Spring 2021

Electric Hydrofoil Board

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I HEREBY RECOMMEND THAT THE THESIS PREPARED
UNDER MY SUPERVISION BY

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ENTITLED

Electric Hydrofoil Board

BE ACCEPTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
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Department Chair(s) Dr. Drazen Fabris date

Electric Hydrofoil Board

By

Zach Flood, Nick Potter, Wesley Sava, and Trent Walker

SENIOR DESIGN PROJECT REPORT

Submitted to
the Department of Mechanical Engineering

of

SANTA CLARA UNIVERSITY

in Partial Fulfillment of the Requirements
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Bachelor of Science in Mechanical Engineering

Santa Clara, California

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Abstract

The electric hydrofoil community has become very popular in recent years with its two major subsections being divided up into those that buy their boards commercially and those that build their own (the DIY community). The commercial boards are extremely expensive and can reach prices of over $12,000. This is the root cause of the rapidly growing DIY community who can build functioning boards for around $3000. Reducing this entry cost has made the sport much more accessible to new members and has allowed both the size of the community and awareness of the sport to increase. For this report the DIY community was analyzed for weak points and major issues or hurdles that they may face. This exposed major safety concerns, and R&D issues as the community lacked the resources and knowledge to solve since each DIY board is a unique build with unique issues. Often, E-Foil boards are built in the fastest manner possible with the cheapest components, adhering to the strict goal of creating an operational device. This creates large gaps in safety for these DIY builds often ignored in favor of speed, battery life, or pricing. Examples of this negligence are, sub-par battery waterproofing, implementing propellers with no duct leaving an exposed blade spinning at several thousand RPM, and potentially utilizing materials that can be dangerous or un-optimized for water sport use. Using Solidworks fluid flow simulations, a duct and propeller system was created that was able to retain 94% of the efficiency of a ductless system while boasting a 30% increase over the open-source duct and propeller used by the community. This explains why the open-source duct is often removed since riders would be experiencing only about 60%-65% of the efficiency as they would without it. To confirm a proof of concept, the designs generated through the duct optimization iteration process were then live tested in water. The results showed that a bad duct design can be dramatically more inefficient creating a device that no longer functions in the water or it can be so efficient that the difference between ducted and un-ducted propeller setups have nearly no noticeable change to the rider's experience. This report outlines these issues in greater detail, explain how they were solved or mitigated, with the importance of making the findings reproduceable within the community. Further recommendations include iterating on the propeller design to find the optimal E-foil propeller, while referencing back to the duct to ensure the new prop does not require another redesigned duct. This could be iterated any number of times in searching for the best duct-propeller combination.

Acknowledgements

Thank you to Dr. Godfrey Mungal for advising this project and providing mentorship throughout the research, design, and development processes. We would also like to thank the Maker Lab here at SCU for providing services regarding printing parts for further testing and analysis. Thank you to SCU Alumnus Peter Collins for also providing mentorship on this project as it is a continuation of the project that he developed last year as well as supporting us by acting as a third-party rider. Additional thanks to the Mechanical Engineering Department for their support and guidance through the Senior Design Classes, and general support. Lastly, thank you to the SCU undergraduate programs grant for funding the research and development performed for this project.

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1 Introduction

1.1 Hydrofoils

The hydrofoil board community has been around and constructing various foil designs since the 1960s. The subsequent development of electronically driven hydrofoils became popular in relatively recent history with a growing DIY community[1] and being introduced into the commercial market in 2017 and 2018[2]. The basic design of a hydrofoil consists of the board for the rider to stand on, a mast that extends into the water and a hydrofoil that cuts through the water and causes lift. This design allows the rider to use downward thrust forces to create forward motion. The E-foil, which is the subject of this document, has a motor mounted to the mast which is then typically connected to a ducted propeller assembly that is used to supply thrust and allow the rider to cruise without physical exertion.

There are two main categories of people in the E-foil community, those who buy commercial boards and those who are part of the “do it yourself” or DIY community. As the sport and hobby has become more and more popular the DIY board community has grown significantly. It has become attractive to hobbyists to build their own designs because it reduces the overall cost of entering the sport and since the build itself can be as simple as the rider wants it to be there is a low skill cap limiting those that want to participate in the build process. As a result, however, an exaggerated lack of concern for proper safety measures has plagued the community. The designs built by individuals tend to solely value efficiency and battery life which has several impacts on the rider, the surrounding ecosystem, and potentially other pedestrians, boats, or fellow riders as there are no commercial or state regulations to control how these boards are built, operated, or maintained. This served two purposes, it helped identify areas for improvement and it indicated what aspects of the board could not be sacrificed to convince these riders that implementing safer alternatives is possible without ruining their riding experience.

Figure 1: Fliteboard Commercial Board “Used Without Permission”

Figure 2: SCU Alumnus Peter Collins Riding the Original Prototype

Figure 1 is an image of the Flightboard which is an example of a typical commercial board. The main components of a typical E-foil can be seen here with the board, mast, and propulsion system all in view. Figure 2 is an image of the prototype that was originally built by Peter Collins and was used for his Senior Design Thesis in 2020[3]. This shows a more realistic image of what a typical DIY build may look like. In this image, note that the battery pack is mounted on the board surface and between the riders' legs, which is not ideal for a final product.

1.2 Motivation

The purpose of this design project was to resolve an under-recognized issue within a community of people that lack the resources, knowledge, and time to develop solutions to them. Last year, alumnus Peter Collins, seen above, worked on this project from a computer engineering standpoint and has been working with us and helping us throughout the development of this project continuation. With its new focus on mechanical engineering principles, this Electric Hydrofoil Team set out to provide the community with safer alternatives to the standard builds seen within the DIY community while also promising sufficient efficiency retention to the riders. This was all done to convince the community that safety measures will not hinder their experience on the water or compromise their battery life while also laying out a guide on how this can be achieved and implemented onto their own board as well.

1.2.1 Directive

Our team, through research, interviews, and discussions with community members, was able to identify the two biggest concerns to safety within a given E-foil build. These came down to the implementation of un-ducted propellers, and the non-reliable battery systems. From this information, our goal was to create a propeller and duct assembly optimized for efficiency. This was done in hopes of replacing the widely used un-ducted designs to make a safer community. In addition to this, the design team set out to create a safe, step by step guide for the proper assembly, and implementation, of the volatile, Li-Po battery constructions as well as the safer but more technical Lithium-ion battery. All of this was done with the stated goal of allowing the user to enjoy the E-foil as they normally would without needlessly endangering themselves, others, or the environment. The rationalization, data analysis, and discussion of the choices made by our team can be seen in the following sections of this report.

2 Technical Background, Research, & Design

2.1 Standards and Existing Research

Unfortunately, there is not a significant amount of research done in this field for propellers or ducts of this size. Typically, the propellers that are analyzed are for large boats or for watercraft like jet skis that unfortunately have significantly different operational conditions. As a result, we studied and gained what knowledge we could from sources concerning these other designs and extrapolated what we could to best fit the needs of this project.

During the initial development stages, it was imperative that existing engineering and federal standards were utilized as the foundation for the reasoning behind the design changes and alterations made to each subsystem in pursuit of a safer prototype. Hence, several standards from the "Code of Federal Regulation" were studied and used to inform the design choices made as well as a few other regulatory codes identified during research.

The Code of Federal Regulations Part 35 [4] section governs the stress testing and analysis of propellers utilized on aviation vehicles among several other things. While the operating conditions are very different and even the overall shape and characteristics of the propeller are significantly different, what this code provides was a benchmark for the kinds of testing that needed to be conducted in the context of material selection to ensure that whatever designs were used, could handle the applied load of the drag forces from the water, and the thrust that is required from the propeller. To follow this, the design team generated a Finite Element Analysis (FEA) of the propeller to inform about the required material properties for testing. Analysis results for a Polylactic acid (PLA) filament can be seen in Table 1 and an image of the software analysis can be seen in Figure 3 below. This study was executed in Abaqus 2020x through the provided software at Santa Clara University.

Table 1: FEA Analysis Variables

Young's modulus	Poisson ratio	Rotational speed	Flow speed	Yield Strength	Density
2.3 GN/m^2	.3	5000 rpm	20 mph	18 MN/m^2	1.24 g/cm^3

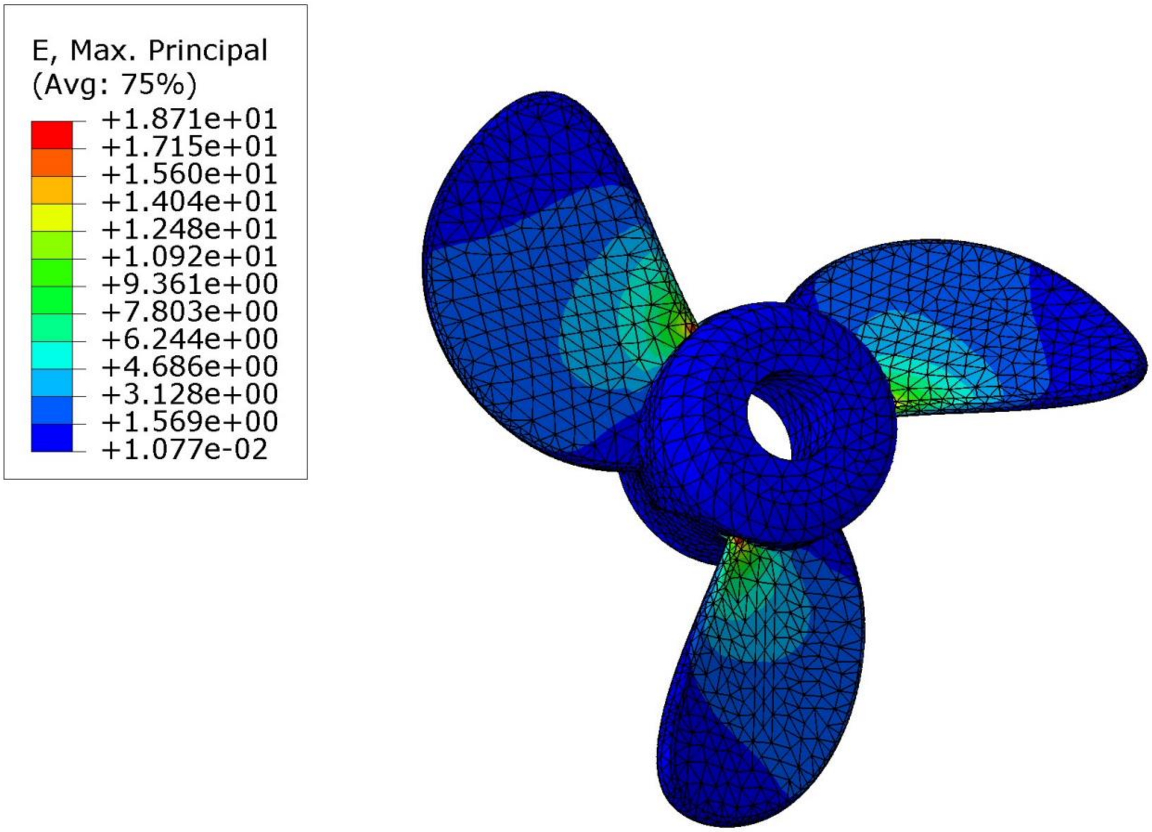


Figure 3: FEA Analysis of Propeller Design [5]

The propeller stress analysis provided the necessary data to inform material selection decisions. As a result, the commonly used PLA 3D print plastic was analyzed to have a high factor of safety, approximately 100, in this application. As a result, testing and data analysis could be performed easily with this material. This material is not suitable for extended use, however, as it is rigid and brittle, making it susceptible to breaking in loading scenarios. Since this was known, it was also decided that for a finished product, carbon fiber would be a suitable material valued for its strength and durability but was deemed too expensive for testing purposes.

This code also provided guidance on testing the capabilities of the motor in relation to the designed propeller. This was helpful because the final propeller design created a problem where the RPMs were too high for the semi-constant voltage and so its design was outside of the KV range which required the design to be eventually scaled down sufficiently to align the torque and KV rating of our selected motor. The KV rating is a term that describes the revolutions per minute that the motor will spin at for every volt supplied. This code guided our redesign process so that we did not waste money on new parts, or time in figuring out exactly how to fix the current draw issue that arose.

Code of Federal Regulations Part 46 [6] speaks on the design and implementation of “propeller guards” as stated within the document or “ducts” within this report, for the Coast Guard’s search and rescue vessels. This provided guidance for a general design for our propulsion system, as these SAR vehicles are generally optimized for speed and handling. This section of the code mostly discussed the distances between the propeller and the guard in respect to safety concerning the high RPM propeller, which is why this code was valued for its guidance on our duct redesign.

Finally, Code of Federal Regulations Part 49 [7] discussed proper care, handling, implementation, and disposal, of volatile and high energy density batteries. Since this is a major portion of any DIY project and one of the larger safety concerns associated with a build, it was imperative that the guides and build instructions this design team generated were not only well informed, and reproducible, but also safe and within regulations. For this reason, the International Electrotechnical Commission’s (IEC) engineering standard IEC 62133-2:2017 [8] was referenced in addition to home and commercial battery guideline UL 2054 [9]. These were all used to aid in proper safety protocols being met, and to streamline the build of the battery sub-assemblies.

2.2 Motors

The motor used for this prototype is the Flipsky 120KV brushless motor, Figure 4. The specification sheet for this motor can be found in Appendix 7 at the end of this report. The major components to keep in mind when utilizing a propulsion system of this kind is the motor’s KV rating, the RPM, and the power draw.

Our prototype utilizes a single battery setup. With a single battery powering the entire system, the overall voltage of the system can be considered constant due to the small difference between the maximum and minimum charge of a battery. This is significant because RPM is directly related to voltage meaning it too can be assumed constant. This was an assumption that introduced minor error but allowed the team to develop strong simulation data within Solidworks as the fluid flow tests require a set RPM value.

While RPM is tied to voltage, the power output of the system is dependent on the current running through the motor. This means as the power and torque required to operate at any given speed increases, the current draw will also increase, leading to an overall shorter battery life. To optimize the design of the duct and propeller, we attempted to create a system that output the maximum thrust possible while minimizing the torque required to operate at a given RPM. The ratio of Thrust (after subtracting the drag) over Torque became what we will refer to in this report as “Efficiency” as it is a good figure of merit to compare the different designs created.

During the testing phase of this project an electronic speed controller (VESC) is used to control the output of the motor which is critical so that the motor can be operated at any speed desired or required by the rider, within the constraints of the motor’s capabilities. This is also beneficial because it provides data collection software that can be used to track rpm, and power draw which guided parts selection in the final stages of this project.

Figure 4: Flipsky Brushless Motor “Used Without Permission”

2.3 Propeller Design

Our primary focus for increasing efficiency was the design of the duct. For this reason, only a single propeller design was created. A common, open-source propeller that is used in the DIY community is shown below in Figure 5. The shape of this propeller can be seen in real world applications on large freighters, but unfortunately, this style of design is primarily used for large slow-moving ships with Accelerating ducts discussed in the next section.

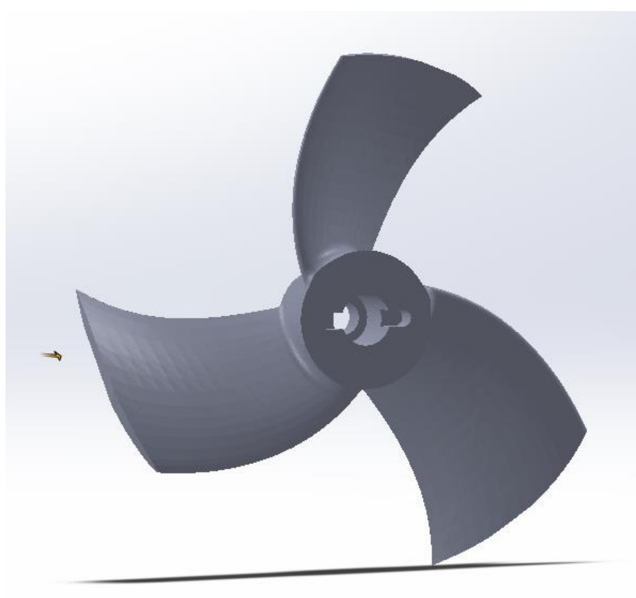


Figure 5: Original Unoptimized Propeller Design

This propeller was unoptimized for our high-speed needs. To guide our design, we looked at common speed boat propellers for off-board motors. While there are slight differences between the propeller here and typical models for these other two industries, creating a design that mimicked these was the first step we took. The new design prioritizes cupping the water to increase the total mass of water pushed backwards by the propeller. Figure 6 presents the new design of the propeller that our team created.

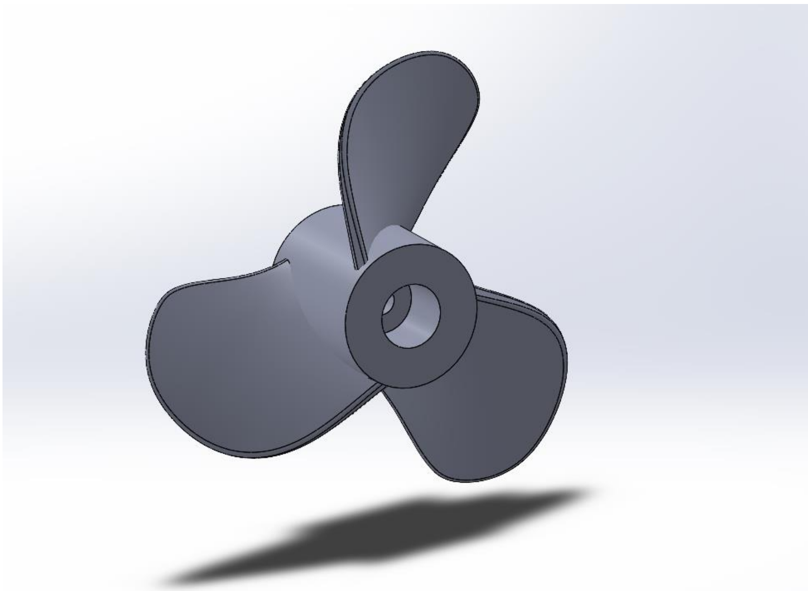


Figure 6: Redesigned Optimized Propeller Design

The redesigned propeller provides a greater surface area and resulting thrust than the original design, as well as rounded blades which will further reduce cavitation at even higher speeds. This along with the cupped blades increased the overall thrust by approximately 42%. Rationale for the redesigned propeller was informed not only by industry propellers but by looking into the history and development of propeller archetypes in the context of submerged applications [10] as well as information on how to best optimize a propeller design [11] [12]. The work by Meg Jenkins helped us to start to determine what exact features of the propeller can and should be optimized from number of blades, the blade type, the blade pitch, and the parameters that are adjusted to simulate each propeller. The work by Kurt Mizzi then helped us specifically with the process of optimizing a propellor for a given situation.

Figure 7 is an image of the reshaped blade that provides this ability and how it was generated in SolidWorks. Further research may be required into the optimization of the propeller for use within E-foils however, the improvement was more than enough for the purposes of this project.

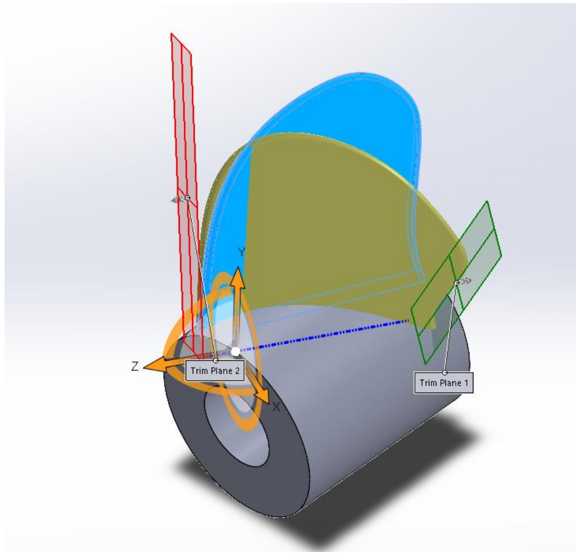


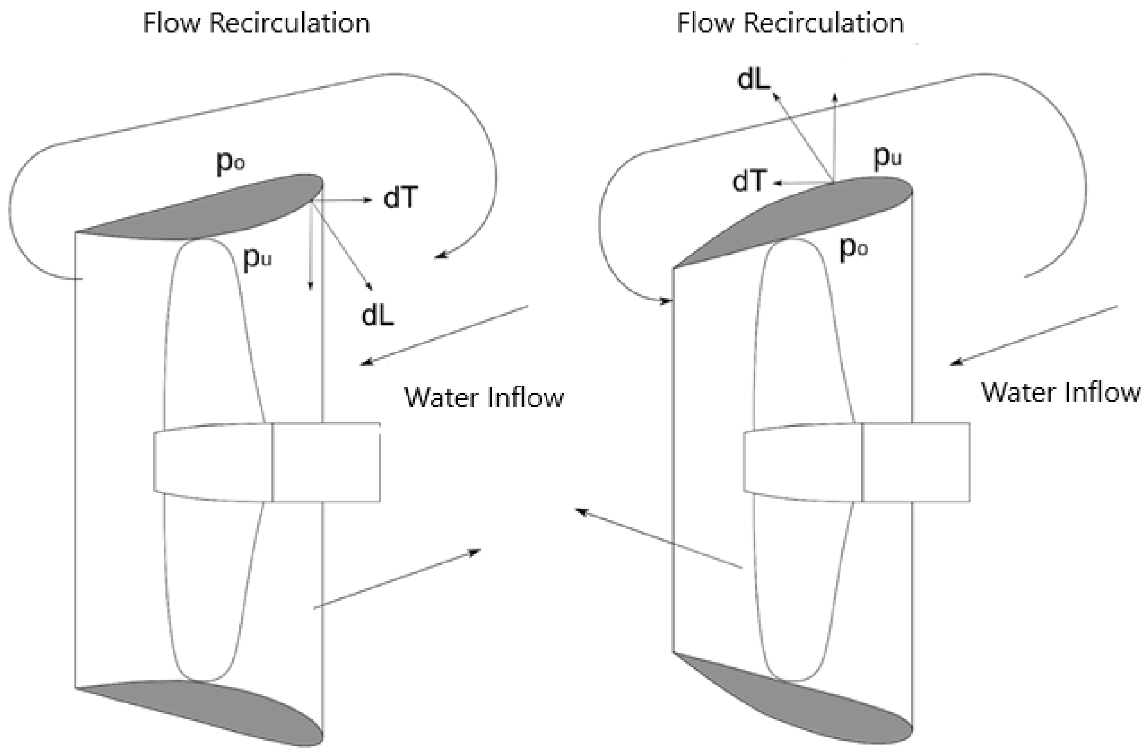
Figure 7: Development of the New Propeller in Solidworks

2.4 Ducts

Most of the research for this project was centered around the design of the duct. The team felt that of the possible changes we could make to the system, the duct had the most improvement possible, while also being able to remain within the time constraints of our project. The duct plays an incredibly important role of guiding the water through the propeller and effecting this flow velocity, turbulence, and direction; however, it is almost always overlooked by the DIY community in place of a simple thin cylinder only focused on safety. These poorly designed ducts, seen in Figure 8, can detract from the system's efficiency, and most riders remove them completely, leading to improved performance, but with a large safety hazard. This duct specifically reduced the overall figure of "efficiency" of the system to 64% of that of a ductless propeller based off our simulation described next. This 64% efficiency was calculated from the percent difference between the figure of efficiency for the ductless propeller and the base duct propellor calculated in our simulation work. This efficiency is what our team hoped to change with a better designed duct.

Figure 8: Old Simple Cylindrical Duct

There are two main duct variations, accelerating and decelerating which can be seen in Figure 9 below [13]. The accelerating duct (left,) is often utilized by larger cargo ships or freighters which operate in low speed, high torque conditions. The design has the curved side of the foil cross section on the inside of the duct to create a low-pressure region where the propeller is rotating. This increases the overall velocity of the water passing through which decreases the overall thrust of the system. However, because these ships are moving slowly, the water pushed through the duct flows out the rear of the system, curls around, and is sucked back into the propeller which can be seen through the arrow looping through the duct in Figure 9 [13]. This creates a large increase in the mass flow rate of water through the duct which provides an overall increase in thrust which compensates for the loss due to the internal pressure decrease.



(a) (b)

Figure 9: Accelerating (a) and Decelerating (b) Ducts with flow direction indicated. [13] “Used Without Permission”

Our project operates in high-speed conditions meaning that this accelerating duct design would be a poor choice to implement into the prototype. The decelerating duct has the curved face on the outer surface of the duct. This makes the region within the duct a high-pressure region rather than the low-pressure of the accelerating duct. This increase of pressure, specifically just along the inner wall, reduces the bubbles created along the edge of the spinning propeller due to cavitation. This cavitation causes vibration across the propeller and creates a turbulent flow, greatly decreasing the efficiency of the system.

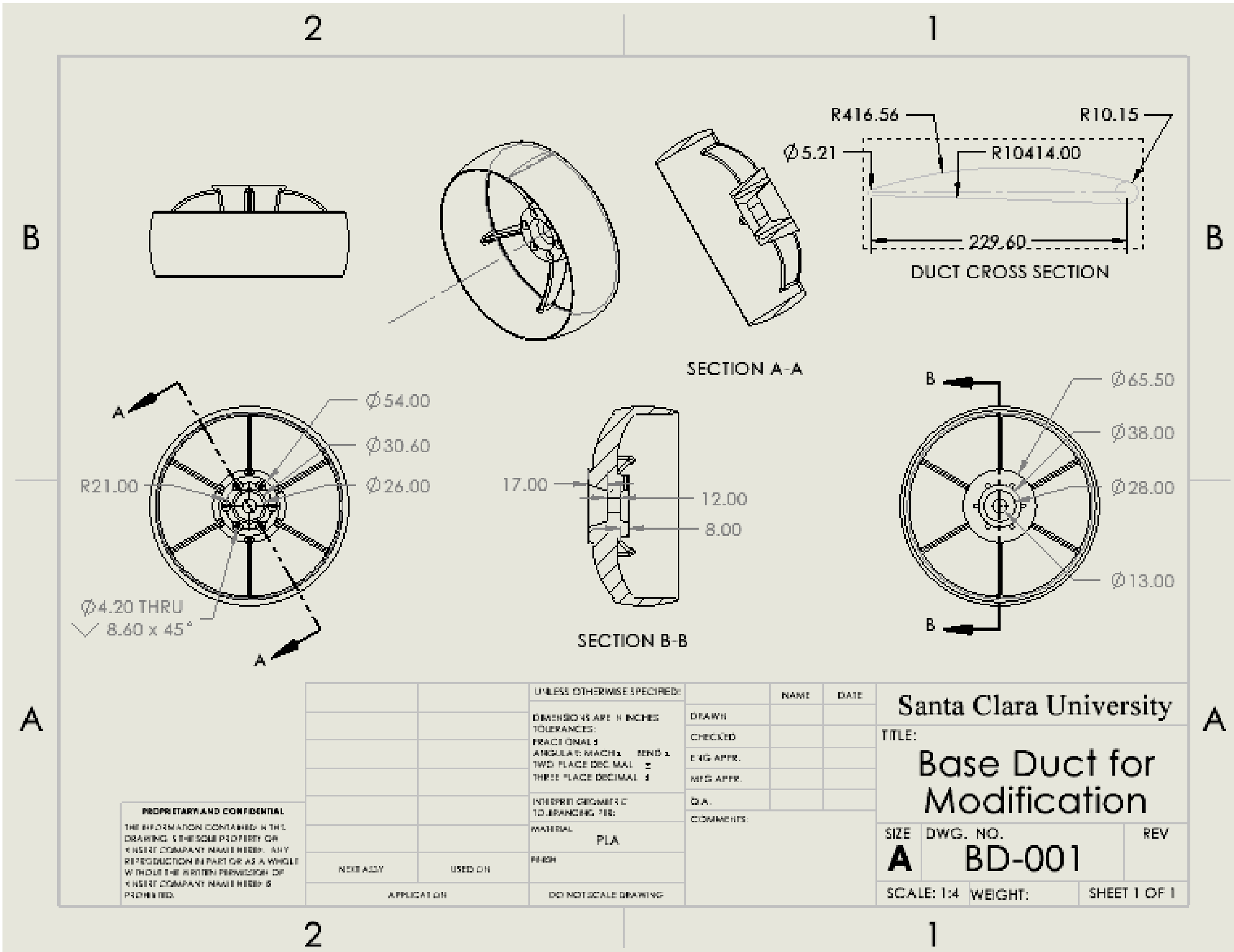


Figure 10: Technical Drawing of Duct Design

Figure 10 shows the base decelerating duct design we used as an initial model. From this model, variations were made by manipulating a single variable (Radius, Camber, spoke number, Spoke Angle, Length, and Duct Angle.) Multiple variations of the duct were created manipulating one of these variables at a time so larger trends would be able to be seen and an optimal value for each could be determined. All 50 versions created were used in simulations which will be discussed further in the Simulation section.

2.5 Propulsion System Analysis

Below, Figures 11-13, are the schematics detailing the design dimensioning of the three major parts that the propulsion system is comprised of, the duct, the propeller, and the motor itself. From these design schematics a 1:1 replica of the propulsion system could be built and assembled in Solidworks where flow simulation analyses could be run seen in Figure 14.

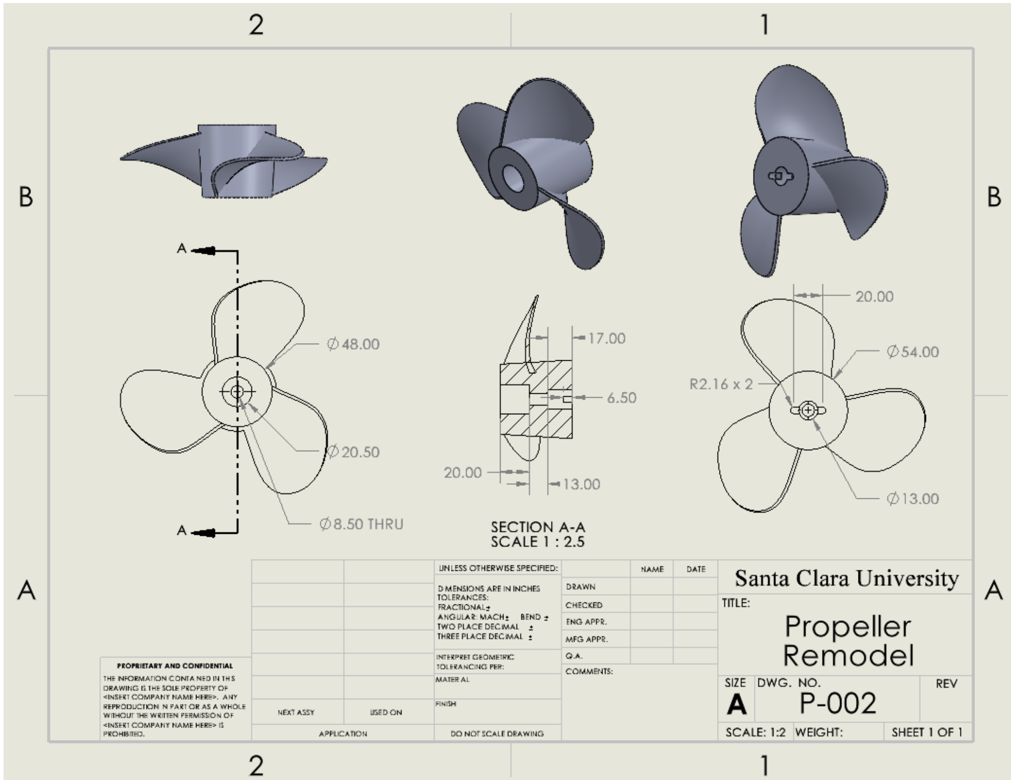


Figure 11: Technical Drawing of Propeller Design

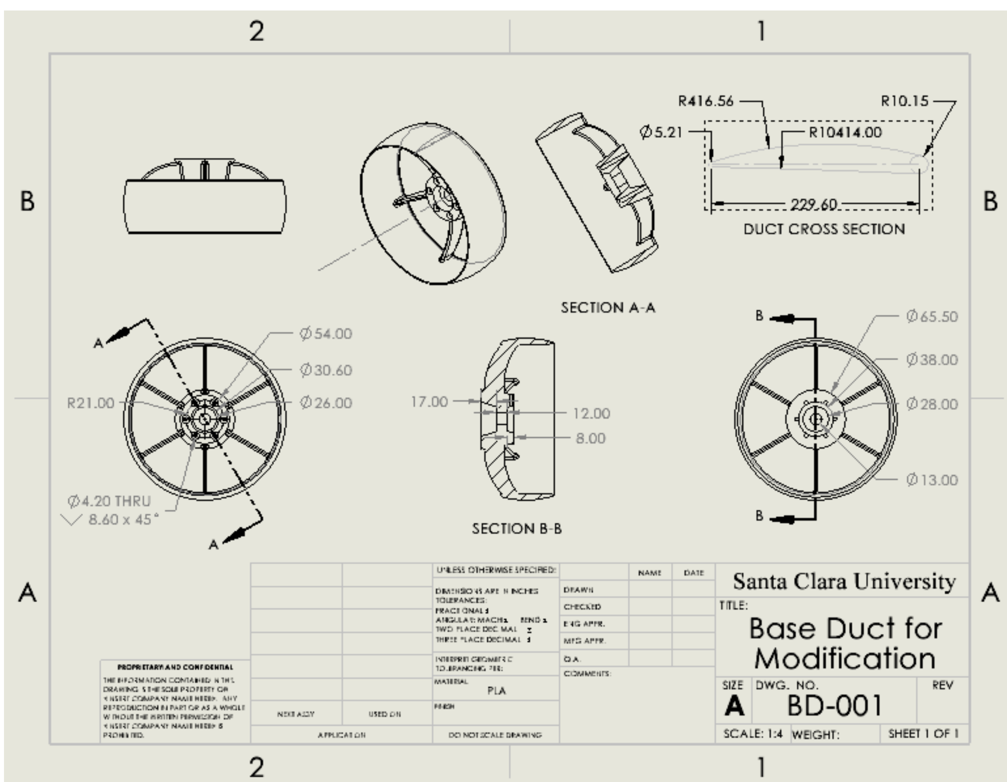


Figure 12: Technical Drawing of Duct Design

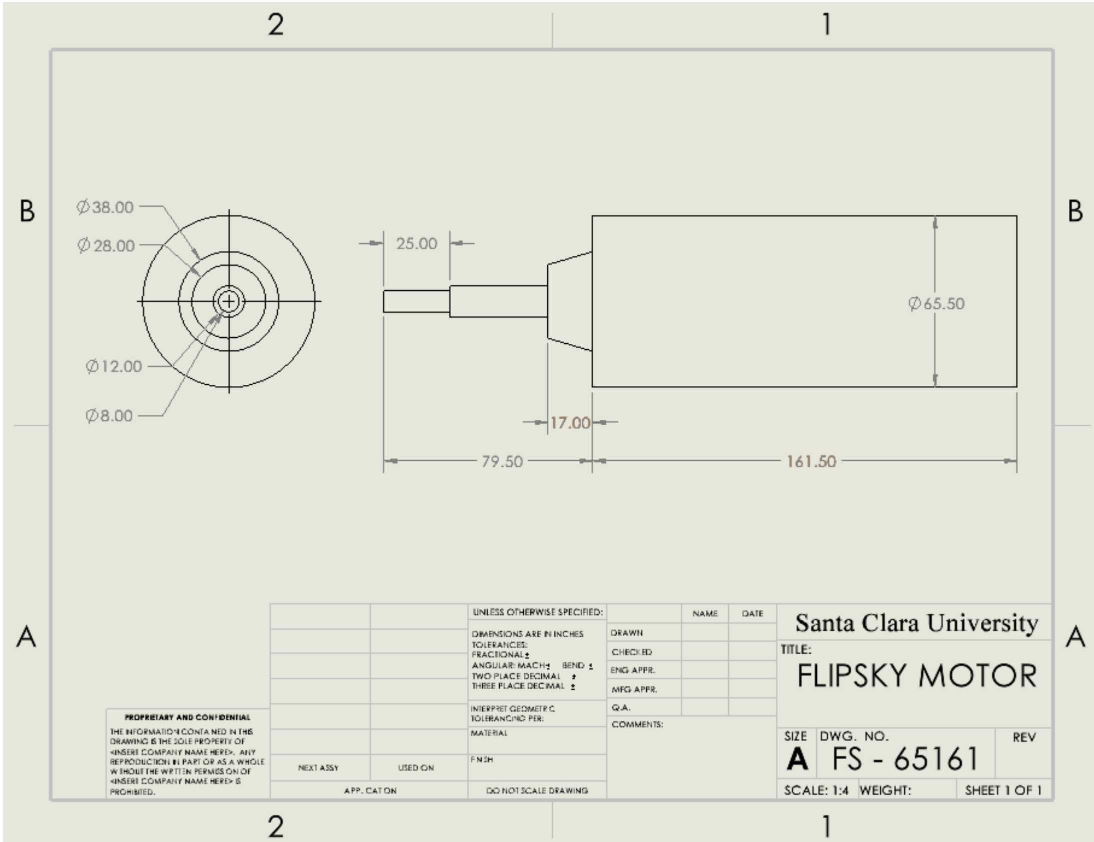


Figure 13: Technical Drawing of Motor

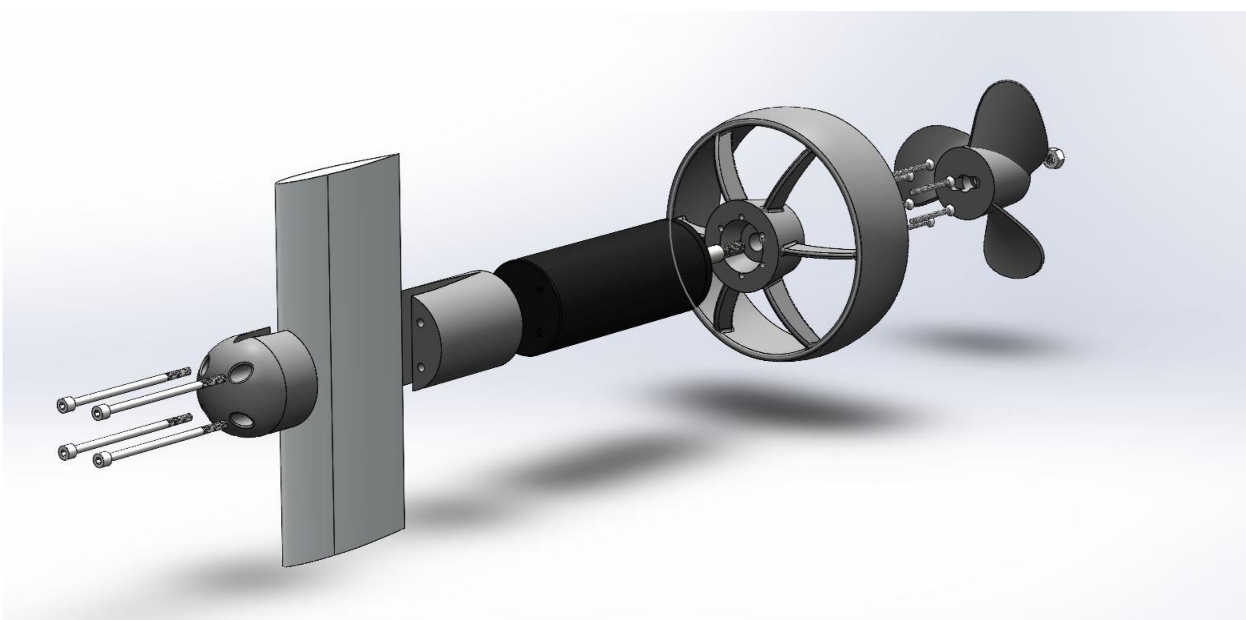


Figure 14: Depiction of the Full-Scale Model of the Propulsion System.

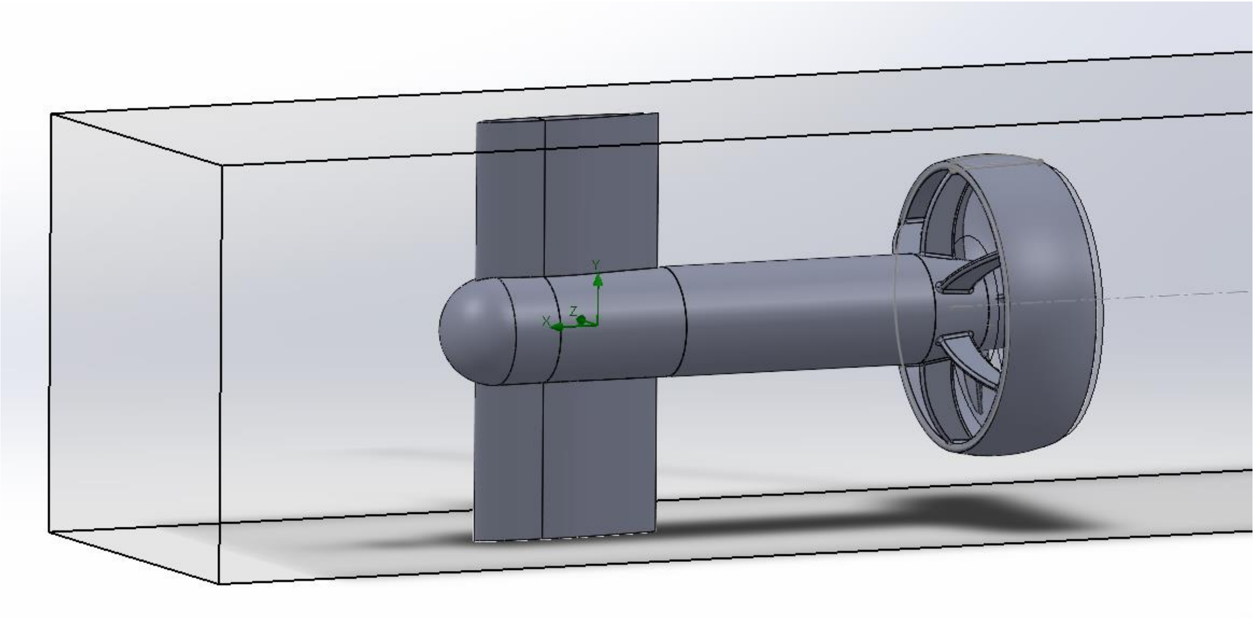


Figure 15: Flow Simulation Setup

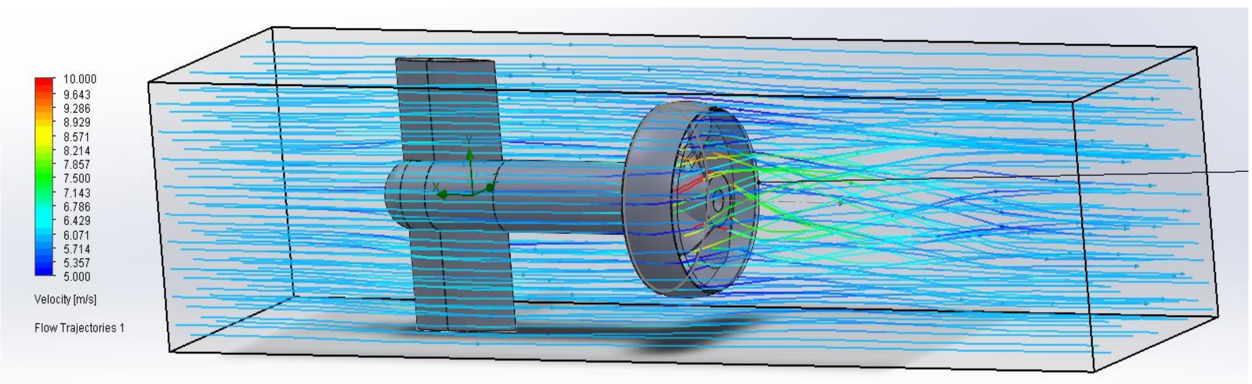


Figure 16: Running Flow Simulation

Figures 15 and 16 show the Solidworks 2020 flow simulation set up and active testing environments. The simulation is set with an inlet flow of 12 m/s and rotational region around the propeller set to spin at a speed of 5000 RPM. These settings are based on the average cruising speed of a E-foil and the typical speed of the propeller when running at that speed. These were the same values used in the FEA analysis allowing us to retain faith in the structural integrity of our parts post-analyzation. This process was informed by a study into propeller computational fluid dynamics written by Muhamad, Husaini & Samad, Zahurin & Arshad, Mohd Rizal [5].

Table 2: Simulation Analysis of Propeller and Duct Designs

Angle of Spokes						
Model	**Thrust (N)**	**Global Force Z (N)**	**Drag (N)**	**Torque (N*m)**	**Efficiency**	**Efficiency %**
Base Un-Ducted	434.57	381.14	53.43	12.672	30.08	100.00%
Base Ducted (Value On Ducted)	389.99	236.29	153.7	11.614	20.35	67.64%
10 Degrees	380.241	244.002	136.239	11.943	20.43	67.92%
20 Degrees	381.88	180.531	201.349	11.917	15.15	50.36%
30 Degrees	416.887	186.437	230.45	12.426	15.00	49.88%
40 Degrees	367.283	189.957	177.326	11.627	16.34	54.31%
-10 Degrees	378.231	209.349	168.882	12.214	17.14	56.98%
-20 Degrees	391.338	214.488	176.85	12.466	17.21	57.20%
-30 Degrees	395.63	228.501	167.129	12.662	18.05	59.99%
-40 Degrees	388.492	243.155	145.337	12.452	19.53	64.92%

As seen in Tables 2, 3 several variables are output from this simulation. Thrust is calculated by finding the force applied by the propeller onto the fluid in the Z direction and "Global force Z" is the summation of all forces in the Z direction. Subtracting the positive thrust from the global force Z gives a negative resistive force which is the total Drag of the system. Finally, the Torque is the resistance for the water on the propeller as it spins. This means that the higher the torque, the harder the motor must work to push the water leading to a higher energy draw.

With these variables in mind, the design iteration of the duct began. Several iterations were performed to test several variables including radius, spoke number, spoke angle, length, camber, and duct angle. The following table lists most of these iterations and color codes each one (Table 3). Red is rated as being the worst (top) and green being the best (bottom). This table was used by the design team to narrow down the different variables that would be worth changing and what the efficiency rating of the changes would be.

To properly test and analyze out design it was imperative that the simulation work mimicked real world conditions as closely as possible. To do this a 1:1 model of the mast, motor, motor mount, propeller, and duct were all created and assembled within Solidworks. From here a flow simulation scenario could be generated.

This initial step offered proof of concept as the previous design saw much greater drag and much less thrust than the new design when only comparing the output of the propellers. Further simulation work came with iterating upon the duct design. By running the 50 iterations of the duct, changing variables such as radius, spoke number, spoke angle, length, camber, and duct angle more or less "efficient" models could be identified. Note that at this point only the new propeller is being analyzed along with the changing duct. The propeller is no longer being iterated on. The changes in efficiency because of the variables being manipulated are seen in Table 3 where they are listed in order of efficiency. The top (in red) is the least ideal design, and the bottom (in green) are the most ideal duct designs for this propeller setup. This allowed us to create a duct with roughly 94% of the efficiency of the un-ducted version of that same setup meaning that a design is possible to implement that would not decrease battery life or cruising speed while also adding in the safety benefits of the duct. This served the purpose of bringing safety back to the DIY community in a meaningful way to ensure that they can build safer boards to enjoy their hobby.

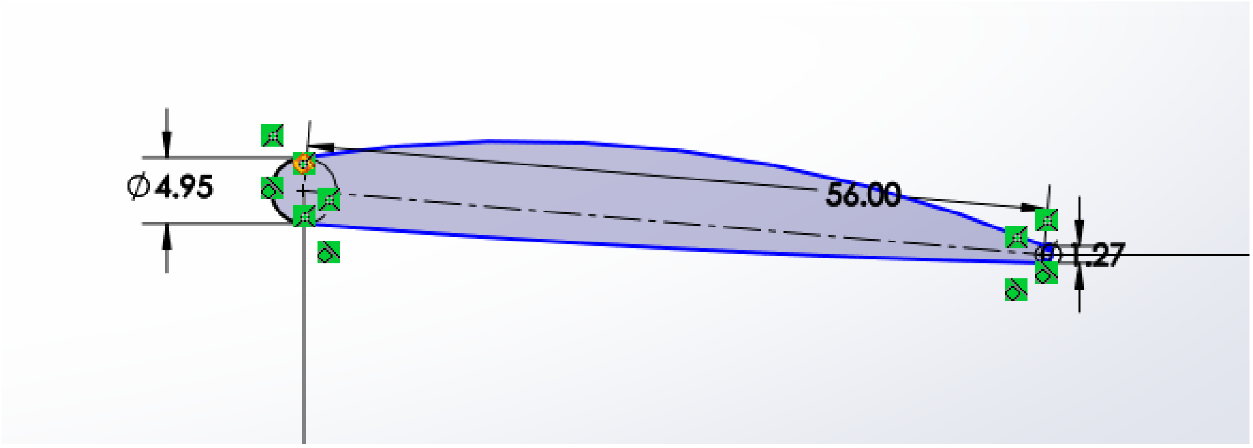


Figure 17: Possible Design Changes of the Duct as far as the Camber, Radius

An important note here is that some of the design iterations show efficiency increases, or even thrust increases that when applied to real world testing no longer creates working parts. For example, the lower the number of spokes, as seen below, the lower the drag and the higher the efficiency but in this case, it weakened the duct too much and would lead to material failure under the high cruising loads. Another example is the angled spokes, these were used to redirect the water to reduce vorticity, seen in red and green in Figure 16, and increase net thrust so that power was not being lost to the rotating water (vorticity). The negative impacts of vorticity are straightforward because energy is lost in terms of propulsion when the water is rotating [14]. This however created substantially higher drag and the efficiency fell dramatically. So, it became crucial to not just identify the best options according to the simulation but to also account for live testing and ensure the product is durable enough to work properly and operate safely given typical riding conditions.

Figure 18: Reduction in Spoke Number Designs

Table 3: Duct Design Iteration and Evaluation

Variation	Model	Thrust (N)	Global Force Z (N)	Drag (N)	Torque (N*m)	Efficiency
Radius	173mm	416.867	129.037	287.83	13.061	9.879565118
Camber	Inner - 500; Outter - 80	348.855	117.482	231.373	11.804	9.952727889
Camber	Inner - 200; Outter - 80	353.666	119.561	234.105	11.867	10.07508216
Camber	Inner - 150; Outter - 80	354.277	130.533	223.744	11.868	10.9987361
Length	62mm	336.096	136.78	199.316	11.711	11.67961745
Camber	Inner - 350; Outter - 80	352.633	141.25	211.383	11.844	11.92586964
Camber	Inner - 500; Outter - 70	354.658	150.719	203.939	12.266	12.2875428
Camber	Inner - 350; Outter - 70	360.161	156.181	203.98	12.349	12.64725889
Camber	Inner - 200; Outter - 70	367.341	170.274	197.067	12.545	13.57305699
Camber	Inner - 500; Outter - 75	353.394	162.385	191.009	11.953	13.5852924
Camber	Inner - 350; Outter - 75	353.821	168.572	185.249	12.046	13.99402291
Camber	Inner - 150; Outter - 70	369.987	183.671	186.316	12.615	14.55973048
Camber	Inner - 200; Outter - 75	362.574	182.432	180.142	12.214	14.9363026
Spoke Angle	30 Degrees	416.887	186.437	230.45	12.426	15.00378239
Spoke Angle	20 Degrees	381.88	180.531	201.349	11.917	15.1490308
Camber	Inner - 150; Outter - 75	364.132	191.585	172.547	12.27	15.61409943
Camber	Inner - 150; Outter - 100	394.477	193.302	201.175	12.36	15.63932039
Spoke Angle	40 Degrees	367.283	189.957	177.326	11.627	16.33757633
Spoke Number	4 Spokes	379.91	201.89	178.02	12.01	16.8101582
Camber	Inner - 500; Outter - 100	387.582	205.767	181.815	12.218	16.84129972
Length	60mm	374.333	201.749	172.584	11.785	17.11913449
Spoke Angle	-10 Degrees	378.231	209.349	168.882	12.214	17.14008515
Spoke Angle	-20 Degrees	391.338	214.488	176.85	12.466	17.20583988
Length	58mm	395.625	216.812	178.813	12.399	17.48624889
Spoke Number	5 Spokes	383.42	210.52	172.9	11.954	17.61084156
Length	64mm	300.589	193.725	106.864	10.892	17.78598972
Spoke Number	3 Spokes	375.13	212.00	163.13	11.907	17.80465273
Spoke Angle	-30 Degrees	395.63	228.501	167.129	12.662	18.04620123
Radius	171mm	374.22	225.22	149	11.987	18.78868775
Camber	Inner - 500; Outter - 150	432.12	253.811	178.309	13.358	19.00067375
Camber	Inner - 200; Outter - 100	392.599	234.504	158.095	12.295	19.07311915
Camber	Inner - 150; Outter - 150	392.542	234.927	157.615	12.278	19.13397948
Camber	Inner - 200; Outter - 150	382.078	234.912	147.166	12.161	19.3168325
Camber	Inner - 350; Outter - 100	386.433	237.815	148.618	12.18	19.52504105
Spoke Angle	-40 Degrees	388.492	243.155	145.337	12.452	19.52738516
Camber	Inner - 350; Outter - 150	366.21	234.952	131.258	11.902	19.74054781
BASE	**Base Ducted (Inner - Flat; Outter - 10(**	**389.99**	**236.29**	**153.7**	**11.614**	**20.34527295**
Spoke Angle	10 Degrees	380.241	244.002	136.239	11.943	20.43054509
Spoke Number	2 Spokes	378.83	248.72	130.11	12.034	20.66810703
Radius	169mm	353.145	255.745	97.4	11.96	21.3833612
Radius	166mm	332.641	251.504	81.137	11.329	22.20001765
Camber	Inner - (500); Outer - 100	538.099	366.487	171.612	14.922	24.5601796
Camber	Inner - (350); Outer - 100	527.875	361.534	166.341	14.71	24.57743032
Duct Angle	4 Degrees	491.521	367.626	123.895	14.17	25.94396613
Duct Angle	2 Degrees	571.858	417.517	154.341	15.758	26.49555781
Duct Angle	6 Degrees	536.126	411.817	124.309	15.114	27.24738653
Duct Angle	10 Degrees	501.317	397.87	103.447	14.475	27.48670121
Duct Angle	8 Degrees	530.976	424.342	106.634	15.043	28.20860201
BASE	**Base Un-Ducted**	**434.57**	**381.14**	**53.43**	**12.672**	**30.07733586**

As a result of all these simulations and data comparisons, a model duct was created (the 8-degree duct) that retained 94% of the efficiency of the base un-ducted setup, proving that it was not only possible to implement a better duct, but it is possible for a builder to do it in such a way where there is no significant advantage to sacrificing safety for efficiency which was a major concern and goal of the build team.

2.5 Duct Results

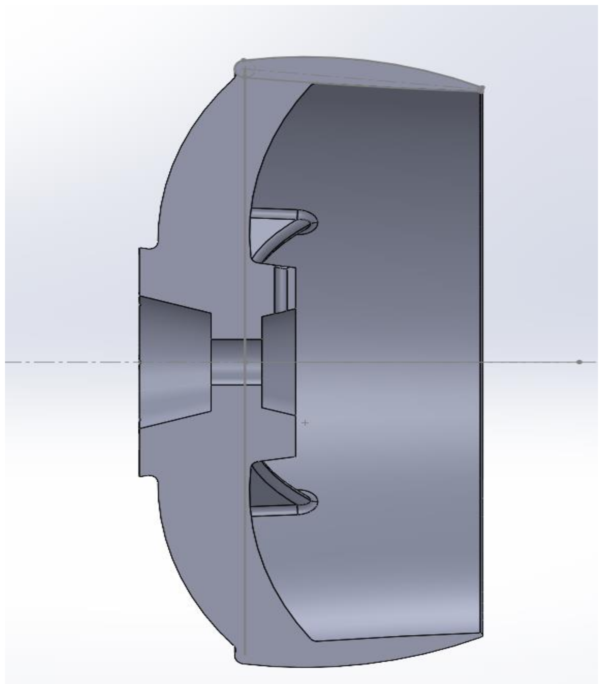


Figure 19: Optimized Duct Design

Figure 19 is an image of the finalized duct this team generated to implement into the final board design. The results of the design iterations are outlined in more detail in section 2.4 of this report, however some of the variables altered include, the radius of the duct, length of the duct, camber, the decelerating duct design, the number of spokes, and the angle of those spokes. This design was able to achieve roughly 94% of the un-ducted efficiency proving both that ducts play a huge role in the efficiency of a propulsion system and that it is possible to have both safety and efficiency when designing one of these E-foil boards.

2.6 Battery design

The other major safety concern addressed by this E-foil design team was the battery. To make this portion of the design safer, a plan to redesign and implement the battery has been developed and is included in Appendix 1. The major steps include providing the means to switch away from Li-Po batteries in favor of an 18650 Lithium-ion battery if necessary/possible which is then housed in a NEMA rated IP-67 case and integrated more fully into the board. An acrylic case was developed to facilitate battery insulation and shorting resistance, and intensive waterproofing techniques were implemented at any weak points, joints, or wiring entry points.

2.7 Mounting System

To use a simple and safe battery system on a motorized hydrofoil board, first the battery system bust be able to be mounted easily. As many members of the DIY community are starting their builds with a paddle board as the base, the goal became to make a retrofittable case that would work on this style of board while also retaining the ability to secure the battery in place in the event of a crash, fall, or other incident. This design was iterated on several times, but the final design utilizes four simple bolt support holes and a metal plate to clamp over 4 buckle straps. All the parts used can be easily sourced from a local hardware store and a more detailed list of the parts can be seen in Appendix 2. A Polycase was also implemented with the final design to make it as easy as possible for a DIY user to implement to satisfy the goal of making the work done here reproducible within the community. Images of the battery housing and general retrofitting process can be seen below, while utilizing Appendix 2 for instructions.

Figure 20: Mounting Apparatus for Retrofitting to Existing Boards

2.8 Battery System Design

The build team started off by doing research into the best way to build a battery system and what the best battery chemistry choices would be. A lot of this data came from Code 49 [11] as well as through talking with experienced members of the community through online forums and through Peter Collins. Next, we developed a list of needs that the battery system must be able to fulfill. First, the battery system must be safe and fully waterproof. There could not be any exception to this rule because should the batteries short it could create a highly volatile and dangerous situation for the rider and other nearby individuals. It could also impact the environment if the damaged batteries were to get lost or leak into the surrounding water in the case of an accident making this a top priority. Secondly, the battery must be able to supply 44.4V to the electric brushless motor that is used in many DIY builds. Third, the system should be able to be constructed easily and without complex manufactured parts to make this a valuable and usable product for new or veteran E-foil builders. Lastly, all components necessary to the operation of the board should be able to fit into a standard box that can be mounted onto the established mounting system, including items such as the motor controller.

The design and build process began first, with two battery chemistries chosen. A Lithium Polymer (LiPo) option and a Lithium-ion option. By making two versions of the battery system, we allow the builders to choose what price point they want for the build. This comes down to how much they are willing to spend to add the safety and energy density of a Lithium-ion battery. The LiPo is beneficial because it requires very little user skill to implement and assemble however they are more volatile and potentially more dangerous than a Lithium-ion battery. The Lithium-ion battery however takes more skill and man hours to create. The added benefits are that it allows the builder to incorporate individual cell fusing which would reduce the risk of catastrophic failure. Additionally, it creates an opportunity to implement a battery management system (BMS) which gives the builders even more security and freedom in their build process. Below both battery systems can be seen, Figures 21, 22. To supply the correct voltage requirement to the motor two LiPo batteries can be used in series, or the 12 rows of Lithium-ions can be used in series. The voltage requirement was to be roughly 45 volts. This value was determined based off of the rpm that our simulations were run at. In order for our real world rpm to match the simulation rpm while using a 120Kv rating motor, a 45 volt battery is required.

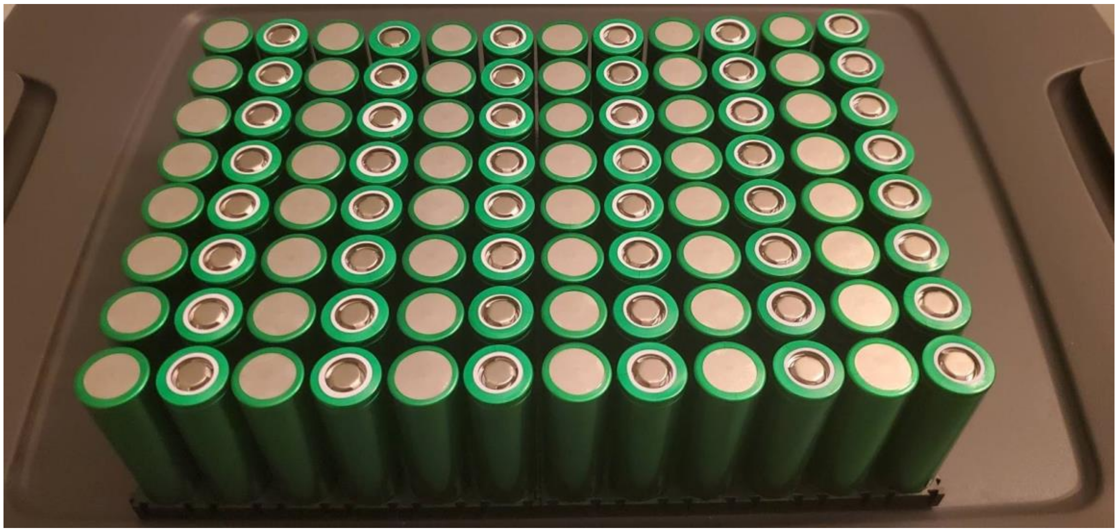


Figure 21: 18650 Lithium-ion Battery Cell Assembly

Figure 22: LiPo Battery Pack

The first part to then building the battery system was to find a method of containing all the parts within a waterproof enclosure that could be disconnected from the motor wires. To do this we choose to use a Polycase Wq-64 IP68 rated waterproof box and install waterproof cable glands from Polycase. This method allowed for easy sourcing of parts from a trusted manufacturer, that all members of the DIY community could access. Finally waterproof connectors were made using two bullet connectors with ¼” acrylic tube surrounding it and epoxied together. The bullet connectors could then be connected inside a pneumatic quick connect fitting to form a waterproof seal. Below the battery boxes can be seen with the battery assemblies within them.

In designing both battery systems the foremost goal was to create a safe and implementable system for both battery systems. There were some similarities between the designs that could be carried over between designs. For example, both designs were built around Polycase WQ-64 waterproof cases and Polycase CP3 cable glands. This design choice was made to ensure consistency of waterproofing throughout all the prototyping efforts. Lastly both designs incorporated an added foam layer on the outside of the box so that the system could absorb shock and vibrations while riding the board to reduce damage to the batteries.

To create the LiPo battery design the first step was to make sure the LiPo is operating within safe conditions as informed by the Code of Federal Regulations Part 49 [7]. To do this simple LiPo alarms were installed that will alert the rider when the batteries dip down to 3.1V at any cell. This is critical because if a LiPo battery is drained below a certain level, permanent battery damage could be sustained, and reuse may be impossible.

Next a system to mount the batteries and the motor controllers inside the battery box was required. To do this a high-density polyethylene (HDPE) plate was cut to the shape of the bottom plate in the case and 6 slots were cut out to line up with the edges of the LiPo batteries that battery straps would run through. Velcro was also attached the plate and the bottom of each LiPo. Six 5mm diameter holes were also drilled lined up with the screw holes in the motor VESC to screw the VESC to the HDPE plate, allowing all parts needed to be mounted securely. The system described with an added cooling system explained next is pictured in Figure 23.

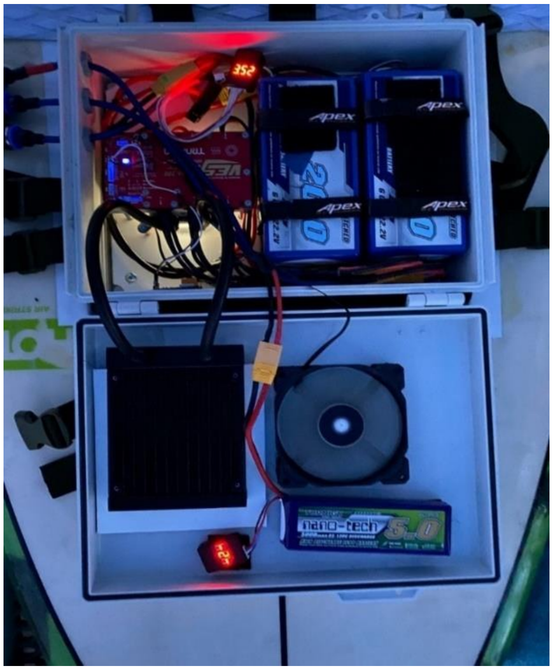


Figure 23 : Battery Box and System

The next sub-system that required additional work was the cooling system. Originally the LiPo system design did not contain a cooling system which resulted in thermal throttling of the board's power as seen in Figure 24.

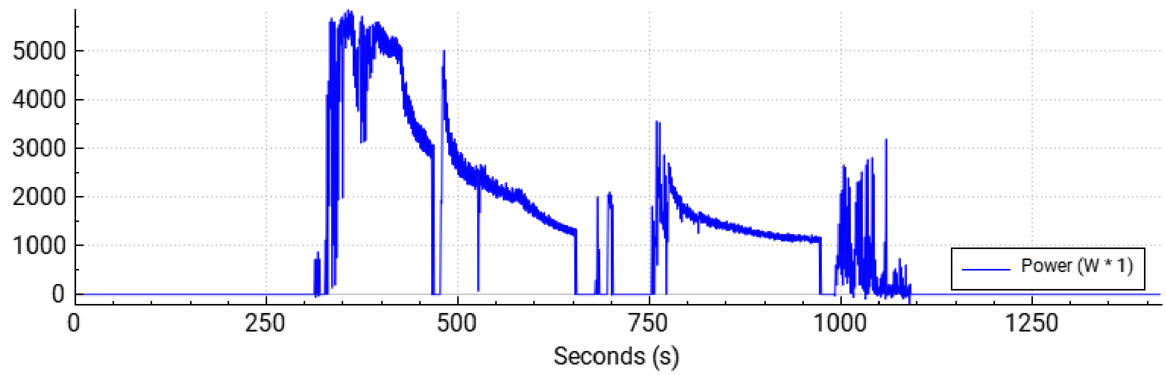


Figure 24: Thermal throttling of the motor

Here the effects of thermal throttling can be seen. As the run time increased and overall temperature rose, the motors output began to steadily decline and perform at sub-optimal levels. To solve this problem, the mounting system was altered to elevate the motor controller and a Corsair H60 CPU water cooling block was placed underneath as shown in Figure 25.

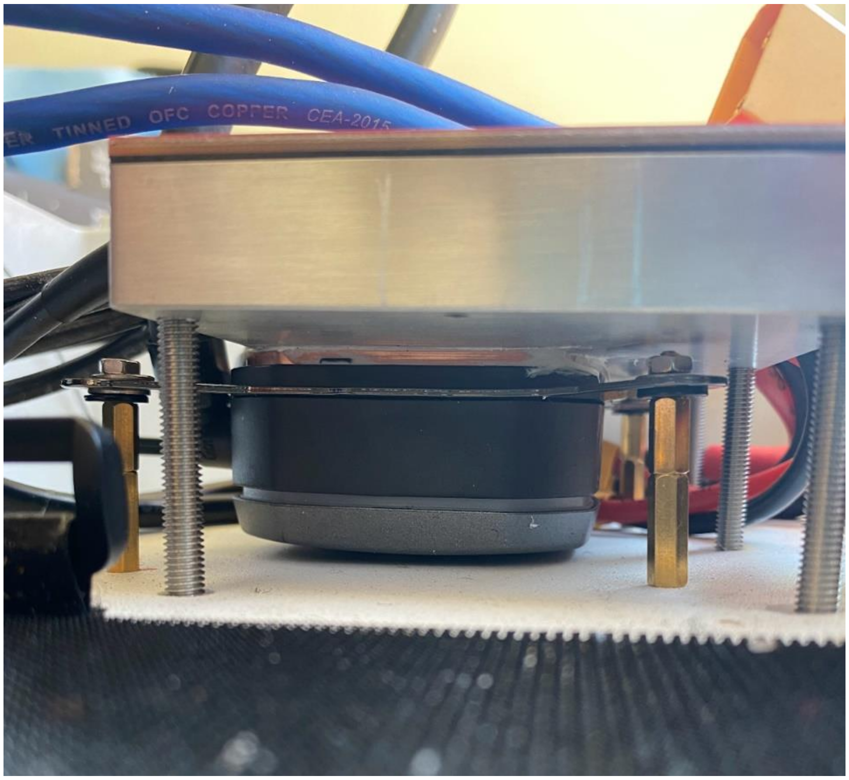


Figure 25: Motor controller cooling system

The water-cooling block was then connected to a radiator that drew the heat away from the motor controller and a fan is used to displace the heat so that the surrounding water could aid in the cooling process. Using thermal imaging we were able to confirm the heat was successfully drawn away from the motor controller and into the radiator. This was further proved by the elimination of thermal throttling during operation.

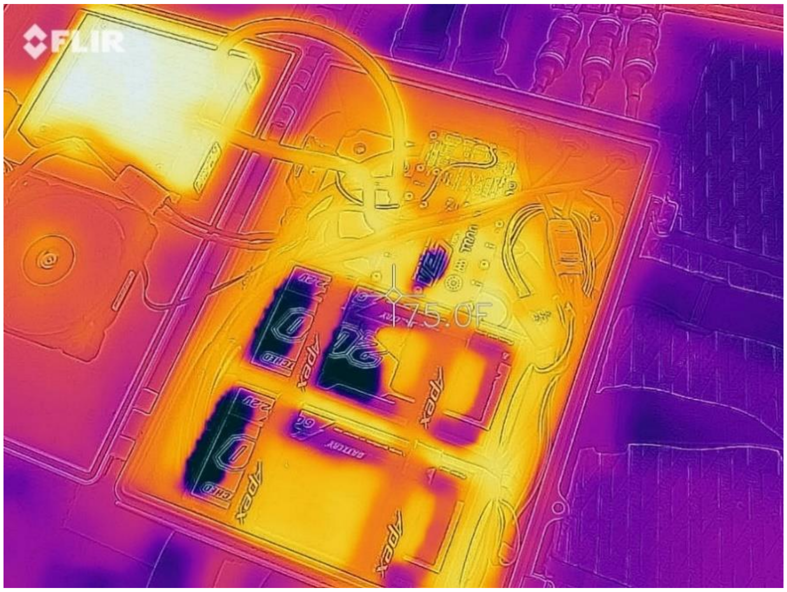


Figure 26: Thermal imaging of LiPo system using FLIR camera

The image above shows the thermal image capture of the redesigned battery storage site with the implemented cooling system. At the top left you can see most of the heat being relocated away from the batteries and controller. This allows for immediate cooling of the critical battery components and provides a consolidated site for the water-cooling system to draw this excess heat out of the system entirely. Once the cooling system proved it worked effectively the design of the LiPo battery system was complete.

Next we designed the Lithium-ion (LiIon) system, which was unfortunately only partially complete at the time of this report due to time constraints and being unable to implement an effective cooling system in time. In creating the LiIon system we stated at the battery itself. To keep the design simple, we used a rectangular layout for the batteries in a 12s 8p layout. This provided a 44.4V battery to keep the voltage the same between the LiPo and LiIon systems. The batteries were assembled using 18650 battery holders and nickel strips were spot welded to the battery. Lastly on the bottom at the positive and ground terminals a copper bus bar was installed to ensure no ampacity limitations at the highest current section of the battery. The whole battery was then wrapped in an insulating tape and mounted using 25 M5 x 80mm bolts onto the case.

Then we took advantage of the ability to use a battery management system (BMS) which is what allowed for the main safety features of the LiIon battery design. By installing a battery management system, we were able to cut off the battery when it hit an indicated voltage, we were able to control the current going into the battery when charging, we were able to monitor the temperatures of the batteries and cut off the system if a battery were overheating and there were even more safety and functionality features we could later install if needed. This was all done using a Daly 200A 12S BMS.

Lastly, on the top of the battery a 25amp fuse was installed to each battery cell, shown in Figure 27, that in the case that any one battery failed it would blow the fuse and the rest of the battery would remain undamaged reducing the risk of catastrophic failure. An external 125amp fuse was installed to prevent the whole battery from over discharging and all these parts were then mounted in and on a laser cut acrylic case. The acrylic case provided an extra layer of protection for the battery to prevent anything from falling on it and shorting any parts. The design with all these parts described is shown in Figure 28.

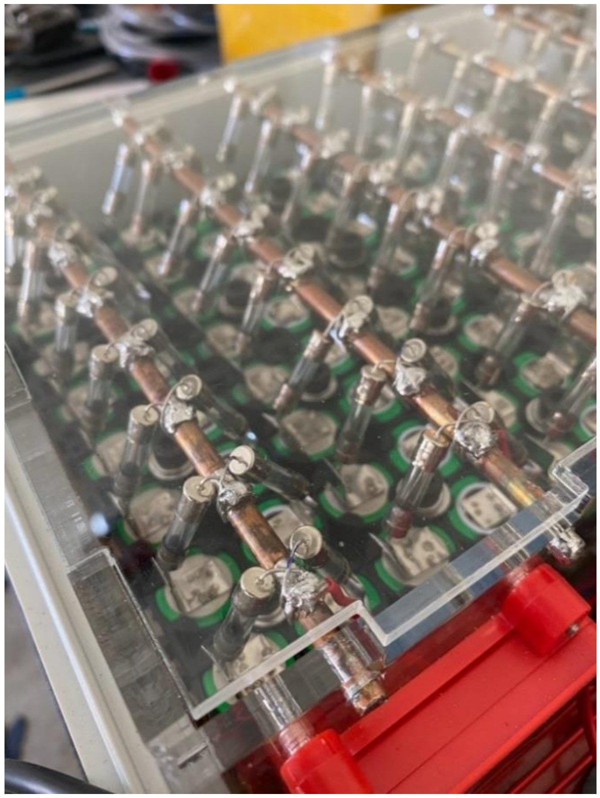


Figure 27: Top of the Lithium-ion battery with individual cell fusing

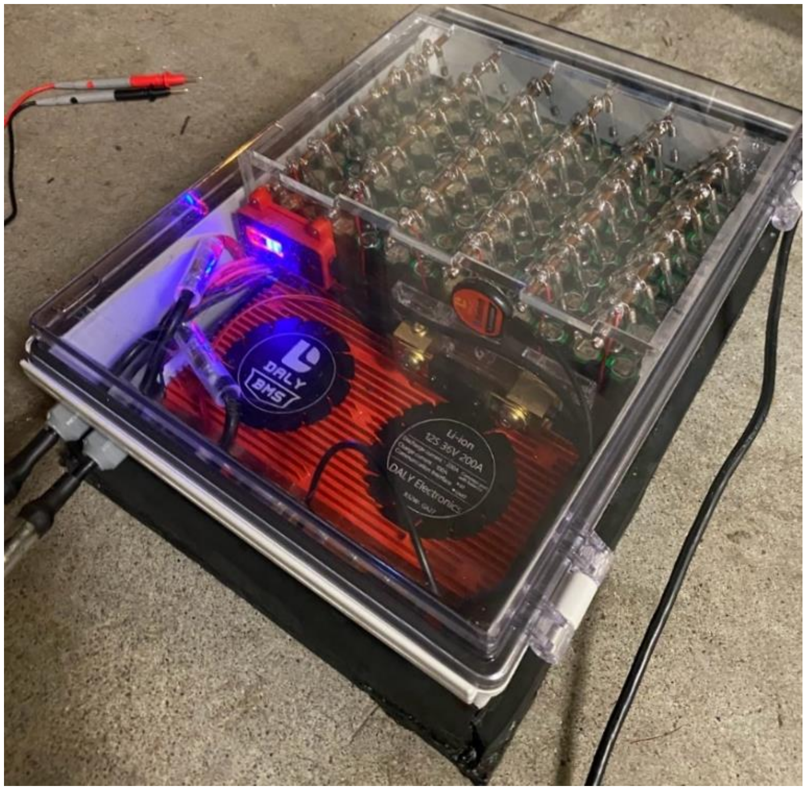


Figure 28: Lithium-ion Battery Box and System

In the final design, after some issues with the motor controller overheating again, we converted the design to more closely resemble the LiPo system where the motor controller was mounted inside the battery box rather than in a separate box. In this redesign a different motor controller was used that contained a built-in water-cooling enclosure and mounted on top of the battery management system. This was necessary since the Lithium-ion design was much larger and therefore left less room in the mounting enclosure for the same cooling methods to be implemented. This alternative cooling method works by drawing in water from the surrounding water and circulating it through the water-cooling enclosure using a 12V water pump. An exit tube pumps the water back out into the surrounding water creating the cooling flow loop. This cooling system can be seen below in Figure 29 followed by the actual controller in Figure 30.

Figure 29: Unwired Motor Controller with Water Cooling Enclosure

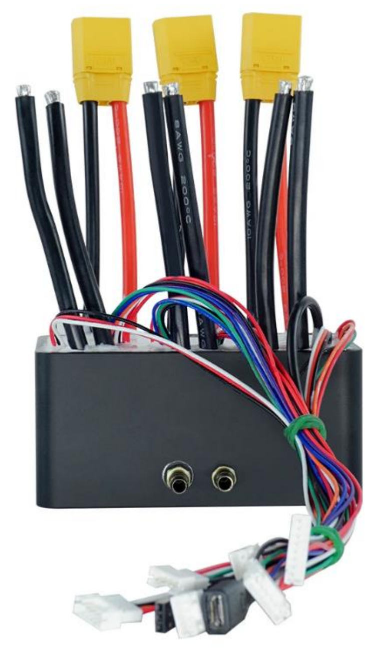


Figure 30: Flipsky FSESC 75200 75V High Current 200A ESC “Used Without Permission”

3 Testing Parameters and Procedure of Data Collection

Once the development of the individual subsystems was completed, a full assembly and live testing with the newly created parts was required to prove the simulations and general expectations were correct.

Given the FEA analysis as well as the new models generated in Solidworks, prototyping began utilizing both Santa Clara University facilities such as the “Maker Lab” as well as a personal 3D printer owned by the team. Here both PLA and PETG were used. We were able to confirm that a standard PLA 3d printed part would be strong enough to hold under the stresses of providing thrust to the E-foil. Knowing this, the design team also decided to use a PETG filament as it provides greater toughness over repeated loading cycles than PLA allowing for more test runs to be completed per part. This was reserved for parts that were promising and required additional testing. The PLA filament was beneficial as parts could be printed in less than a day to be used quickly on the board for testing. This allowed us to test good and bad ideas alike without wasting an excessive amount of time or resources.

The next task was to prep the parts for testing before they could be placed on the board the parts needed to be waterproofed and sanded to avoid unintended drag increases. 3D prints use an infill during printing which leaves a space that could potentially fill with water and would then generate unreliable data. To solve this problem all incoming parts were sanded, then a layer of xtc3d 3D print filling epoxy was applied. Next, Resin Research surfboard epoxy was applied to fully seal and strengthen the parts and lastly any areas where epoxy had gathered was sanded smooth to create a flat uniform surface for testing.

The actual testing and data collection occurred using the motor controller and a phone mounted inside the battery case. This allowed for power draw data to be collected in relationship to the RPM speed and several other parameters. This was then captured through the VESC software. This software was included with the Electronic Speed Controller that is used by the rider and was how the graphs below were generated. The team was unable to access a water tunnel given the restrictions on lab space and in person gatherings that were implemented throughout the year, so testing was more difficult than anticipated and came with increased uncertainty. The two main methods of testing were proof of concept tests and data collection tests. The proof-of-concept testing consisted of submerging the motor into a deep enough bucket of water, running it at cruising speed for a minute and observing how the parts stood up to the test. Data collection was then completed with the verified parts and had to be completed at Half Moon Bay CA. By testing there, we were able to get relative data points to compare average power draws over the course of foiling runs to compare how the efficiency changed as different ducted-propeller assemblies were implemented on the board. During these tests, a wind speed sensor, seen in Figure 30, was mounted to the board to determine head winds which may affect power draw. In addition, a length of tape was attached to the mast. The tape was a known length which could then be used as a scale to measure the height of the board out of the water when captured on video. The purpose of this was such that, should power draw spike or fall, and the board is clearly higher or lower in the water, the outliers in the data could be explained. This allowed the team to confirm if the data from the computer simulations and the data from the live tests were corroborating the results the team collected. Next steps to further reduce the data error would be to add a water speed pitot tube style sensor mounted to the board. The logistics of this are still being considered by the design team and has not been officially implemented into the prototype.

Figure 31: Wind Speed Sensor “Used Without Permission”

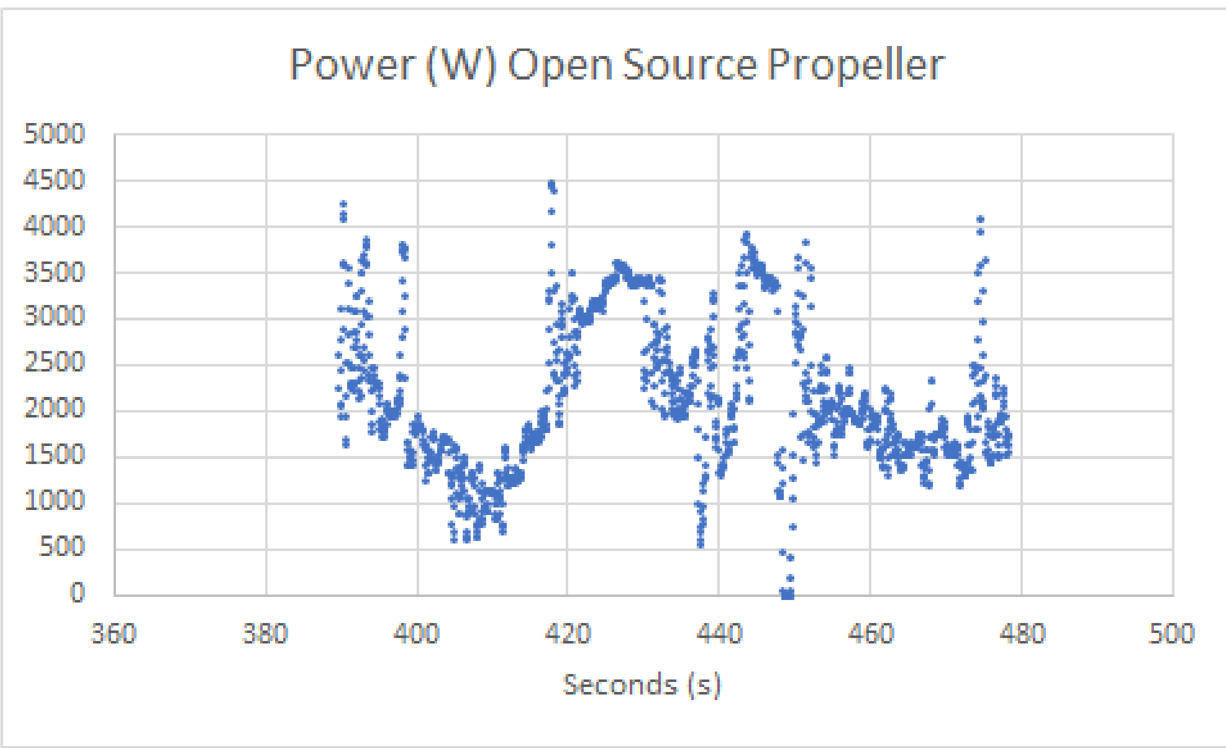


Figure 32: Open-Source Propeller with No Duct Power Test

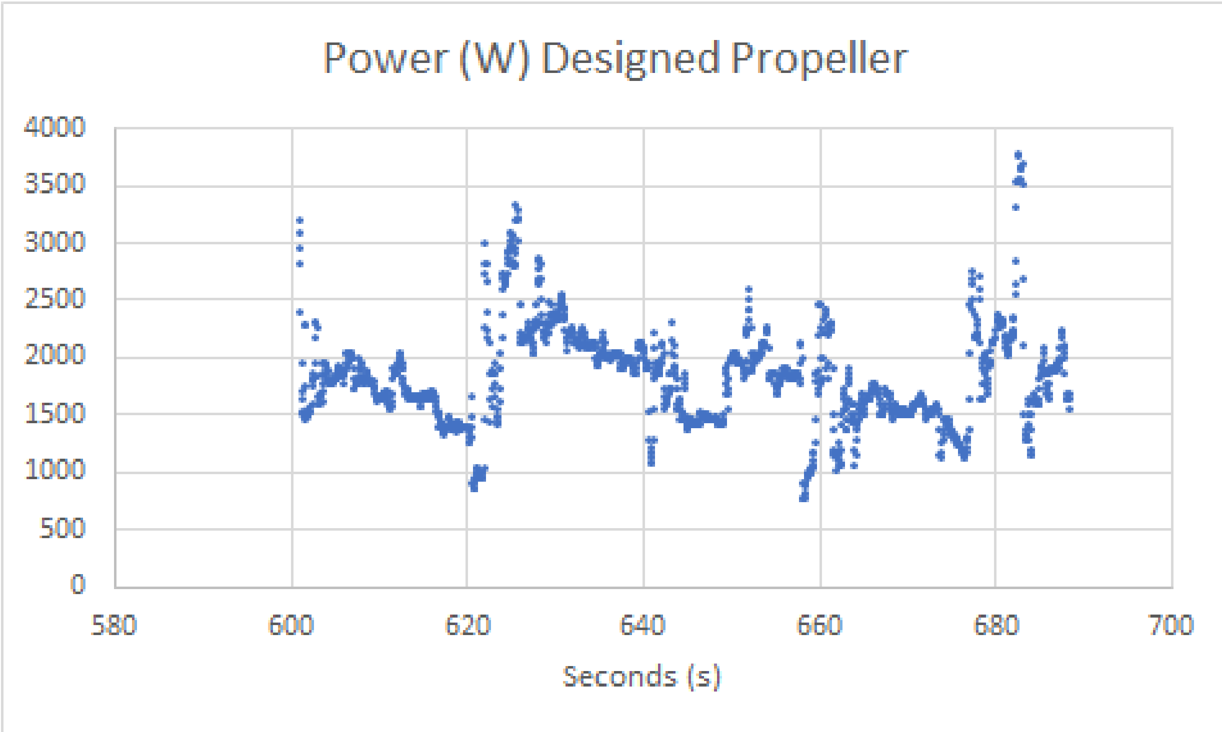


Figure 33: Newly Generated Propeller with No Duct Power Test

Figure 32 above represents the power draw from the propeller that is typical to find within the community while Figure 33 represents data from the new propeller created and printed. The resulting data, using the average power from these Figures show, that our propeller dropped the power required to foil from 2150 W to1824W for an efficiency gain of 15%. As the average speed over the course of both test runs was 12mph, the resulting data has low enough uncertainty to show that our propeller is in fact increasing the efficiency.

Figure 34: Data Collection Test ride - Photo Credit: Wesley Sava

In Figure 33, Advisor and test rider Peter Collins is shown test riding the completed hydrofoil board in order to collect data on the board, propeller, and duct. For this testing we ran our board from the docks at the Pillar Point boat launch in Half Moon Bay, California. When testing, the board was launched from the docs and ridden in loops of 50m in distance. This allowed us to keep the board within swimming distance of the dock while allowing the loop to be wide enough, so tight turns were not required, allowing Peter to be more consistent in his riding. For most of our testing at the beginning of testing this plan was only roughly followed as we were dealing with a couple part failures and propeller incompatibility talked about previously.

This team also had planned out testing plans to improve the quality of the data as follows. First, we planned to mount a wind speed sensor, and quantify important data points in relation to cavitation, board landing and take-off and other data points. The testing plans described previously we were unable to follow. We recommend that future iterations of this project use the testing plans laid out or if feasible, test in a water tunnel.

In our testing itself we were only able to collect very simple data. The data we collected involved Peter completing 8 of the described laps. This was done for each of the propeller test setups with a phone in the battery box collecting data from the VESC motor controller. For data collection the VESC collected data on the power and electrical components in 50ms intervals and GPS speed data was collected every 600ms and all written out to .csv files. The electrical data was read to 0.1V and 0.1A uncertainty meaning all power data was high accuracy. This means that the power data collected only contained significant uncertainty associated with the testing procedure and inconsistency associated with human test riding.

4 Patent Disclosure

The design team used several existing patents for aid in our development for out designs. Most notably was the propeller because, as discussed previously the open-source propeller used within the DIY community is sub-optimal at best so following industry trends allowed us to identify a new propeller that could offer better hydrodynamic properties. One patent was created with the specific goal of improving a motorboat streamline impeller [15]. This patent for a motorboat impeller had several shortcomings in its installation and design that lead to inefficiencies in its performance. Another patent from 1996 was filed for an easily correctable motorboat propeller [16]. This patent however had an issue where the propeller would have a shifted center of gravity and the only identified solution was to remove material to realign it properly. This patent was able to provide documentation on an improved propeller with a streamlined profile that allows for the transfer of a much higher amount of water which would increase the overall thrust of the propulsion system.

Further patent searches identified another idea that had similar working conditions to our project with a different application. This patent set out to create a non-metallic propeller that performs at high RPMs without deformation [17]. The goal was to provide a cheap alternative that could be retrofit into most motor configurations. The result was a plastic produced of RYNITE 555 material which is within acceptable levels of corrosion resistance and deformation resistance. Where this design falls short is if the propeller were to strike a solid object in the water. Because of the new material, the propeller will shatter rather than deform. The purpose of this is to protect the engine, transmission, and/or driveline from damage which is beneficial because it is cheap to replace and cuts down on maintenance or repair costs which offers substantial financial benefit to the customer. Our project similarly aims to be easily accessible, affordable, and implementable on different build styles as well. Our propeller and duct system are downloadable as 3D printable designs and can be made from a variety of thermoplastics available with most 3D printers. This cuts down on cost, and the file can be altered by the end user if necessary to work with virtually any build.

5 Impact Evaluation

This propulsion system redesign addresses a few ethical impacts. Typically, the hydrofoil boards are built by inexperienced builders who prefer speed, and battery life, to safety and concern for the environment. By adding in a duct, the safety of our board is increased by removing an exposed blade that could injure the rider, other people, property, wildlife, or even damage itself on a hard surface. Since the propeller operates at roughly 5000 RPM the damage it can cause should not be underestimated. The redesigned model solves the ethical dilemma of builders willfully creating and riding a device that is unsafe to them, the public, and the surrounding environment while still promising the users the same speed and battery life they want out of their design.

Additionally, the battery maintenance system developed and discussed in section 2.8, contains advancements in waterproofing techniques, and the step-by-step guide for how to properly, build, encase, protect, and implement the battery design. This decreases the risk of damage to the rider from exposed wiring, damage to the battery from external system impact, and through proper safety and implementation the possibility of thermal runaway is greatly mitigated. This is crucial as the board operates in a high energy density state and can severely injure the rider, should catastrophic failure occur.

This leads into the environmental impacts. By creating a safer, more comprehensive battery design and installation plan, there is a reduced risk of e-waste entering waterways where these boards are used. This lowers the potential for water pollution which can have substantial negative effects on the surrounding environment and wildlife. Additionally, hydro foiling is an electric sport, meaning that the hydrofoils are potentially removing gas powered engines from the watersport's community. By removing these gas-powered engines in favor of electric motors decreased pollution levels can be expected as a byproduct of watersports considering how rapidly the E-foil community is growing [2] A sample calculation of the environmental impacts of switching to electric motors will be discussed below as a proof of the claims made above alongside several sources outlining the environmental hazards of gas-powered watercraft.

Essentially the goal of the following calculations is proof of concept. The calculations will demonstrate how the addition of electric hydrofoils into the watersports community would have a net positive environmental impact. The assumptions made started with the scale of industry growth. In the last 5 years we have seen the commercial industry grow by 11 businesses [2] from the original 1 in 2016-2017. Seeing how this is a growth of roughly 240% per year commercially, and the DIY community is an equally sized if not larger subsection of this market we decided to underestimate the growth of the industry to a near minimum. This way, any conclusions made are seen as the least significant value with only room to become larger and more substantial. For this reason, we chose a market growth of about 1% in case nearly no one builds or buys an e-foil in the next year.

Based on the DIY e-foil forum [1], there are well over 50,000 people that are active members. So, if only some individuals own a board, it was estimated that on this single forum 20,000 users would have or be in the process of building a board. This lowered number was used to try and minimize overestimating the impacts calculated from this point forward. So, using a

20,000-member community growing at 1% it can be estimated that there will be 200 new boards on the water in the next year.

The next step was to assume that for everyone opting in for an e-foil, they are opting out of a motorized alternative. This is a rather large assumption to make however because we have been underestimating everything up to this point this assumption should not affect error by a significant. This means that 200 gas engines are being removed. Given that Pontoon boats are rated at using roughly 5-10 gallons an hour based on speed [22], that speed boats use roughly 25 GPH [23], and that jet skis (the likely alternative to our product) uses about 10 gallons an hour [21], the environmental impact was assessed assuming that each engine removed was reducing gas consumption by 11GPH per engine. Given 200 engines at 11GPH you get 2200GPH for all the engines. If a recreational day is 4 Hours this becomes 8800 GPD. Looking at The United States Energy Information Administration [19] a gallon of gas produces 19.6 lbs. of CO_2. 8800 Gallons times 19.6 pounds per gallon gives 172,480 pounds of CO_2 in each day which is not an insignificant number. It is important to keep in mind here how much underestimating was done to achieve this answer which means the total impacts could be potentially much higher. Additionally, this does not consider the seepage of fuel and oil into the surrounding water by even the highest quality engines which is completely eradicated by electric alternatives. Lastly, due to the size, weight, and HP of a typical e-foil, the “mixing depth” is much shallower than a typical mixing depth of a boat or other watercraft. This means that the E-foils would not be playing as large of a role in increasing water turbidity[20]. Water turbidity is basically the concentration of particles floating in it and increases in turbidity increases water temperature and lowers oxygen concentration which is harmful to wildlife and indirectly humans. All of this is used as evidence to support the claims that our product has a nearly net zero environmental impact as well as advocating and paving the way to a more sustainable future using non-petrol-powered devices or vehicles.

6 Conclusion

As a result of the work done by this design team, the goals of creating a safe and efficient propulsion system, as well as a waterproofed, safe battery design were accomplished. In addition, we were also able to meet the goal of making the work reproducible to benefit the DIY community. The dozens of duct iterations, the propeller redesign, and the battery system development all resulted in a project that accomplishes the task of achieving advanced safety, strong battery life, and sustained efficiency in an E-foil build. The ability to have accomplished all the goals we originally identified indicates overall design success. Future testing and analysis are recommended however, to find a better or more optimized propeller for this application. A noteworthy observation from the rider and data collection software is that there was harsh rider feedback when cavitation occurred which may call for a propeller rework.

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Appendix 1. LiPo Battery Construction

LiPo Battery

- Parts needed
    - 5 ft 8 AWG wire
    - 9 XT-90 connectors
    - Wq64 Polycase Case
    - 3 waterproof cable glands
    - Trampa VESC Motor Controller
    - 2 6s 20000mah LiPo batteries
    - 1 3s 5000mah battery
    - 3 LiPo Alarms
    - Anti-spark Switch
    - H60 Corsair water cooler
    - HDPE plate with cutouts for LiPo straps
    - Thermal paste
    - 4 LiPo battery straps
    - ½" thick Neoprene foam

General Step by Step LiPo Battery Build

1. Install 3 cable clans in the box
2. Cut 6 slots 20mm wide on HDPE plate for LiPo straps
3. Cut 4 3mm holes and 5 6mm holes to line up with motor controller and cooling clock in HDPE plate
4. Mount cooling block upside down on HDPE plate using 30mm spacer and 34mm m3 bolts
5. Apply Thermal paste to block and mount VESC to top on the motor controller with the cooling block offset to motor wire side of VESC
6. Solder three Xt 90 connectors to battery and motor side wire and 3 xt90 connectors and anti-spark switch to harness of 8awg wire to connect battery
7. Mount LiPo to HDPE using 10lbs Velcro and 4 LiPo battery straps
8. Attach battery alarms to all batteries set to a 3.2V cut-off alarm. This alarm keeps the rider from riding the battery too long and draining the battery under 3V under voltage sag.
9. Apply foam to the bottom and side of outside of case

Appendix 2. Lithium-Ion Battery Construction

Lithium-Ion Battery

- Parts needed
    - 96 18650 Lithium-ion batteries
    - Wq64 Polycase cse
    - 5 waterproof cable glands
    - 8 4x6 battery holders
    - 96 25-amp fuses
    - 1 125-amp fuse
    - 2 110mm ⅛” by ½” copper bar
    - 2 60mm 1/16” by ½” copper bar
    - 24 85mm m5 bolts
    - 24 m5 nuts
    - 24 m5 washers
    - 24 m6 washers
    - 2 meters of .3mm by 6mm nickel strips
    - Matchbox acrylic case
    - Daly BMS
    - Bluetooth module
    - 6” 8awg
    - 12s balance wires
    - Water pump
    - ¼’ tubing
    - 75-300A motor controller with water cooling block
    - Fuel gauge
    - 6 110mm ¼” diameter copper rod

General Step by Step LiIon Battery Build

1. Install 5 cable glands in the box
2. Assemble batteries into 12 by 8 setup in holders
3. Mount BMS, 125A fuse, fuel gauge, and VESC to the internal base plate of the matchbox case
4. Wire battery by spot welding ladders of nickel strips to bottom of the battery and run them on the side to 110mm copper bus bar with 8awg wire soldered to end
5. Connect balance wires to the battery
6. Solder 96 25A fuses to 96 40mm nickel strips
7. Using holes drilled in battery holders, mount battery to the baseplate with 80mm m5 bolts washers, and nuts
8. Spot weld and solder fuses to battery and copper bars slotted into an acrylic box.
9. Install acrylic plate with all wiring connected into the poly case box
10. Using 2 remaining free gable glands route water tubing to VESC and to the water pump with one water tube exhaust and one routed into the motor holder or onto the foil.

Appendix 3. Material Selection and Reasoning

As discussed within the physical report a preliminary FEA analysis was conducted on the propeller. This was done to analyze the overall design of the propeller and the subsequent loads applied by utilizing it in the water. For this testing, we set the parameters to what we expected cruising operation to be which was 5000 RPM and 20 MPH. When this analysis was executed, it was determined that for rapid prototyping PLA would be an acceptable material. With a factor of safety of 100, this was deemed to be an appropriate material because we knew it would stand up well to short term rides and testing especially after it gets treated with epoxy, surfboard wax and is sanded back to flat and smooth conditions. For this reason, most of our printed parts utilize PLA.

It was determined however, that a better material should be implemented for long term use. For this reason, a Carbon Fiber filament was identified as a very promising material to utilize. This created its own challenges however because Carbon fiber can be semi-hazardous to work with and it also requires a steel filament extruder which is not "stock" with most 3D printers. A steel filament and carbon fiber filament were purchased and fit into our team's 3D printer which created the possible avenue for printing better, stronger, and more durable ducted-propeller assemblies for a functional E-Foil. The kit purchased for this upgrade is the Micro Swiss MK10 All Metal Hotend Upgrade kit which can be found on Amazon.

Appendix 4. Motor Specifications

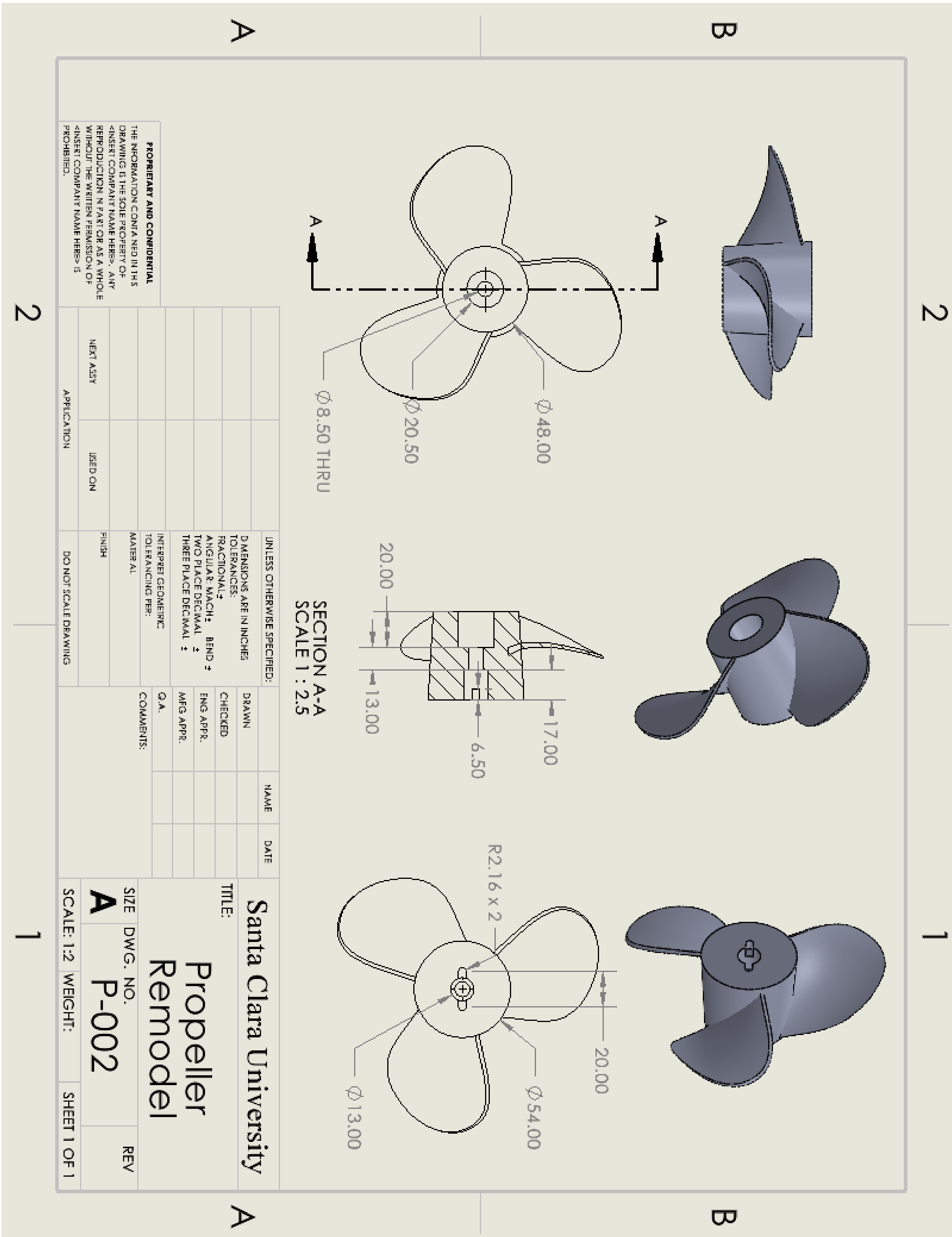
[24]

- Voltage range: 6-20S (25.2-84V)
- Max Spin Speed (RPM): 16380
- KV(RPM/V): 120KV/100KV
- Max Power:6000W, rated power 3000W
- Peak current: 200A
- The number of poles: 6
- Max torque at 60%:9NM
- Dimension: D65*L161mm
- Max working temperature: 120 °C
- Insulation voltage & leak current: AC500V/10MA/3S
- Lead wires extension: 8AWGx1300mm
- Waterproof level: IP68
- Weight:3kg
- Plug: 8.0mm
- Motor wire: 8AWG

.

Appendix 5. Engineering Drawings

1) Propeller



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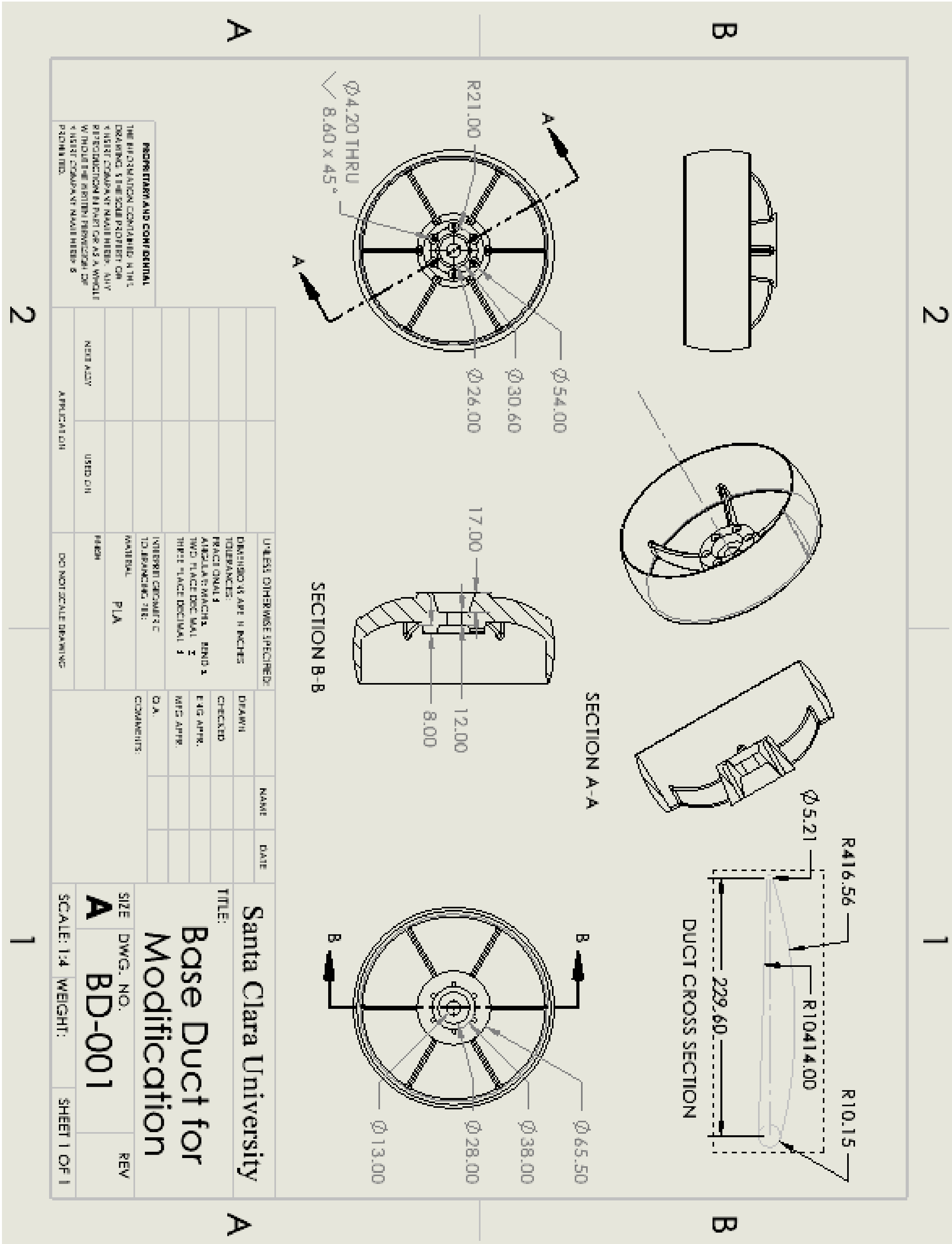
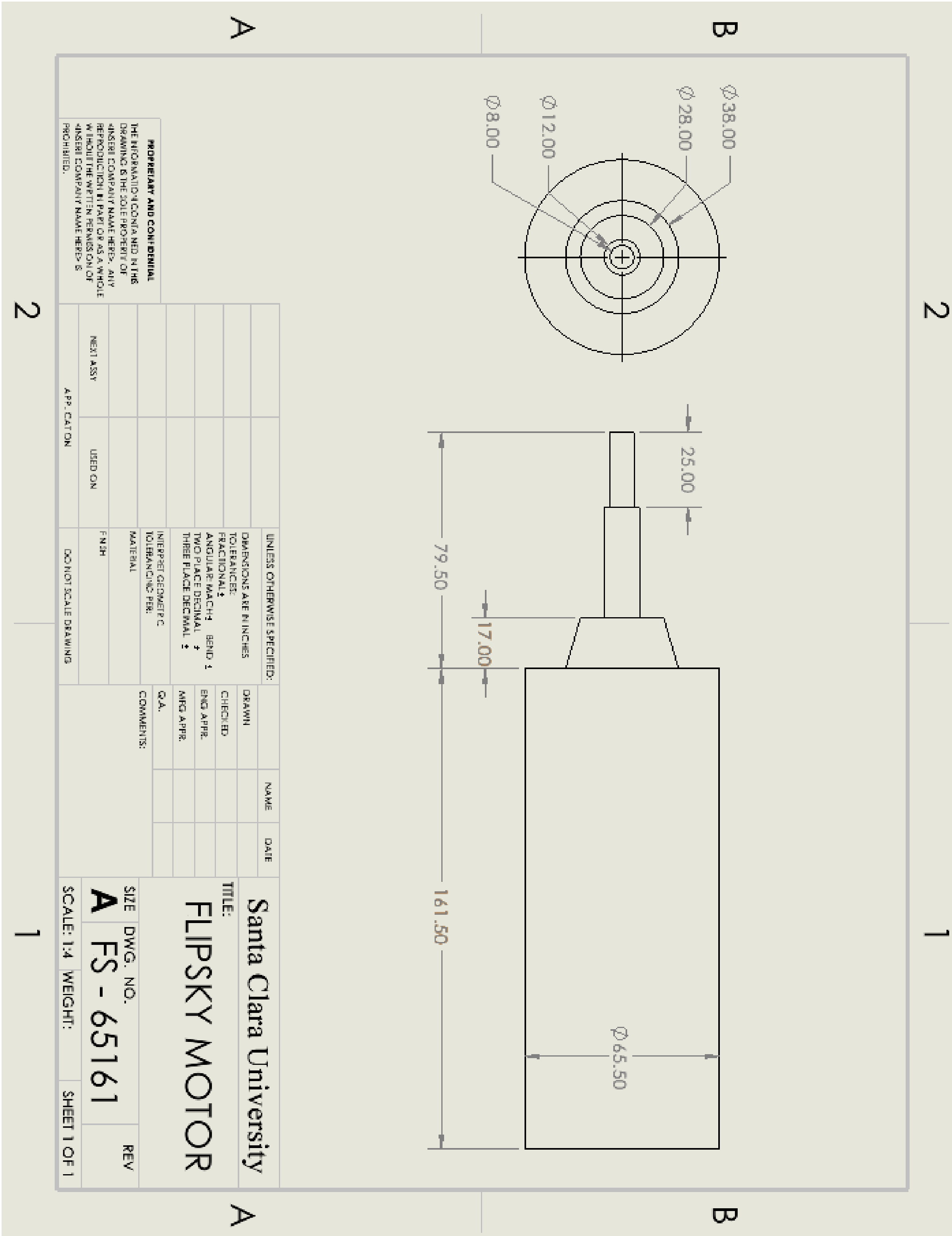
2) Duct



SECTION A-A
SECTION B-B
DUCT CROSS SECTION
R21.00
Ø4.20 THRU
8.60 x 45°
Ø54.00
Ø30.60
Ø26.00
17.00
12.00
8.00
Ø5.21
R416.56
R10414.00
R10.15
229.60
Ø65.50
Ø38.00
Ø28.00
Ø13.00
PROPRIETARY AND CONFIDENTIAL
UNLESS OTHERWISE SPECIFIED:
MATERIAL
PLA
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
NAME
DATE
Santa Clara University
TITLE:
Base Duct for Modification
SIZE
A
DWG. NO.
BD-001
REV
SCALE: 1:4
WEIGHT:
SHEET 1 OF 1

3) Motor Replica



Appendix 6. Senior Design Conference Presentation Slides

SANTA CLARA UNIVERSITY

Motorized Hydrofoil Board

Wesley Sava, Trentan Walker, Zachary Flood, Nick Potter

1

The E-Foil

- Electric hydrofoils became commercially available in '17
- DIY community developed due to high prices
- Lack of unity and engineering practices within DIY community
- Large efficiency losses from inexperienced builders
- Safety concerns went unaddressed by the builders

"Fliteboard." Fliteboard, 27 Nov. 2020, us.fliteboard.com/shop/.

2

Project Objective

1. Increase overall safety through added duct
2. Increase safety through better waterproofing and general battery design
3. Design a better/standardized propeller for the hydrofoil board
4. Retain efficiency of the board designs
5. Create a plan for future builders

3

Engineering Standards

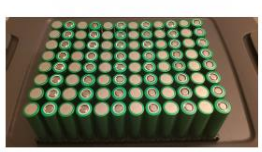
- Code of Federal Regulations part 35 FEA, fatigue tests,Overspeed and overtorque analysis
- Code of Federal Regulations part 46- "Propeller guard" (Duct)
- Code of Federal Regulations part 49-Testing procedures, packaging, Proper hazard communication, Proper disposal

- IEC 62133-2:2017 - additional battery safety
- UL 2054 2nd Edition- household and commercial batteries

4

Battery Types

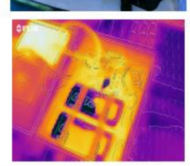
- Li-Po Battery
  - Volatile
  - Cheap
  - Easy to use with minimal setup
- Lithium Ion
  - Expensive
  - Requires assembly of cells
  - Modular
  - Energy Dense
  - Stable



5

Lithium Polymer (LiPo) Battery System

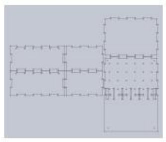
- Cheaper
  - ~$1300 including high quality motor controller
- Easy to use with minimal setup
- Design Implements Cooling system to internally cool the motor controller and keep the adjacent LiPo cooled.
  - Cooled using computer CPU water cooler
  - Simple alarm system safety implemented



6

Lithium Ion Battery System

- Battery boxes are all built around Polycase IP68 rated waterproof cases with IP68 clamping cable glands
- Casing Built in Maker Lab
- Very safe implementable battery system into board.
  - Individual cell fusing, battery management system and more stable battery chemistry
- ~ $1500 price point plus labor


7

Board and Battery

- Modular mounting design to be used across battery and control systems
  - Required to hold 5kg case under 3g's of acceleration in crash event
  - Allows case to be removed for charging and transportation.
- Final Design




8

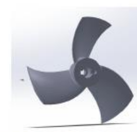
Electric Motor Propulsion

- RPM is based on Voltage
  - Voltage will stay constant
- Torque is based on Current
  - This will vary depending on drag and prop design
- GOAL
  - Create a Duct / Propeller combination that increases the amount of thrust per unit Torque


9

Old Propeller and Duct

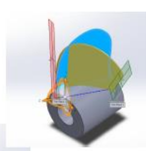
- Propeller
  - Little to no pitch
  - Sharp squared edges
  - Small Surface area
  - Significantly smaller than duct
- Duct
  - Simple shape
  - Standard flat cross section
  - Oversized for the prop
- Both made as simple fast prints, prioritizing accessibility over efficiency




10

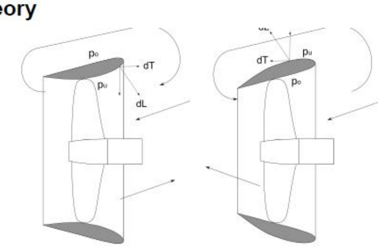
New Propeller

- Extruded the shape of the blade
- Used Solidworks flexing tool to reshape
- Overall Design
  - Larger more fluid dynamic blades
  - Curved edges to reduce cavitation
  - Increased Pitch




11

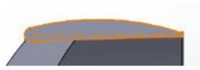
Duct Theory

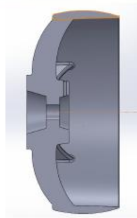


Accelerating Decelerating

12

Duct Design

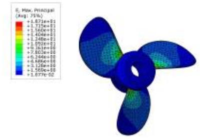




- Hydrofoil operates at higher speeds, so decelerating duct was chosen
- Cross section made into a foil with easy to manipulate features
- Base cross section revolved and connected to mounting core
- Kept duct same overall radius as current duct as a constraint

13

Material Selection

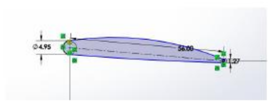


- Granta Edupack Software
- Building prototype parts
  - PETG and PLA filaments were used to 3d print parts
- Waterproofing and Finishing Procedure
  - Sanded parts
  - Coated in 3D-XTC
  - Added Surfboard research epoxy
  - Sanded away excess

14

Variables

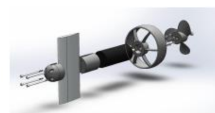
- Radius
- Number of spokes
- Angle of Spokes
- Length
- Camber
- Angle

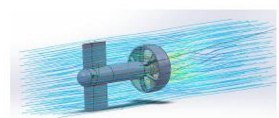


15

Simulation

- SOLIDWORKS Fluid Flow Simulation
- 1:1 replica of motor, mounts, and foil
- Rotational region simulates Prop turning at 5000 RPM
- Incoming flow at 12 m/s
- Water flow pattern shows potential cavitation and vorticity





16

Data Analysis

- SOLIDWORKS Outputs
  - Thrust
  - "Global Force Z"
  - Torque

Angle of Spokes						
Model	Thrust (N)	Global Force Z (N)	Drag (N)	Torque (N*m)	Efficiency	Efficiency %
Base Un-Ducted	434.57	381.14	53.43	12.672	30.08	100.00%
Base Ducted (Value On Ducted)	389.99	236.29	153.7	11.614	20.35	67.64%
10 Degrees	380.241	244.002	136.239	11.943	20.43	67.92%
20 Degrees	381.88	180.531	201.349	11.917	15.15	50.36%
30 Degrees	416.887	186.437	230.45	12.426	15.00	49.88%
40 Degrees	367.283	189.957	177.326	11.627	16.34	54.31%
-10 Degrees	378.231	209.349	168.882	12.214	17.14	56.98%
-20 Degrees	391.338	214.488	176.85	12.466	17.21	57.20%
-30 Degrees	395.63	228.501	167.129	12.662	18.05	59.99%
-40 Degrees	388.492	243.155	145.337	12.452	19.53	64.92%

- Drag = Global Force Z - Thrust
- "Efficiency" = Global Force Z / Torque
- All 50 Variations input to Excel file for comparison

17

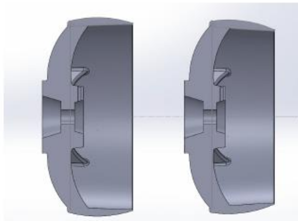
Overall Trends

- Angled Spokes
  - Increase in thrust but extremely poor efficiency
- Radii
  - The closer to the Propeller the better, however this trend declines any closer than 2 mm away from the tip of the prop
- Camber
  - A flat to slightly bulging inner wall works best, as does an outer radius of 100
- Spoke Number
  - 2 spokes and 6 spokes work the best, however anything under 3 spokes compromises structural integrity

18

Most Efficient Designs

- Duct Angle
  - 8 Degree angle - 94%
  - 10 Degree angle - 92%
  - 6 Degree angle - 91%
- Honorable mentions
  - Camber: Inner: (350); Outer: 100 - 82%
  - Camber: Inner: (500); Outer: 100 - 82%
  - Radius: 169 mm - 72%
  - Spoke Angle: 10 Degrees - 68%



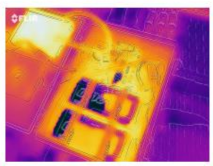
Ducts do Matter

- Duct Efficiency range:
  - Low - 33%
  - Base - 68%
  - High - 94%
- Largest Radius had the lowest efficiency

Variation	Model	Thrust (N)	Global Force Z (N)	Drag (N)	Torque (N*m)	Efficiency	
Radius	173mm	416.867	129.037	287.83	13.061	[illegible]	32.93%
Camber	Inner - 500; Outer - 88	348.856	117.482	231.373	11.804	9.952727988	33.18%
Camber	Inner - 200; Outer - 88	353.666	119.561	234.105	11.807	10.07598216	33.58%
Camber	Inner - 150; Outer - 88	354.277	130.533	223.744	11.800	10.9987361	36.66%
Length	60mm	339.098	138.78	188.319	11.711	11.67981745	38.93%
Camber	Inner - 350; Outer - 88	352.633	141.25	211.383	11.844	11.92590984	39.75%
Spoke Angle	-40 Degrees	388.492	243.156	145.337	12.462	19.52738516	65.09%
Camber	Inner - 350; Outer - 150	366.21	234.952	131.258	11.902	19.74054781	65.80%
BASE	**Base Ducted (Inner - Flat; Outer - 10(**	**389.99**	**236.29**	**153.7**	**11.614**	**20.34527295**	**67.82%**
Spoke Angle	10 Degrees	380.241	244.002	136.239	11.943	20.43054580	68.10%
Spoke Number	2 Spokes	378.83	248.72	130.11	12.034	20.66810783	68.89%
Camber	Inner - (350); Outer - 100	527.875	361.534	166.341	14.71	[illegible]	81.92%
Duct Angle	4 Degrees	491.521	367.620	123.900	14.17	25.94390013	86.48%
Duct Angle	2 Degrees	571.858	417.517	154.341	15.758	26.49555781	88.32%
Duct Angle	6 Degrees	536.126	411.817	124.309	15.114	27.24733653	90.82%
Duct Angle	10 Degrees	501.317	397.87	103.447	14.475	27.48670121	91.62%
Duct Angle	8 Degrees	530.976	424.342	106.634	15.043	28.20990201	94.03%
BASE	**Base Un-Ducted**	**434.57**	**381.94**	**53.43**	**12.072**	**30.07733986**	**100.00%**

Safety Testing and Procedures

- Controlled Environment Motor Test Bench
  - Strength and Thermal Testing
- Parts Monitoring with FLIR thermal imaging camera
- Electrical connections submerged in water and monitored with voltmeter



Testing Procedures

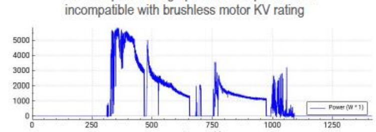
- Efficiency Calculations from Nick
- Data Matrix
  - Time reference, i.e. cavitation, turning
- Wind Speed
  - Handheld sensor mounted on board (Kestrel 5000)
- Board Height
  - Different heights induce different aerodynamic properties
- Dry Run & Water Testing prior to Data Collection
  - Motor Test Bench

Test Results and Uncertainty

- Due to the lack of access to a water tunnel to run efficiency testing our uncertainty in our data were greater than desired
- Average Power to Foil
  - Common Open Source propeller : 2150 W
  - Our Design:1824W
  - Efficiency gain of 15% ± 10%

Failures

- Casing for Lithium ion battery
- Motor controller failed due to overuse and lack of anti spark key
- First LiPo battery case was insufficiently cooled leading to throttling
- One Propeller and two ducts failed
- First Propeller design provided torque that was incompatible with brushless motor KV rating



Conclusion / Greatest Impacts

- **Health and Safety:** Duct/Propeller provide safety at minimal efficiency loss
  - Protects against falls (propeller) and electronics issues (shorting, exploding)
- **Manufacturability:** Ease of access and reproduction for E-Foil DIY community
- **Economic:** Comparatively cheap option vs top brands (i.e. Flite)
- **Sustainability:** "Electrifying Water Sports" - cutting down on fossil fuels

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