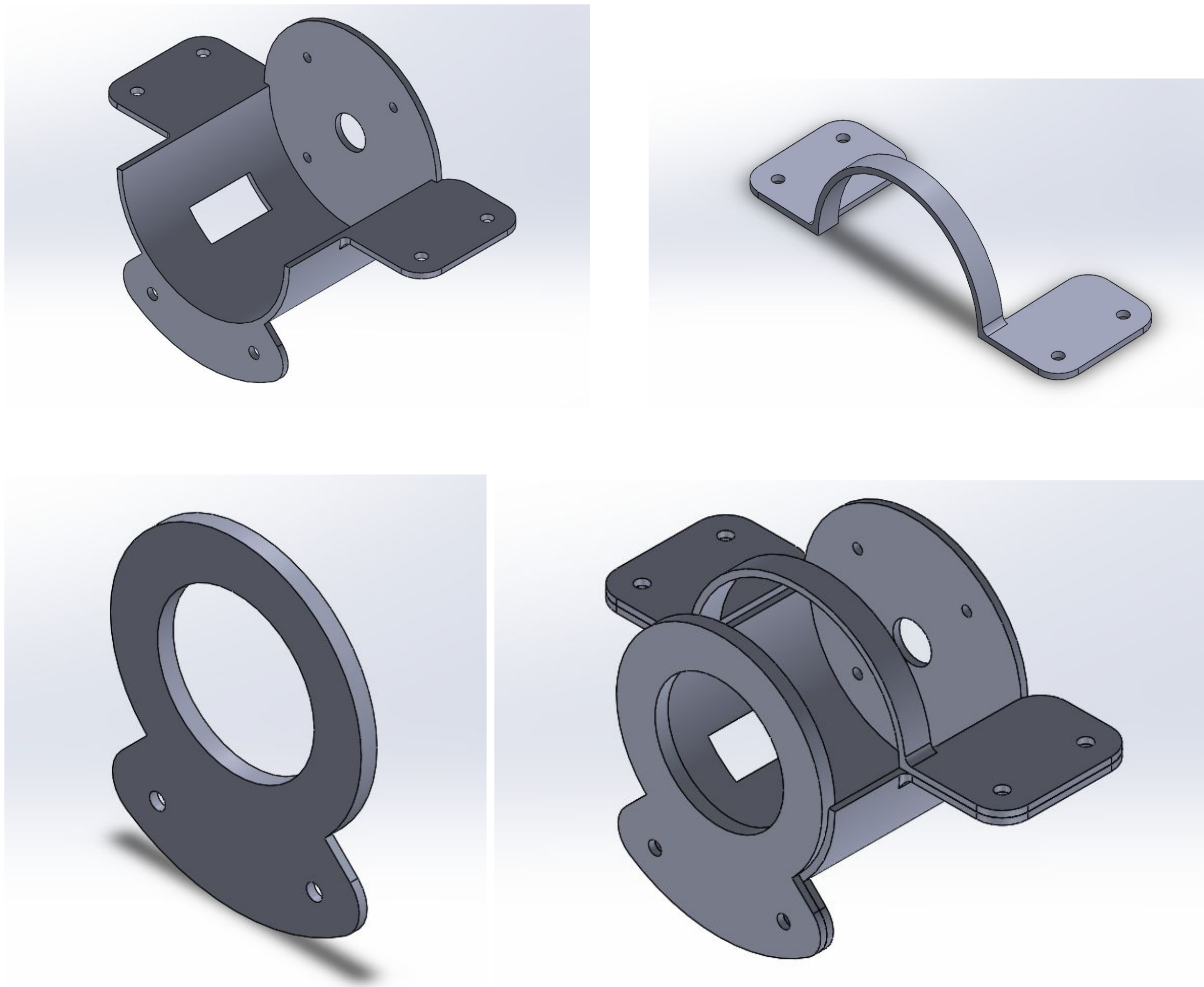

Figure A2: ME0913 Motor Mount Assembly

Voltage Volts DC	Current AMPS	Speed RPM	Torque NM (Ft Lb)	Power KW (HP)	Efficiency %
48	300	1275	90.25 (66.5)	11.2 (15)	78
	250	1400	70.23 (51.8)	9.7 (13)	81
	220	1520	59 (43.5)	8.6 (11.6)	82
	205	1700	54.11 (39.9)	8.2 (10.9)	83
	180	1780	44.8 (33)	7.2 (9.6)	83
	170	1850	42.38 (31.3)	6.8 (9.0)	83

Voltage Volts DC	Current AMPS	Speed RPM	Torque NM (Ft Lb)	Power KW (HP)	Efficiency %
72	300	1938.4	90.25 (66.5)	18.3 (24.5)	82
	250	2119.2	70.23 (51.8)	15.6 (20.9)	84
	220	2240	59 (43.5)	13.8 (18.5)	86
	205	2329.6	54.11 (39.9)	13.2 (17.7)	88
	180	2472.8	44.8 (33)	11.6 (15.5)	88
	170	2560	42.38 (31.3)	11.4 (15.3)	90

Voltage Volts DC	Current AMPS	Speed RPM	Torque NM (Ft Lb)	Power KW (HP)	Efficiency %
90	300	2423	90.25 (66.5)	22.9 (30.7)	84.8
	250	2649	70.23 (51.8)	19.48 (26.1)	86.6
	220	2800	59 (43.5)	17.3 (23.2)	87.4
	205	2912	54.11 (39.9)	16.5 (22.1)	89.4
	180	3091	44.8 (33)	14.5 (19.4)	89.5
	170	3200	42.38 (31.3)	14.2 (19)	92.8

Voltage Volts DC	Current AMPS	Speed RPM	Torque NM (Ft Lb)	Power KW (HP)	Efficiency %
144	300	3876	90.25 (66.5)	36.6	85
	250	4238	70.23 (51.8)	31.2	87
	220	4480	59 (43.5)	27.7	88
	205	4659	54.11 (39.9)	26.4	90
	180	4945	44.8 (33)	23.2	90
	170	5120	42.38 (31.3)	22.7	93

Note:
Data at 72 and 144 VDC is estimated data. Data at 48 and 90 VDC is actual data taken on a Dynamometer using a hard (constant) voltage supply.

Figure A3: ME1002 Specification Sheet

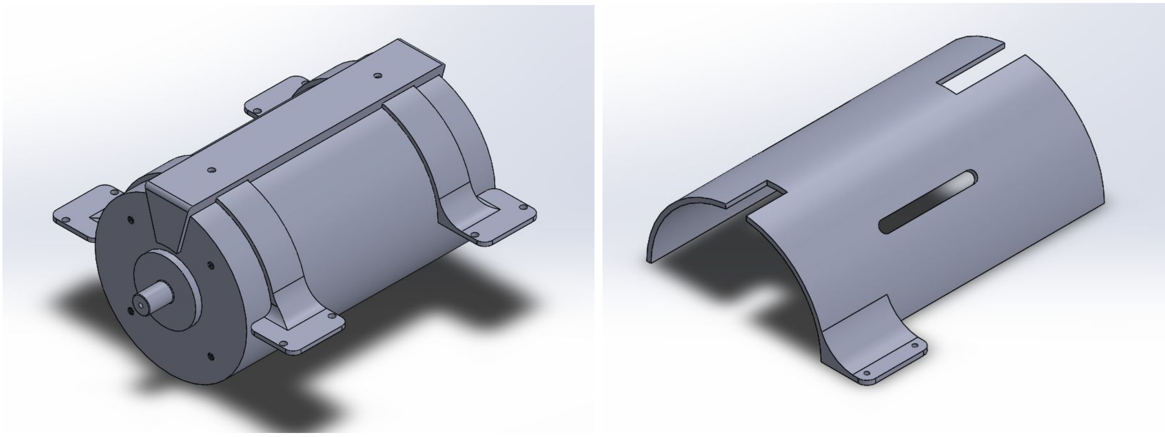

Figure A4: ME1002 Initial CAD Designs

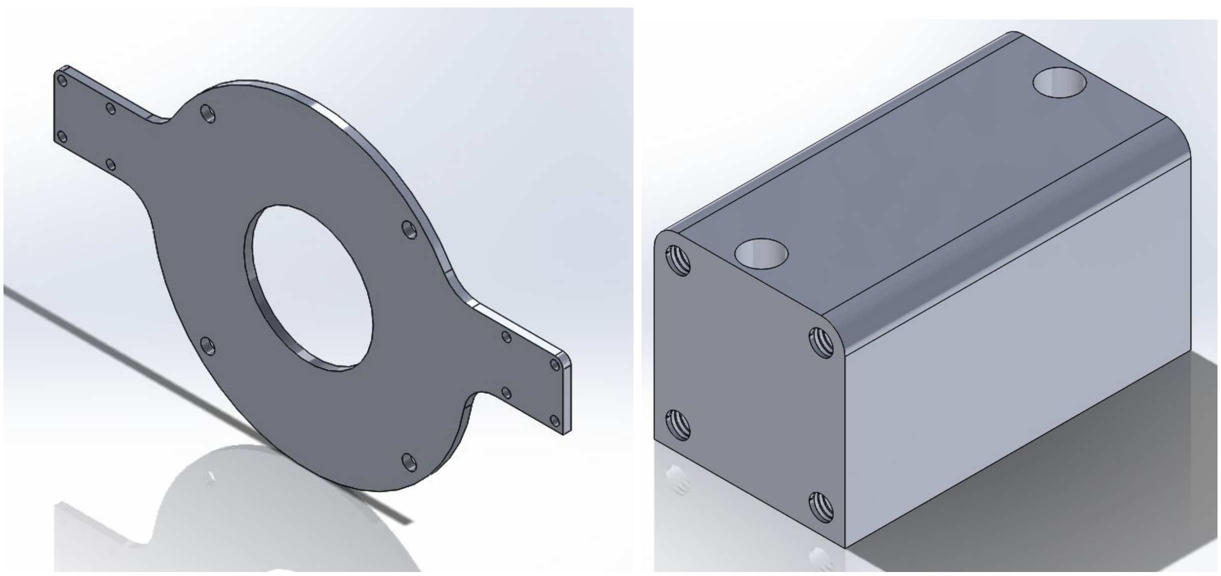

Figure A5: ME1002 Final Mount Front Plate & Side Block CAD

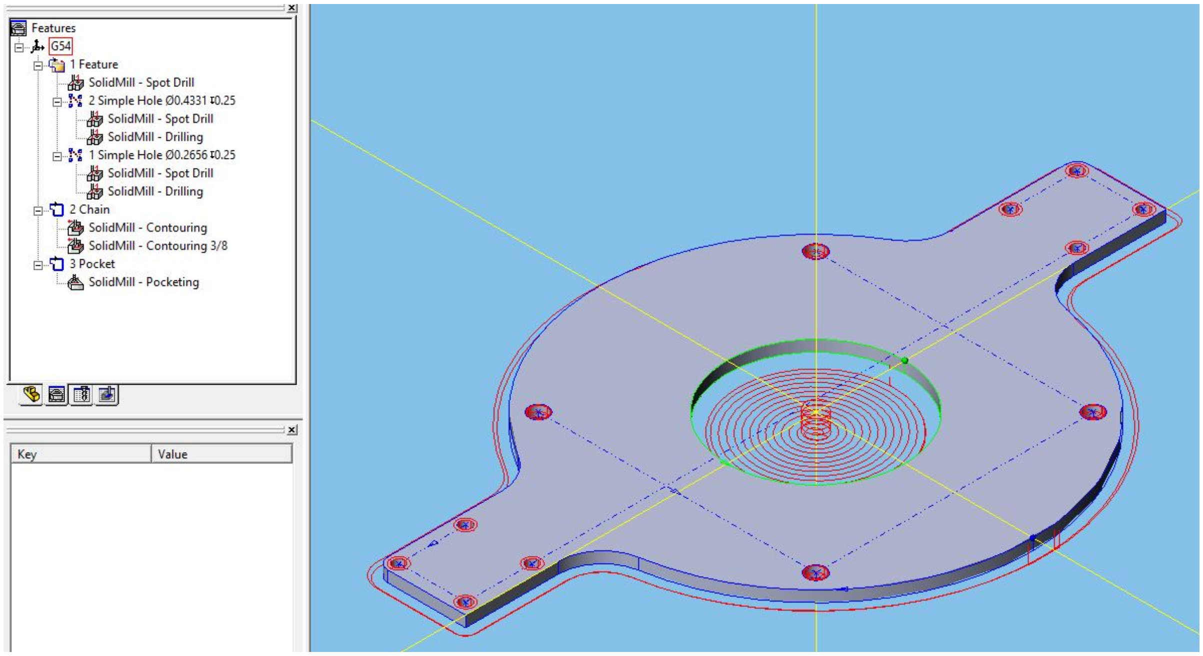

Figure A6: Motor Mount Front Plate ESPRIT

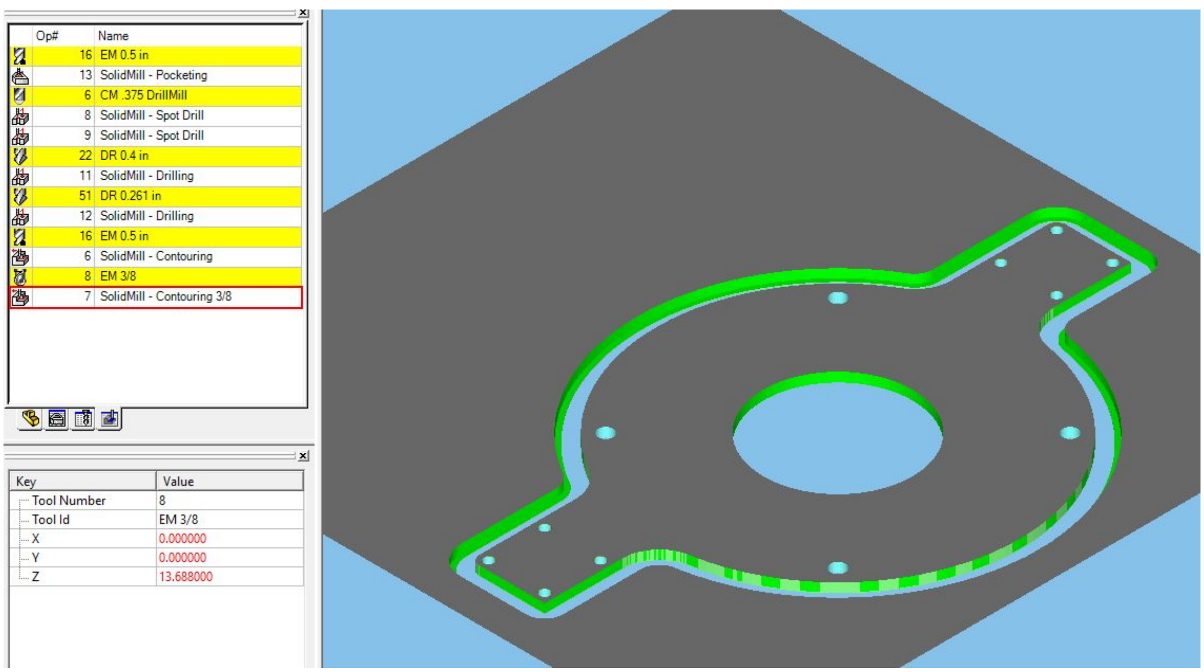

Figure A7: Motor Mount Front Plate ESPRIT Simulation

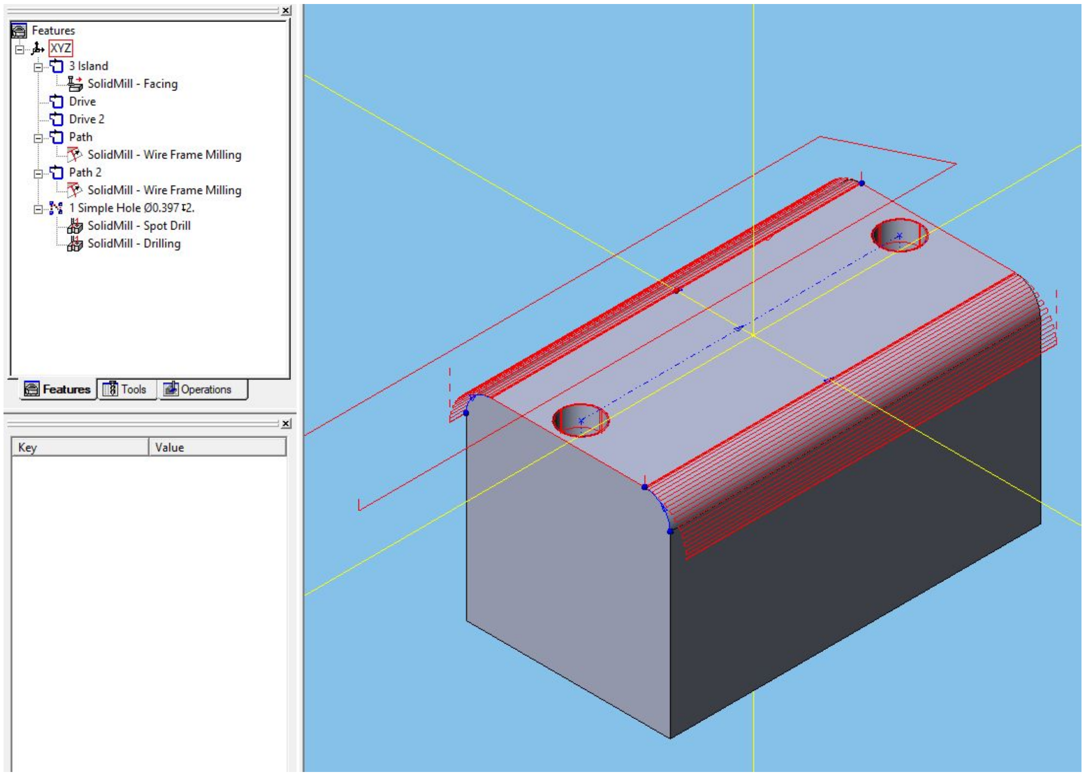

Figure A8: Motor Mount Side Block ESPRIT

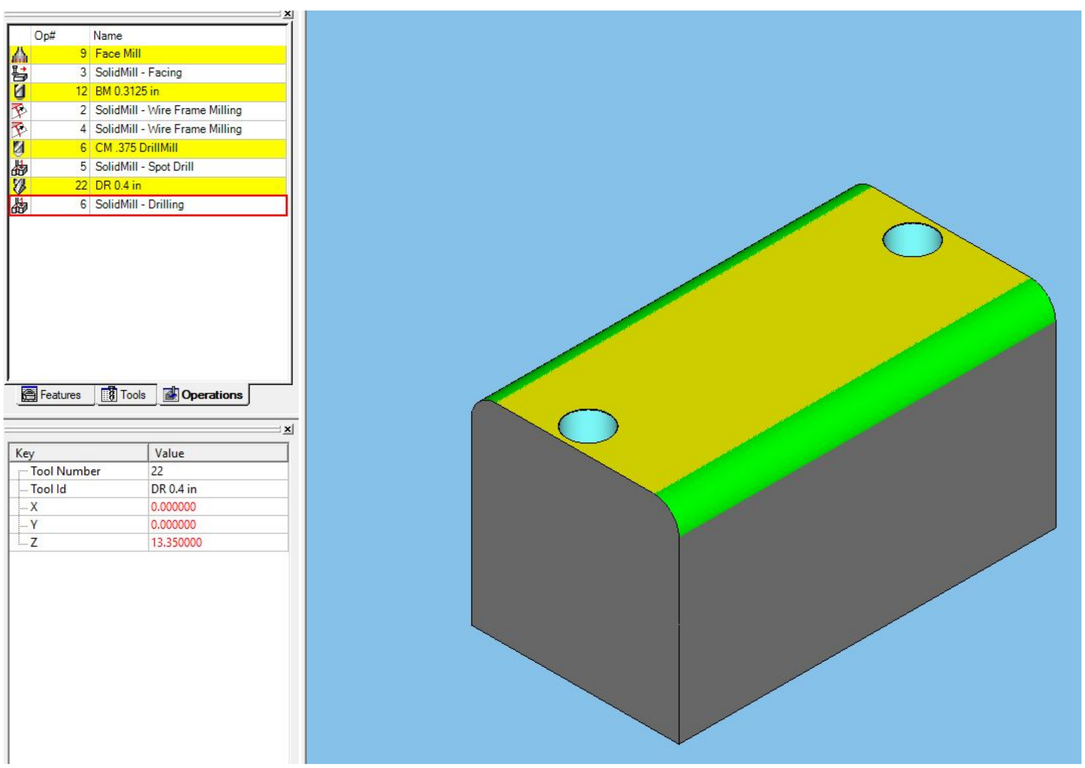

Figure A9: Motor Mount Side Block ESPRIT Simulation

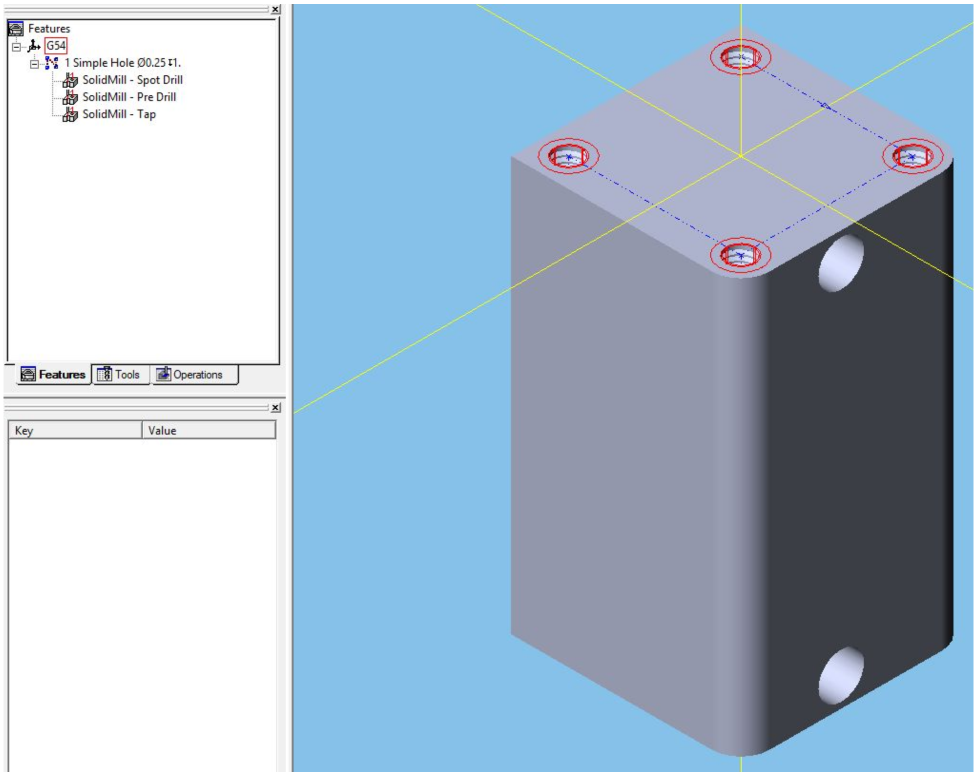

Figure A10: Motor Mount Side Block Threads ESPRIT

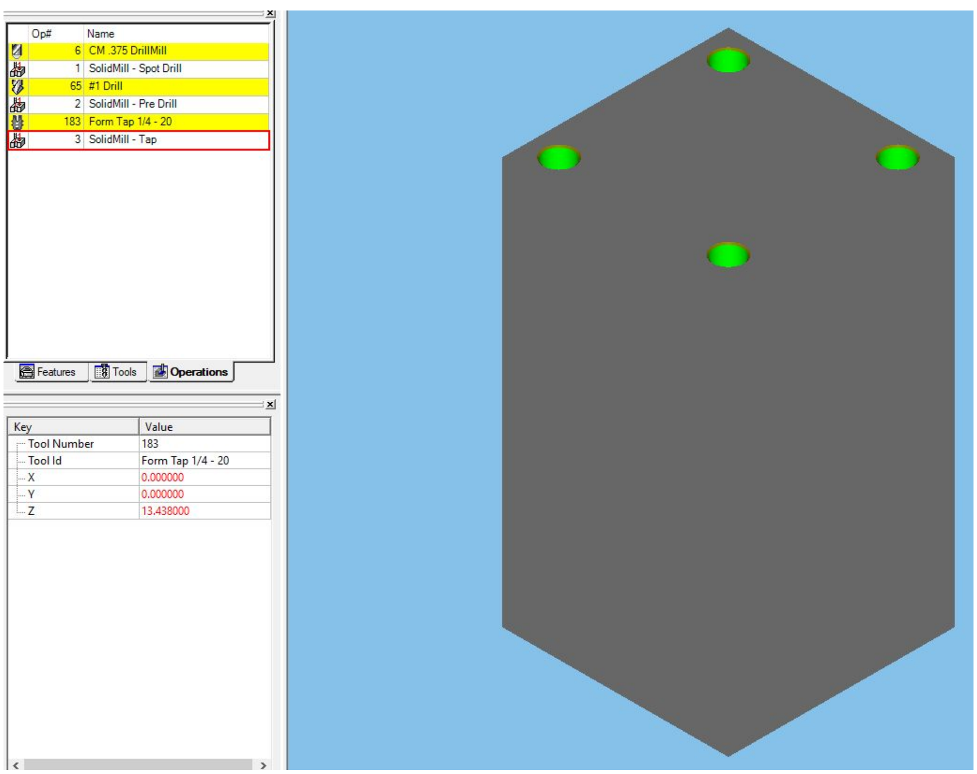

Figure A11: Motor Mount Side Block Threads ESPRIT Simulation

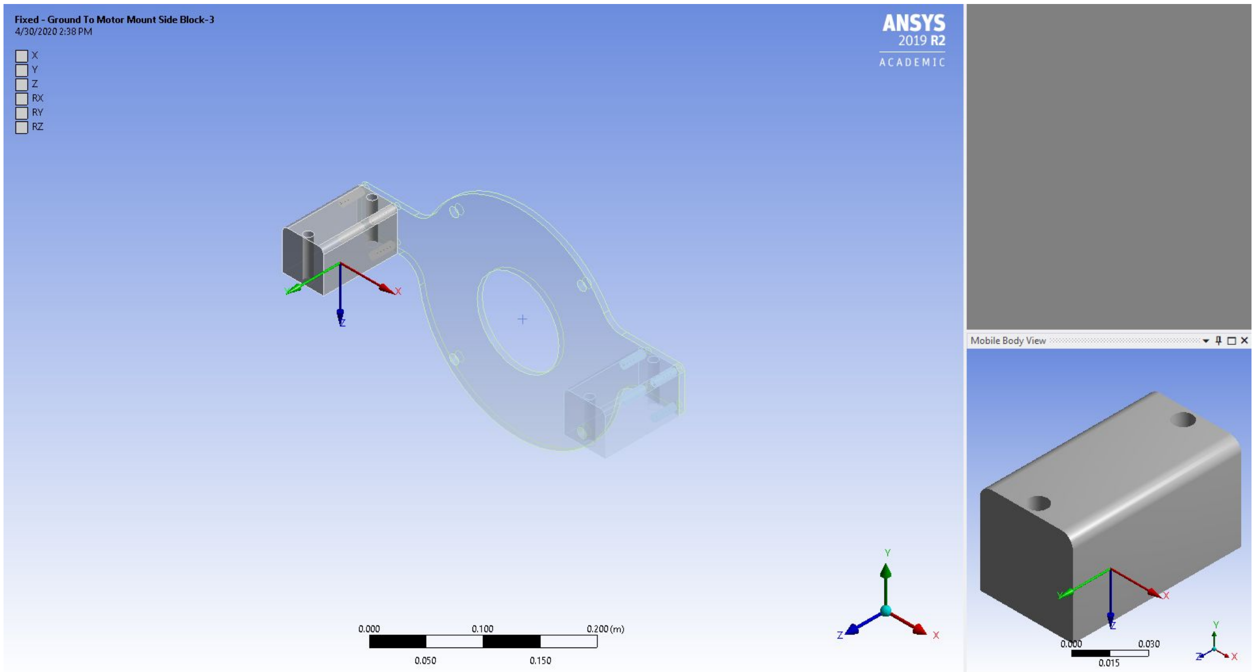

Figure A12: Motor Mount Boundary Conditions 1

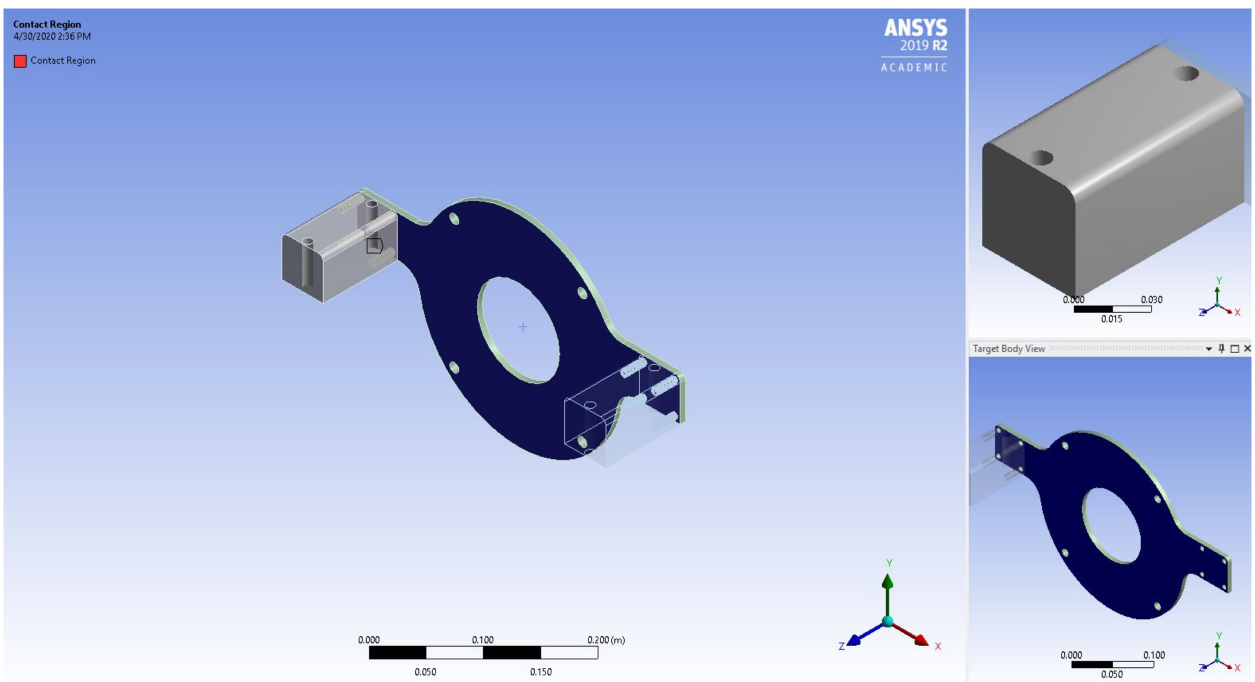

Figure A13: Motor Mount Boundary Conditions 2

Appendix B: Battery Housing

Figure B1: Battery Housing Initial 3D-Printed Prototype Bottom

Figure B2: Battery Housing Initial 3D-Printed Prototype Top

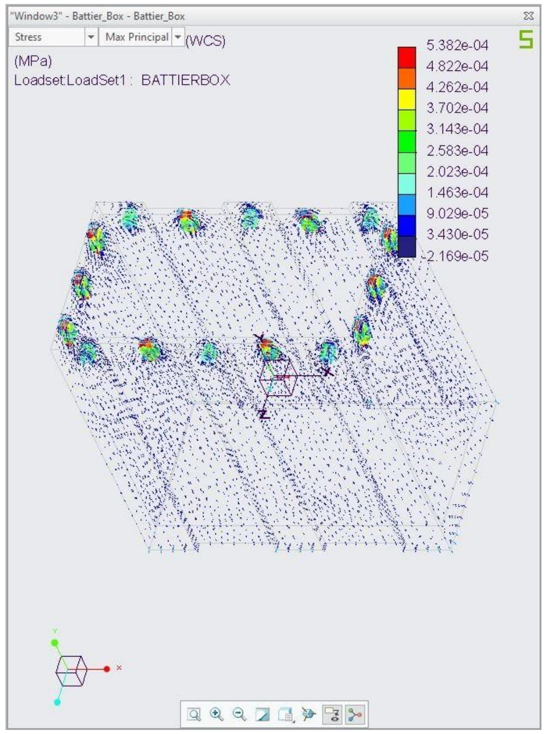

Figure B3: Battery Housing Load Set

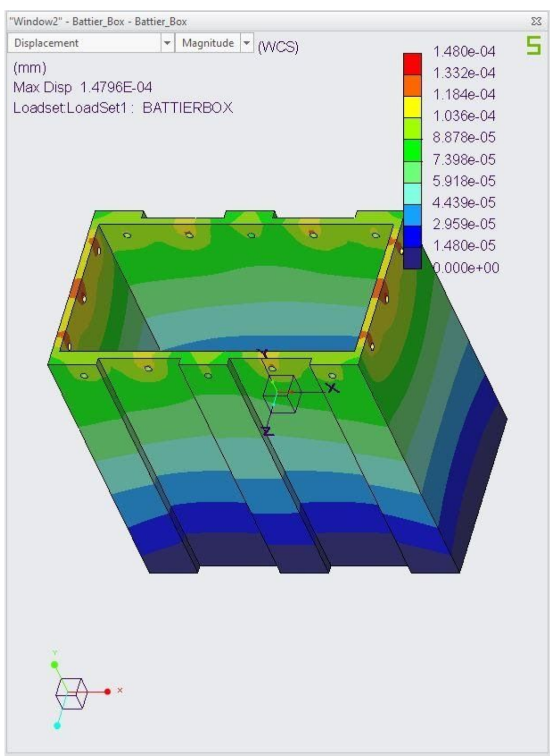

Figure B4: Battery Housing Max Displacement

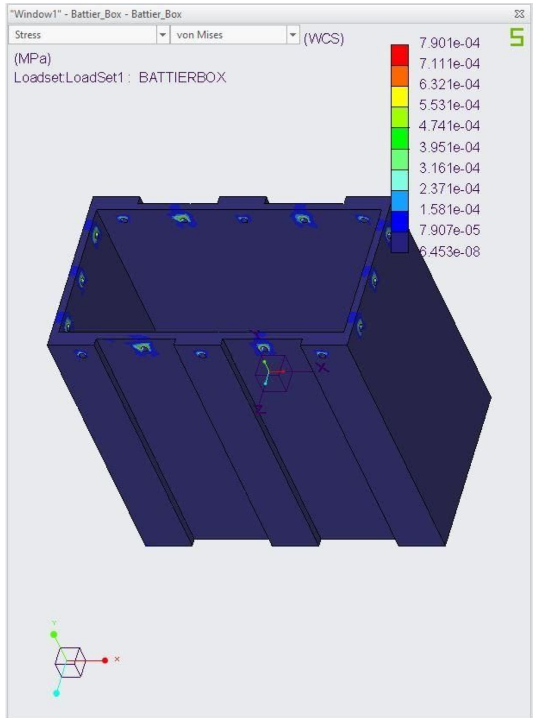

Figure B5: Battery Housing Hole Loadset

Appendix C: Drive Shaft

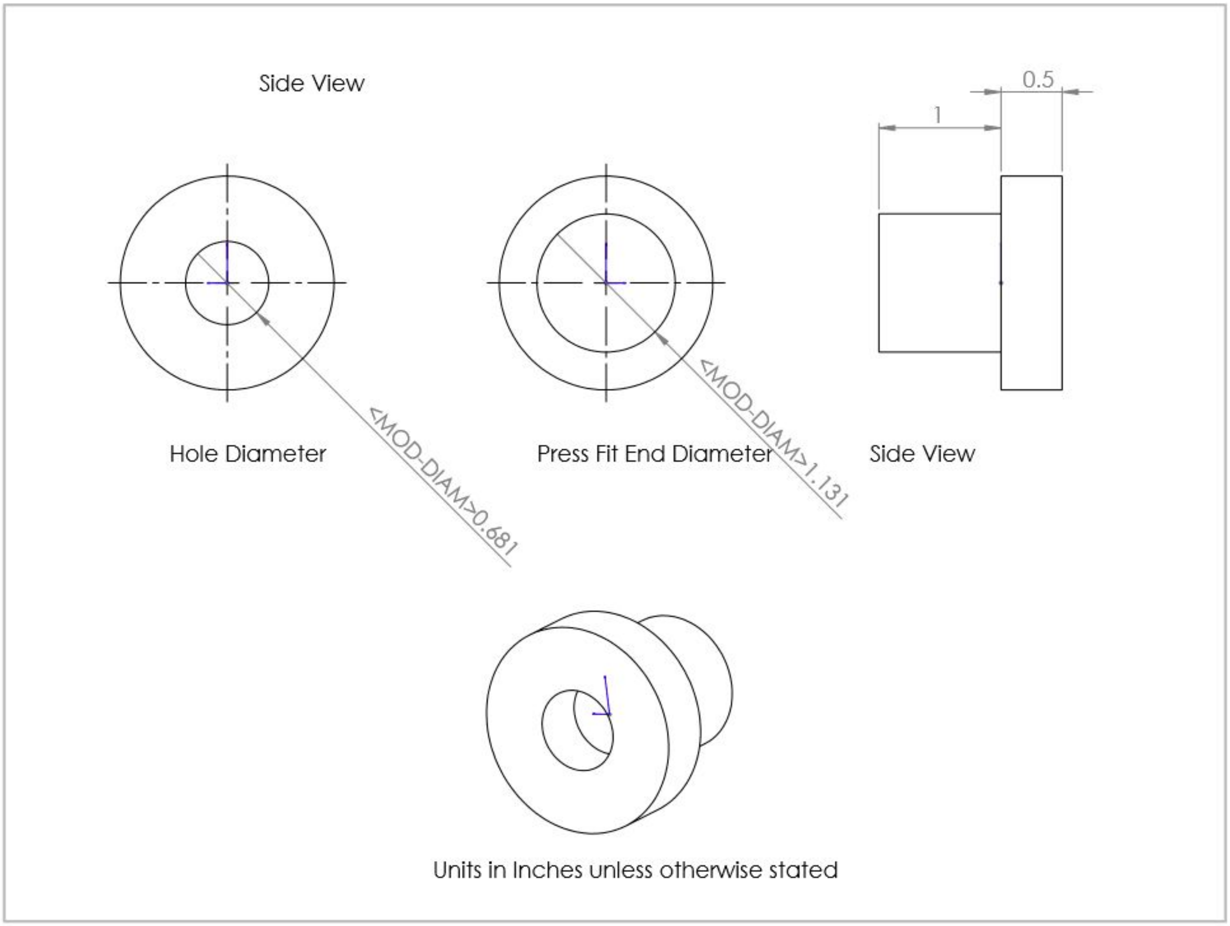

Figure C1: End Cap Part

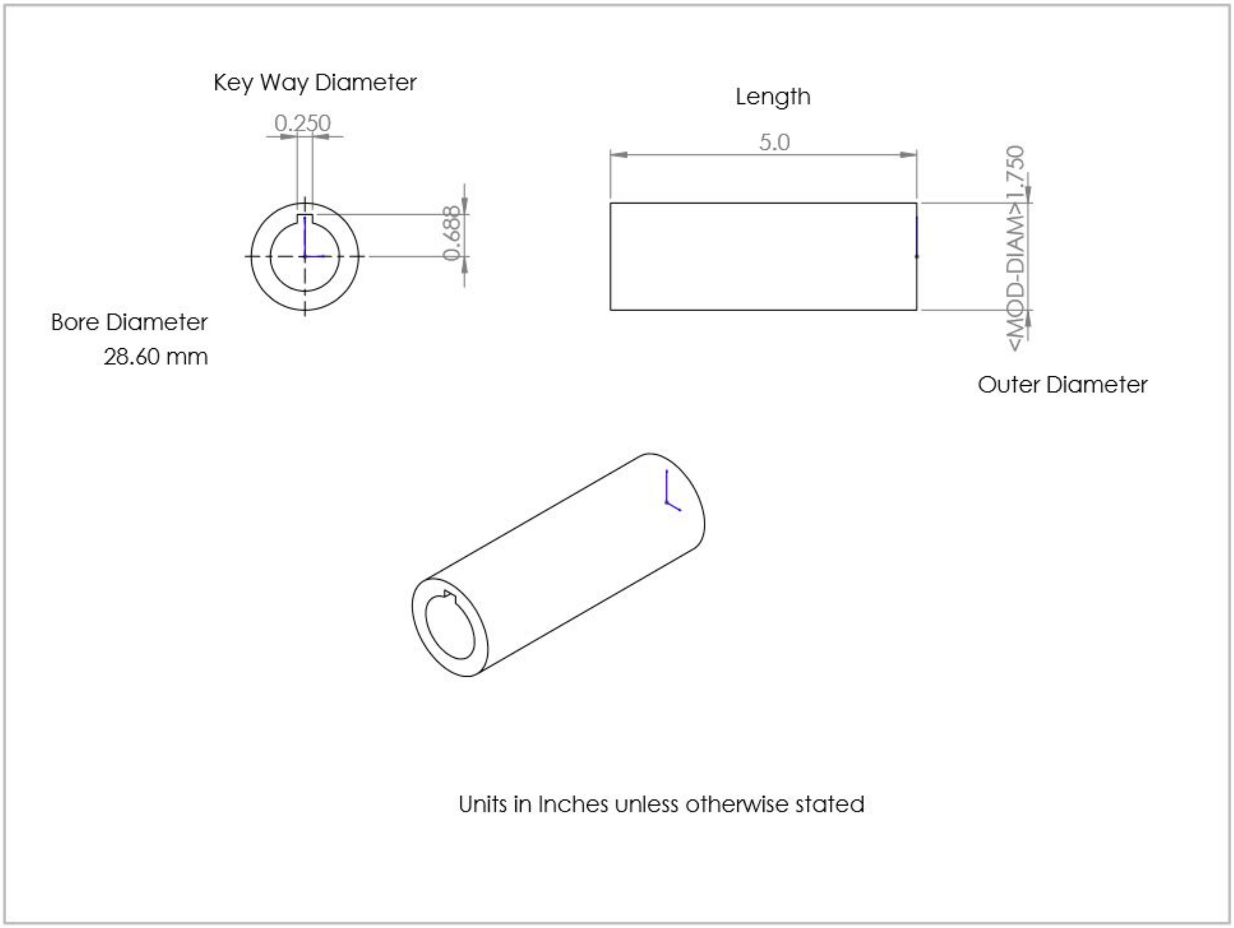

Figure C2: Sleeve Part

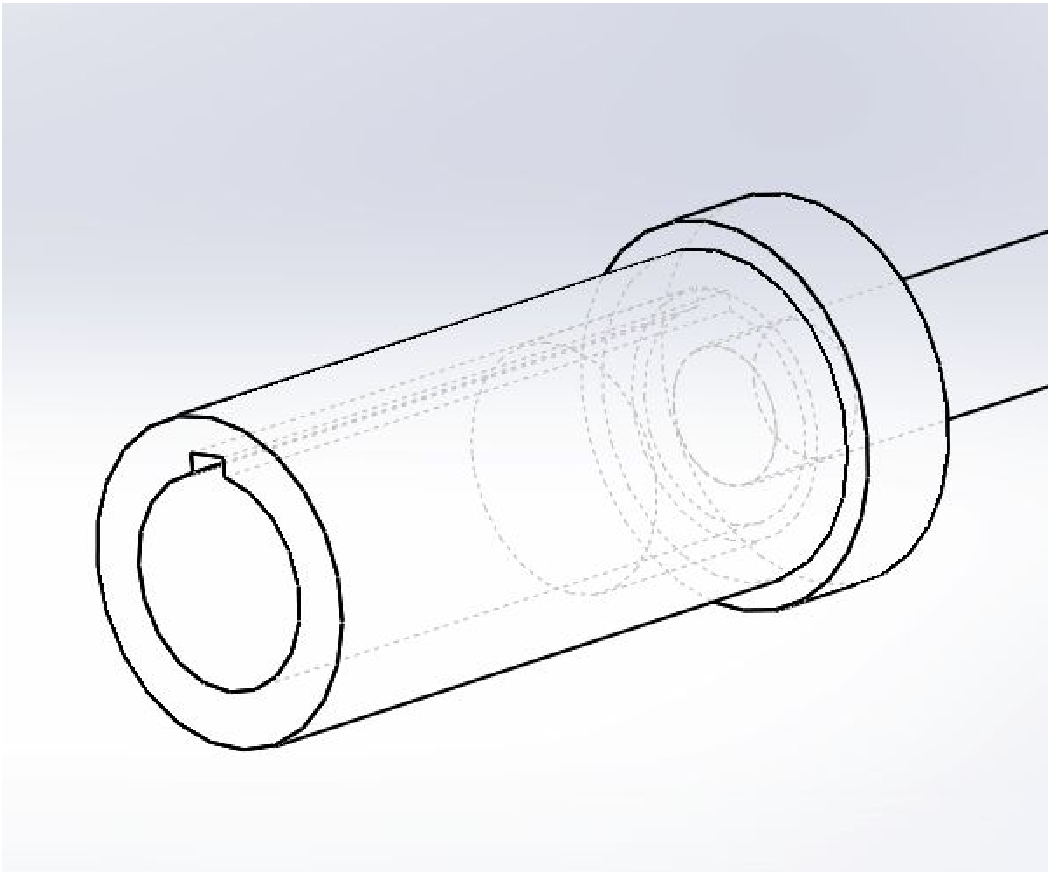

Figure C3: Transparent View of Driveshaft, Sleeve, and End Cap Assembly

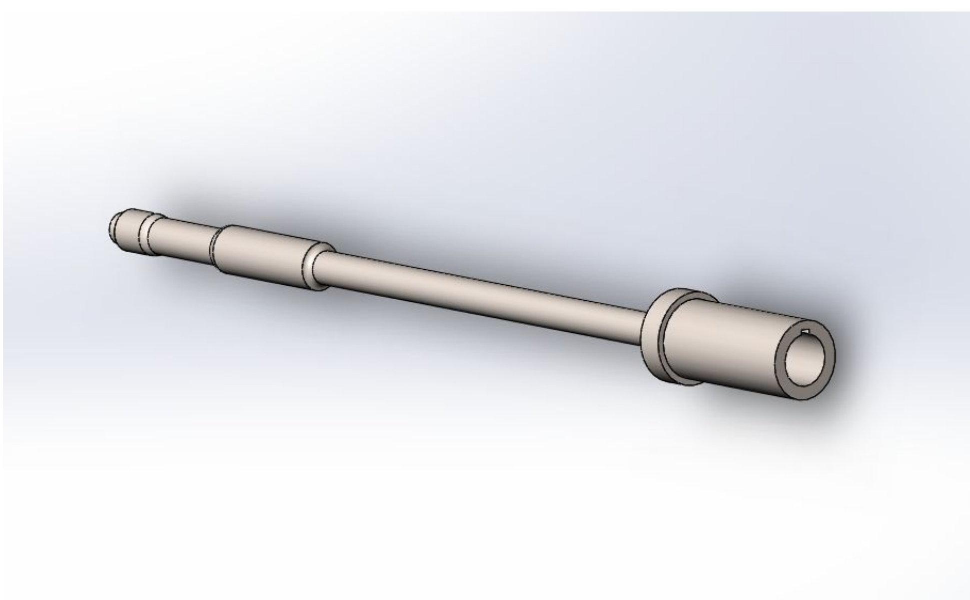

Figure C4: Drive Shaft Assembly

Figure C5: Original Driveshaft for SeaDoo SPX 1997

Figure C6: Prototype Adapter for Driveshaft

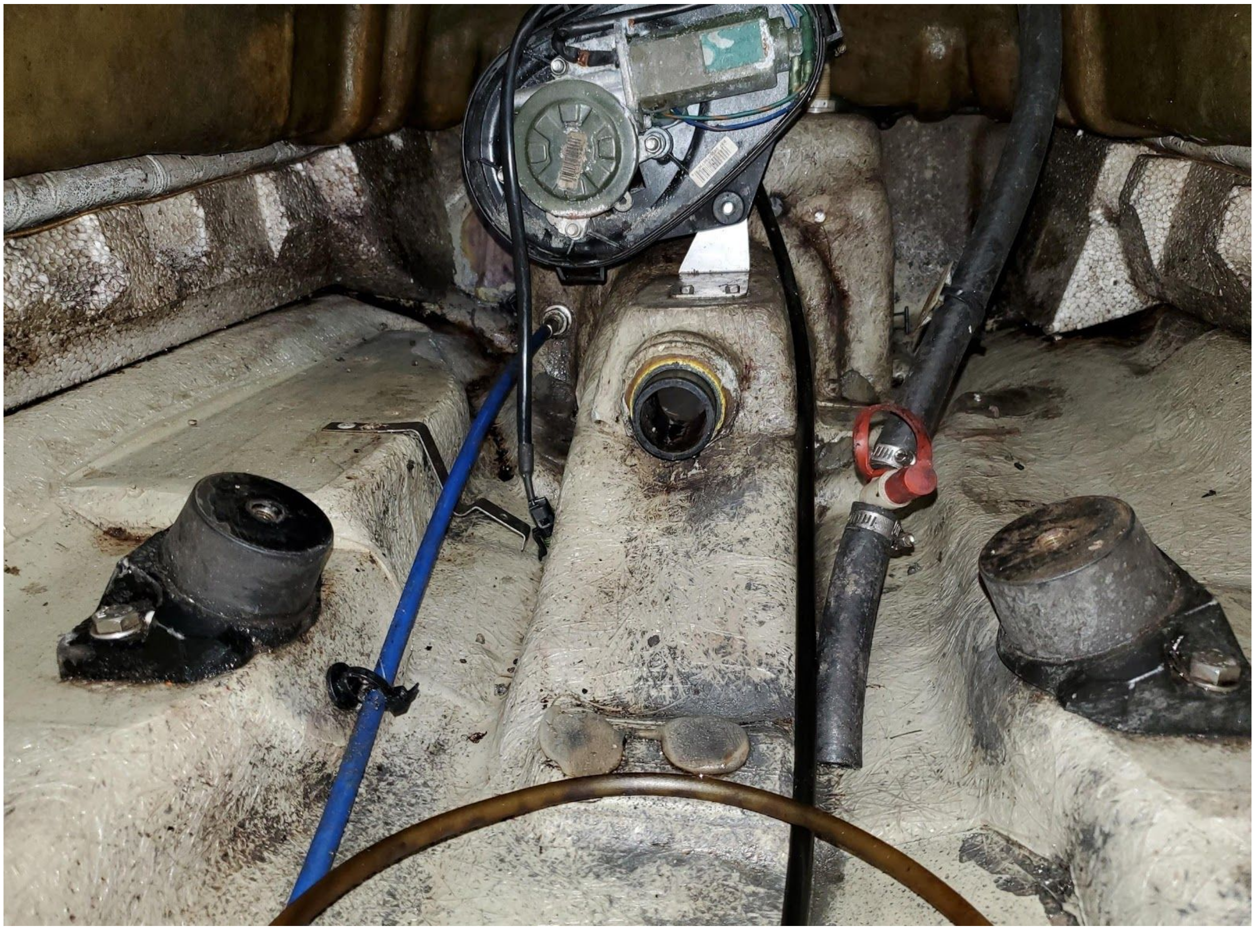

Figure C7: Rear of Hull

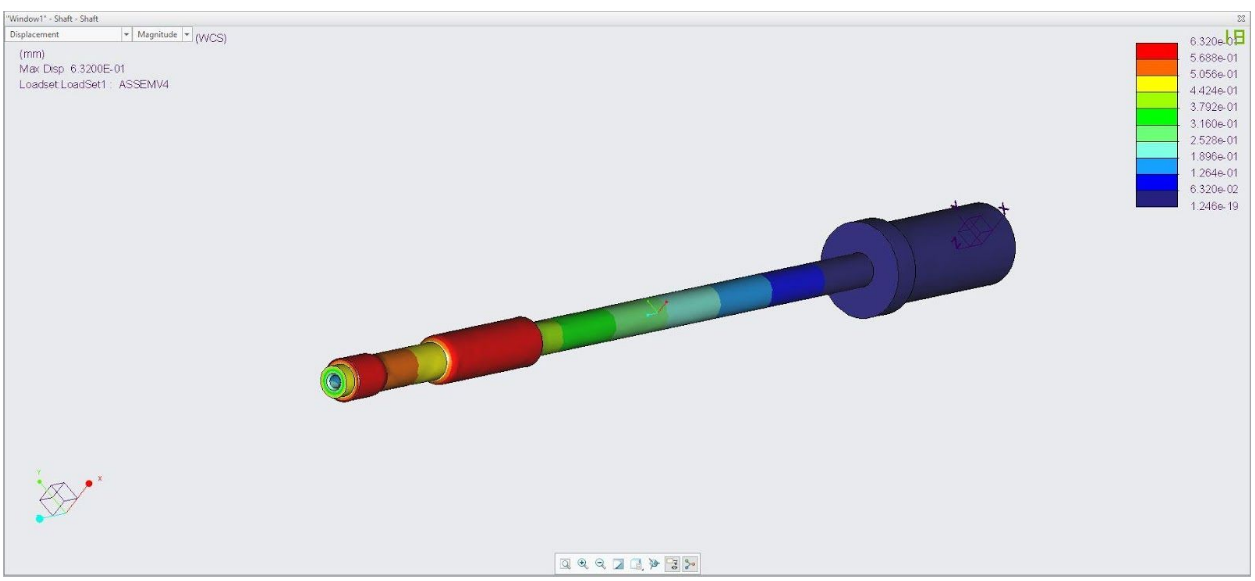

Figure C8: Displacement under 100 N.m Torque at Impeller End

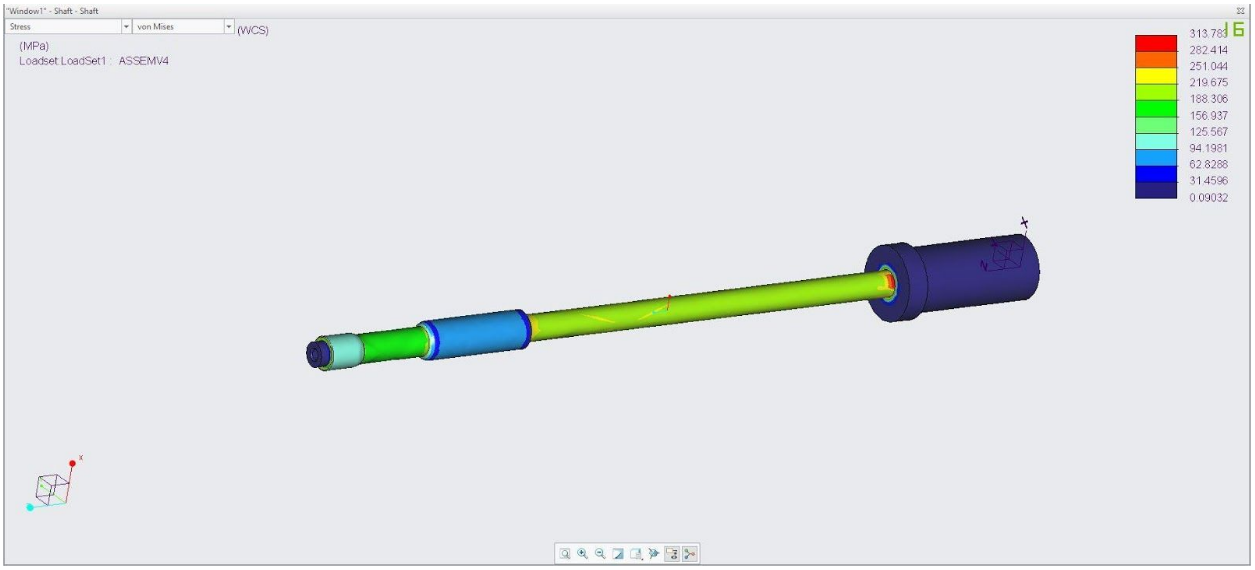

Figure C9: Von Mises Stress Analysis

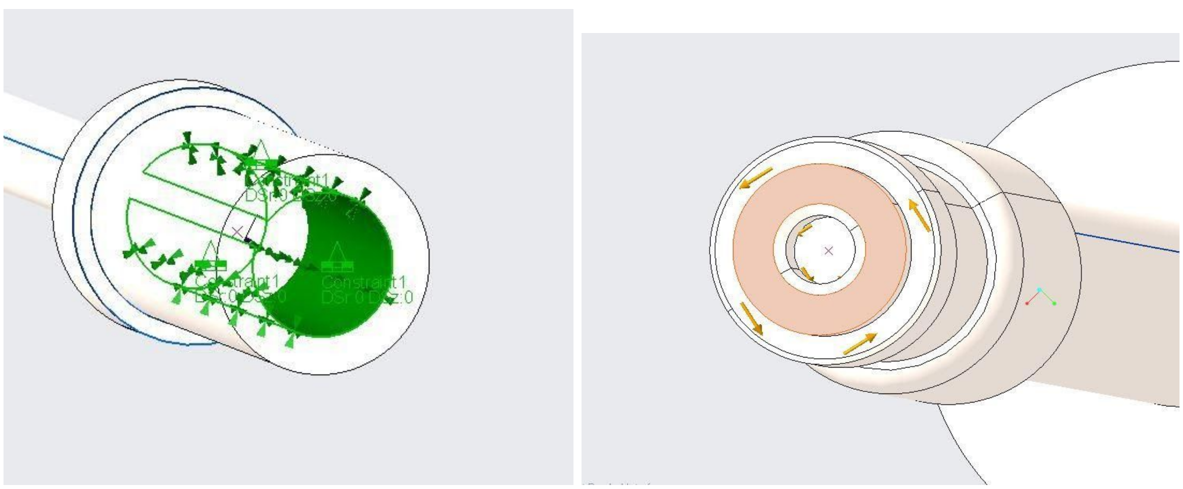

Figure C10: Boundary Condition Fixturing

Appendix D: Electrical System

Motor Controller and Accessories		
Item	Price	Link
KLS-8080H - Sealed Sinusoidal Wave Brushless DC Motor Controller (96V) (500A)	699.00	https://www.kellycontroller.com/shop/kls-8080h/
Bluetooth Adapter	29.00	https://www.kellycontroller.com/shop/bluetooth-adapter/
Controller Programming Cable USB to RS232 with Micro USB Adapter	29.00	https://www.kellycontroller.com/shop/usb-to-rs232/
		Total
		757.00

Nissan Leaf Batteries		
Item	Price	Link
Nissan Leaf 48v Battery G1 Lithium Ion 7 kWh 500 watt per module Lot of 14	746.64	https://www.ebay.com/itm/Nissan-Leaf-48v-Battery-G1-Lithium-Ion-7-kWh-500-watt-per-

Battery Management System		
Item	Price	Link
BMS Controller (thunderstruck.com)	450.00	https://www.thunderstruck-ev.com/bms-controller.html

Figure D1: Motor Controller, BMS, and Nissan Leaf Module BOM

Throttle Control			
Item	Description	Price	Link
1	WUXING Electric Thumb Throttle 3 Wires Connector for 24V 36V 48V Universal Electric Scooter Electric Bicycle	13.59	https://www.amazon.com/WUXING-Electric-Throttle-Connector-Universal/dp/B07NVPBGY1/ref=sr_1_32?dchild=1&keywords=thumb+throttle+electric+motor&qid=1576116808&sr=8-32
1	EBIKELING Twist Thumb Throttle E-Bike Speed Control Electric Bike Bicycles	19.99	https://www.amazon.com/EBIKELING-Throttle-Control-Electric-Bicycles/dp/B07C821341/ref=sr_1_4?dchild=1&keywords=half%2Btwist%2Bthrottle&qid=1576118456&s=sporting-goods&sr=1-4&th=1
1	Arduino UNO	0 (already have)	
1	Cylewet 5Pcs KY-040 Rotary Encoder Module with 15×16.5 mm with Knob Cap for Arduino (Pack of 5) CYT1062	8.99	https://www.amazon.com/Cylewet-Encoder-15%C3%9716-5-Arduino-CYT1062/dp/B06XQTHDRR/ref=sr_1_3?keywords=rotary+encoder+arduino&qid=1576127066&sr=8-3
		Total	42.57

Figure D2: Throttle Control BOM

Motor Controller Bill of Materials

Index	Quantity	Part Number	Manufacturer Part Number	Description	Customer Reference	Available	Backorder	Unit Price	Extended Price USD
1	5	PIC18F47Q10-I/P-ND	PIC18F47Q10-I/P	128KB FLASH 3.6KB RAM 1024B EEPR		5	0	1.8	9.00
2	5	MCP1826T-3302E/DCCT-ND	MCP1826T-3302E/DC	IC REG LINEAR 3.3V 1A SOT223-5		5	0	0.68	3.40
3	3	MIC4606-2YTS-CT-ND	MIC4606-2YTS-TR	IC GATE DRVR HALF-BRIDGE 16TSSOP		3	0	2.1	6.30
4	3	MIC28514T-E/PHACT-ND	MIC28514T-E/PHA	IC REG BUCK ADJUSTABLE 5A 32VQFN		3	0	2.24	6.72
5	5	MCP6024-E/P-ND	MCP6024-E/P	IC OPAMP GP 4 CIRCUIT 14DIP		5	0	1.91	9.55
6	5	MCP6541RT-E/OTCT-ND	MCP6541RT-E/OT	IC COMP 1.6V SNGL P-P SOT23-5		5	0	0.36	1.80
7	20	399-15252-1-ND	C410C100K1G5TA7200	CAP CER 10PF 100V C0G/NP0 AXIAL		20	0	0.185	3.70
8	8	IRFP4468PBF-ND	IRFP4468PBF	MOSFET N-CH 100V 195A TO-247AC		8	0	5.95	47.60
9	1	DM182029-ND	DM182029	PIC18F47Q10 CURIOSITY NANO EVALU		1		14.99	14.99
10	1	DM164136	DM164136	PIC MICRO MCU CURIOSITY HIGH PIN COUNT (HPC) DEVELOPMENT BOARD		1	0	55.35	55.35
								TOTAL	158.41

Battery Pack Accessories

Index	Quantity	Part Number	Manufacturer Part Number	Description	Customer Reference	Available	Backorder	Unit Price	Extended Price USD
1	1	43374573060	43374573060	1' x 2' DIAMOND TREAD ALUMINUM SHEET		1	0	17.98	17.98
2	3	887480023817	887480023817	WING NUT ZINC 5/16 10TPI		3	0	1.18	3.54
3	4	887480022278	887480022278	5/16 THREADED ROD 36''		4	0	3.38	13.52
4	1	37103136480	37103136480	WISS LEFT CUT SNIPS		1	0	13.97	13.97
								TOTAL	49.01
			1/0 awg cables						
			1/0 awg ring terminals						
			10mm/13mm/16mm bolt						

Figure D3: Motor Controller BOM