Final Design Review

6/17/20

CALIFORNIA SOLAR REGATTA

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Due to the effects of COVID-19
The 2020 SMUD competition was canceled and machine shops were closed. This restricted the amount of work that the team as able to complete and the changed the goals for this year's team. Enough of the production was done to piece together a singular unit with slight modifications to allow the build to be completed at home while practicing proper social distancing for the safety of the team and community at large. Some of the members of this team as well as some from the boat hull team will be returning in Fall 2020 to complete a modified design. Alongside those returning members a new senior project team has been created to build the boat for next year's competition. The two teams from this year will be passing on our designs, models, and data to lighten the load for next year's team, only requiring them to modify a few components to potentially increase the boat's efficiency.

Abstract

This Final Design Review report details the research, analysis, and design conducted by a Cal Poly Mechanical Engineering senior project team working on the propulsion system for a solar powered boat. Working in coordination with another senior project team responsible for making the hull, the two teams comprised the Cal Poly team who entered the Sacramento Municipal Utility District (SMUD) 2020 California Solar Regatta Competition. The SMUD Solar Regatta is an annual competition for high school and college students to design and build boats powered by solar power. The solar panels are provided by SMUD, and the battery storage is limited by competition regulations. The scope of this project was to design a propulsion system that would efficiently transfer energy, be easily integrated into the hull design and be competitive in the three races: endurance, slalom, and sprint. This document covers research conducted, objectives for the design, design concepts considered, the chosen final design, manufacturing and verification plans, and project management.

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1. Introduction

For the past eight years the Sacramento Municipal Utility District (SMUD) has hosted an annual competition called the SMUD California Solar Regatta for both high schools and colleges to enter. The program was established to promote renewable energy through solar technology and innovation. The competition consists of three races: the sprint race, slalom race, and endurance race. Additional points are awarded for a presentation of the design, along with bonus points for innovative design, sustainability, and artistry. The slalom race focuses on maneuverability, the sprint race prioritizes speed, and the endurance race emphasizes efficiency. The races make up half of the total score, while the oral presentation and bonus awards make up the other half.[18]

For the first time ever, the Cal Poly Mechanical Engineering Department entered this competition with a team of students using it as their Senior Project. The team, advised by Dr. Brian Self, was comprised of eight Mechanical Engineering students split into two sub-teams consisting of four students each. One group designed and built the hull while the other designed and implemented the propulsion system. This final design review report is for the Propulsion Team and will outline how the propulsion system for the solar powered boat was designed, built, and tested.

2. Background

To prepare for designing a propulsion system for a Solar Regatta, we first conducted research to become more informed about the competition and the technology involved. In our research, we found information about previous competitors, other solar powered boats, solar panels, and water propulsion systems. Our findings are detailed in the following sections. As a tournament project, our team and the other senior project team are the main customers.

2.1. Previous Competitions

Boat designs and their results from previous competitions were examined and will be used as benchmarks during the design process. While some benchmarked metrics can be found in Appendix A in the Quality Function Deployment (QFD), many of the specific performance characteristics of competitors' boats were unknown or hard to measure.

In 2018, the City College of San Francisco won the Solar Regatta by taking 1st place in the Slalom race, 1st place in the Sprint race, 5th place in the Endurance race, and winning some of the bonus prizes. These scores totaled to a winning score of 70. Their winning design was a low-profile twin hulled boat powered by a single propeller positioned on the centerline of the boat. During the same year the UC Davis team finished second place overall with 50 points using a single-motor monohulled design, despite placing 6th in Slalom, 6th in Sprint, and 13th in Endurance [7,15]. This demonstrates that while a high performing boat is important to the overall score, other scoring categories that are independent of performance must be prioritized as well. A full list of race data from 2018 can be found in Appendix C.

A Solar Regatta design created by high school students in Laguna Creek in 2012 was also used as a benchmark for our design. However, some aspects of the competition have changed since they competed, so not all statistics are comparable to this year's competition [14]. See Appendix B for pictures of boats from previous years.

2.2. Similar Existing Products

The first boat to drive under solar power appeared in 1985, with the first commercial marine solar vehicle to follow in 1995 [19]. Since then, global attention on climate and pollution has prompted groups interested in advancing solar vehicle technology to create competitions that involve teams across the globe. A report from the Istanbul Technical University Solar/Electric Boat Team details their experiences in 2007 and 2008 at the Solar Splash Event - Intercollegiate World Championship of Solar/Electric Boating [6]. At the time of Istanbul's publication, the event was on its 15th year. While the long-running competition has higher limits on battery size, many factors are similar. These include a length, width, and freeboard limit of 6m, 2.4m, and 1.5m respectively, 480W solar input, and 1kW•hr endurance battery. The only major difference is that the CA Solar Regatta limits the battery to 180 W•hr (18% of the Solar Splash limit). Even the trio of races are of same name and similar structure.

By studying the history of the vehicles used in these competitions and learning from the design progressions and failures they detail, our team will be competitive with the most experienced teams, bridging a gap of knowledge and experience.

2.3. Relevant Technical Aspects of Solar Panels

A large design consideration for maximizing the power transfer from the solar cell to the drivetrain is done by reducing losses [2,3]. Another way to increase the efficiency of solar panels is to increase the amount of light that hits the panel. This increases the irradiance (Ir, W/m^2) on the panel, which can then increase the power output. The most common way this is done is to place reflective surfaces in strategic positions to redirect light onto the solar panels, as shown in Figure 2.1. Using mirrors to reflect light onto the solar panels can increase solar panel output by up to 30% [8].
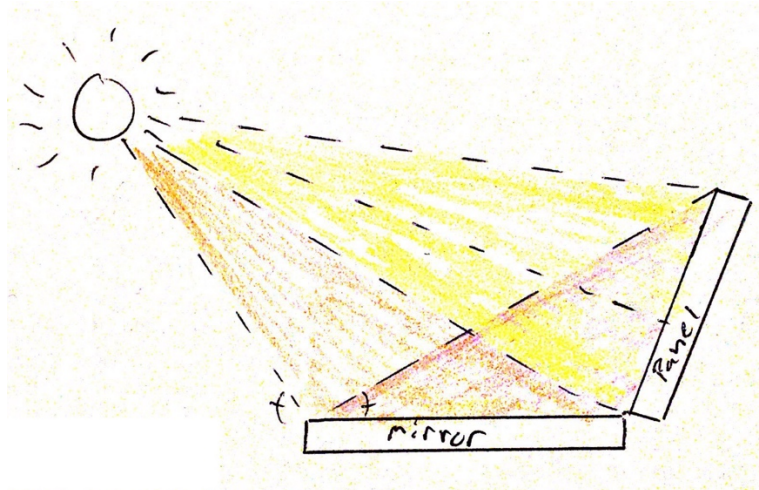
Figure 2.1 Mirror reflection method for increasing irradiance on solar panels.

However, there are issues with increasing the irradiance on the surface of the panels. The main problem is the increased temperature of the panel surface. Solar panels are rated for certain ranges of operable temperatures, and heating past their limits will both hurt efficiency of the panels and possibly damage components.

Another way to increase the power output of Photovoltaic (PV) solar panels is to cool them down. Solar panel efficiency increases with decreasing temperature, at a rate of roughly 0.45%/°C for crystalline Silicon modules, like the ones we will be using. Cooling can be achieved by a variety of methods, such as water cooling, conduction, or convective air cooling. In a study of water cooling by the Raisoni College of Engineering in Nagpur, India, it was discovered that cooling the top surface of the panels was the most effective way to decrease temperature and increase efficiency [5]. However, if an active cooling system is implemented, it must be ensured that the amount of energy being used to cool the panels is not greater than the additional energy that is provided by the cooler panels. A passive method may be more beneficial, such as connecting the panels to the lake with thermally conductive material. An even simpler alternative would be to spray the panels with water directly before the races.

According to the data sheets for the solar panels provided by SMUD, the panels to be used will increase power output by 0.45% for every °C decrease, with T = 25°C considered the 100% efficient temperature (where the power output is 235 W). Decreasing the temperature of the cells will allow us to get higher than 100% efficiency. These solar panels have operating temperatures between -40 and 85°C- this means that the power output can range from 300W to 170W, a swing of 56% [18]. However, the specifications were measured at Ir = 1000 W/m^2, T = 25°C, and AM = 1.5, not the conditions we expect for the day of the race [16]. AM stands for Air Mass, which is a unitless ratio of the distance sunlight will travel through the atmosphere compared to the minimum possible distance it must travel to reach sea level. Based on this, it is safe to assume that the standard output of the solar panels as delivered will be less than 235 W.

The specifications for the solar modules provided by SMUD are located in Appendix P. We will be using the JKM-235P model.

2.4. Electrical Components

Running solar cells without a battery is not common practice but is required for the sprint and slalom races. Since the power coming from the cell is not constant and changes throughout the course of a day, PV modules can only be used as a direct power source if they are being used on a motor that can handle variable input. We plan to use motors that have this capability.

Solar cell outputs do not only vary at different times of day; there is also considerable signal fluctuation every second. This variation in known as solar noise and is caused by the fluctuation in the radiation the sun gives off. In order to account for this solar noise, the use of a solar regulator is required. A solar regulator is a series of capacitors and inductors that smooths the electrical signal that runs through them, eliminating the solar noise. Multiple units can be used to reduce the noise even further. These solar regulators are designed to eliminate nearly all the solar noise for an average day and can be programmed for your location and time of year to adequately utilize this process. These devices are allowed to be used in the competition, as the capacitors inside are not designed to store energy.

The use of an electric controller to ensure that the same amount of power is being delivered to each one of the motors is also essential to ensure our models match reality. These controllers have an input and two outputs with a simple interface that allows the user to determine the amount of power going to each of the output terminals. The controller will need to be slightly oversized since it will be essential in the final circuit for the boat to run at its highest efficiency.

2.5. Propulsion Systems

The most commonly used water propulsion system is a propeller and drivetrain. Originally called water screws, propellers were used for water transportation for years before they were used in aviation [20] and can been seen in Figure 2.2a. After their incorporation into avionics, the research into propeller design took off. Since information gathered on propeller designs through air can be translated into usage in water with given fluid properties, research has been conducted by other engineers and scientists on both air and water-based propellers. Important variables that go into the design of propellers include length to width ratios, pitch, curvature, drag coefficients, and number of blades. Each one of these variables can be varied to achieve maximum efficiency of power transfer [1].

Another type of propulsion that arose from research is waterjet propulsion by use of pumps. This is an interesting idea that was created out of the desire for higher energy transfer efficiencies by the driving mechanical system, a full system is shown in Figure 2.2b. The mechanical energy transfer efficiency needs to be maximized for all types of propulsion.[4] This propulsion system is beneficial because it utilizes the efficiency of water pumps and is commonly used with boats due to the ease of access to a water source. Important things for consideration with waterjet propulsion include efficiency of the pump system, inlet and outlet diameters, fluid properties of the water going into the system, quality of water source, integration into hull design, and system weight. All these parameters can be determined analytically from known information, but many of them would have to be tested before being reasonably considered for use in this project.

https://www.boatus.com/magazine/archives/reasons-to-change-your-prop.asp

http://www.marinedieseleurope.com/blog/2015/02/25/water-jet-propulsion-packages/

(a)   (b)

Figure 2.2 Motorboat Prop (a) and Water Jet (b) propulsion systems.

An out-of-the-box propulsion concept discovered through research was a hydrofoil. This type of propulsion system would have to be agreed upon by the propulsion and hull team, since it would heavily affect both designs. The main concept that makes this enticing is the drastic decrease in drag force on the boat that this system allows. The hydrofoil acts as a "wing" underwater, generating lift as the velocity of the boat increases [9]. This causes the main hull to come above the water level while the propulsion system remains submerged as shown in Figure 2.3. Raising it above the water reduces the amount of surface area that is in contact with the water, and therefore reduces drag from the water. Since the drag coefficients of water are significantly higher than air, the total amount of force opposing the motion of the boat drops dramatically [13,17]. Things to consider when reviewing this idea include initial required thrust for liftoff, speed requirements for efficient ascension/descension, complexity of the design, competition limitation and rules, storage and stability.

https://wordlesstech.com/hydros-retractable-hydrofoil-boat/

Figure 2.3 Motorboat powered by a hydrofoil system.

After deliberating on each of these design ideas, propellers were chosen for the final boat design over hydrofoils or a waterjet system. More information about our decision-making process can be found in Section 4.3. Research on propeller design is shown in the following section.

2.6. Propeller Design

2.6.1. Propeller Geometry

The first step to understanding propeller design is to understand the many different geometric dimensions that are used in the design process. A list of common geometric dimensions and their symbols is shown for reference in Table 2.1.

Table 2.1. Common geometric dimensions of propellers.

Dimension	Symbol	Figure(s) Shown
Diameter	D	2.5
Radius	R	2.5
Hub Diameter	D_h	-
Hub Radius	R_h	-
Number of Blades	Z	-
Pitch	P	2.5, 2.7
Pitch Angle	ϕ	2.4, 2.5, 2.7
Pitch Ratio	P/D	-
Max Section Thickness	t	2.4
Blade Thickness Ratio	t/D	-
Chord Length	c	2.4
Radial Blade Coordinate	r	2.5, 2.6
Disk Area	A_0	-
Expanded Area	A_E	-
Expanded Area Ratio	EAR	-
Skew	θ_s	2.7
Rake	i_p	2.7
Rake Angle	θ_{ip}	-

Propellers blades are designed with airfoil cross sections in order to produce thrust from lift as they rotate and interact with the surrounding fluid. Typically, each blade is designed with a certain standard airfoil shape and the chord length c and thickness t are varied along the radial axis. Figure 2.4 shows an airfoil section with marked angles used in design. TE is the trailing edge point and LE is the leading-edge point.
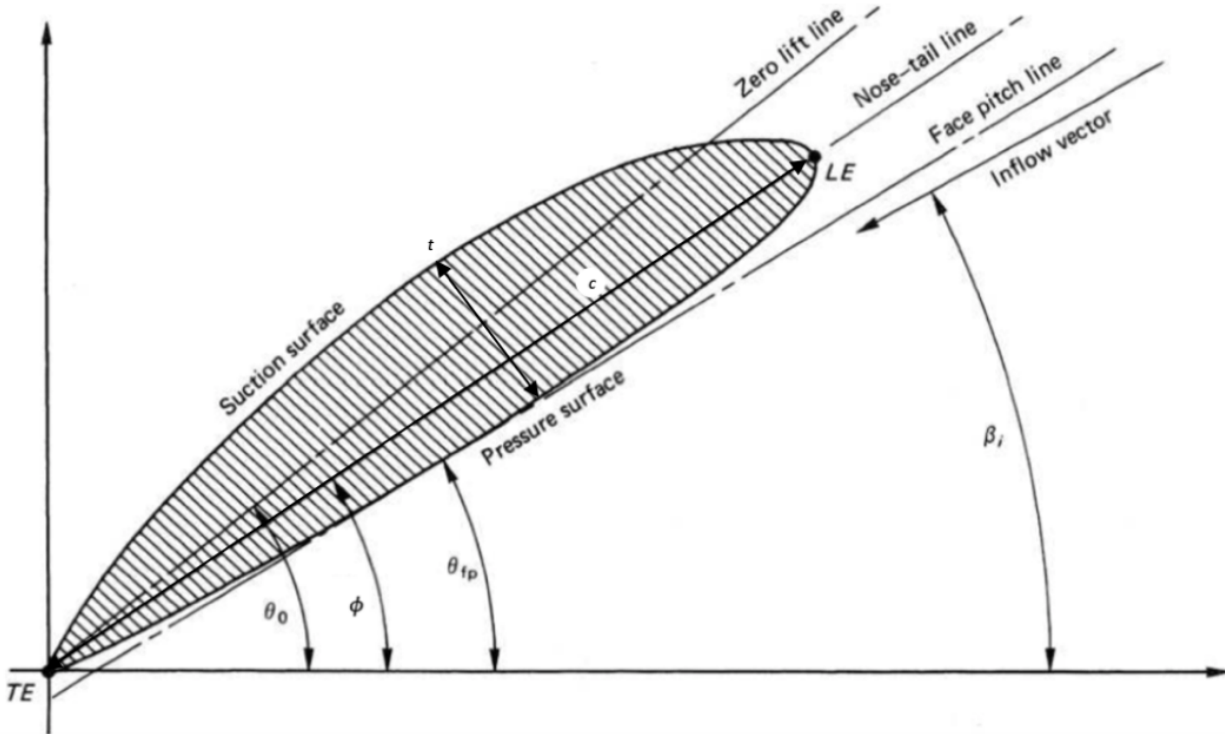
Figure 2.4. Airfoil shape of blade cross section.[21]

Pitch and pitch angle are critical to determining a propeller's performance. Pitch is defined as the total axial (x) distance that a blade would travel with no slip and can be determined from the pitch angle ϕ, as shown in Figure 2.5. Figure 2.6 shows the coordinate system that is typically used with propellers. This system will be used throughout our analysis of propellers as well.

Two other important characteristics of blade geometry are rake i_p (or rake angle θ_{ip}) and skew θ_s of a blade. Rake angle is the angle at which the blades are bent forward axially, as shown in Figure 2.7. A rake angle is commonly used for propellers that sit partially out of the water and run at high RPMs, to force water to "stick" better to the blades and produce higher thrust. Skew is implemented to help with cavitation issues along the leading edge, as described in section 2.5.2. Skew is also shown in Figure 2.7.

The disk area A_0 of the propeller is defined as the total area that the blades sweep through, while the expanded area A_E is the rough estimate of total blade surface area as seen from the front (pressure side) of the propeller. These can be calculated using the equations below:

$$A_0 = \pi D^2/4 \qquad\qquad A_E = Z \int_{R_h}^{R} c\, dr$$

where c is the chord length of each radial cross section of the propeller at radius r. Propellers are commonly characterized by the expanded area ratio EAR, where $EAR = A_E/A_0$. EAR affects thrust produced and efficiency of the propeller, with higher EAR values producing more thrust at lower RPMs, but also causing a lower efficiency due to more drag on the blades. Typical propellers have an EAR between 0.3 and 0.9.
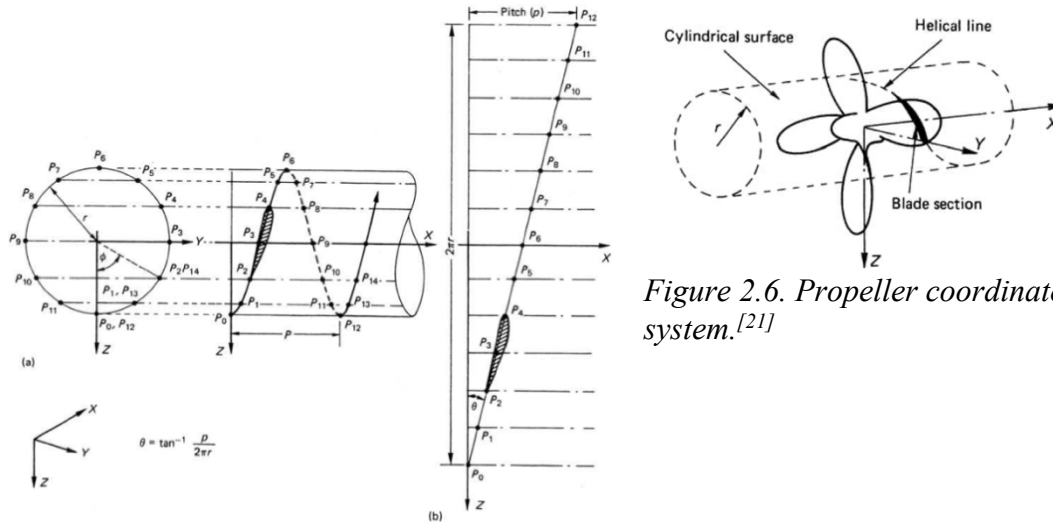
Figure 2.6. Propeller coordinate system.[21]

Figure 2.5. Definition of pitch: (a) helix definition on a cylinder of radius r and (b) development of helix on the cylinder.[21]
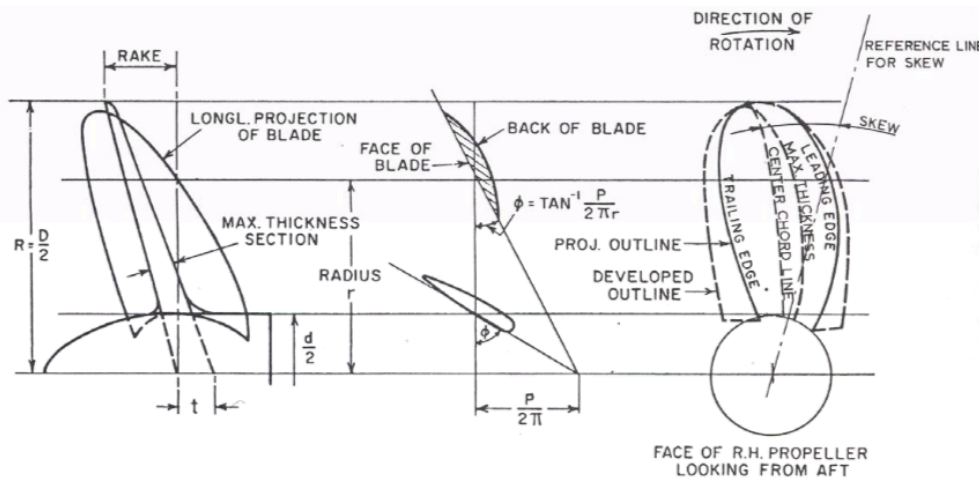
Figure 2.7. Visual representation of skew and rake.[22]

2.6.2. Propeller Performance

Propeller performance generally relies on five variables: Thrust (T), inflow speed (V_a), rotational speed (N), torque (Q), and efficiency (η). All of these variables are interrelated to each other in complex ways and can change depending on the operating conditions and the blade geometry. To design a propeller for a certain operating condition, it is common to use non-dimensional versions of each parameter. Dimensioned quantities associated with propeller design are shown in Table 2.2 along with their non-dimensional counterparts.

There are two types of performance curves that are commonly used in propeller design, with each proving useful for different types of design analysis. An example of a traditional propeller

performance chart shows curves for η, K_T, and K_Q as functions of J. Each chart holds multiple curves for different P/D, and each chart represents a single value of EAR. This plot is useful for determining propeller characteristics when J can be calculated directly. An example of this type of chart is shown in Figure 2.8.

A different type of performance plot can be used when information about input power is known or desired. The power-based performance chart shows curves for η and δ as functions of P/D and B_P. Like traditional propeller performance charts, these charts are for a single value of EAR. An example of this type of chart can be found in Figure 2.9.

Table 2.2. Common performance parameters used in propeller design.

Variable	Symbol	Equation
Diameter	D	-
Inflow Velocity	V_a	-
Ship Speed	V_s	-
Resultant Velocity	V_R	$\sqrt{V_a^2 + [2\pi n(0.7R)]^2}$
Rotational Speed	$N\ [rpm], n\ [rps]$	-
Thrust	T	-
Torque	Q	-
Delivered Power	P_D	-
Fluid Vapor Pressure	P_v	-
Reference Pressure	P_0	-
Fluid Pressure	P	-
Fluid Density	ρ	-
Advance Coefficient	J	$\dfrac{V_a}{nD}$
Thrust Coefficient	K_T	$\dfrac{T}{\rho n^2 D^4}$
Torque Coefficient	K_Q	$\dfrac{Q}{\rho n^2 D^5}$
Power Coefficient	B_P	$\dfrac{P_D^{1/2} n}{\rho^{1/2} V_a^{5/2}}$
Inverted Advance Coefficient	δ	$1/J$
Alternate Thrust Coefficient	C_T	$\dfrac{T}{0.5\rho V_a^2 A_0}$
Alternate Torque Coefficient	C_Q	$\dfrac{Q}{0.5\rho V_a^2 A_0 R}$
Cavitation Number	σ	$\dfrac{P_0 - P_v}{0.5\rho V_R^2}$
Pressure Coefficient	C_P	$\dfrac{P - P_0}{0.5\rho V_R^2}$
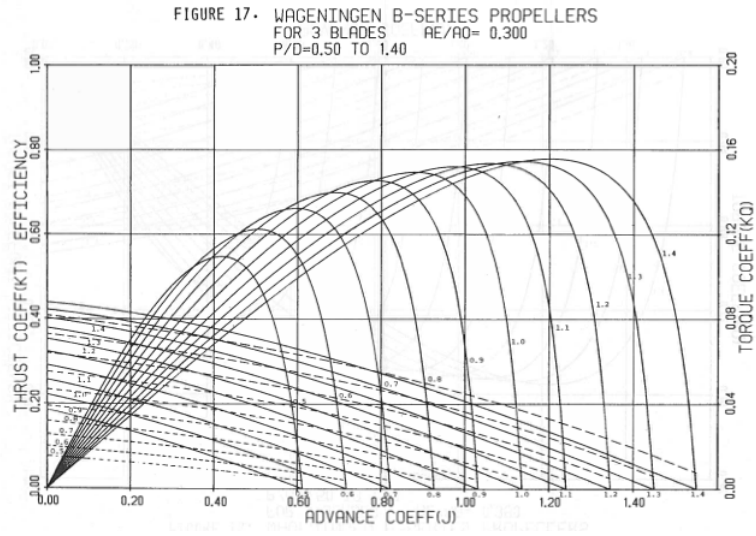
Figure 2.8. Traditional propeller performance chart with EAR = 0.300.[26]

$$\delta = \frac{N}{V_a} \cdot D$$

$$Bp = \frac{N}{V_a} \cdot \sqrt{\frac{P}{V_a^3}}$$
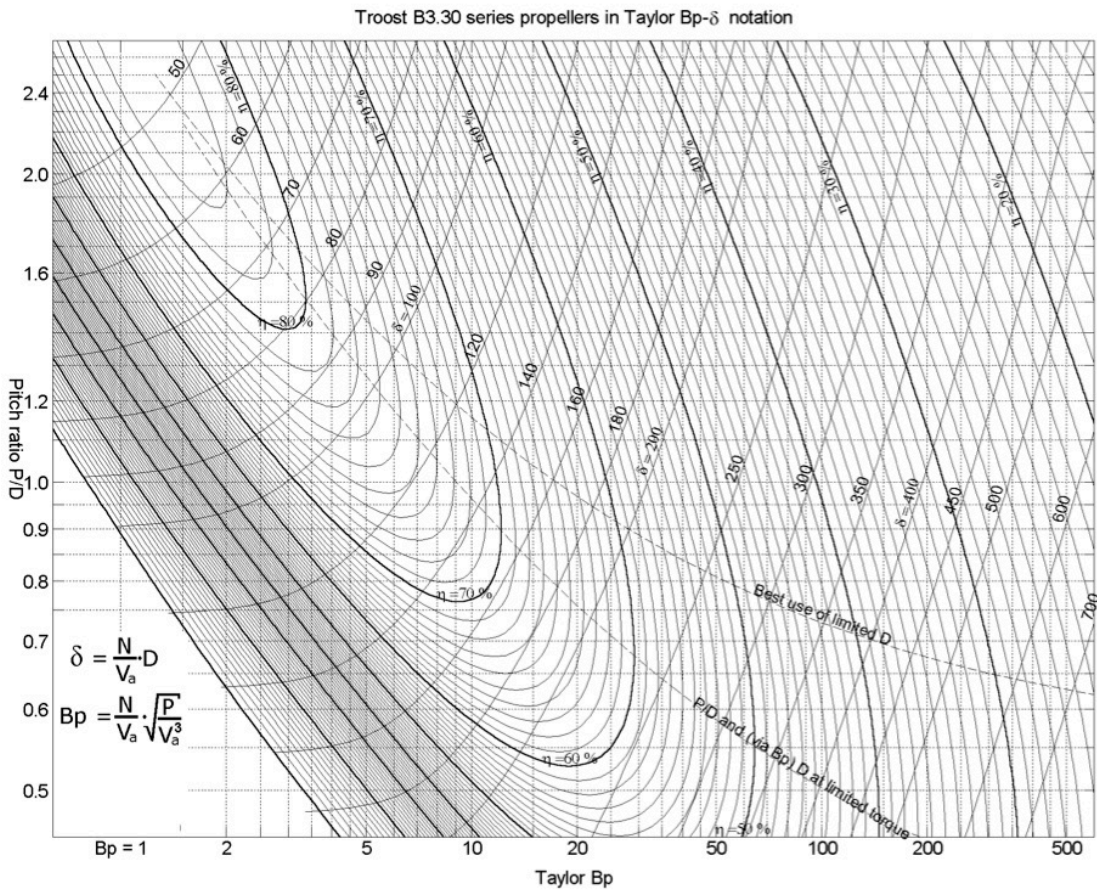
Figure 2.9. Power-based propeller performance chart with EAR = 0.300.[23]

The alternate thrust and torque coefficients C_T and C_Q are also occasionally used for design, though they do not show up in traditional performance charts.

Cavitation in propellers occurs when the pressure at the blade surface (P) drops below the vapor pressure of the fluid, causing the fluid to vaporize. This leads to a lower efficiency of the propeller and over time can damage the blades. To define when cavitation occurs, the cavitation number σ is used in conjunction with the pressure coefficient C_P. With some algebra, it can be shown that cavitation will occur when $-C_P/\sigma \geq 1$.[25]

σ is calculated using the relative velocity V_R, which is calculated at $r = 0.7R$ where cavitation is typically highest. Figure 2.10 shows the velocity diagram for inflow on a propeller.

$2\pi nr$
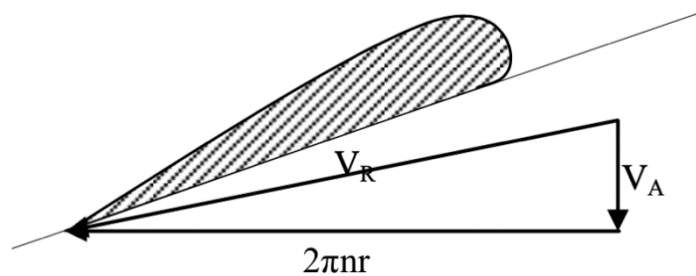
Figure 2.10. Velocity diagram for cavitation.[25]

Cavitation occurs first on the leading edge of the propeller blades, and can be reduced by adding skew to the blades. The skew removes the part of the blade where cavitation occurs, effectively removing cavitation altogether. Cavitation can occur again at too high skew angles; there is an optimal skew angle for each design condition where no cavitation occurs. This can be seen in Figure 2.11.

$\theta_s = 4.5 \deg.$　　　　$\theta_s = 45 \deg.$　　　　$\theta_s = 60 \deg.$　　　　$\theta_s = 75 \deg.$
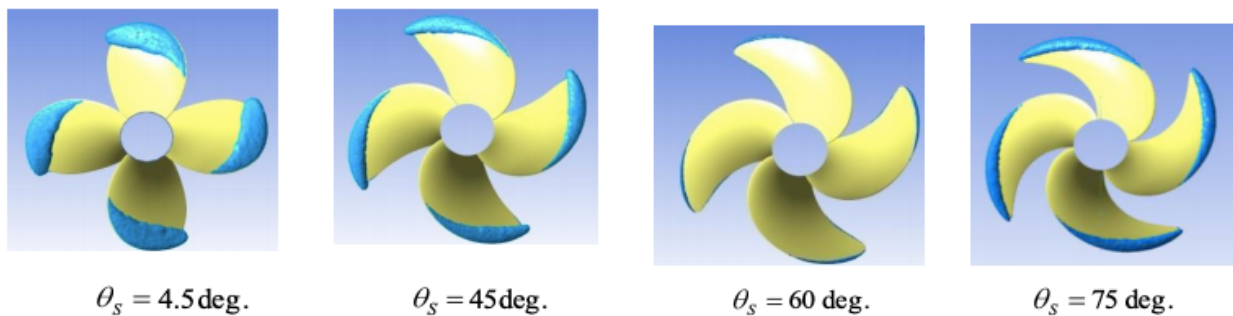
Figure 2.11. Cavitation on propeller blades.[28]

All of this information was used in our propeller design to design a propeller to have a maximum efficiency for our given operating conditions. The final propeller design is covered in more detail in section 5.5.

2.7. Water Channel Testing

Our team initially had plans to use a Water Channel to verify the theoretical propeller design and confirm assumptions about stress concentrations, cavitation, drag, and other parameters about the

propellers. A water channel has a straight test section where uniform flow is reached and is similar to a wind tunnel.

The Cal Poly Aerospace Department had a decommissioned water channel that we planned to use for our testing of the propellers. However, it hadn't been operational for over two years and required the Variable Frequency Drive (VFD) to be replaced. Electric Motor Wholesaler was gracious enough to support this project and sent us a replacement VFD at no cost. The Water Channel is the Rolling Hills Research Corporation Model 0710 University Desktop Water Tunnel, shown in Figure 2.12.

Figure 2.12. Rolling Hills Research Corporation Model 0710 University Desktop Water Channel used for propeller design verification.

Once the water channel has been restored, it can be used for future tests. See section 8.1.4 for more details about proposed testing with the water channel. Due to Covid-19 our team was never able to conduct testing with the water channel, but hope next year's team will be able to do so.

3. Objectives

The SMUD Solar Regatta competition is judged on top speed, maneuverability, and endurance, and has awards for subcategories such as aesthetics, sustainability, and innovation. To be competitive, our team requires an energy-efficient solar powered drive train for our boat that allows it to have a top speed of at least 7 mph. This is necessary because Cal Poly needs to be well-represented among other universities and win first place.

Figure 3.1 shows our boundary diagram for this project. As the propulsion group, we are responsible for the propulsion system and all components that connect it to the solar panels and battery. The purple dotted line shows our scope for this project. The solar panels must be removable for the endurance race, during which the boat will run completely on battery power.
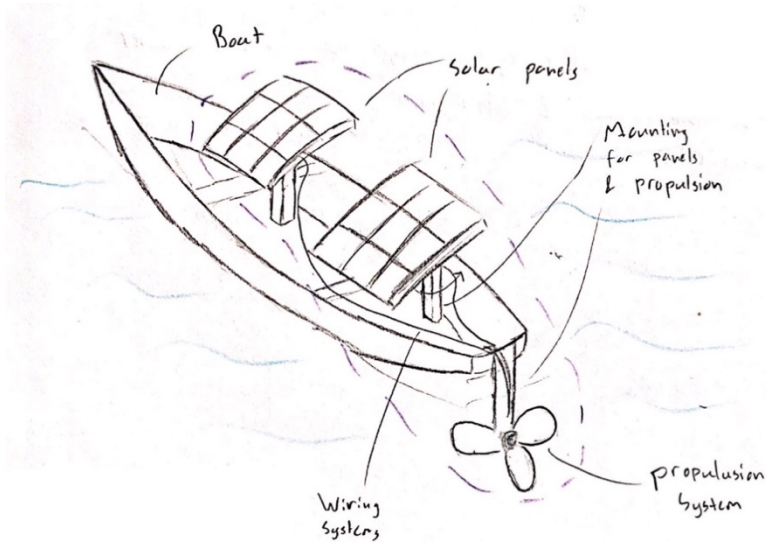
Figure 3.1 Boundary diagram used for problem definition. The dotted line represents the scope of the project for the propulsion team.

3.1. Quality Function Deployment

To make sure that our project was planned and executed as efficiently as possible, we performed a Quality Function Deployment (QFD) process. This allows us to organize the wants and needs for the design based on the tournament specifications, as well as determine our own specifications that will ensure that we meet those needs. As a tournament project, the needs and wants are well defined and documented in the competition packet. In this process, our design was benchmarked against teams that competed previously in the competition in 2018 and one that competed in 2012. Initial goals for each specification were set, though they may be changed over time as more research is done regarding each specification. The specifications are outlined in more detail in the next section. For the full QFD analysis performed, see Appendix A.

3.2. Needs and Wants

Table 3.1 shows the needs and wants that were determined for the propulsion system for the Solar Regatta. Each item was determined from interviews with the boat team and from requirements listed in the competition packet [18].

Table 3.1 Design Needs and Wants.

Needs	Wants
High top speed	Fun to pilot
Maneuverability	Easy to operate
High endurance	Reliable
Easily integrated with hull	Light weight
Safety	Aesthetic design
Solar powered	Original design
Battery powered	Custom drivetrain
	Sustainable design

Needs were defined as items that were determined to be critical for the competition, including characteristics that are awarded points by the judges along with race performance. For the Solar Regatta to perform well in competition, it must have a high top speed, good maneuverability, and high endurance. The competition requires the design to be safe and for the propulsion system to be able to run on solar or battery power. In order to be useful and viable, our design must be able to be incorporated with the hull that the boat team designs.

Wants were defined as anything additional that provide extra non-race points, properties that will help achieve needs, or items that will make the design more enjoyable to operate and build.

3.3. Technical Specifications

Table 3.2 shows the technical specifications that were determined for the propulsion system for the Solar Regatta. Each specification was determined based off of performance and characteristics of past race competitors, competition rules, and background research. In the Risk column, H, M and L stand for high, medium, and low, respectively and refer to the risk level of not achieving that objective. In the Compliance column, A, S, and T stand for Analysis, Similarity, and Test, respectively.

Table 3.2. Technical specifications for Solar Regatta propulsion system.

Spec. No.	Specification Description	Target Value	Tolerance	Risk	Compliance
1	Top speed	7 mph	Min	H	T
2	Acceleration	0 to max speed in 10s	Min	M	T
3	Turning Radius	15 ft	Max	L	T
4	Battery Life	25 min at max power	Min	L	T
5	Battery Energy	175 W•hr	Min	L	T
6	PV Energy Conversion	95%	±10%	H	A, T
7	Electrical Power Transfer	95%	Min	M	S, T
8	Motor Efficiency	80%	Min	M	T
9	Drivetrain Efficiency	95%	Min	M	S, T
10	Weight	30 lbs	Max	L	A, T

The first four specifications were chosen with regards to the boat's performance in competition. Based on race data from previous years, the fastest average speed during the sprint race was just over 5 mph (100 yards in 40 seconds [18]). Based on this, a target of 7 mph top speed was chosen

to ensure a faster speed than the best competitor. If the boat is to perform well in the sprint race, it must also accelerate quickly enough to get to top speed. A target time to top speed of 10s was estimated based on the time for the entire sprint race.

Turning Radius estimates were determined from the specifications of the slalom race. There are five buoys placed over a 150 yard (450ft) distance, as shown in Figure 3.2. From this, the buoys were estimated to sit about 70 ft apart. From this, a 15 ft turning radius was set as the target.
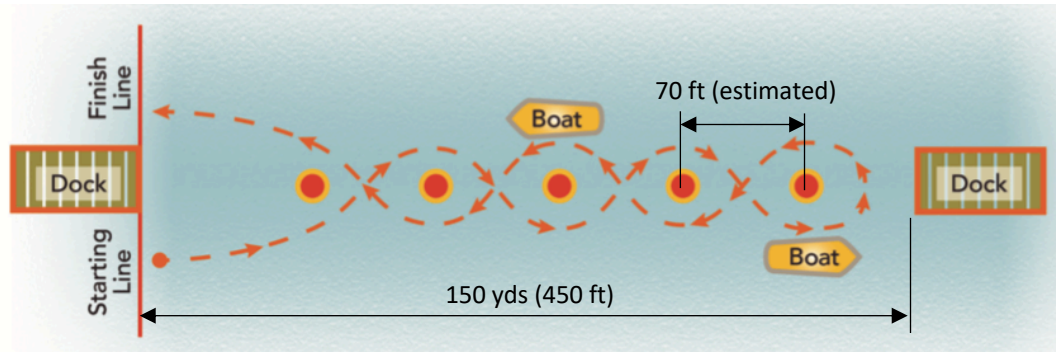
Figure 3.2. Slalom race diagram with dimensions added to figure as specified in the race packet.[18]

Target battery life was set solely based on the specifications of the endurance race. The race lasts 25 minutes or until the battery runs out, and the goal is to have battery power at max power output for the entire race.

Each of the efficiency targets were based off background research into typical efficiencies of each system. More information about the solar panel efficiency is located in Section 2.3. The total weight of the solar panels alone is 84 lbs (42 lbs each). An estimate for the remaining total weight was made based weight estimates of mounting components, motors, and the battery.

Plans to test each of these specifications can be found in Section 7, Design Verification Plan.

The hardest specifications to meet (highest risk) will likely be top speed and PV energy conversion. Top speed depends on factors outside of the scope of the propulsion team, such as drag on the hull. The goal is to be the fastest of any team that competes, which could prove to be difficult to achieve. However, we believe it to be beneficial to aim for the best performance, even if we are unable to achieve it in the end. Additionally, the PV energy conversion goal forces us to consider ways to cool the solar panels to increase their relative efficiency. Due to the age and condition of the cells we receive from SMUD, this could also be difficult to accomplish.

4. Concept Design

4.1. Ideation Process

The team determined three main functions that would be essential for the development of a final product: integration with the hull, steering, and power transfer. Each of these will be critical in determining the concept designs that will be integrated into the final design. Different ideation processes were used for determining a large list of ideas under each function, which were later reduced to include only the more realistic options. Some initial ideas had been thought of in previous meetings and meetings after our ideation day, but the bulk of the ideas came from the three processes we used in class.

The first process we used was brainstorming, where we thought of as many ideas we could and said them out loud as we wrote them on the board. A time limit of 15 minutes was given for the process and one team member acted as a moderator to keep the team on track. We used this method to get ideas for the integration with the hull. We came up with a list of 43 ideas that are listed in Table D.1 that range from basic fasteners to complex integration techniques. To facilitate creative ideas and out of the box solutions we encouraged wild, unrealistic, and humorous suggestions throughout the brainstorming process.

The second process the team used is the SCAMPER method (Substitute, Combine, Adapt, Modify, Put to other use, Eliminate, and Reverse) to evaluate three types of steering methods. The steering methods we looked at were the use of a rudder, differential thrust, and a thrust vector. The scamper method allowed us to broaden the view of each one of the processes and find overlap between the three design ideas. The results of the SCAMPER process are presented in Table D.2. These ideas were later turned into design concepts for testing and selection.

The third and final process used was brainwriting, a method that promotes individual creation and ideation. The method has everyone write down ideas on a sheet of paper without saying anything to the others before passing on their sheet for other team members to add their ideas. This process was used to come up with power transfer methods for electrical-to-mechanical and mechanical-to-thrust power. All ideas that each team member came up with can also be found in Appendix D. Each one of the expanded-upon concepts was discussed in the concept prototype and selection stages.

4.2. Top Alternatives

During the ideation process, we came up with multiple design concepts. In one of our class periods, we used a combination of Legos, popsicle sticks, foamboard, and other crafting materials to create simple concept models of some of the ideas that we came up with. Photos of our top 6 concept models can be found in Figures 4.1-4.6.

Figure 4.1 shows a concept model with a single prop attached to the rudder. The steering wheel is linked to the angle of the rudder and rotates both the rudder and prop together. Solar panels are located on each pontoon in the center for an even weight distribution.

Figure 4.2 shows a dual thrust concept with solar panels mounted to a shaft in the center of the boat. The solar panels can rotate side to side to maximize the solar irradiance that hits the panels, increasing their power output.
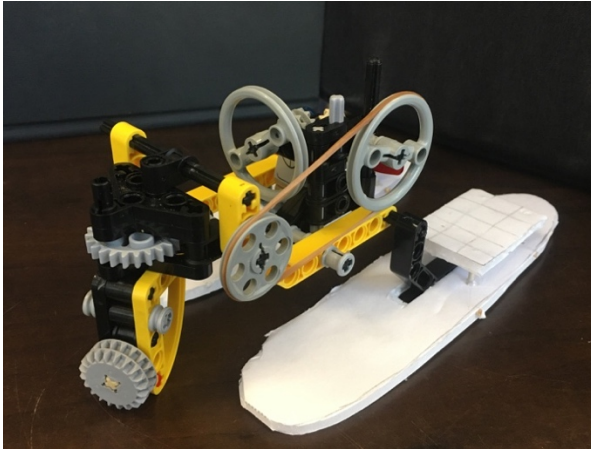
Figure 4.1. Rudder with attached single prop.
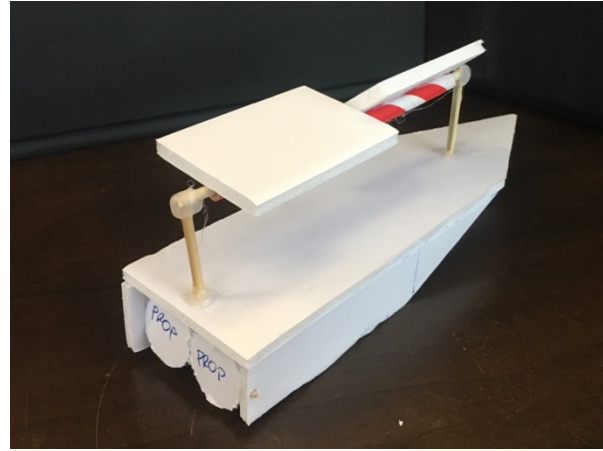
Figure 4.2. Dual thrust with adjustable solar panel position.

Figure 4.3 shows a model of a prop inside of a pontoon. There would be no additional drag force acting on the motor and rudder because they do not exist outside of the pontoons. Figure 4.4 shows a model with a height-adjustable prop. The prop is connected to a linkage system that can raise or lower the prop height in the water to the optimal position.

Figure 4.5 shows a solar panel with reflective material around the outside at an angle. This would reflect more sunlight onto the panels and increase power output. Figure 4.6 shows a model with two pontoons with one prop attached to each. Steering would be achieved by adjusting the power to each prop to make one faster than the other.

Figure 4.3. Prop inside hull pontoons.
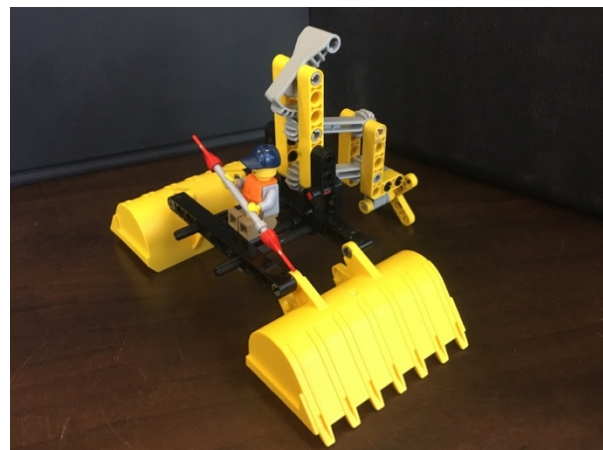
Figure 4.4. Adjustable prop height through linkage system.

Figure 4.5. Mirror design for extra sunlight on solar panels.
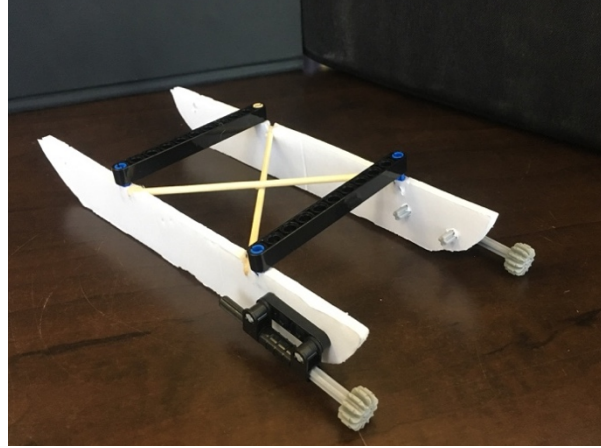
Figure 4.6. Dual prop design with pontoons.

4.3. Selection Process

To decide which design to use for this project, we used a series of different selection processes. First, Pugh Matrices were created for our four main functions: steering, integration with the hull, and mechanical and electrical power transfer. Each Pugh Matrix evaluated 4-6 different concepts that we had come up with and scored them off of a baseline design, the first design in the matrix. Each Pugh Matrix can be found in Appendix E.

Next, the results from each Pugh Matrix were consolidated into a morphological matrix. The designs were arranged and ranked as they were scored from the Pugh Matrices to see which design concepts would perform well in combination. From this, seven full design concepts were created and compared against each other in a weighted decision matrix. This decision matrix and each design chosen are shown in Figure 4.7.

Based on our weighting and scoring process, three designs performed well enough to be considered. These were design 1 (single prop attached to rudder, out boarded), 2 (single prop attached to rudder, direct drive), and 6 (dual thrust inside pontoons with props, with additional rudder). Because designs 1 and 2 are very similar, we chose to eliminate the lower scoring design 1. Our final designs that we are choosing between are the single prop attached to a rudder with a direct drive, and a dual prop system inside the pontoons with an additional rudder. However, this decision matrix will likely change as we conduct more research. For example, we currently have no information on how the top speed will vary between the designs, so for now each concept was scored a 5 for Top Speed.

California Solar Regatta Propulsion

Criteria	Weight	Options													
		1		2		3		4		5		6		7	
		Score	Total	Score	Total	Score	Total	Score	Total	Score	Total	Score	Total	Score	Total
Cost	2	5	10	6	12	2	4	6	12	2	4	4	8	5	10
Maneuverability	5	7	35	7	35	4	20	4	20	4	20	5	25	5	25
Ease of Manufacturing	4	5	20	5	20	4	16	6	24	2	8	4	16	5	20
Top Speed	5	5	25	5	25	5	25	5	25	5	25	5	25	5	25
Low Drag	4	4	16	4	16	6	24	5	20	6	24	5	20	4	16
Aesthetic Design	3	5	15	5	15	8	24	3	9	8	24	7	21	3	9
Lightweight	3	5	15	5	15	6	18	6	18	4	12	6	18	5	15
Reliable	3	4	12	5	15	5	15	3	9	2	6	5	15	4	12
Ease of Integration with Hull	4	6	24	6	24	5	20	7	28	2	8	5	20	7	28
Total:	-	172		177		166		165		131		168		160	

Designs

1 Single prop attached to rudder, outboarded
2 Single prop attached to rudder, direct drive
3 Dual thrust inside pontoons with props, direct drive
4 Dual thrust outside pontoons with props, strapped
5 Dual thrust inside pontoons with props, internal driveshafts
6 Normal rudder, dual thrust inside pontoons with props
7 Normal rudder, dual thrust on sides of pontoons with props

Figure 4.7 Weighted decision matrix of concepts generated in ideation process.

After more analysis was conducted, many of these ratings did not match up to what we discovered. Our final option ended up being a combination of a couple of these ideas, and is described in more detail in section 4.6, and in section 5 on Final Design.

4.4. Preliminary Alternative Concept Ideas

At the time of the PDR, we decided to research further the second design (single prop attached to rudder with a direct drive), and the sixth design (dual thrust inside pontoons with props with a normal rudder), both seen in decision matrix in Figure 4.7. The sixth design was rated lower than the second design, but until we conducted more research into the true characteristics of each model, we did not want to settle on one solution. These two remaining concepts were researched and tested more thoroughly before the final decision was made.

The second design combines the steering of a rudder and the propulsion of a prop into one design. The entire system would be a ridged body attached to the center platform of the boat. The system would be able to rotate around the vertical axis and move the direction of the driving and opposing forces in the water. This change of force direction would be how the steering was accomplished. A basic computer aided design (CAD) drawing of the system is shown in Figure 4.8a and a functional concept prototype is shown in Figure 4.8b. With the single motor and direct drive, electrical and mechanical losses would be reduced as opposed to a model with a longer drive train. The rudder and prop dimensions were dependent on the dimensions of the boat, and were finalized after the hull was designed. This design would likely require a larger prop compared to a model with dual props. The rudder would be made from carbon fiber or fiberglass to reduce the weight and the stresses on the mounting system. The system would also have an adjustable lowering mechanism to position it in optimal depth in the water to produce the necessary thrust. The prop would be made from either carbon fiber, CNC milled aluminum, or

19

3D printed material, all of which would be polished to reduce the drag on the blades. After testing the prototypes, we planned to manufacture a modified design for competition that was optimized for our specific performance. Different prop designs may be used for different races depending on the efficiencies and drag created at the different speeds. Testing would be done to determine if this is necessary.

| (a) | (b) |
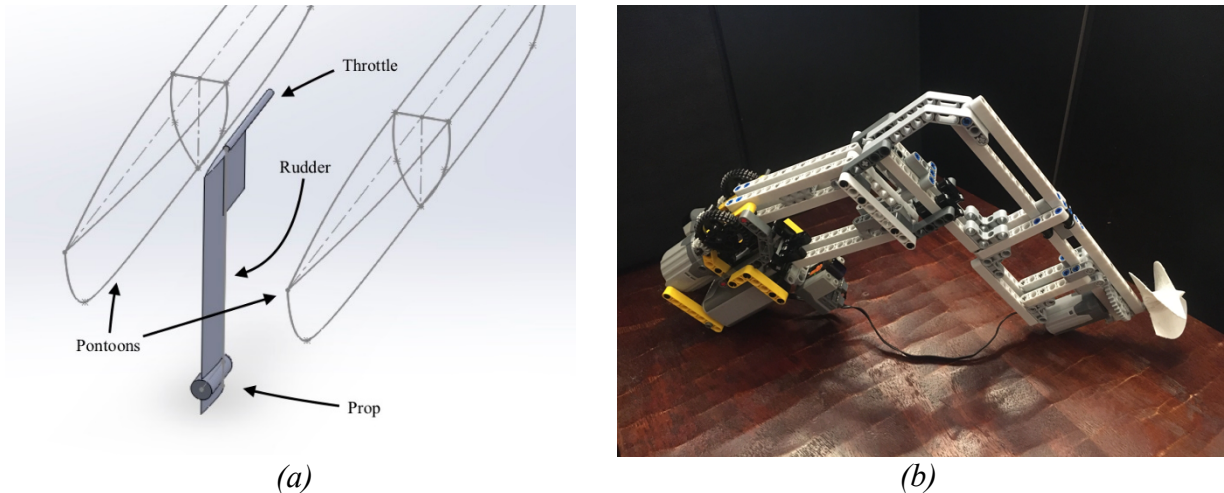
Figure 4.8 The second design integrates the motor and prop into the rudder.
Shown above are (a) the CAD model and (b) the concept prototype.

The sixth design from the decision matrix combines the steering and propulsion into one by using differential thrust and a rudder. Our team believes that the sprint and endurance races would not require the rudder with this design, and therefore we can eliminate the drag losses on the rudder. However, the slalom race may require a smaller turning radius, so the incorporation of a rudder may be inevitable. The differential thrust allows for a pair of unbalanced thrust forces on each pontoon which would create a moment about the center of the boat, causing it to turn. The thrust would be created by a hybrid propeller-waterjet design that creates a large mass flow out of the end of the pontoons and pushes the boat forward. A CAD design of the system is shown in Figure 4.9a and a concept model is shown in Figure 4.9b. In this design, the water would be pulled in from beneath the pontoons to not disturb the boundary layer of the flow around the boat hull. The diameter of the tubing and internal prop would be determined once the final dimensions of the boat are determined. The number of blades required to get the required flow for the desired thrust forces would have to be determined through testing and analysis. The internal channel required for the waterjet to function would be purchased stock and CNC milled to the exact dimensions and features our design requires. The driving shaft would be stock aluminum milled and press fit into the motor, set screws would be used to attach the props, and a triple seal bearing would be used to keep water away from motor. The prop would be designed and manufactured in the same manner as the prop for the rudder-prop system would be made.
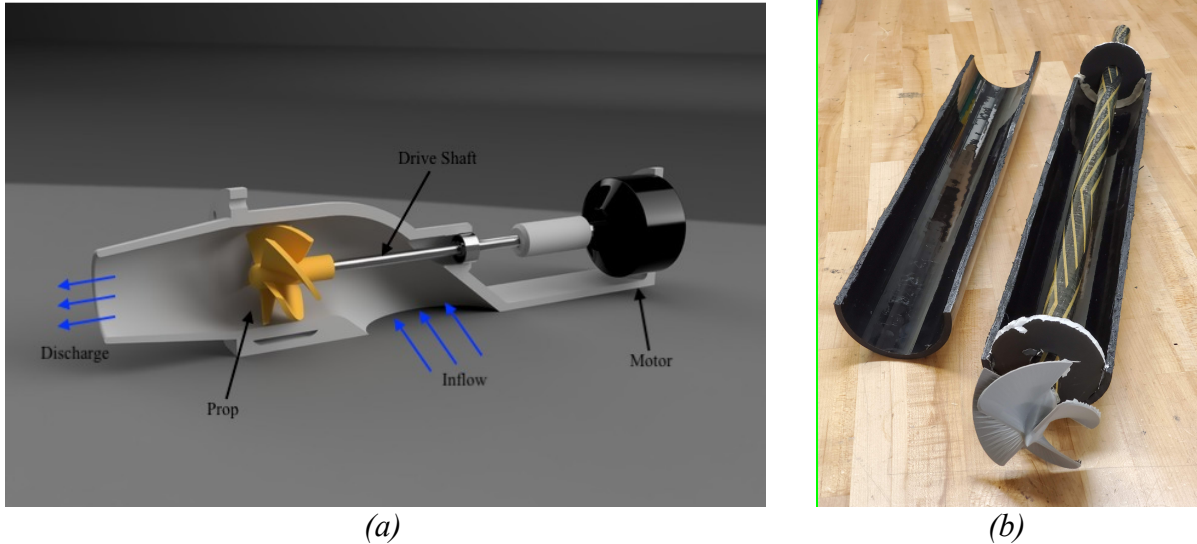
Figure 4.9 The sixth design utilizes a ducted prop integrated into the hull.

4.5. Preliminary Risk Analysis

Risk increases significantly with designs that involve advanced analysis and unproven technologies. To determine the risk introduced by each component of the propulsion system, we considered the impact and likelihood of component failure. First, we considered the components that will be included regardless of which design choices we made from this point forward. A major concern in any watercraft drivetrain is water ingress through the shaft bearing where the boundary exists between the lake-water and motor housing. Many boats use sealing systems based around stern tubes. These long bushing surfaces employ water pressure fed from a tank in the boat placed above the surface of the water. The positive differential from inside to outside prevents ingress of seawater. This system necessitates another seal between the stern tube and motor itself. Additionally, commercially available shaft sealing systems - even the smallest - are built for relatively large shafts that transmit hundreds of pounds of thrust. Therefore, we will attempt to use a triple sealed bearing to seal our motor components from the propeller. In risk reduction testing, we will expose the bearing to a depth of water equal to the depth and loads present at operation in the competition.

The risks in the electrical system are significant as well. Since we are not allowed to use capacitors for power storage, the power from the solar panels will travel directly to the motor controller. To remove issues with solar noise, we will have to obtain a solar converter that maintains as constant of an output as possible. Maintaining a constant voltage output from solar panels without the use of capacitors would require changing the current draw rapidly to keep the panels at their optimal peak power voltage. In tests, we worked with other Cal Poly students and professors researching solar panels (Professor Davol, Cal Poly Microgrid PV Array Senior Project, Dr. Dolan, Cal Poly Electrical Engineering professor and Professor Banadaki, Cal Poly Electrical Engineering professor) to test our electronic speed controller and electric motor with the inverter we select. In the event that our motor controller cannot handle the output current variation, and either is destroyed or cannot deliver power efficiently, we may invest in a more robust controller that is designed to deal with variations in power delivery.

We must also consider personal safety hazards and risks. One of these is the risk of a fast-spinning propeller with sharp blades. During each race, the team members wade through the water to first put boat in the water and then push it out from shore. Mounting the propeller externally would require the kill switch to be activated during the pushout. However, using a waterjet would contain the propeller inside of a fairing completely, removing the risk of a loose propeller becoming a projectile and hitting someone. This would increase safety when deploying the boat in the water.

Exposure to electricity is the final personal risk to discuss. Wet objects normally have a higher conductivity, meaning that the threshold for injury from voltage exposure could be lower. However, the lake water we will be competing in does not have a significant salt content that would require us to lower the threshold of the voltage at the operation point. At most, our system will run at 40V DC, and will only be repaired or altered when fully dried to minimize risk.

Further evaluation of risks and safety hazards can be found in Appendix F.

4.6. Changes to Design Direction After Performance Analysis

Since the PDR, we have made slight modifications to our design based off of advice from various professors and our own performance analysis. We decided to incorporate the best elements of the two designs discussed above into our final design. The concept of our final design is to have two propulsion subsystems, one mounted to each pontoon. The motor will be mounted at the top of the rudder and power is directed to the prop through a reduction transmission at the bottom of the rudder. The rudder will be attached to a steering wheel via cables, which are connected to a steering column in the center of the boat. The rudders will be linked with a rigid bar to keep their turning angles equal, and the motors will be controlled by one throttle to keep the props at equal speeds.

These changes were implemented due to two key findings in our analysis; it was discovered that two smaller propellers would be more efficient than one single propeller, and each propeller has one speed at which it reaches maximum efficiency. Because of this, two propellers were chosen for the design, and each had to be kept at a constant speed. To achieve this and allow for the boat to turn, each propeller was made to rotate with a rudder on the end of each pontoon. The final design is described in more detail in the next section.

5. Final Design

This section includes a description of the final design, an explanation of its functionality, design justification, material choices, safety considerations, and cost analysis.

5.1. Comprehensive Final Design

Out final design is shown in Figure 5.1 with the full boat assembly created by the hull team. The model incorporates all of the ideas that were envisioned in the preliminary analysis and concept design and has a simple integration with the hull. The entire boat is designed to be modular, and each pontoon can be separated from the overall assembly by removing a few bolts. Each propulsion system can be easily removed from the pontoons as well. In addition, the entire

bridge assembly can easily be shifted up or down the length of the pontoons to optimize a center of mass, and the distance between the pontoons can be adjusted to optimize steering capabilities.
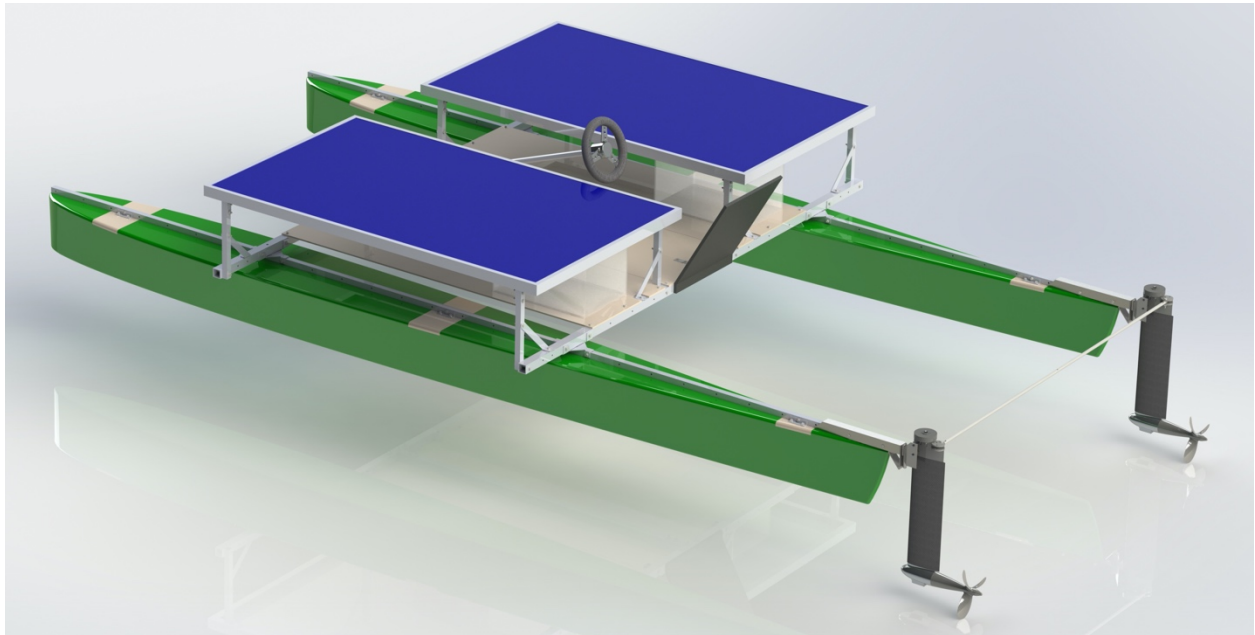
Figure 5.1. Comprehensive CAD model of the final design.

5.2. Propulsion Subsystems

The boat will utilize two propulsion subsystems, one on the back of each pontoon and linked together with a rod to keep them at the same turning angle. A close-up view of the two propulsion systems is shown in Figure 5.2. Additionally, Figure 5.3 and Figure 5.4 show more detailed views of the propulsion system with components labeled.
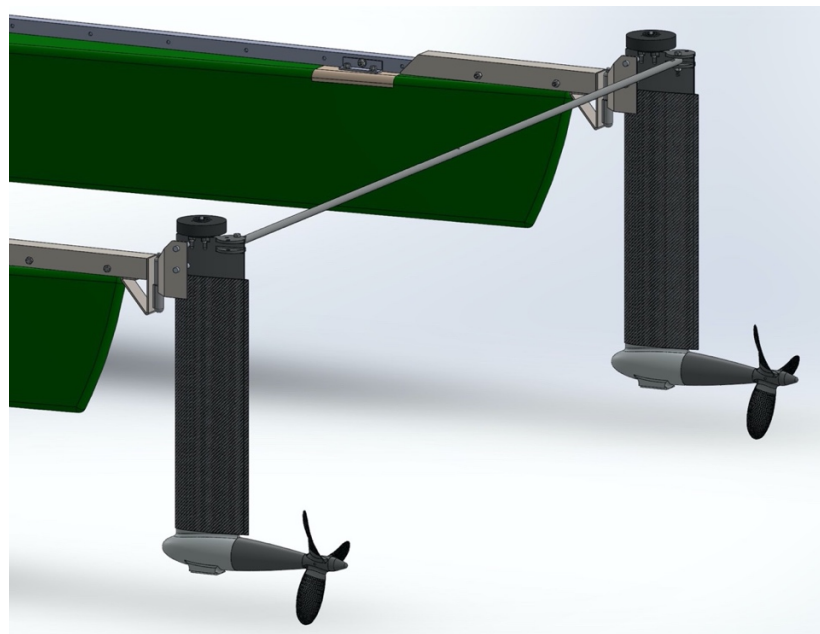
Figure 5.2. Propulsion units attached to the back of the pontoons.
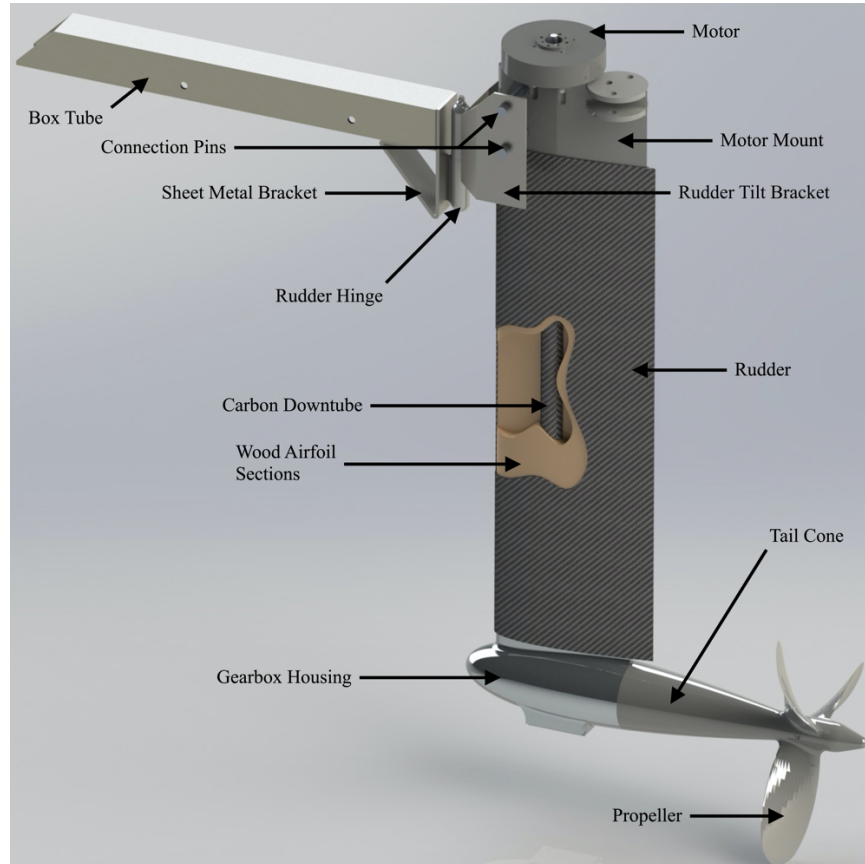
Figure 5.3. Overall components of a single propulsion unit.
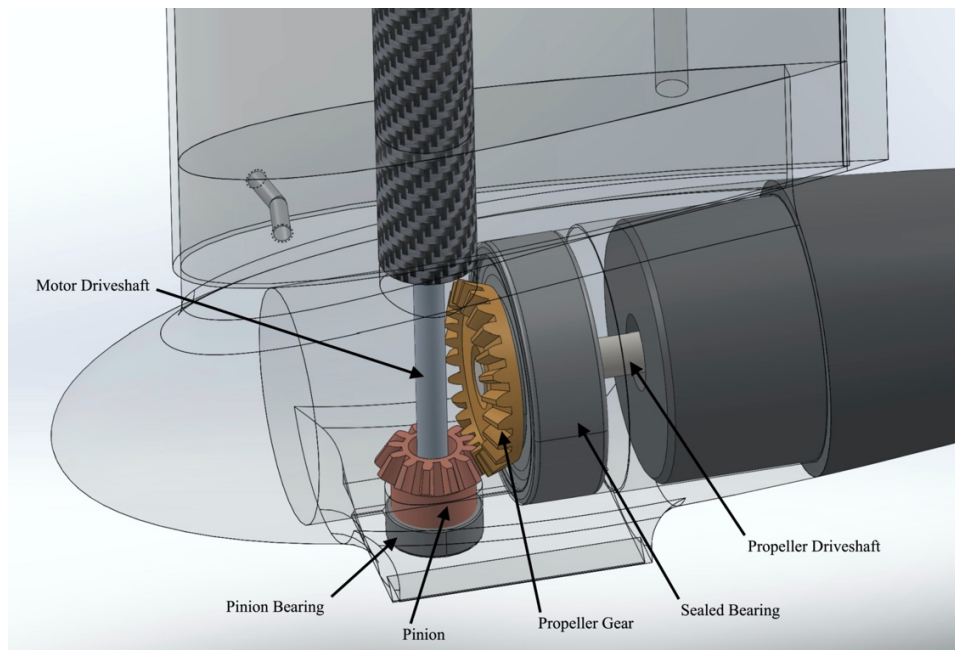
Figure 5.4. Internal components of the transmission housing.

Each Gearbox Housing is to be manufactured from aluminum using a 5-axis CNC mill, and the Motor Mounts will be 3D printed. These two components will interface directly with the Rudder Downtube. The Rudder is made up of stacked wood panels shaped like airfoils that will be wrapped in carbon fiber. The Rudder Downtube is also made of carbon fiber and will go through a hole in each wood airfoil in the core. This will provide space to run the Motor Driveshaft from the Electric Motor to the Transmission Housing.

The Gearbox Housing can be seen in Figure 5.4 and contains a set of bearings and bevel gears. The gears provide a 2:1 speed reduction and are secured by the press fit bearings and the Propeller Driveshaft and Motor Driveshaft. The Tail Cone is designed to be 3D printed and will insert into the end of the Gearbox Housing to complete the revolved airfoil profile of the gearbox up until the base of the propeller. A set screw is threaded through the propeller driveshaft to connect it to the propeller. This can be seen more clearly in Figure 5.5. A secondary bearing is also located at the end of the tail cone for support for the propeller driveshaft.
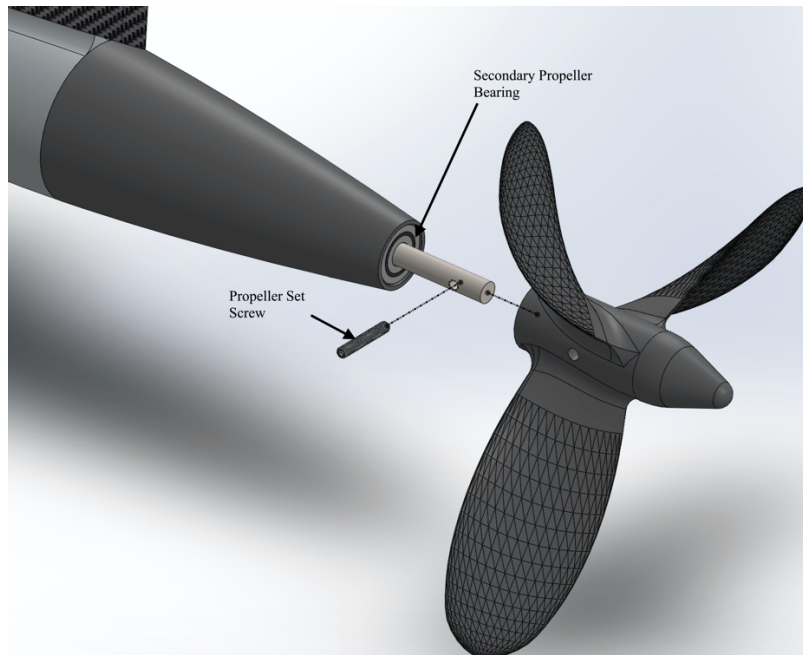
Figure 5.5. Propeller assembly diagram.

The propulsion unit is attached to the hull though the Box Tube that interfaces with the hull, as can be seen in Figure 5.2. Welded to the Box Tube is the Sheet Metal Bracket, which connects to the Rudder Hinge. The other end of the Rudder Hinge is connected to the Rudder Tilt Bracket. Through the use of two pins, the Motor Mount/Rudder subassembly is secured to the Rudder Tilt Bracket and is able to be tilted up 90 degrees to allow for safe transportation, maintenance, and storage. Figure 5.6 shows this mechanism in more detail.
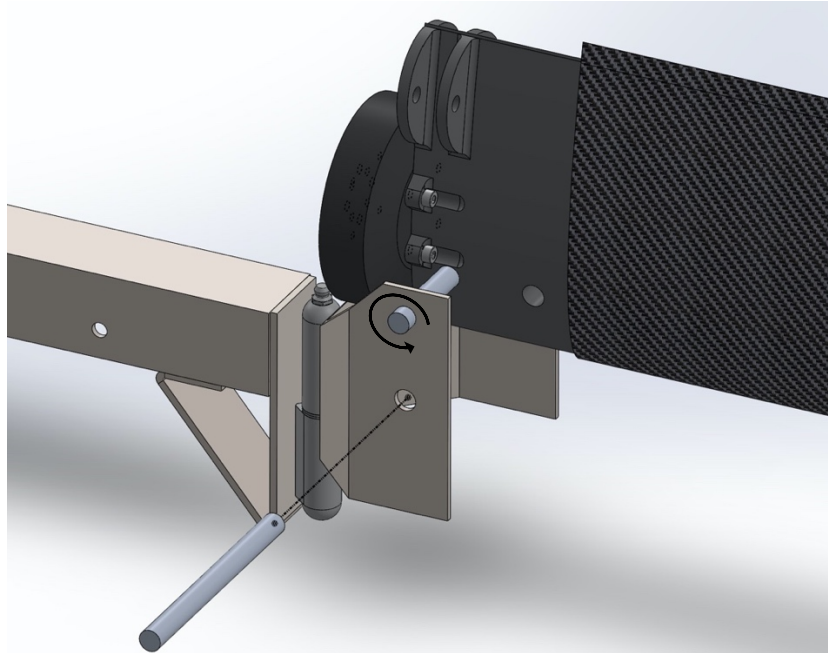
Figure 5.6. Demonstration of rudder assembly rotation for inspection and maintenance.

Unfortunately, because of complications with COVID-19 many of these components were unable to be manufactured or assembled into a full propulsion system. Finishing manufacture and assembly of the propulsion system and full boat will be passed on to next year's team.

5.3. Steering Mechanism

After deciding to use two, rotating propulsion units, the simplest steering method seemed to be via a cabling system. The propulsion units on the back of each pontoon are linked together to keep them at the same turning angle. A cable will be run along the length of the pontoon from each motor mount and wrapped around a steering column to allow the driver to steer. A diagram of the steering system is shown in Figure 5.7.
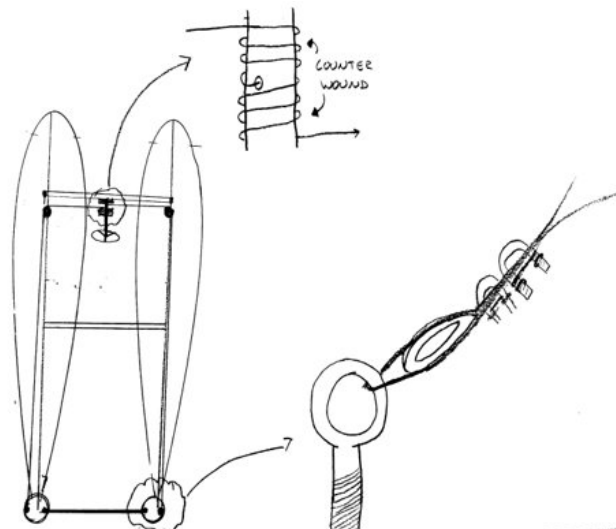
Figure 5.7. Steering diagram.

The cables will be tied with extra length at the ends, allowing for the steering system to be adjusted for any potential position of the bridge. A more detailed analysis of the steering system will be performed to ensure that the driver has adequate control over the positions of each propulsion unit. A fixture made from wood will be used to test the different variables of the steering system that can be adjusted such as the lever arm and the diameter of the drive shaft. A schematic of the system setup can be found in Appendix T.

5.4. Material Choices

The rudder will be constructed with a wood core base that is covered in layer of carbon fiber. This causes it to have a high strength-to-weight ratio, while still being relatively easy to manufacture. Thin, ¼ inch wood airfoil sections with circular holes in the middle and end are to be stacked on top each other to form the rudder core.

The hinge flange, box tubing, and box tubing support were all chosen to be aluminum so that the aluminum rudder hinge can be welded to both.

The differential housing is to be machined from aluminum for ease of manufacturing and low cost. It will not be welded to anything, and therefore does not have to be the same material as other components.

The propeller, motor mount, and tail cone are to be 3D printed. The motor mount and tail cone can be printed out of PLA at the innovation sandbox at Cal Poly. Prototype propellers made from PLA were printed at Cal Poly, though the final propeller will likely be outsourced to a company with printers large enough to complete the print as one part. Hard resin is being considered for the propeller material because it is light, stiff, and produces one of the best surface finishes of any 3D printed material.

5.5. Propeller Design/Specification Descriptions

To design the propeller for our boat, we used a MATLAB program called OpenProp. OpenProp was developed by MIT and Dartmouth college to analyze propeller performance given a number of inputs. It computes propeller performance using Lerb's analysis method in conjunction with a lifting-line analysis on the blade surfaces, code similar to what is used in computational fluid dynamics (CFD).[27] This method designs based on inputs of diameter, rotational speed, inflow velocity, thrust desired, and various geometric inputs. The code then iterates to create a propeller to reach the thrust desired at the maximum possible efficiency, and outputs the resulting propeller characteristics and full geometry.

Our boat has a limitation of a little less than 230 W of power for each of the two propellers, and we want to design for an unknown maximum inflow velocity and maximum efficiency. However, OpenProp designs a propeller using a thrust-based method, not power-based method, making it difficult to use for our specific needs. To remedy this, additional code was written to analyze propellers in a way that makes more sense for our specific requirements.

To obtain a rough idea of what values to plug into OpenProp initially to produce a propeller that met our requirements, hand calculations were done using power-based and traditional

performance curves for a Wangeningen B-series propeller (see Figure 2.8 and Figure 2.9), assuming an input power of 200 W and inflow velocity of 5.5 mph. Initial estimates produced an optimal rotational speed of 500 RPM, diameter of 11.03 in, and efficiency of 79.5%. These hand calculations are located in Propeller Hand Calculations in Appendix H.

To provide a more robust estimate of diameter, rotational speed, and expanded area ratio (EAR), code was developed in OpenProp to iterate over a range of input values to determine which produced the highest efficiency. Results of this iteration are shown in Figure 5.8, which shows efficiency for lines of various diameters as rotational speed is varied. Code was developed to create new plots for different values of EAR; Figure 5.8 shows the value of EAR that produced the highest efficiency, equal to roughly 0.325.
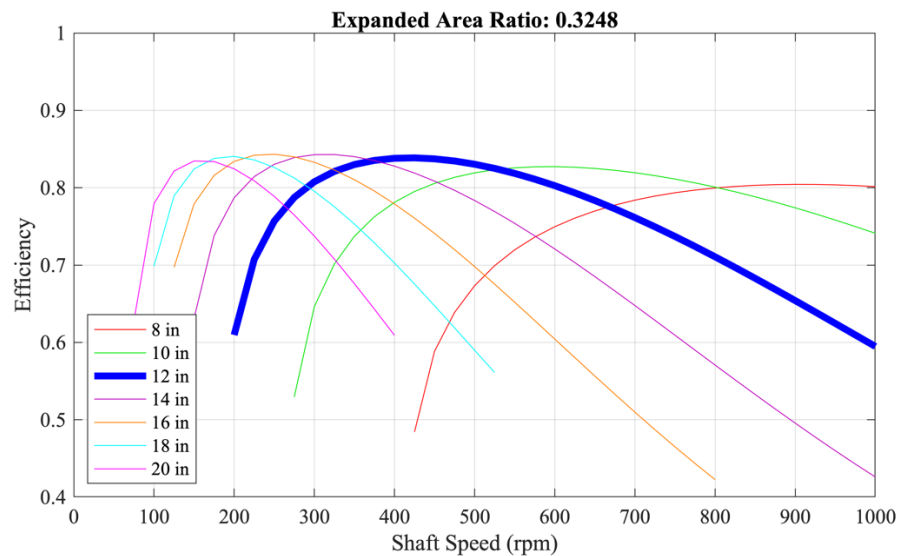
Figure 5.8. Parametric study varying efficiency and shaft speed for a specific EAR.

Each point on the curves in this plot represents a completely new optimized propeller design. Based on the results, we can assume a best possible efficiency of around 84%, with max efficiency increasing with larger diameters. However, larger propellers only reach their maximum efficiency at a smaller range of RPMs, which would be more difficult to achieve. We chose a diameter of 12 in (blue bolded line) for our final design, as it has nearly the same maximum efficiency as higher diameter propellers and has a wider range of acceptable RPMs. Additionally, 12 in is a much more reasonable size to manufacture.

Another key parameter that affects what our top speed will be is the drag on each hull of the pontoons of the boat. The drag coefficient C_dA can be used to determine the required thrust to achieve a maximum speed by using the following equation:

$$T_{req} = C_dA * (0.5\rho V_{a,max}^2)$$

The boat team (Up a Creek) has estimated C_dA of each hull to be around 0.05 ft². However, estimates of drag are hard to get exact without testing a hull once it is fully built, so likely the final value of C_dA will be different than what is predicted. OpenProp code was iterated over

different C_dA assumed for propeller designs and different actual values of C_dA to see how they would affect top possible speed; the results of this test can be seen in Figure 5.9.
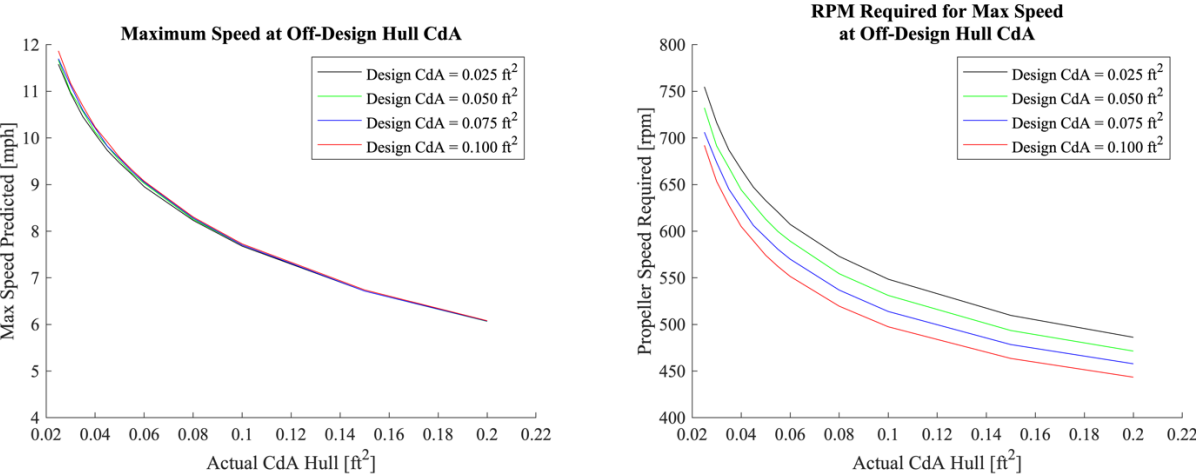
Figure 5.9. Hull drag coefficient analysis for propeller design.

From these plots, it is clear that assuming different C_dA values for the propeller design does not affect the top possible speed at all; the only difference is the rotational speed that the propeller must be run at to achieve this top speed. This is very useful to know for our propeller design, as it shows that even if we see a drag coefficient that is different than what is expected, our propeller can still be run to achieve the same top speed as if we had seen exactly what we expected. After seeing this, we decided to use a value of $C_dA = 0.1$ ft^2 as an input into OpenProp, as a conservative estimate. This value would lead to a predicted top speed of about 7.7 mph, above our goal of 7 mph. Higher speeds are also achievable if C_dA is reduced.

The number of blades (Z) was chosen with a similar iteration process. In general, efficiency decreases with increasing number of blades, while thrust increases. We chose to use three blades for our design; two would be more efficient, but also had the possibility of adding more vibrational issues if the blades were not manufactured to be perfectly balanced.
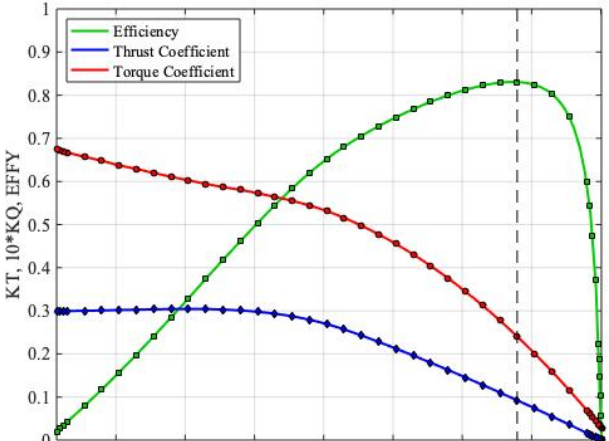
Figure 5.10. Traditional performance chart for our propeller design created by OpenProp.

Once values for EAR, D, Z, and C_dA were chosen, setting an input power of $P_{in} = 230$W allowed for all design constraints to be established for the code to run. The propeller was designed using a NACA66 series airfoil[29] thickness with NACA a=0.8 meanline, which are typical airfoil shapes of propellers. Figure 5.10 shows the traditional performance curve for the designed propeller, and Figure 5.11 shows a version of the same information with dimensioned instead of non-dimensional variables for a better understanding of what the performance chart shows.
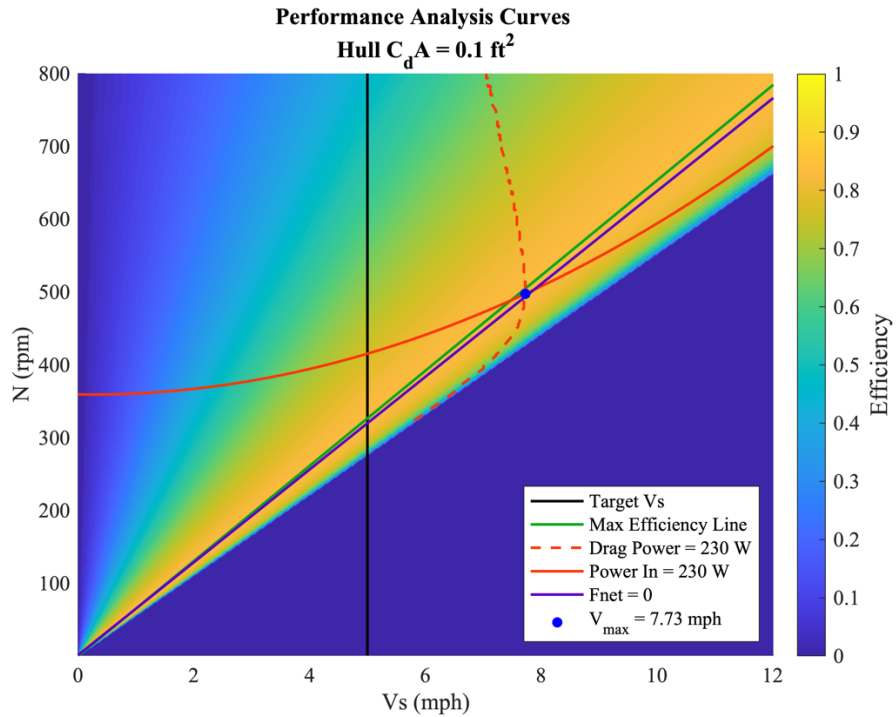
Figure 5.11. Performance chart with dimensioned variables.

Using Figure 5.11, we can see what our predicted performance of the propeller will be more clearly. The color background represents efficiency, with the green line representing the maximum possible efficiency. From this chart, we can see that our input power limits the top propeller speed to about 350 rpm when the boat is at rest, but as the boat gains speed the propeller speed can increase. The blue dot represents the best performance point, where all input power is being used to overcome drag. Points above the purple line represent states where there is excess force that can be used to accelerate, but below the line drag dominates and causes a deceleration. With our current input estimates, a maximum speed is predicted to be 7.73 mph.

All key design characteristics from this analysis are shown in Table 5.1. Propeller design was done for a single propeller at a time, using half of the total power and hull drag that the entire boat will see in operation.

Table 5.1. Propeller design characteristics.

Geometric Variables	Value		Performance Variables	Value
Diameter D	12 in		Ship Speed V_s	7.73 mph
Hub Diameter D_h	1 in		Rotational Speed N	500 RPM
Number of Blades Z	3		Thrust T	12.4 lbf
Expanded Area Ratio EAR	0.325		Torque Q	38.9 lbf•in
Meanline	NACA a=0.8		Input Power P_{in}	230 W
Thickness	NACA 66		Efficiency η	83.1%
Pitch Ratio P/D	1.49		Hull Drag $(C_d A)_{hull}$	0.1 ft^2

After calculating the geometric dimensions, OpenProp creates a 3D image of the full propeller in a 3D MATLAB plot. However, to convert this into a usable CAD file, it was necessary to turn this 3D data into the correct file format. A function was written in MATLAB to convert the 3D data points that make up the propeller into an STL file, which could then be imported into SolidWorks or Fusion 360 to edit the features of the hub.

OpenProp also contains a function that checks the blades for cavitation. This code was used with our design conditions, and the results from this test are shown in Figure 5.12. Cavitation occurs when $-C_P/\sigma \geq 1$; for our parameters, this value never exceeded 0.06, signifying that we will not have a problem with propeller cavitation.
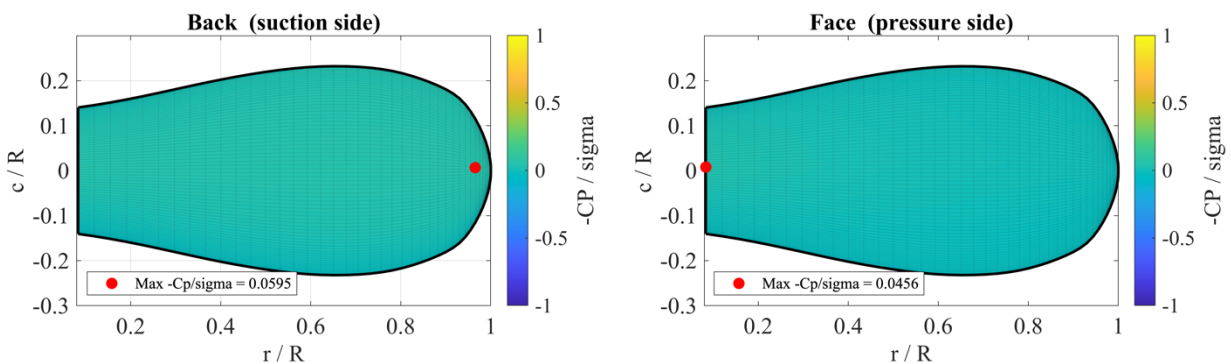
Figure 5.12. Blade cavitation diagrams from OpenProp.

To ensure that our blades would not break under stresses when in operation, a stress analysis was done in OpenProp as well. The results of this test can be seen in Figure 5.13. With our design conditions, the maximum blade stress is only about 3.4 MPa, much lower than the yield strength of any material that we would use to make it. We will 3D print our propellers either out of PLA or epoxy resin, which have estimated yield strengths of 26 MPa and 75MPa, respectively; this would give us a factor of safety between 7 and 22, signifying almost no possible risk of blade yield.

This stress analysis does not take into account the full propeller and does not account for stress concentrations where the blade connects to the hub. However, according to Carlton,[21] a fillet that is equal to the maximum thickness of the blade at r=0.25R will be sufficient to support the blade. For our propellers, this fillet will have a radius of 0.4 in.
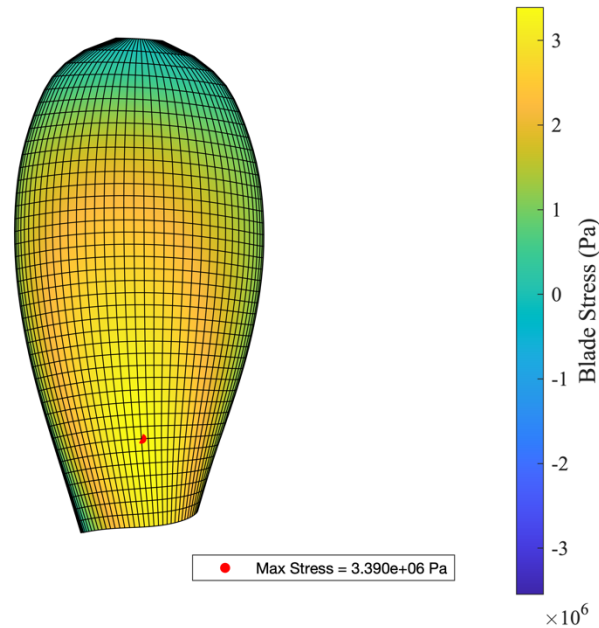
Figure 5.13. Blade stress analysis using OpenProp.

5.6. Electrical System

The electrical system is made up of nearly all off the shelf components that are wired together for our system to operate. The solar cells are wired to a solar regulator, which are wired to a kill switch, which are wired to the two ESC motor controllers, which are wired to the motors. A diagram of this system can be found in Appendix I. With the desire to reduce losses in the electrical system as much as possible the desire to use off the shelf parts arose. These parts have been designed and re-designed to be as efficient as possible and that is why they were chosen for our design. The regulator and controllers are kept in a sealed plastic box on the boat during operation to eliminate the chance of water interaction with the components.

5.7. Safety, Maintenance, and Repair Considerations

Since the boat will be used just for the competition this year the maintenance and repair considerations are going to be specific to getting the boat to compete. The safety considerations will include safe practices for manufacturing, transportation, and operation of the boat.

5.7.1. Safety

Since a majority of the manufacturing is going to be done with some type of CNC tool center there are already a lot of safety measures in place to protect the operator of the machines when in use. These protections include safety walls and glass surrounding the part while it is being made. When transporting the boat to Northern California the sections of the boat must be properly secured to the bed of a truck. In order to accomplish this, custom mounts will be manufactured to ensure the boat is attached to the truck bed and cannot fall off. The motors and propellers are going to be easily removed and will be transported inside the vehicle. When operating the boat safety paint will denote moving parts that need to be kept clear of. Electrical components will be

a sealed plastic container so people cannot interact with live wires. Life vests, safety flags, airhorns, and a paddle will be on the boat during usage, in case of emergency.

5.7.2. Maintenance

Since the system is designed to be used for a single day of competition there is not much planned for maintenance. All rotating and sliding parts will be oiled or greased to prevent frictional ware. Cleaning after practice runs and testing will reduce the chance of any buildup on the system.

5.7.3. Repair Considerations

All major components will have spares made in case of failure on the day of competition. This includes driveshafts, rudders, props, controllers, and motors. The modular design makes replacements for these parts easier to do on the beach the day of competition. Additional carbon fiber patch kits, electrical wire, and tools will be on site as well. In case of failure in the transmission box an additional premanufactured unit used to change direction without reduction will be brought in case there are major issues on the day of the race

5.8. Cost Analysis

The four subsystems to be cost-analyzed in this section are: powertrain, hull-mounting, electronics, and steering.

The powertrain makes up most of the cost due to the expense of highly efficient motors. The desired T-motor U8II is $319.99, with the associated motor controller costing $60.00. Other high-cost components in the powertrain are the gearing housing and motor-mount due to their complexity that necessitates a 5-axis CNC to produce them. Due to a sponsorship by a local company with donated machine time and materials, these manufacturing costs have been reduced to zero. Finally, the propeller would be expensive to manufacture if 3D printing was not as mature and reliable as it is now, and if the powertrain had an input power of more than 3kW, which would exceed the yield strength of inexpensive materials.

The hull mounting subsystem components are manufactured from stainless steel donated by Stainless Steve Fabrications. Because the size of these components is small, the cost would not be above $50.00 for materials.

SMUD provided the solar panels, which otherwise would have cost a total of $500.00. The other electronic components include a power optimizer, costing $109.67, and wiring, which will cost between $25-$40.

The cables, eyebolts, column, and wheel that make up the steering system will cost less than $50.00 because none of the components are uncommon or made of expensive materials. Since funding for the selected motors and the matched controllers is not guaranteed through MESFAC, inexpensive alternatives have been selected that will enable race-worthy functionality – but fall between 10 and 20% short of the targeted performance. This would reduce the total required funding to fit within the $1000 budget supplied. This was not needed since MESFAC did fun the motors and controllers. A full budget sheet can be located in Appendix N.

6. Manufacturing Plan

This section of the report will outline the steps needed to get all raw materials, how to process those materials into parts, how to assemble the parts together, and what will be outsourced. Materials that were donated and services donated do not have associated cost and are called out as donated throughout this section. Drawings of parts to be manufactured are located in Appendix M, and links to parts that we are buying off the shelf are located in Appendix O.

6.1. Procuring Materials

The most used material for this product is aluminum and is likely to be the costliest material used. The team was able to find local vendors that were willing to donate the aluminum and reduce the cost of the system. Wooden plywood or MDF sheets will be used for the rudder/water-foil, they will be purchased from Home Depot. Along with the wood core, Carbon Fiber will be used for the exterior and interior supports. The interior supports will be purchased online from a yet to be determined source, while the exterior carbon has been donated by the SAMPE club on campus. The Motors were purchased online from Arrow Motors. The bearings, gears, ball joints, steering rods, housing, and related parts will be purchased from McMaster. The box tubing, sheet metal, eyebolts, solid aluminum rods, bolts, nuts, and washers will be purchased from Home Depot. The Solar Panels are provided by SMUD and have been brought down to San Luis Obispo. The Solar Regulator and ESC will be purchased from T-motors online. Any additional parts needed for fabrication will primarily be donated from local vendors or purchased from them.

6.2. Manufacturing and Assembly

This section describes a step-by-step process for creating each part of the propulsion assembly. Any parts that are planned to be outsourced will have a comment in this section before describing how the part will be integrated with the other components of the system. The timeline for manufacturing, assembly, and testing can be seen in the Gantt Chart found in Appendix F.

6.2.1. Mechanical Drive Steps
1. Convert CAD models into CAD/CAM and product G-Code script to produce the differential housing, motor mounts, and shaft adapter.
2. Machine differential housing with 5-axis CNC (outsourced)
3. Machine motor mount with 5-axis CNC (outsourced)
4. Machine motor-shaft adapter 5-axis CNC (outsourced)
5. Press pinion into small bearing with a bearing driver
6. Press gear into large bearing with press and vice
7. Press small bearing into housing with a bearing driver
8. Press pinion-shaft into pinion with press and vice
9. Press gear into housing with a bearing driver
10. Press prop-shaft into gear with press and vice
11. Bond differential into rudder/water-foil with epoxy and two through bolts
    a. This step and following to be done once other parts have been manufactured, specifically the water-foil, motor mount, and differential housing

12. Bond motor mount into rudder/water-foil with bolt through down-shaft and epoxy to connect bottom surface of the mount and the top of the water-foil
13. Run long shaft through carbon tube with bearing supports on top and bottom to ensure alignment
14. Install motor adapter onto motor with bolts and hand wrench
15. Mount motor onto motor mount over long shaft
16. Tighten the set screw on the motor adapter onto the shaft
17. Install 0.5-13 Helicoil into prop hub
    a. This step and the next are to be completed once props are ready to be attached
18. Screw prop onto prop shaft

6.2.2. Propeller Steps
1. Produce STL file with OpenProp through MATLAB given design conditions of water and boat
2. Convert STL to solid and 3D Print out of Resin (Outsourced)
3. Tap hole on rear or prop for mounting
4. Attach shaft with duel sided threads onto prop and then to differential

6.2.3. Rudder/Water-foil Steps
1. Using NACA airfoil generator software create an airfoil with around a 1" maximum height. Make sure the length to height ratio is at least five. (NACA 0018 was used) with a 0.75" diameter hole at the center of the tallest length
    a. Drawings shown in Appendix L-9
2. Make cutting pattern for 2' by 4' wood panels out of the airfoil generated in the previous step with a depth of 1" (may use different depth depending on the tools available) in CAD/CAM software and export for laser cutters
3. Cut out enough airfoils to create a height of 36" (2x18") with the laser cutter in Mustang 60
4. Slide the wood pieces onto the purchased carbon fiber tubes with an exterior diameter of 0.75" one at a time adding epoxy to the top of each piece before adding next, except for the last one
    a. Let it dry
5. Cut prepreg carbon fiber rectangles with a height of 18" and a width of the perimeter length of the airfoil
    a. A string wrapped around the airfoil can produce an accurate perimeter reading.
6. Wrap the airfoils in the cut carbon fiber sheets and cure at manufactures recommended cure cycle
7. After cure cover end of airfoil with an additional epoxy treatment to ensure the end is sealed
8. Sand and water seal the entire carbon fiber section to ensure no water ingress
9. Drill holes through carbon fiber and wood with drill press and proper drill bits (be sure to wear proper PPE's)
    a. A wooden fixture is suggested for drilling accurate holes in curved carbon fiber walls

10. Apply rubber gasket around holes before putting bolts through to ensure no water ingress
11. Bolt on motor mount and differential
    a. Use epoxy to seal and secure these to the rudder

6.2.4. Steering Steps
1. Cut half inch aluminum linkage tube to distance between pontoons
    a. If this distance is to be variable, cut at largest possible width
2. Drill 0.25" holes through aluminum tube at both ends and, in the center with a center tap and drill press
3. Slide low profile bushings between the tube and rudder mounting points
    a. This and all following steps are to be completed once motor mounts are complete
4. Run bolt through both the mounting holes and the tube holes
5. Tighten nuts onto the free end of the bolts and apply Loctite
6. Use reciprocating saw to cut a slot in the steering tube of 0.625"
7. Slide low profile bearings between the slot and the middle of the linkage tube
8. Bolt together the linkage and steering tubes and apply Loctite
9. Slide ball joint pivot over the free end of the steering tube
10. Bolt pivot down to the aft cross member of the bridge
11. Confirm both motor mounts are attached and bolt assembly to hull

6.2.5. Motor Tilt Out of Water Steps
1. Cut 0.1" thick sheet metal to height of the combined length of all the sides of the flange with a width of 4" with sheet metal cutter
    a. Drawings shown in Appendix L-5
2. Cut with an angle of 225-degrees and 3" from each end. Will create section 2" height in the center of the sheet where the width is still 4"
3. With template printed out from drawing mark and drill all holes (3 sets to line up, or a total of 6) with drill press
4. Mark off 3" from the top and bottom of the sheet (where the previous cuts were) and the 2" high portion of the sheet score the exterior for alignment on the brake (there should be 4 lines)
5. With the brake in one of the shops on campus bend along each of the scores 45-degrees so that the holes align up across from each other
6. Bolt together to keep shape prior to installing and to ensure proper alignment when attaching motor
7. Weld bracket to box tubing and support
8. Once water-foil is prepared attach with two bolts, one permanent and one removable
    a. Rubber spacers are placed between the holes in the hinge and the ones in the motor mount to ensure proper centering of water-foil
9. Bolt box tubing and support to hull with carbon spacer between the stainless steel and aluminum

6.2.6. Motor to Hull Steps

1. Cut 1.5" Square stainless-steel tubing with a wall thickness of 0.1" to a length of 15" with metal bandsaw
2. Cut tube at an angle such that the resulting side length is 13.65" with metal bandsaw.
    a. Drawings shown in Appendix M
3. Cut 0.125" thick piece of stainless-steel to a length of 6.725" and a width of 1.4" with metal band saw
4. Mark 3" from one side for bending
5. Bend plate 140-degrees, or until one side is 40-degrees from itself with "big-boy" brake
    a. Drawings shown in Appendix M
6. MIG weld plate onto tube with a resulting 90-degree angle from face of tube to longer bend of plate (wooden fixture with clamps to ensure proper angle)
7. Attach to motor tilt as stated in previous section and then to boat hull

6.2.7. Electrical System

1. Mount solar panels on to boat hull
    a. This step is being done by the hull team and is outlined more completely there
2. Run wire from the anode and cathode hookup on the bottom of each panel and run to the solar regulator input
    a. They will be attached to the same input, so they are run in parallel
3. Run wire from solar regulator output directly battery bank and kill switch
4. Run wires from both battery bank and kill switch toto ESC input
5. Wires are then run from the two outputs of the ESC to each of the electric motors
    Note: The solar regulator and ESC will be in a sealed plastic container with wires running in one side from the panels and out the other to the motors
6. Test by charging batteries with trickle charger and running motors without drive shafts hooked up

6.2.8. Outsourced Parts

As mentioned throughout the manufacturing and assembly section, there are four parts that we plan to outsource. Each part will be designed by the team, but due to complexities in the parts we will not be manufacturing them ourselves. These parts are the motor mount, differential, motor shaft adaptors, and the propellers.

The gearbox (differential) housing was outsourced due to the complexities of their designs and need of a 5-Axis CNC to produce accurate parts within tolerances. The first prototype was manufactured at Zone 5 Tech with the assistance of team member Eric Rinell.

The propellers are planned to be outsourced so they could be made from a stronger material then the 3D printers on campus are able to print (PLA). The off-campus printing would also allow for a better surface finish, reducing the amount of sanding required to keep the drag coefficient low while reducing post process material removal that would change the shape of the prop. However, it was also found that after fine-tuning the printer settings and optimizing the prop design for a

nine-inch diameter, that printing on campus could work as well. These options will be weighed more by the team next year.

7. Design Verification Plan

Our team planned to do extensive testing of the propulsion system and its components to ensure that all our design specifications were met before the regatta. A list of the design specifications can be found in Table 3.2, and a breakdown of the full design verification plan can be found in Appendix I. Each of the specifications are listed in order below along with a description of the planned testing.

1. Top speed

    Test out the boat and its capabilities in Laguna Lake once it is completed. Top speed can be measured during these tests using a free phone application, and we can also time the boat as it does laps to get an estimate of speed during a slalom or endurance race.

2. Acceleration

    Acceleration will also be tested with the full boat once it is completed. We planned to obtain an accelerometer device to measure the acceleration from the boat directly as well as conducting a timed test of the boat's acceleration in the water.

3. Turning Radius

    Like acceleration and top speed, turning radius would be tested with the full boat. A rough estimate can be used by turning between buoys in the water that are spaced a certain distance apart.

4. Battery life at max power draw

    The battery life at max draw can be measured by conducting a timed test of the propulsion system when it is hooked up to the battery. This test should also be completed with the full boat assembly by running it as long as possible until the battery runs out of power. Additionally, the batteries can be tested beforehand by simply hooking them up to a similar load.

5. PV panel efficiency

    The solar panel output and efficiency can be tested using the equipment stored near the solar balcony in building 13. We planned to run multiple tests of the panels for a couple hours in both sunny and cloudy conditions to see what output we should expect. A full uncertainty analysis would be performed using the data collected.

6. Electrical Power Transfer

    Electrical power transfer through the wires and solar converter can be tested by measuring the power loss through the system when it is powered separately and together with the full propulsion system. This can be done using a simple wattmeter.

7. Drivetrain (Propeller, driveshaft, and transmission) efficiency

    Originally, we had planned to use the water channel described in section 2.7 to complete extensive testing of smaller scale models of the propellers that we intend to use for our

final design. However, due to schedule pressure, we postponed the tests until after the competition.

To test the efficiency of the driveshaft and transmission, we would have hooked the sub-assembly up to a motor and measure the speed and torque outputs without the propeller attached. This test can be done using a dynamometer that is in the electrical power labs on campus.

8. Weight of propulsion assembly

The weight of the entire assembly can be simply measured using a scale once the assembly has been completed. It can also be estimated by adding the weights of each different component.

8. Testing Plan

This section contains the procedures for tests on both components of the propulsion system and on the full boat. Some of these tests were completed, but others had to be postponed due to complications with COVID-19. Test procedures for each test listed can be found in Appendix S.

8.1. Component Tests

8.1.1. Motor Tests

For the propulsion system to be efficient, the propellers and motors must both operate at their maximum efficiency at the same time. To determine what loading conditions this will occur at, it was necessary to use the torque-speed curves for the motors. However, the motors that were chosen, T-motor U8II-KV85, did not have a torque-speed curve specified in their specifications. Therefore, the motors had to tested using a dynamometer in the EE power lab at Cal Poly to find their torque-speed curves. Once the torque speed curves of the motors were found, the propellers could be designed to reach maximum efficiency at the same torque and speed that the motors reach maximum efficiency.

For each test, the motor was connected to the dynamometer with a test jig, shown in Figure 8.1 and Figure 8.2. Once the motor was aligned to the dynamometer shaft, it was connected to the battery and run up to full power. The torque on the motor from the dynamometer was raised until the motor stalled out, taking speed data at certain intervals to produce the torque-speed curve.
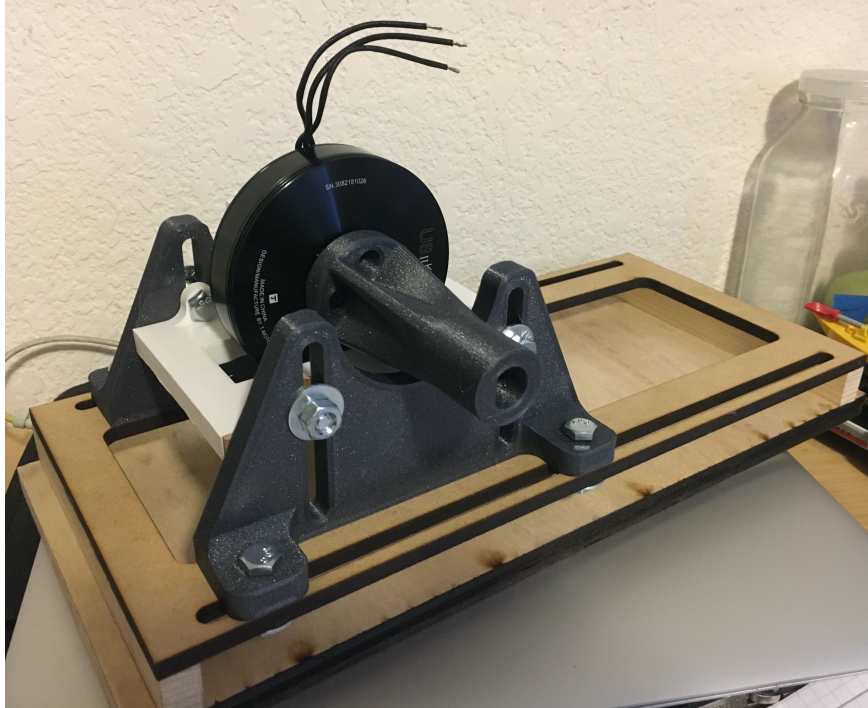
Figure 8.1. Motor test jig for dynamometer test.

Figure 8.2. Motor test jig setup with dynamometer.

One test was conducted for the T-motor U8II-KV85 motors. The torque-speed curve determined for the motor is shown below in Figure 8.3, and the tabulated data is shown in Table 8.1.

Table 8.1. Raw data taken from dynamometer test of T-motor U8II-KV150.

Torque [lbf•in]	Speed [RPM]	Voltage [V]	Current [A]	Input Power [W]	Efficiency %
0	0	23.1	0.0307	0.6	0
0.69	1842	23.06	0.661	14.35	104.5%
1.98	1769	22.97	1.931	44.17	93.6%
4.04	1688	22.84	3.853	87.90	91.5%
5.99	1613	22.71	5.65	128.2	88.9%
8.05	1535	22.58	7.55	170.2	85.7%
10.01	1416	22.47	9.16	205.2	81.5%
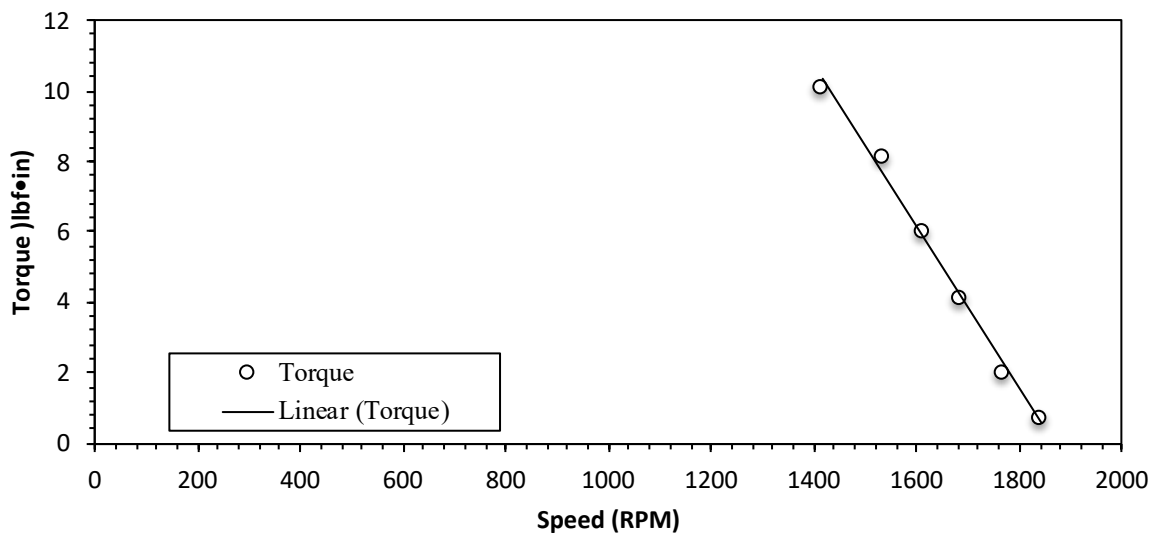
Figure 8.3. Torque-speed curve for T-motor U8II-KV85 motor.

From this test, it was discovered that the motors would stall out at around 10 lbf•in of torque, which did not meet the requirements for top speed as determined from propeller calculations. The 9-inch propeller requires 19.0 lbf•in of torque to reach top speed, and the 12-inch propeller requires 33.6 lbf•in to reach top speed. With a 2:1 gear reduction in the gearbox, the requirements come to be 9.5 lbf•in for the 9-inch propeller and 16.8 lbf•in for the 12-in propeller. While this motor could barely reach the requirements for the 9-inch propeller, fluctuations in water current would likely cause variations in torque that could raise above the stall for the motor.

Based on these results, we determined that the motors that we had were not adequate to power the propulsion system and new motors were purchased for testing. These motors were T-motor U8II-KV150, which would produce more torque at a lower speed. These motors were ordered and arrived just before the end of winter quarter; however, due to COVID-19, the EE power lab was shut down before the motors could be tested to determine their torque-speed curves. This is one of the first things that must be completed once the project picks up again next year.

8.1.2. Solar Panel Tests

For the competition, two JKM235P-60 solar modules that were provided to us by SMUD. Before using them, we wanted to test the panels against their provided specifications to see if they would perform as expected. To conduct this test, we received help from Professor Dale Dolan from the Cal Poly Electrical Engineering department. He provided the equipment necessary to test the panels and helped us run the tests and compile the results. Figure 8.4 shows the test setup for one of our tests.

Figure 8.4. Solar module testing setup.

To test the panels, we connected a solar measuring device provided by professor Dolan to the leads from one of the panels. The panel was oriented towards the sun using chairs that were in the courtyard where the tests were conducted. For each trial, the solar measuring device measured the power and current coming from the panel and sent the data to a computer. More details about the test procedure can be found in Appendix S.

In total, five tests were conducted on one of the solar panels. These tests covered various angles between the panel normal and the sun and different shading levels. More details about each test can be found in Table 8.2.

Table 8.2. Solar Panel Test Results.

Test no	Time	Temperature °C	Tilt Angle °	Solar Angle °	Shading -	Irradience W/m^2	Max power W	NOTES
1	10:35:20 AM	46.15	62.27	2.77	N	1024.6	222.37	Normal to sun
2	10:39:53 AM	#N/A	62.57	3.07	Y	1066.3	142.23	Normal to sun with 9 in^2 shading
3	10:46:43 AM	47.29	18.20	-41.30	N	910.0	189.32	flatter
4	10:50:09 AM	47.32	1.44	-58.06	N	705.8	147.01	flat on ground
5	10:59:25 AM	#N/A	1.44	-58.06	Y	702.4	154.69	flat on ground shaded

Two of the tests conducted, tests 2 and 5, tested different amounts of shading on the panels. Figure 8.5 and Figure 8.6 show the shading that was used in each test. In test 2, one full square cell was shaded, and in test 5 only a small portion of two cells were shaded.

The power-current plots from each of these tests can be found in Figure 8.7.

Figure 8.5. Shading ($\approx$9 in^2) used in test 2 (Panel normal to the sun).

Figure 8.6. Shading from test 5 (Panels flat on ground)

The results from these tests provided some very important insights into the design the mounting for each solar panel on the boat. While the solar module met specifications almost exactly in conditions without shading, the conditions with shading caused very catastrophic drop-offs in power. In test 2, the maximum power was cut by nearly a third from test 1, which was identical but without shading. This, we came to realize, was because of the way that the individual cells are connected in the panels. There are three sections of the panel, three parallel groups of cells that are individually wired in series. When a single cell is shaded, current cannot be passed through it without causing damage to the cell. Therefore, an electrical safety system is built into the panel to cut off any cell that is not in the sunlight. If one cell is blocked, then the entire third of the panel is cut off to prevent damage.

Test 5 included a much smaller amount of shading for comparison. While there was not nearly a one-third power loss as in test 2, there was still a noticeable drop in current and power past 17 V as seen in Figure 8.7(e). This drop was not nearly as harmful to the overall output, but it is still desired to be avoided.

Because of these results, it was clear that shading was an extremely important thing to avoid in our final design. Previously, there had been a small risk of the pilot shading the one of the panels as he/she sat in between them. This issue would be resolved by having the pilot ride prone during races that required solar power.
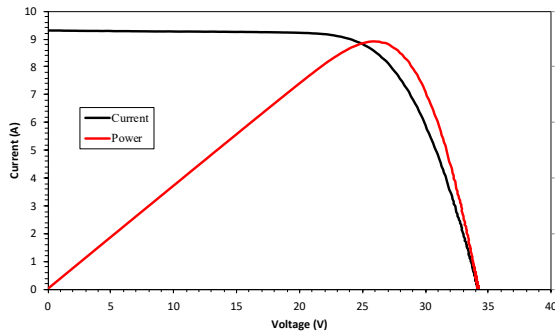
(a) Normal to Sun
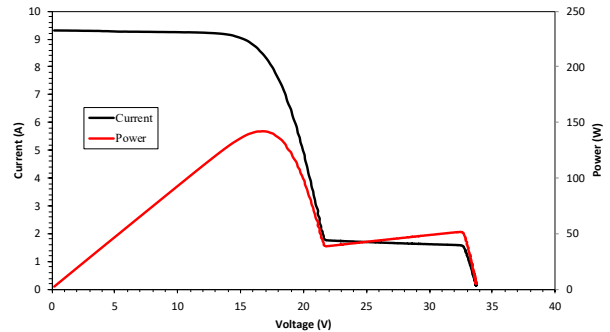
(b) Normal to sun with ≈9 in² shading (see Figure 8.5)
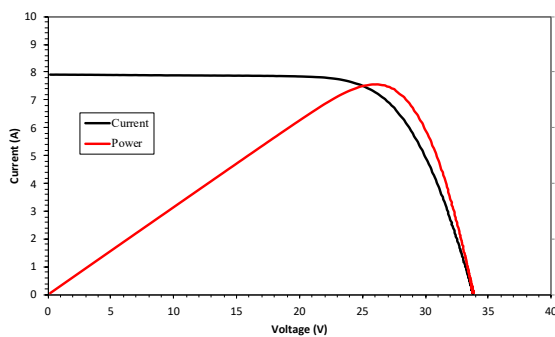
(c) ≈45° offset from Sun
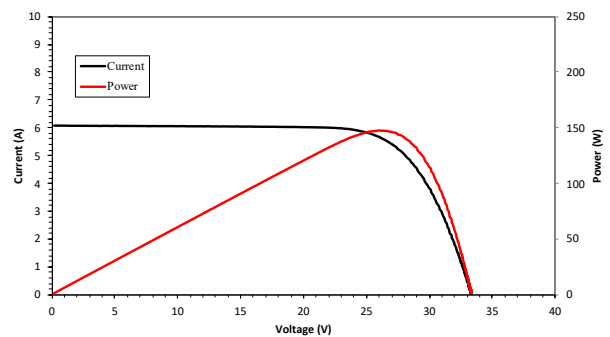
(d) Panel flat on ground
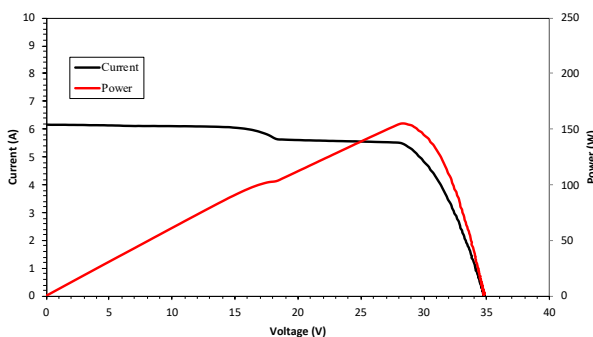
(e) Flat on ground with slight shading (see Figure 8.6)
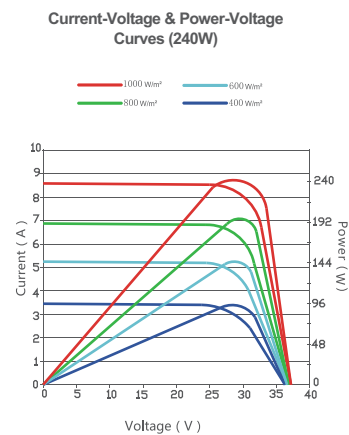
(f) Power-current curves from specifications sheet (see Appendix P)

Figure 8.7. Power-current plots for each of the 5 tests conducted on the JKM235P-60 Solar module.

The other factor changed between tests was the angle between the panel normal and the sun. Changing this angle changes the irradiance that is incident on the panel's surface, which drops off following a cosine function of the angle between the sun and the panel normal. Initially, we had planned on keeping the panels flat on the boat and not angling them towards the sun; however, from these tests we determined that that could cause us to lose up to 30% of our total power output. Therefore, we decided to change our design to include pivots for the panels to rotate around so they could be aimed directly at the sun.

Unfortunately, due to COVID-19 we were not able to finalize the design for the panel mounting. This task has been assigned to the team that will finish the project next year.

8.1.3. Battery Life Tests

To ensure that each battery will perform as desired, each one will be tested for lifetime at max power draw. This test will be conducted both with the propulsion system as a separate unit, and with the full boat. As a goal, the batteries should be able to last 25 minutes at max power draw, the amount of time for the endurance race.

Unfortunately, due to COVID-19 this test was not completed this year. It is planned to be completed when the boat and propulsion systems are finished in Fall or Winter quarter of next year.

8.1.4. Propeller Efficiency Tests

Each propeller was designed using software to determine the contours necessary for the most efficient propulsion at the given conditions of speed, torque, and power that the boat will experience. To verify these calculations, a test was originally planned to be conducted with a scale model of the propellers in a water channel at Cal Poly. Due to time constraints, this test was reduced to a simple flow visualization of the water moving around the propeller using dyes; however, since the test was unable to be completed this quarter anyway due to COVID-19, it is possible that the original full efficiency test may be able to be conducted before competition next year.

8.1.5. Additional component Tests

Other planned tests include testing wires for low resistance at the given electrical loads, measuring the weight of each propulsion system, and evaluating the efficiency of the gear train assembly. These tests are outlined more in Appendix S. Each of these tests is planned to be completed before next year's competition.

8.2. Full Boat Tests

8.2.1. Speed and Acceleration Tests

Once the boat and propulsion systems are completed, we plan to test the boat's capabilities on the water. Two of the crucial tests will be top speed and acceleration, which will directly affect how the boat performs in competition. Unfortunately, because of COVID-19, the boat will not be completed by spring and these tests will have to be postponed until the boat is finished sometime next year.

The speed test will determine the average speed of the boat for 100m (the length of the sprint race) and top speed. Measurements will be taken by a phone GPS application, with the phone located onboard the boat. The phone will be in a plastic bag/box to ensure that it does not get wet during the tests. Each speed test will be run three times to ensure that the results accurately depict the capabilities of the boat.

The acceleration test will determine how quickly the boat can get to top speed. For each test, the time it takes for the boat to go from 0mph to top speed will be measured. As a target, this time should be less than 10 seconds. Each test will be recorded using the same phone GPS application that will be used in the speed test. Additionally, each test will be run three times to ensure accuracy of results.

8.2.2. Turning Radius Tests

Three different tests were designed to determine the turning ratio from steering wheel to rudder, the turning ratio from the steering wheel to the turning radius of the boat in the water, and the required torque for maximum turning. These tests require the use of a protractor, rope, and a torque gauge. Unfortunately, these tests were not able to be performed due to the inability to finish building the boat due to limited access to machine shops and raw materials.

The first test to determine how much the propulsion units rotate from the steering wheel will need to be completed twice: once out of the water and once inside the water to ensure the results do not change with the interactions between the boat and water. First remove the steering wheel from the steering wheel column and mark a straight line radiating from the center of the column. For the propulsion units attach a protractor to the end of the mounting tubing with the center of rotation above the pin attaching the propulsion unit perpendicular to the mounting bar and mark a straight line on the propulsion unit that can rotate ±90°. Rotate the steering column in fixed intervals and record the angle change of the propulsion unit. There should be a linear relationship between the two angles, though the constant will change depending on which of the adjustment holes the steering cable is attached to on the propulsion unit.

The second test will be completed in the water and like the last test will have different results depending on which adjustment hole the steering cable is attached to. With the boat in the water, tie one side of a rope to the approximate center of the boat and have the other end extend to another individual standing in the water. Have the driver of the boat turn to different angles and lock the steering column in place. As the boat moves it will extend the distance between the driver and the stationary individual unit it reaches a constant length: The radius of curvature, ρ. This test may result in variation due to different speeds and the forces on the rudders varying non-linearly so a recommendation of testing at 25%, 50% and 100% throttle should be done for quality results.

The final test can be completed at the extreme of the second test with a torque bar attached to the steering column. Max rotation of the steering column should be applied at varying throttle with an expected max torque at max speed. This torque would be the maximum expected required torque to operate the boat. This also varies depending on which adjustment hole is used and can be adjusted for ease of use by the driver if needed.

9. Tasks Left for Next Year

Due to complications with COVID-19 pandemic, we were unable to finish manufacturing the full boat design this year, and the SMUD competition for 2020 was cancelled. This section contains all items that we had planned to do but were unable to complete this year as a reference for future teams that pick up this project for later competitions.

9.1. Motor Testing

Since our first motor test with T-motor U8II-KV85 motors did not produce the results that we had hoped for, a second test of a different type of motor, T-motor U8II-KV150, was originally scheduled for finals week of winter quarter. However, the test was unable to be completed, as the EE power lab where we had been conducting out tests was shut down that week in response to COVID-19. The test would have been conducted to determine the torque-speed curves of the new motors to determine the maximum torque before stall.

This test is currently planned to be conducted as soon as possible, which as of now appears to be the first week of fall quarter 2020, pandemic permitting. The data from this test will allow us to finalize the design of the propellers before we send for them to be manufactured, as it will allow us to design the propellers to operate with the same conditions for maximum efficiency as the motors.

See section 8.1.1 for more details on the motor tests.

9.2. Manufacture and Assemble Full Propulsion Systems

We will accomplish a variety of small tasks during summer quarter 2020 to bring the rotating parts of the assembly to a functional state by the start of fall. These tasks include drilling and tapping set-screw holes in the bevel gear, installing shafts into gears with set screws, and pressing the large bearing into the gearbox housing. If the gears mesh smoothly, we can accomplish a torque holding test with a torque wrench and combination wrench – holding the input still while torquing the output. This is a prerequisite to assembling the rest of the system around the gear box because disassembling after this stage would damage the rudder. With torque and gear mesh smoothness verified, the rudder, motor mount, and gearbox housing can all be bonded together in the carbon layup. After this stage of bonding, we will be able to perform a static thrust test in water under our maximum expected power output of 250W. Next, the team will duplicate the unit and await installation into the pontoons.

9.3. Assemble Full Boat

Once the pontoon sections are put together each one will need to be covered in fiberglass with an epoxy wet layup. They will then need to attach the bridge, the solar panels, and batteries along with all the electrical components required to operate the boat. Wires will be run to the motors along each pontoon. Prior to giving power to the motors the steering system should be installed and tested. Instructions for attaching the propulsion units and steering system are included in the User's Manual in Appendix T and should be followed to properly integrate system to the hull.

Once the propulsion units are attached and hooked up to the electrical system the entire boat should go through the full boat tests listed under the Testing Plan section.

9.4. Test Boat Performance

Most of the tests that were planned to be performed this quarter were unable to be completed due to COVID-19 and will be pushed back to Fall 2020. Descriptions of each test can be found in Section 8 of this report, and detailed test procedures can be found in Appendix S. The only test fully completed was the solar panel test; each other test listed must be finished before competition next year.

10. Project Management

The project was managed using a Gantt Chart, featured in Appendix F. The team had weekly status reports with their advisor, Dr. Brian Self, to ensure they stayed on schedule.

10.1. Design Process

The design process started with background research on existing designs and solutions to perceived challenges related to solar powered boats. Defining the customer as a combination of the pilot, Hull Team, and the competition rules and regulations, we attempted to understand their wants and needs. We began the design with conceptual ideation and developed and discussed those ideas throughout the ideation phase. After building conceptual models, we tested the models. After testing we moved forward with the most promising ideas and built a functional concept prototype. The prototype was benchmarked against the design specifications and was improved accordingly. The Preliminary Design Review was completed and reviewed by our peers and advisor to check our progress and make sure we were heading in the right direction. The Critical Design Review was used to present our final design and seek advice from faculty and peers before starting the manufacturing of a verification prototype. We used the verification prototype as a fully functional model to prove out manufacturing techniques and gather preliminary test data before completing the final design.

10.2. Special Techniques

According to the Solar Panel specifications found in the Competition Packet, the solar panels are more efficient at lower temperatures [18]. If we were to cool the panels to zero degrees Celsius, the panels would produce 256W compared to 230W at room temperature, good for an eleven percent power increase. A potential method being discussed uses dry ice to cool the panels. This method will be tested on our prototype. More details are specified in section 2.3.

To design our propellers, we used the open source MATLAB software OpenProp developed by MIT to optimize propeller geometry for our specific design conditions to achieve a maximum possible efficiency. We plan to 3D print the propellers.

10.3. Timeline and Key Activities

Table 10.1 contains all of the critical deliverables and their due dates, both for our senior project class and the competition. SP signifies a senior project deliverable and CSR signifies a deliverable for the Solar Regatta competition.

Table 10.1 Key Deliverables.

Deliverable	Date Due	Category
Scope of Work	10/19/19	SP
CSR Application Form + Equipment Waiver	10/31/19	CSR
Preliminary Design Review (PDR)	11/12/19	SP
Interim Design Review	1/16/20	SP
SMUD CSR Orientation in Sacramento	1/17/20	CSR
Critical Design Review (CDR)	2/4/20	SP
Video of Progress Check	2/14/20	CSR
Manufacturing and Test Review	3/12/20	SP
SMUD Liability Waiver & Media Release	3/13/20	CSR
Proof of Boating Safety Attendance	3/13/20	CSR
Competition Day*	5/2/20	CSR
Final Design Review	5/26/20	SP
Senior Project Expo*	5/29/20	SP

*These events were cancelled due to COVID-19.

10.4. Future Application

The design and manufacturing processes developed this year will be used by the 2021 Cal Poly Solar Regatta team. The prototype unit will be used for testing and optimization before completing two final units to be used in competition next year. This design could also be modified for personal use for boats with low speed requirements such as fishing trawlers and water taxis.

11. Conclusion

Competing against experienced collegiate teams in such a unique event presented both the propulsion and hull teams with unique opportunities and challenges. By following a process designed to account for factors that make or break any project, the team represented Cal Poly in the development of an ultra-efficient electric watercraft. While the team was eager to demonstrate the unique experiences and skills a polytechnic university fosters, they were also excited to create novel solutions to challenges surrounding efficiency that will push other competitors to innovate in the future. Due to COVID-19 the competition was cancelled and our manufacturing was halted. While we were disappointed we couldn't fully assemble and compete with our designs this year, we are excited to support next year's team as they take Cal Poly to its first Solar Regatta in 2021!
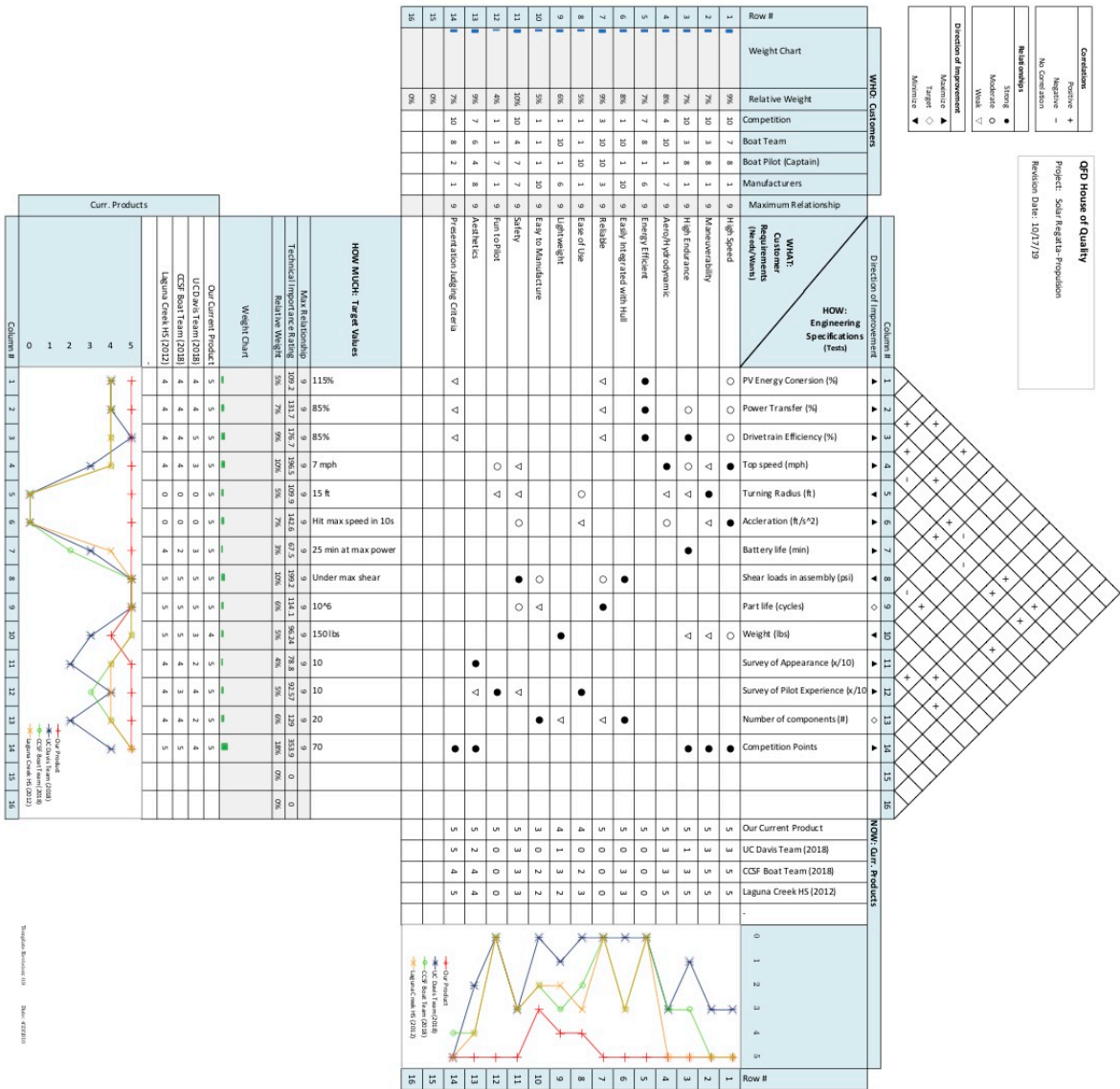
12. References

1) Nurachman, Dendi. "Propulsion System Analysis For Solar-Powered Electric Water Recreational." *3rd International Tropical Renewable Energy Conference "Sustainable Development of Tropical Renewable Energy" (i-TREC 2018)*, EDP Sciences, 26 Nov. 2018, https://www.e3s-conferences.org/articles/e3sconf/abs/2018/42/e3sconf_i-trec2018_04010/e3sconf_i-trec2018_04010.html.

2) C. S. Postiglione, D. A. F. Collier, B. S. Dupczak, M. L. Heldwein and A. J. Perin, "Propulsion system for an all-electric passenger boat employing permanent magnet synchronous motors and modern power electronics," *2012 Electrical Systems for Aircraft, Railway and Ship Propulsion*, Bologna, 2012, pp. 1-6.

3) W. Sung, J. Shin and Y. Jeong, "Energy-Efficient and Robust Control for High-Performance Induction Motor Drive With an Application in Electric Vehicles," in *IEEE Transactions on Vehicular Technology*, vol. 61, no. 8, pp. 3394-3405, Oct. 2012.

4) "Recent Design Optimization Methods for Energy- Efficient Electric Motors and Derived Requirements for a New Improved Method—Part 2." *MDPI Proceedings*, 14 Feb. 2018, pp. 1–5.

5) Tiwari, et al. "Enhancing the Performance of Solar PV Water Pumping System by Water Cooling over and below the PV Array." *Journal of Solar Energy Engineering*, 22 October 2019, https://asmedigitalcollection.asme.org/solarenergyengineering/article/doi/10.1115/1.4044978/1031132/Enhancing-the-performance-of-solar-PV-water.

6) Ozden, M Cansin, and Ersin Demir. *The Successful Design and Construction of Solar/Electric Boats Nusrat and Muavenet: An Overview*. Istanbul Technical University, 2009, *The Successful Design and Construction of Solar/Electric Boats Nusrat and Muavenet: An Overview*.

7) Mueller, Keith J. "SMUD Solar Regatta 2018 - CCSF Engineering Club." *CCSF Engineering Club*, CCSF Engineering Club, 14 Aug. 2018, sites.google.com/a/mail.ccsf.edu/ccsf-engineering-club/spring-2018/smud-solar-regatta-2018.

8) Mills, Allison. "Shining More Light on Solar Panels." *Michigan Tech News*, Michigan Technological University, 17 July 2019, www.mtu.edu/news/stories/2015/october/shining-more-light-solar-panels.html.

9) Boericke, H. *Hydrofoil*. US2906229A. United States Patent and Trademark Office, 29 September 1959.

10) 晟 黄. Traffic ship using wind energy and solar energy as main power source. CN101337579A. Chinese Patent and Trademark Office, 7 January 2009.

11) Osborne, E. *Electric Boat Motor*. US4610632A. United States Patent and Trademark Office, 9 September 1986.

12) Thorsen, P. *Boat Hull*. US3216389A. United States Patent and Trademark Office, 11 September 1965.

13) Gornstein, R. and Rust, R. *Hydrofoil Propulsion System*. US4962718A. United States Patent and Trademark Office, 16 October 1990.

14) Harris, John. "How To Win a Solar Boat Regatta." *Chesapeake Light Craft's Solar Powered Electric Boat Kit*, Oct. 2012, www.clcboats.com/life-of-boats-blog/high-school-wins-solar-regatta.html.

15) Dickson, Bonnie. "UC Davis Solar Boat Team Places Second in 2018 Solar Regatta." *College of Engineering UC Davis*, UC Davis, 7 June 2018, engineering.ucdavis.edu/blog/uc-davis-solar-boat-team-places-second-in-2018-solar-regatta/.

16) Niclas. "Standard Test Conditions (STC): Definition and Problems - Sinovoltaics - Your Solar Supply Network." *Sinovoltaics*, Sinovoltaics, 4 Nov. 2011, sinovoltaics.com/learning-center/quality/standard-test-conditions-stc-definition-and-problems/.

17) Tsigonis, Abraham. "Hydrofoils and How They Work." *Physicsofhydrofoils*, University of Alaska Fairbanks, 25 Nov. 2002, ffden-2.phys.uaf.edu/211_fall2002.web.dir/Abraham_Tsigonis/page2.htm.

18) Kamins, R. "SMUD 2020 SolarRegattaPacket." Sacramento Municipal Utility District, 9 Sept. 2019, https://www.smud.org/-/media/Documents/In-Our-Community/Solar-Regatta-Packet.ashx?la=en&hash=2D30108D15CC9467128C958F05DE7302C9ABD173

19) "Solar Power Hits the Boating World." *Blue Sky Solar & Roofing*, Blue Sky Solar & Roofing, 7 June 2019, blueskysolarandroofing.com/2019/06/07/solar-power-hits-the-boating-world/.

20) Jones, Alan. "The Truth About Props." *Boating World*, 1 Feb. 2014, www.boatingworld.com/engines/the-truth-about-props/.

21) Carlton, J. S. *Marine Propellers and Propulsion*. Elsevier Butterworth-Heinemann, 2007.

22) Techet, A H. "Marine Propellers." Hydrodynamics for Ocean Engineers. web.mit.edu/13.012/www/handouts/propellers_reading.pdf.

23) Söderberg, Johan. "Propeller Design Charts in Bp-Delta Notation." *Propeller Design Charts in Bp-Delta Notation*, 21 Feb. 2008, hem.bredband.net/lagaren/props.htm.

24) Dekanlik. "Part 6: Cavitation." Ship Hydrodynamics Lecture Notes. 2 Jan. 2020, ninova.itu.edu.tr/en/courses/faculty-of-naval-architecture-and-ocean-engineering/3160/gem-341e/ekkaynaklar?g438082.

25) Brennen, Christopher E. "Cavitation Parameters." *Index - An Internet Book on Fluid Dynamics*, Caltech, 6 Oct. 2006, brennen.caltech.edu/fluidbook/.

26) Bernitsas, M M. *KT, KQ, and Efficiency Curves for the Wangeningen B-Series Propellers*. University of Michigan, 1981, *Deep Blue*, deepblue.lib.umich.edu/handle/2027.42/3557.

27) Epps, Brandon. "OpenProp." *Http://Engineering.dartmouth.edu/Openprop/*, 3.3.4, Dartmouth College, Dec. 2013, engineering.dartmouth.edu/openprop/.

28) Mosaad, M A, and W Yehia. *INT-NAM 2011*. 1st International Symposium on Naval Architecture and Maritime, 2011, *INT-NAM 2011*, www.int-nam.yildiz.edu.tr/2011/cd/12_shippropulsion.pdf.

29) Carmichael, Ralph L.: *Algorithm for Calculating Coordinates of Cambered Naca Airfoils At Specified Chord Locations.* AIAA Paper 2001-5235, November 2001.

Appendix A. Quality Function Deployment House of Quality

QFD House of Quality
Project: Solar Regatta–Propulsion
Revision Date: 10/17/19

Correlations
Positive +
Negative –
No Correlation

Relationships
Strong ●
Moderate ○
Weak ◁

Direction of Improvement
Maximize ▲
Target ◇
Minimize ▼

WHO: Customers — Competition, Boat Team, Boat Pilot (Captain), Manufacturers, Maximum Relationship

WHAT: Customer Requirements (Needs/Wants): High Speed, Maneuverability, High Endurance, Aero/hydrodynamic, Energy Efficient, Easily integrated with Hull, Reliable, Ease of Use, Lightweight, Safety, Fun to Pilot, Aesthetics, Presentation Judging Criteria

HOW: Engineering Specifications (Tests)

Col #	Engineering Specification	HOW MUCH: Target Values	Relative Weight
1	PV Energy Conversion (%)	115%	5%
2	Power Transfer (%)	85%	7%
3	Drivetrain Efficiency (%)	85%	9%
4	Top speed (mph)	7 mph	10%
5	Turning Radius (ft)	15 ft	5%
6	Acceleration (ft/s^2)	Hit max speed in 10s	7%
7	Battery life (min)	25 min at max power	3%
8	Shear loads in assembly (psi)	Under max shear	10%
9	Part life (cycles)	10^6	6%
10	Weight (lbs)	150 lbs	5%
11	Survey of Appearance (x/10)	10	4%
12	Survey of Pilot Experience (x/10)	10	5%
13	Number of components (#)	20	6%
14	Competition Points	70	18%

NOW: Curr. Products — Our Current Product, UC Davis Team (2018), CCSF Boat Team (2018), Laguna Creek HS (2012)

Curr. Products legend: Our Product, UC Davis Team (2018), CCSF Boat Team (2018), Laguna Creek HS (2012)

Appendix B. Competitors From Previous Years

https://sites.google.com/a/mail.ccsf.edu/ccsf-engineering-club/spring-2017/smud-solar-regatta-2017

Figure B.1. City College of San Francisco's 2017 Design.

https://sites.google.com/a/mail.ccsf.edu/ccsf-engineering-club/spring-2018/smud-solar-regatta-2018

Figure B.2. City College of San Francisco's winning 2018 design.

Figure B.3. UC Davis' second place design from 2018 with solar panels removed.

Figure B.4. Laguna Creek High School's winning design in 2012.

Appendix C. Race Data From 2018 SMUD Solar Regatta

Summary

Team #	Team Name	Slalom		Sprint		Endurance		Overall Score (x/54)	Rank	Point Total
1	Delta	1:57	2	0:40	4	14	5	43	4	10
2	Santa Clara	2:57	8	1:19	14	11.5	7	25	8	0
3	Chico	2:26	6	0:45	6	12.25	6	36	6	0
4	Sonoma	3:54	11	0:57	8	8.5	11	24	9	0
5	SF	2:14	5	0:29	1	14.25	4	44	3	15
6	ARC	DNF	18	2:45	16	4	16	4	16	0
7	Ohlone	DNF	18	DNF	18	DNF	18	0	18	0
8	Butte	9:15	15	1:04	10	11.25	9	20	13	0
9	Skyline	2:50	7	1:10	12	11.5	7	28	7	0
10	Contra Costa	4:23	12	1:32	15	4.75	14	13	14	0
11	Humboldt	4:56	13	0:54	7	7.5	12	22	12	0
12	Bakersfield	3:12	9	0:58	9	7.5	12	24	9	0
13	CRC	1:55	1	0:30	2	18	1	50	1	40
14	Davis	DNF	18	DNF	18	4.25	15	3	17	0
15	Chabot	8:40	14	1:15	13	0.5	17	10	15	0
16	Maritime	3:28	10	1:08	11	9.75	10	23	11	0
17	Sequoias	2:11	4	0:43	5	15.75	3	42	5	5
18	HS	2:05	3	0:36	3	18	1	47	2	25

Highlighted Team: # Name — 13 CRC

SLALOM: Approximately 150 yards in each direction, 5 buoys; hitting or missing a buoy is a 20 second penalty

SPRINT: Length is between 70 to 100 yards depending on vegitation at time of competition

ENDURANCE: 1 point per lap to nearest quarter lap, 1/2 lap penalty for hitting/missing buoy

Scoring	
Each race:	Points
1st	15
2nd	10
3rd	5

SMUD 2019 Race Times

Race	Start Time	Slalom Team #	Team Name	Time	Sprint A Team #	Team Name	Time	Sprint B Team #	Team Name	Time	Endurance Race	Start Time	Team #	Team Name	Score
1	10:00	8	Butte	9:15	2	Santa Clara	1:47	12	Bakersfield	1:06	1	10:00	15	Chabot	0.5
2	10:15	17	Sequoias	2:11	18	HS	0:42	5	SF	0:32			1	Delta	14
3	10:30	4	Sonoma	3:54	7	Ohlone	DNF	8	Butte	2:23	2	10:30	10	Contra Costa	4.75
4	10:45	14	Davis	DNF	3	Chico	0:45	17	Sequoias	0:43			13	CRC	18
5	11:00	6	ARC	DNF	9	Skyline	2:52	4	Sonoma	1:41	3	11:00	2	Santa Clara	11.5
6	11:15	11	Humboldt	4:56	16	Maritime	1:08	14	Davis	DNF			18	HS	18
7	11:30	15	Chabot	8:40	12	Bakersfield	0:58	6	ARC	DNF	4	11:30	7	Ohlone	DNF
8	11:45	1	Delta	1:57	5	SF	0:29	11	Humboldt	0:54			3	Chico	12.25
Lunch Break															
9	1:00	10	Contra Costa	4:23	8	Butte	1:04	15	Chabot	1:15	5	1:00	9	Skyline	11.5
10	1:15	13	CRC	1:55	17	Sequoias	0:45	1	Delta	0:40			16	Maritime	9.75
11	1:30	2	Santa Clara	2:57	4	Sonoma	0:57	10	Contra Costa	1:33	6	1:30	12	Bakersfield	7.5
12	1:45	18	HS	2:05	15	Chabot	1:20	13	CRC	0:37			5	SF	14.25
13	2:00	7	Ohlone	DNF	6	ARC	2:45	2	Santa Clara	1:19	7	2:00	8	Butte	11.25
14	2:15	3	Chico	2:26	11	Humboldt	0:57	18	HS	0:36			17	Sequoias	15.75
15	2:30	9	Skyline	2:50	15	Chabot	DNF	7	Ohlone	DNF	8	2:30	4	Sonoma	8.5
16	2:45	16	Maritime	3:28	1	Delta	0:43	3	Chico	0:57			14	Davis	4.25
17	3:00	12	Bakersfield	3:12	10	Contra Costa	1:32	9	Skyline	1:10	9	3:00	6	ARC	4
18	3:15	5	SF	2:14	13	CRC	0:30	16	Maritime	1:12			11	Humboldt	7.5

Appendix D. Brainwriting and Brainstorming

Table D.1. List of 43 ideas generated in brainstorming process for different methods of attaching components to the hull.

Zip ties	Static attraction	Tin foil
Nuts and bolts	Super glue	Folded over metal plating
Welding	Woven in	Built in
Duct tape	Rivets	Plastic wrap
rope	Staples	Shrink wrap
Velcro	Brazed	Expanding foam
Single cast part	Rubber bands	Tacky tape
Nails	Mount included in hull mold	Wires
Clips	Epoxy	C-clamps
Hot Glue	Friction and Gravity	Framing/Caging
Screws	Press fit	Hose clamps
Magnets	Zippers	Pressure vessel
Clamps	Gum	Clam goo
Tiedowns	Melted together	Crushing gaskets
Human strength		

Table D.2. Concepts for steering generated from using the SCAMPER method.

	Rudder	Differential Thrust	Thrust Vector
Substitute:	Material - Rubber	Type of propulsion - prop, screw, waterjet	Material of vector boundary
Combine:	With Motor	Boat Hull	With rudder / Prop guard
Adapt:	Extra Propulsion - Flap/Rip stick	Regenerative braking	Differential thrust with thrust vector
Modify:	Air rudder, Differential Drag	More than two propulsion systems, thrust array	Variable pitch
Put to other use:	Alternate Paddle	Rotate down to produce lift	Braking changes direction of flow
Eliminate:	Use hands	Controlled, Purely mechanical	Controlled purely mechanically
Reverse:	Put on front of boat	Each propulsion system can rotate 360 degrees	Location - front, back, or center

Figure D.1. Brainwriting page 1, focusing on the use of mirrors to increase efficiency.

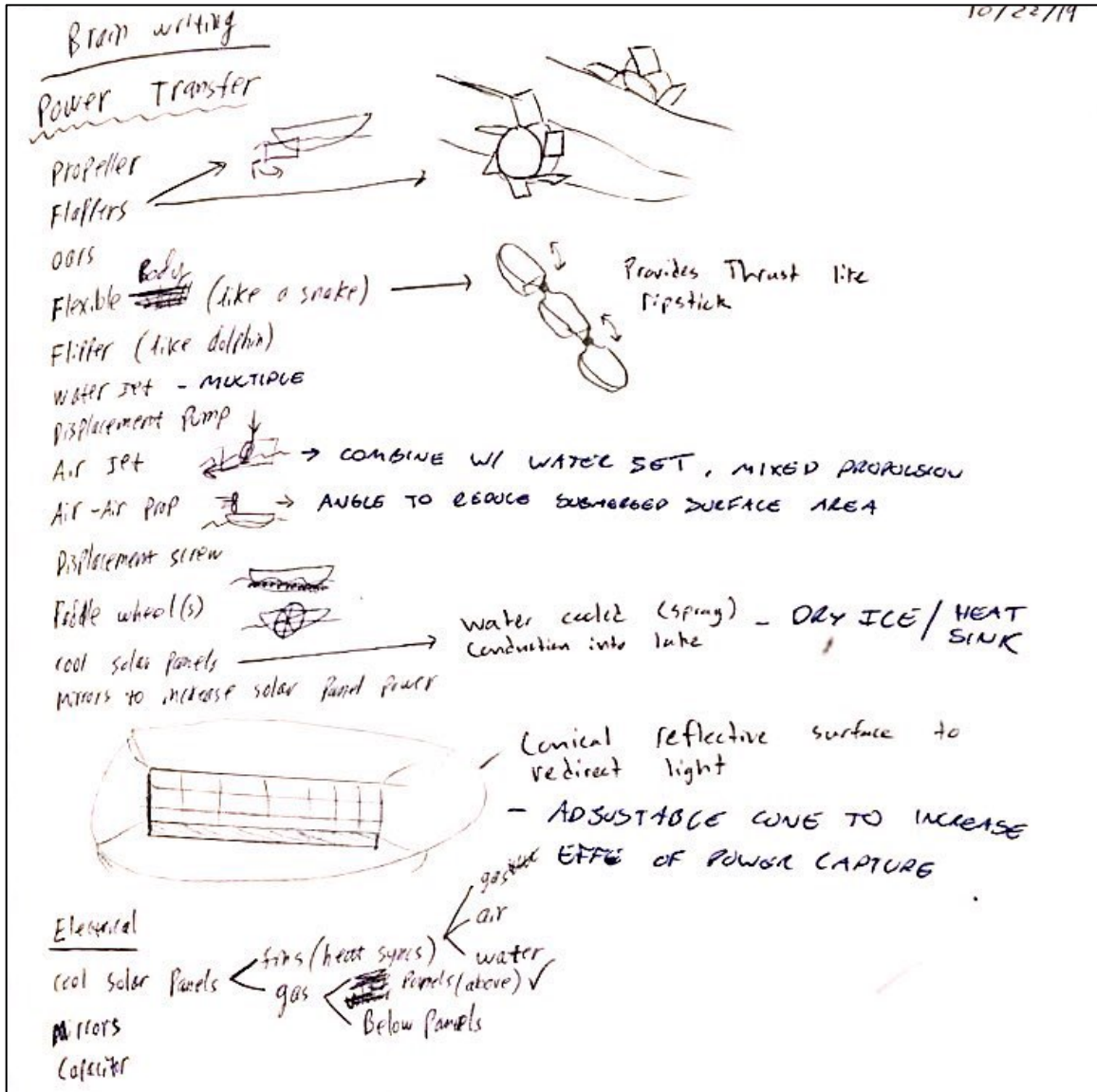*Figure D.2. Brainwriting page 2 focusing on power transfer.*

Figure D.3 Brainwriting page 3 focusing on the power transfer between the solar cells and water.

BRAIN WRITING

POWER TRANSFER

POWER COLLECTION

/ Aim at ideal sunlight positi~
/ use mirrors for extra light

- HANG PANELS ON SIDE OF BOAT FOR EASY ROTATION ALONG THE LONGITUDINAL AXIS.
- BRING A TANK FOR SCUBA DIVING THAT HOLDS ENOUGH PRESSURE TO KEEP PANELS UNDER 0°C FOR SPRINT & SLOLAM.
- USE A BOOST CONVERTER FOR HIGH VOLTAGE TRANSFER, STEP DOWN TO DESIRED VOLTAGE RIGHT BEFORE MOTOR.
- PLACE PANELS CLOSE TO MOTOR FOR SHORTER WIRES.

HEAT MNG.

- COOL MOTOR WITH LAKE WATER (WATER JACKET AROUND MOTOR)
- DONT COOL MOTOR IF NOT NECESSARY.
- use dry ice or compressed air to cool panels/motor ⟶ Conduction thro~ Boat

E → M

- RUN MOTORS BELOW 850 OF MAX THROST / POWER DESIGN PROP AROUND THAT RPM. (ALMOST 2x η/w of THRUST)
- use thick wires to reduce resistance
- use step up/step down transformers ⟶ nice!
- Run motors in pulses - PWM

M → thrust

- use fairing to direct thrust
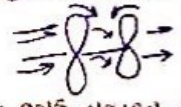
Figure D.4 Brainwriting page 4 focusing on power transfer and heat management.

10/22 BRAIN WRITING   POWER TRANSFER: 19

E → M
REDUCE WIRE USAGE
TO DECREASE LOSSES

M → T
TWIN WATER SET

M → T
COUNTER ROTATING PROPS

· ONE HOLLOW SHAFT THAT
A SMALLER SOLID SHAFT PASSES
THROUGH, COUNTER ROTATE.

ARRAY OF PROPS

M → T
PROP IN BACK, GUIDED WATER
W/ HULL TO USE DRAG
AS BENEFIT / REDUCE
EFFECTS
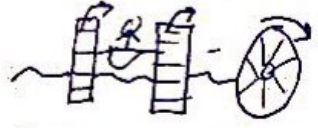
FRONT

USE THRUST TO MAKE A HYDROFOIL
LIFT OFF AT LOW SPEEDS / LOW POWER.
        CAPACITORS?

REDUCING + EXPANDING
ORIFIS TO CREATE HIGHER
VELOCITY JETS W/ PUMP

WATER WHEEL / NO HULL

· ELECTRONIC /RC CONTROL OF BOAT
TO REMOVE WEIGHT OF CONTROLS, REMOVES
VISIBILITY REQUIREMENT FOR PILOT.

Figure D.5 Brainwriting page 5 focusing on power transfer.

Appendix E. Pugh and Morphological Decision Matrices

Steering Pugh Matrix

Ideas / Needs	Integrated Thrust & Rudder	Differential Thrust	Separate Rudder	Dual Rudders
Maneuverability	S	+	S	+
Aero/Hydrodynamic	S	+	S	−
Energy Efficient	S	−	S	−
Easily Integrated with Hull	S	−	S	S
High Speed	S	+	S	−
	0	+1	0	-2

Figure E.1 Steering Pugh Matrix.

Pugh Matrix (Integration to Hull)

	Out Boarding	In (Two) Pontoons	Dual Pipe Attached	On Boarding	Strapped Down
Reliable	S	+	S	S	−
Ease of Use/Main	S	−	S	−	+
Efficient	S	+	+	S	−
Incorporation Difficulty	S	−	S	−	+
Maintence Constraints	S	S	S	−	+
Aesthetics	S	+	S	+	−
Aero/Hydro Dynamic	S	+	−	+	−
	0	+2	0	-1	-1

Figure E.2 Integration with hull Pugh Matrix.

PUGH MATRIX
FORCE TRANSFER METHOD

	WATER-JET	DUAL MOTOR	DUALSCREW	PADDLES	GEARED Pris
ALLOWANCE FOR CUSTOM DESIGN	S	S	+	S	S
EASE OF MANUFACTURE	S	+	−	−	S
FIT INTO BOTH PONTOON & MONOHULL?	S	S	−	S	S
LOW DRAG OF SUBMERSED COMPONENTS	S	−	−	−	+
POWER USE EFFICIENCY	S	+	S	−	S
	0	+1	-2	-3	+1

Figure E.3 Mechanical power transfer Pugh Matrix.

Power Transfer: Electrical

Concept / Criteria	Gas Cooled	mirrors	Capacitor	Heat sync
High speed	S	+	+	S
AERO/ Hydrodynamic	S	−	+	−
Energy Efficient	S	+	+	+
Lightweight	S	S	+	+
Easily Integrated	S	S	S	S
	0	+1	+4	+1

Figure E.4. Electrical power transfer Pugh Matrix.

Figure E.5. Morphological Matrix of ideas discussed in Pugh Matrices.*

*Capacitors were eliminated after checking with SMUD organizers, who informed us that they would be allowed.

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Appendix F. Gantt Chart
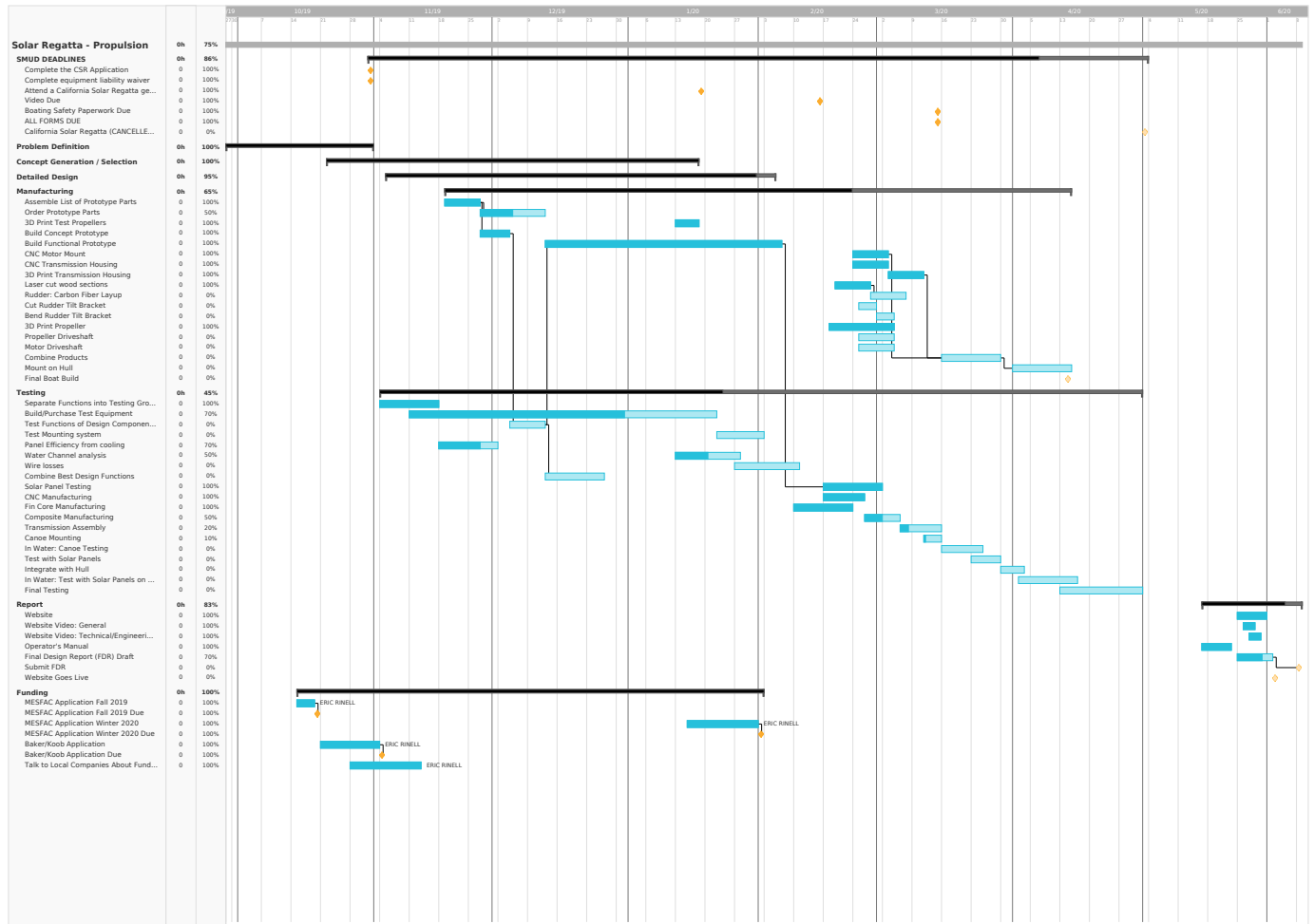
Appendix G. Design Hazard Checklist

DESIGN HAZARD CHECKLIST

Team: **Solar Regatta Propulsion**   Advisor: Self   Date: 11/7/19

Y   N

☒ ☐   1. Will the system include hazardous revolving, running, rolling, or mixing actions?

☒ ☐   2. Will the system include hazardous reciprocating, shearing, punching, pressing, squeezing, drawing, or cutting actions?

☐ ☒   3. Will any part of the design undergo high accelerations/decelerations?

☒ ☐   4. Will the system have any large (>5 kg) moving masses or large (>250 N) forces?

☒ ☐   5. Could the system produce a projectile?

☐ ☒   6. Could the system fall (due to gravity), creating injury?

☐ ☒   7. Will a user be exposed to overhanging weights as part of the design?

☐ ☒   8. Will the system have any burrs, sharp edges, shear points, or pinch points?

☐ ☒   9. Will any part of the electrical systems not be grounded?

☐ ☒   10. Will there be any large batteries (over 30 V)?

☒ ☐   11. Will there be any exposed electrical connections in the system (over 40 V)?

☐ ☒   12. Will there be any stored energy in the system such as flywheels, hanging weights or pressurized fluids/gases?

☐ ☒   13. Will there be any explosive or flammable liquids, gases, or small particle fuel as part of the system?

☐ ☒   14. Will the user be required to exert any abnormal effort or experience any abnormal physical posture during the use of the design?

☐ ☒   15. Will there be any materials known to be hazardous to humans involved in either the design or its manufacturing?

☐ ☒   16. Could the system generate high levels (>90 dBA) of noise?

☐ ☒   17. Will the device/system be exposed to extreme environmental conditions such as fog, humidity, or cold/high temperatures, during normal use?

☐ ☒   18. Is it possible for the system to be used in an unsafe manner?

☒ ☐   19. For powered systems, is there an emergency stop button?

☒ ☐   20. Will there be any other potential hazards not listed above? If yes, please explain on reverse.

For any "Y" responses, add (1) a complete description, (2) a list of corrective actions to be taken, and (3) date to be completed on the reverse side.

Description of Hazard	Planned Corrective Action	Planned Date	Actual Date
Rotating blades have sharp edges, could cut someone while spinning	Tips of props will be painted yellow and will have guards placed around them when boat is not in the water.	4/15/20	N/A*
Long rotating parts throughout the boat system.	All drivetrain components will be covered and not able to be accessed unless not in use.	4/15/20	N/A*
Rudder could have pinch points when turned to an extreme in either direction	Stops will be installed to prevent rudder from reaching the required amount of motion to cause the pinch point.	4/15/20	N/A*
Large kinetic energy of boat could cause damage if crashed	The boat will be painted in a way to be very visible, along with safety flags on board during usage.	4/15/20	N/A*
Rotating pieces could potentially detach during operation, create projectile	All people conducting tests will use proper PPE. Additional housings will be used to create redundancies in projectile prevention.	4/15/20	All times
Solar cells used in series have a total voltage of up to 40V- shock hazard with water	Proper wires and insulation will be used to reduce the amount of potential exposure. Potentially live wires will be denoted with red warning signs.	4/15/20	N/A*
Boat's steering or motors get stuck and are unable to be controlled with onboard controller	The kill switch will be easily accessed while boat is in usage; a paddle will be on board in case of emergency.	4/15/20	N/A*
Drowning possibility	All boat operators will have life vests, and everyone in the water will have completed through a boat safety course to be a licensed driver.	2/7/20	N/A*
Travel Safety	Only licensed drivers will operate vehicles.	All times	N/A*
Tools could break during manufacturing processes or when components are being assembled	Proper PPE will be used when working on or operating any piece of equipment related to this project.	All times	All times
The boat will be operated in water with low visibility to submerged moving parts	The motor and drive will be able to rotate 90-degees out of the water for inspection if necessary.	4/15/20	N/A*
*could not be completed due to Covid-19			

11/30/19   Prop Calcs   48

Estimated   Design   Condition: $P_D = 400\,W = 0.536\,hp$

$V_a = 6.3\,mph = 9.2\,ft/s = 5.47\,knots$

$n = 500\,rpm$

From this: $B_p = 5.22$ (conventional)

⭐Smaller values of A_E/A_0 are more efficient — The tradeoff is thrust

Chosen: $A_E/A_0 = 0.3$ — not as much thrust critical as efficiency critical

From charts: $(B_p - \delta)$

$\delta = 100$

$\boxed{\eta_{max} = 77\%}$

$J = 1.013$

$D_{opt} = 1.095\,ft$

$P/D = 1.25$

From prop characteristic chart:

$k_T = 0.15$ $k_Q = 0.033$

$F_T = k_T \rho n^2 D^4 = 29.0\,lbf$ ⟶ Not quite enough to get to 63 Mph

↳Actual speed: 6 mph

$Q = k_Q \rho n^2 D^5 = 7.055\,lbf \cdot ft$ Iterate

Split half power: $P_D = 200\,W = 0.268\,hp$ $A_E/A_0 = 0.3$

$B_p = 3.64$ ⟵ { $V_a = 6.3\,mph = 9.24\,ft/s = 5.47\,knots$

$n = 500\,rpm$

From $B_p - \delta$:

$\delta = 84$ ⟶ $J = 1.266$ $P/D = 1.45$

$\boxed{\eta_{max} = 79.3\%}$ ↳ $D_{opt} = 0.919\,ft$

From prop characteristic:

⭐ $k_T = 0.14$ $k_Q = 0.035$

$F_T = 13.75\,lbf$ ⟶ $V_{actual} = 5.8\,mph$

$Q = 3.041\,lbf \cdot ft$ ↳ Iterate

Appendix I. Design Verification Plan (DVP)

Table I.1. Design Verification Plan and Report as of 2/3/20.

Senior Project DVP&R											
Date: 6/02/2020	Team: Without a Paddle		Sponsor: Sacramento Municipal Utility District		Description of System: Propulsion system for Solar-Powered Boat					DVP&R Engineer: Niko Banks, Nathan Carlson, Eric Rinell, Alex Larson		
TEST PLAN									TEST REPORT			
Item No	Specification #	Test Description	Acceptance Criteria	Test Responsibility	Test Stage	SAMPLES		TIMING		TEST RESULTS			NOTES
						Quantity	Type	Start date	Finish date	Test Result	Quantity Pass	Quantity Fail	
1	1	Top speed test	Vmax ≥ 7 mph	Alex	FP	1	Sys	4/6/20	N/A	-	-	-	
2	2	Acceleration test	0 to max in ≤ 10s	Niko	FP	1	Sys	4/6/20	N/A	-	-	-	
3	3	Steering mechanism test	Turn Radius ≤ 15ft	Alex	FP	1	Sys	4/6/20	N/A	-	-	-	
4	N/A	Water channel prop flow visualization	N/A	Nathan	FP	6	C	5/19/20	N/A	-	-	-	
5	4,5	Battery life and power	25 min, 175 W•hr	Eric	FP	2	C	3/12/20	N/A	-	-	-	
6	6	PV panel energy conversion	95%	Niko	FP	10	C	2/25/20	2/25/20				Solar Angle more critical than anticipated
7	7	Electrical power transfer (Wires)	η ≥ 95%	Alex	FP	2	Sub	3/12/20	N/A	-	-	-	
8	8	Electrical power transfer (Motors)	η ≥ 80%	Niko	FP	4	C	3/4/20	3/4/20	FAIL	0	1	Motor does not reach adequate torque
9	9	Shaft and geartrain efficiency	η ≥ 95%	Eric	FP	1	Sub	3/12/20	N/A	-	-	-	
10	10	Weight of full propulsion assembly	≤ 30 lbs	Nathan	FP	1	Sys	4/6/20	N/A	-	-	-	

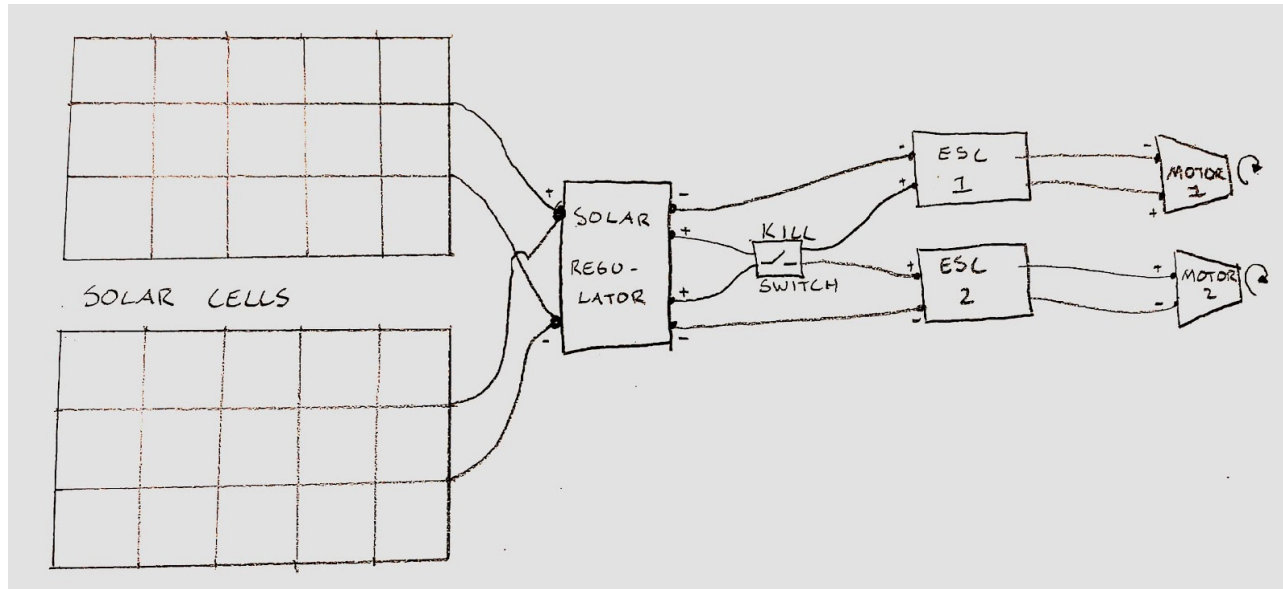I-1

Appendix J. Electrical Wiring Diagrams

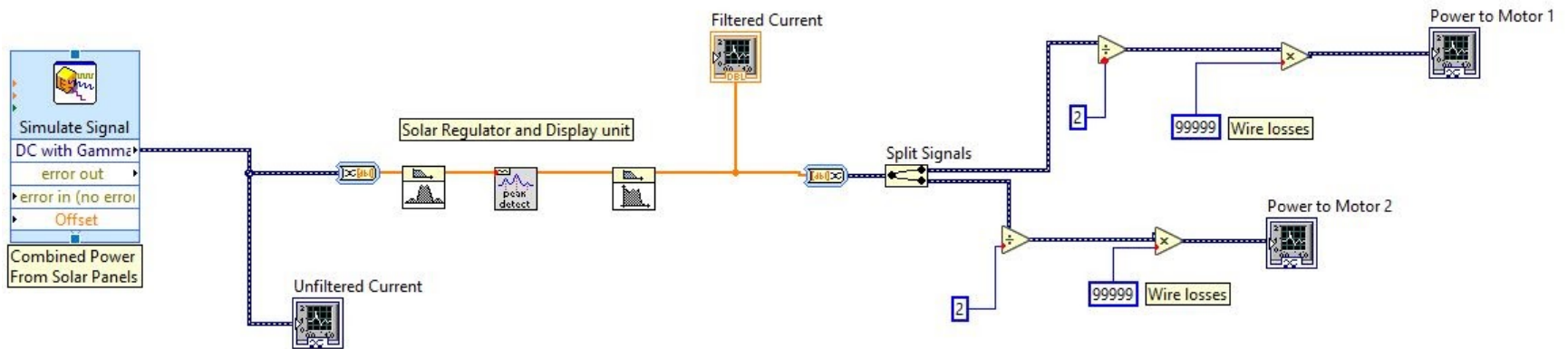*Figure J.1. Conceptual solar module wiring diagram.*

Figure J.2. Solar module wiring diagram made using Virtual Instrument software.

Appendix K. Design Failure Modes and Effects Analysis

Design Failure Mode and Effects Analysis

Product: Solar Regatta Propulsion System

Prepared by: Whole Team

Team: Solar Regatta Propulsion

Date: 1/23/20

System / Function	Potential Failure Mode	Potential Effects of the Failure Mode	Severity	Potential Causes of the Failure Mode	Current Preventative Activities	Occurence	Current Detection Activities	Detection	RPN	Recommended Action(s)	Responsibility & Target Completion Date	Action Results				
												Actions Taken	Severity	Occurence	Criticality	RPN
Energy Efficient	Not enough energy converted from PV panels to Mech. Power	a) Boat cannot move b) Boat is not fast enough c) Boat heats up	8	1) PV panels blocked 2) Cooling ineffective 3) Wire resistance high 4) Motors not efficient	1) Calculate heat transfer 2) Reduce wire resistance 3) Calculate ideal motor characteristics	8	1) Test PV panels- power and heat 2) Measure wire resistance 3) Test cooling 4) Test motors	3	192	1) Test panels earlier	Entire Team 2/13/19		8	8	2	128
	High Friction	a) Boat cannot move b) Boat is not fast enough	8	1) Bad bearings 2) High motor friction	1) Get low friction bearings 2) Grease/oil motor	2	1) Test bearings 2) Test drivetrain	4	64							0
	Inefficient Prop	Slower boat speed and acceleration	6	1) Non-optimal blade pitch 2) Non-optimal rpm 3) Non-optimal torque 4) Rough surface finish	1) Calculate optimal pitch 2) Calculate optimal rpm 3) Calculate optimal torque	5	1) Test multiple props	3	90							0
Ease of Use	Difficult to Steer	a) Slower race time b) Crash boat	9	1) Handle hard to turn 2) Too much drag on rudder 3) Too little drag on rudder 4) Hull too streamlined 5) Bad tuning on electrical thrust variation	1) Calculate required rudder size	6	1) Test steering on full model	4	216	1) Test scaled model prototype	Entire Team 2/13/19		9	3	2	54
	Difficult to Control Speed	a) Slower race time b) Crash boat c) Jerky motion	9	1) Controls slow to respond 2) Transmission ratios too far apart	1) Calculate optimal torque	2	1) Test controls on full model	2	36							0
Aesthetics / Appearance	Clashing Colors	a) Poor score in aesthetics	2	1) Unpaintable surfaces	none	3	1) Visual	3	18							0
	Mishapen or mismatching parts	a) increase drag b) glue and fasteners showing	6	1) Composite structures don't match machined parts	1) Establish tolerances and use CAD models for accurate matching.	6	1) Double check measurements before fabrication	3	108							
	Mismanaged Wiring	a) Poor score in aesthetics b) Electrical problems difficult to diagnose	5	1) Cannot quickly separate wires to diagnose each system component	1) Create wiring block diagram to organize wires for easy location 2) Use tiedowns for wiring	5	1) solve issues in final design by moving wires if necessary	3	75							
Aero / Hydrodynamic	Upstream flow to prop unstable	a) Prop has low thrust	7	1) Flow analysis does not portray prop accurately	1) Test multiple props in water channel	3	1) Water channel test	3	63							0
	Exposed underwater rotating compenents	a) induce high friction losses b) disturb flow of water before propeller	6	1) rotating components swirl the water	1) seal off rotating components besides propeller.	3	1) bearing seal test	5	90							
Maneuverability	Lack of displaced water	a) lack of steering authority	9	1) Poor rudder placement/attachment	1) observe classical rudder designs	2	1) test on scaled model	3	54							0
	lack of responsiveness	a) unpleasent user experience	6	1) props cannot provide accleration response	1) find classical prop designs that provide good acceleration performance	4	1) Water channel test	4	96							
Top Speed	solar energy cannot be efficiently transfered into thrust	a) boat moves slowly b) boat cannot steer using differential thrust	8	1) props are inefficient at high speeds 2) props don't provide enough thrust	1) use OpenProp and CFD to analyze prop performance 2) check with hand calcs with classical designs	7	1) Water channel test	2	112							0
Max Acceleration	Not competitive in the sprint race	Boat cannot speed up fast enough	8	1) Props cannot provide enough thrust force 2) High amount of drag forces	1) Designing props for max thrust transfer through startup 2) Streamlinging the boat design	5	1) Accelerometer test of final design	2	80							0
Max Power	Not enought energy Collecteed	a) boat moves slowly b) Motors run at ineffecient speeds	7	1) electrical effeciencies are low 2) Not enought sunlight	1) minimized electrical components of loss	4	1) Check PV outuput with Multimeter	2	56							0
Integration with Hull	Propulsion system is unstable	a) Propulsion system moves/rotates b) Propulsion system falls off	8	1) Insufficient mounting	1) FEA analysis of structural attachment to hull	2	1) Test structure stability by looking at deflection on final model	2	32							0

K-1

Appendix L. Indented Bill of Materials

Indented Bill of Material (BOM)
Solar Regatta - Propulsion

Assembly Level	Part Number	Lvl0	Lvl1	Lvl2	Lvl3	Lvl4	Vendor	Qty	Cost	Total Cost
0	100000	Full System					------			
1	101000		Propulsion Assembly				------			
2	102001			U8II-KV150 Motor			T-motor	2	$ 319.00	$ 638.00
2	102002			**Motor Mount**			Cal Poly	2	$ -	$ -
2	91290A148			M4x0.7mm Socket Screw			McMaster	8	$ 1.15	$ 9.22
2	102003			**Connection Pin**			McMaster	4	$ 0.08	$ 0.32
2	102004			**Rudder Tilt Bracket**			CoastAl	2	$ 10.00	$ 20.00
2	3636A220			Hinge			McMaster	2	$ 8.50	$ 17.00
2	102005			ESC			T-motor	2	$ 85.00	$ 170.00
2	102006			Gearbox			------			
3	5972K46				Large Bearing		McMaster	2	$ 10.90	$ 21.80
3	6153K25				Small Bearing		McMaster	2	$ 12.42	$ 24.84
3	103001				**Housing**		CoastAl	2	$ -	$ -
3	2515N11				Bevel Gear		McMaster	2	$ 56.24	$ 112.48
3	2515N12				Bevel Gear Pinion		McMaster	2	$ 33.80	$ 67.60
2	102007			**Main Downshaft**			McMaster	2	$ 8.00	$ 16.00
2	102008			Carbon Downtube			Dragon Plate	2	$ 57.10	$ 114.20
2	102009			**Box Tube**			CoastAl	2	$ 15.00	$ 30.00
2	102010			**Sheet Metal Bracket**			CoastAl	2	$ 10.00	$ 20.00
2	102011			Rudder			-----			
3	103002				**Airfoil Sections**		Home Depot	136	$ 0.74	$ 100.00
3	103003				Carbon Wrap		Cal Poly	2	$ -	$ -
2	102012			Steering			------			
3	103004				Rods		McMaster	4	$ 8.00	$ 32.00
3	103005				Pivot		Mcmaster	1	$ 2.00	$ 2.00
4	104001					Eyebolts	McMaster	2	$ 1.00	$ 2.00
4	104002					Pivot Ball	McMaster	1	$ 10.00	$ 10.00
2	102013			**Propeller**			Cal Poly	2	$ -	$ -
2	92029A158			M4 Set Screw			McMaster	2	$ 4.29	$ 8.57
2	102014			**Tail Cone**			Cal Poly	2	$ -	$ -
2	102015			**Propeller Shaft**			McMaster	2	$ 8.00	$ 16.00
2	5972K222			Tail Cone Bearing			McMaster	2	$ 5.35	$ 10.70
1	101001		Solar Panels				SMUD	2	$ -	$ -
1	101002		Wiring				HobbyKing	1	$ 40.00	$ 40.00
1	101003		MPPT Solar Inverter (Renegy Rover)				Amazon	2	$ 110.00	$ 220.00
	Total Parts							**201**		**$ 1,702.73**

Appendix M. Drawing Package

The following pages contain drawings for all parts to be manufactured.

| Cal Poly Mechanical Engineering | | PN: 101000 | Title: PROPULSION ASSEMBLY | | Drwn. By: NIKO BANKS |
| ME SENIOR PROJECT | Dwg. #: 01 | Nxt Asb: 02 | Date: 6/1/2020 | Scale: 1:3 | Team: WITHOUT A PADDLE |
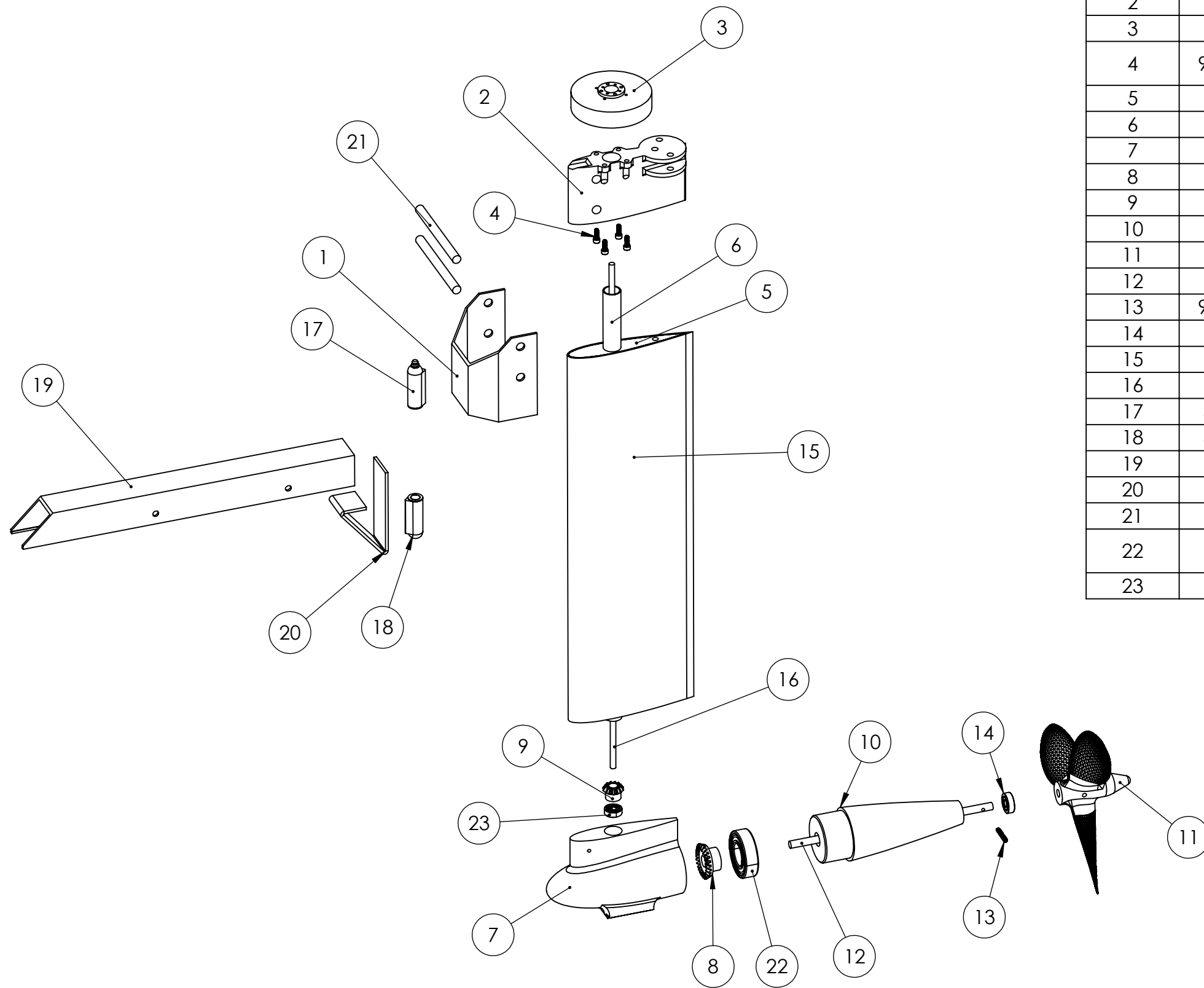
ITEM NO.	PART NUMBER	COMPONENT NAME	QTY.	Dwg #
1	102004	RUDDER TILT BRACKET	1	05
2	102002	MOTOR MOUNT	1	03
3	102001	U8II-KV150	1	-
4	91290A148	M4x0.7mm SOCKET SCREW	4	-
5	103002	AIRFOIL SECTION	68	10
6	102008	CARBON DOWNTUBE	1	-
7	103001	GEARBOX HOUSING	1	06
8	2515N11	BEVEL GEAR	1	-
9	1515N12	BEVEL GEAR PINION	1	-
10	102014	TAIL CONE	1	12
11	102013	9 IN PROPELLER	1	11
12	102015	PROPELLER SHAFT	1	13
13	92029A158	M4 SET SCREW	1	-
14	5972K222	TAIL CONE BEARING	1	-
15	103003	CARBON WRAP	1	-
16	102007	MAIN DOWNSHAFT	1	07
17	3636A220	HINGE	1	-
18	3636A220	HINGE	1	-
19	102009	BOX TUBE	1	08
20	102010	SHEET METAL BRACKET	1	09
21	102003	CONNECTION PIN	2	04
22	5972K46	LARGE GEARBOX BEARING	1	-
23	6153K25	SMALL GEARBOX BEARING	1	-
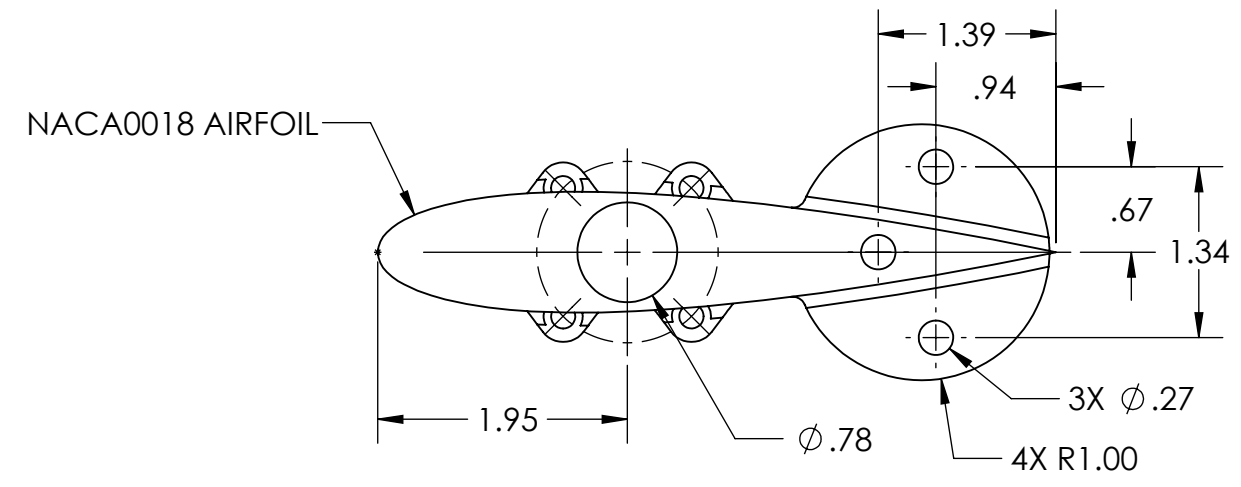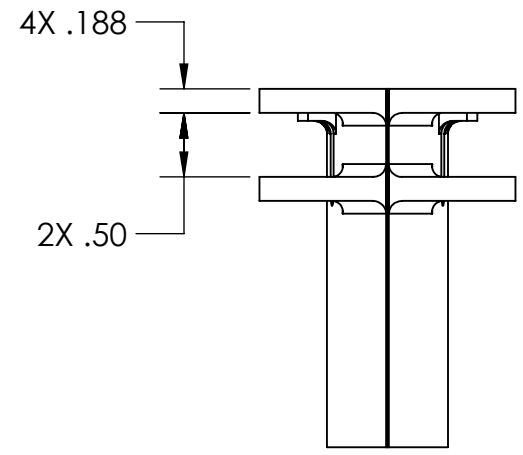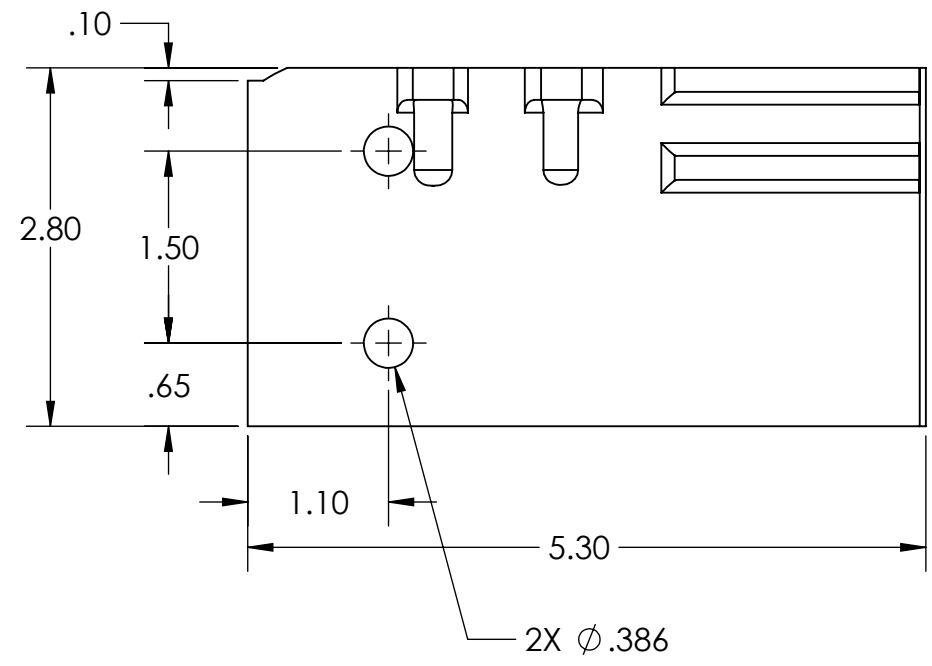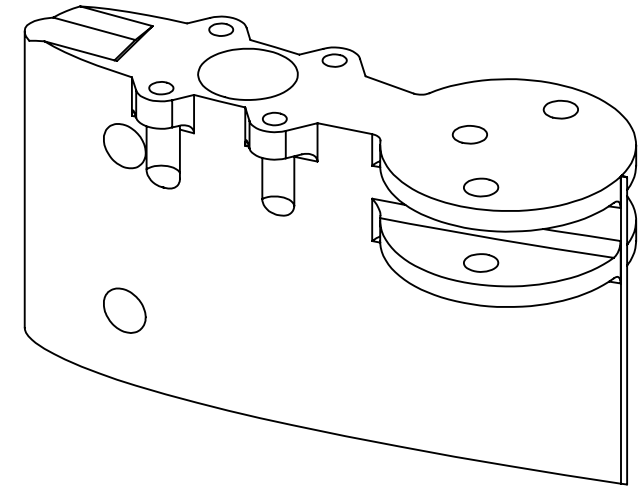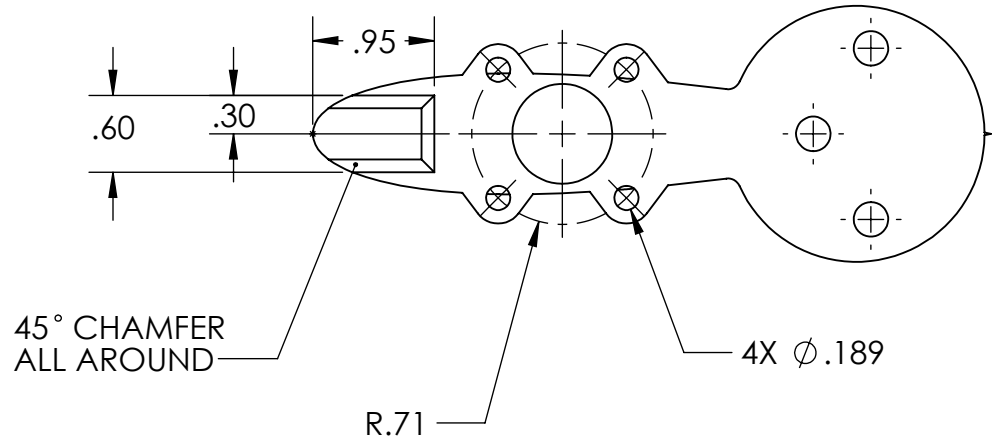
Cal Poly Mechanical Engineering		PN: 101000	Title: PROPULSION ASSEMBLY		Drwn. By: NIKO BANKS
ME SENIOR PROJECT	Dwg. #: 02	Nxt Asb:	Date: 6/1/2020	Scale: 1:5	Team: WITHOUT A PADDLE

.95
.60
.30
45° CHAMFER ALL AROUND
R.71
4X ⌀.189

.10
2.80
1.50
.65
1.10
5.30
2X ⌀.386

4X .188
2X .50

NACA0018 AIRFOIL
1.39
.94
.67
1.34
1.95
⌀.78
3X ⌀.27
4X R1.00

UNLESS OTHERWISE SPECIFIED:
1. ALL DIMENSIONS IN INCHES
2. TOLERANCES:
   X.XX = ±0.01
   X.XXX = ±.005
   ANGLES = ±1°
3. INSIDE TOOL RADIUS 0.05 MAX
4. BREAK SHARP EDGES 0.05 MAX
5. MATERIAL: PLA
6. SEE CAD FILE FOR DETAILS

Cal Poly Mechanical Engineering ME SENIOR PROJECT		PN: 102002	Title: MOTOR MOUNT		Drwn. By: NIKO BANKS
Dwg. #: 03	Nxt Asb:	Date: 6/1/2020	Scale: 2:3		Team: WITHOUT A PADDLE

UNDERLINE OTHERWISE SPECIFIED:
UNLESS OTHERWISE SPECIFIED:
1.   ALL DIMENSIONS IN INCHES
2.   TOLERANCES:
         X.XX = ±0.01
         X.XXX = ±.005
         ANGLES = ±1°
3.   INSIDE TOOL RADIUS 0.05 MAX
4.   BREAK SHARP EDGES 0.05 MAX
5.   MATERIAL: Al 6061-T6

4.50

⌀ .375

2X ⌀.375
THRU ALL

1.15

.50

1.50

4.00

2.40

.75

2X 45°

// .005 A

2.00

1.00

3.80

1.90

A

2.75

⊥ .005 A

.10 THICKNESS

UNLESS OTHERWISE SPECIFIED:
1.   ALL DIMENSIONS IN INCHES
2.   TOLERANCES:
          X.XX = ±0.01
          X.XXX = ±.005
          ANGLES = ±1°
3.   INSIDE TOOL RADIUS 0.05 MAX
4.   BREAK SHARP EDGES 0.05 MAX
5.   MATERIAL: Al 6061-T6
6.   SEE CAD FILE FOR DETAILS

Ø.75 ▽ 3.69

2.88

#8-32 Tapped Hole

2.00 — 1.38

Ø 2.09 ▽ 1.57

Ø 2.05 ▽ 2.32

Ø 1.85 ▽ 4.00

1.28   2X 45°

1.75

.26

.25   1.50

UNLESS OTHERWISE SPECIFIED:
1. ALL DIMENSIONS IN INCHES
2. TOLERANCES:
        X.XX = ±0.01
        X.XXX = ±.005
        ANGLES = ±1°
3. INSIDE TOOL RADIUS 0.05 MAX
4. BREAK SHARP EDGES 0.05 MAX
5. MATERIAL: Al 6061-T6
6. SEE CAD FILE FOR DETAILS

Cal Poly Mechanical Engineering		PN: 103001	Title: GEARBOX HOUSING		Drwn. By: NIKO BANKS
ME SENIOR PROJECT	Dwg. #: 06	Nxt Asb:	Date: 6/2/2020	Scale: 1:2	Team: WITHOUT A PADDLE

UNLESS OTHERWISE SPECIFIED:
1. ALL DIMENSIONS IN INCHES
2. TOLERANCES:
    X.XX = ±0.01
    X.XXX = ±.005
    ANGLES = ±1°
3. INSIDE TOOL RADIUS 0.05 MAX
4. BREAK SHARP EDGES 0.05 MAX
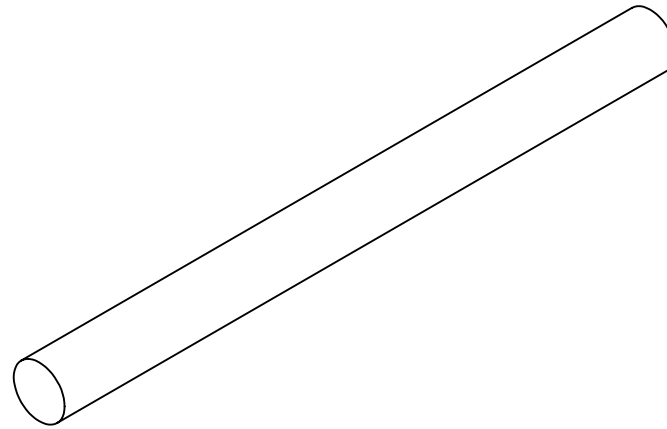5. MATERIAL: Al 6061-T6

Ø.24

24.80

UNLESS OTHERWISE SPECIFIED:
1. ALL DIMENSIONS IN INCHES
2. TOLERANCES:
    X.XX = ±0.01
    X.XXX = ±.005
    ANGLES = ±1°
3. INSIDE TOOL RADIUS 0.05 MAX
4. BREAK SHARP EDGES 0.05 MAX
5. MATERIAL: Al 6061-T6

13.65

45°

6.00

3.00

15.00

1.25

12.00
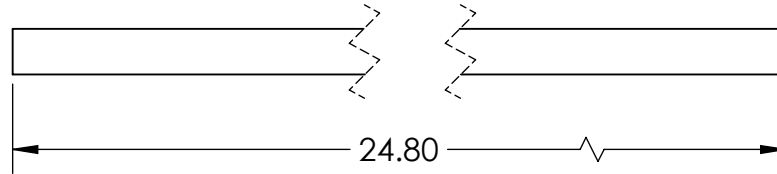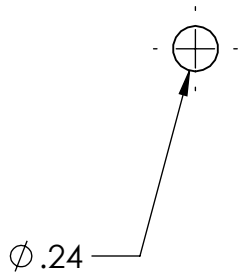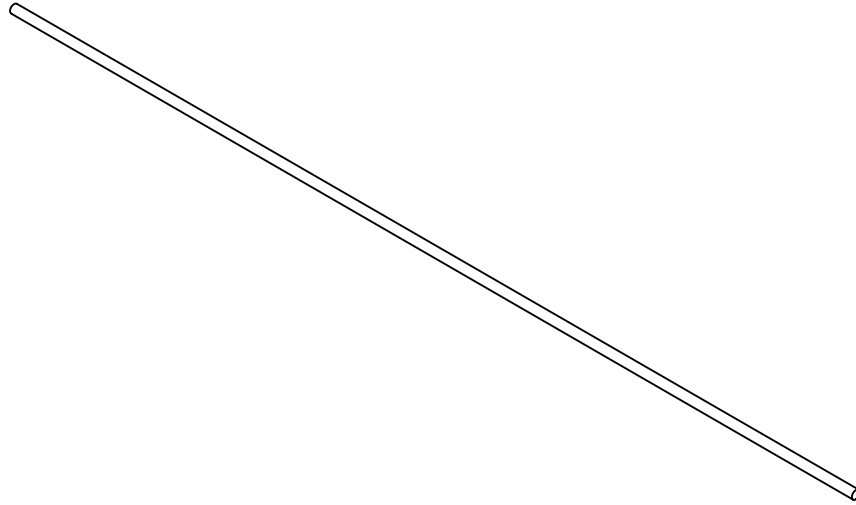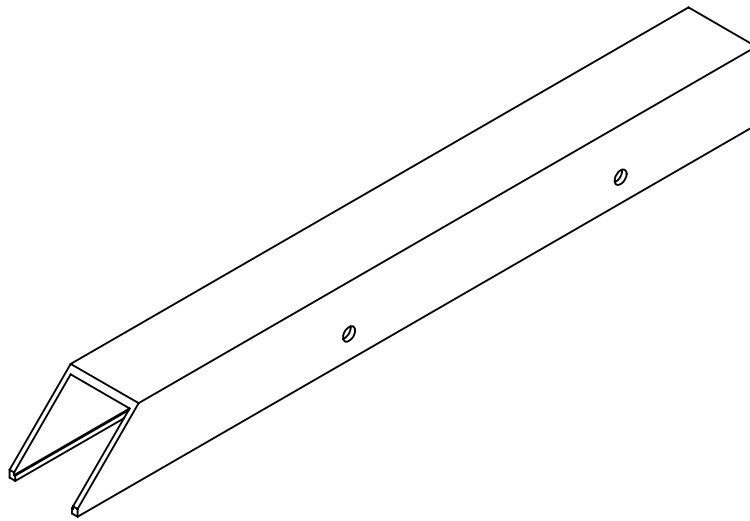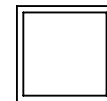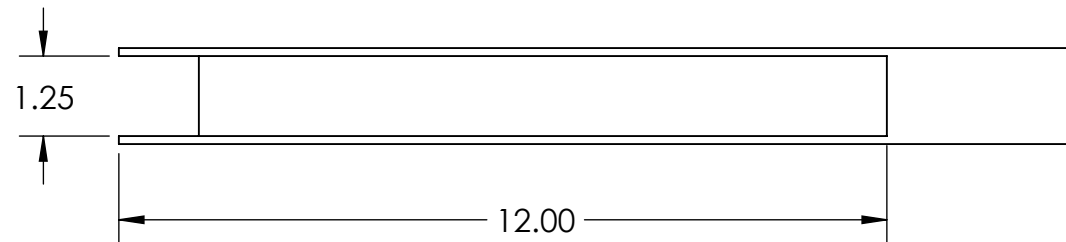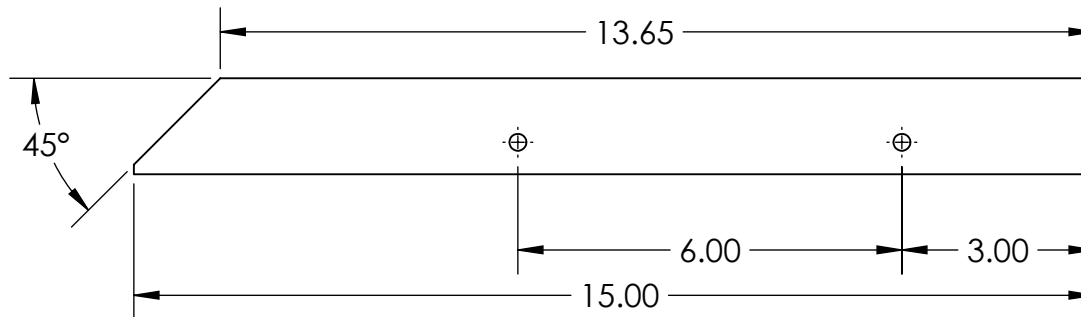
BOX TUBING 1.50 x 0.10

Cal Poly Mechanical Engineering		PN: 102009	Title: BOX TUBE		Drwn. By: NIKO BANKS
ME SENIOR PROJECT	Dwg. #: 08	Nxt Asb:	Date: 6/2/2020	Scale: 1:3	Team: WITHOUT A PADDLE

1.4

2.0

1.2

1.5
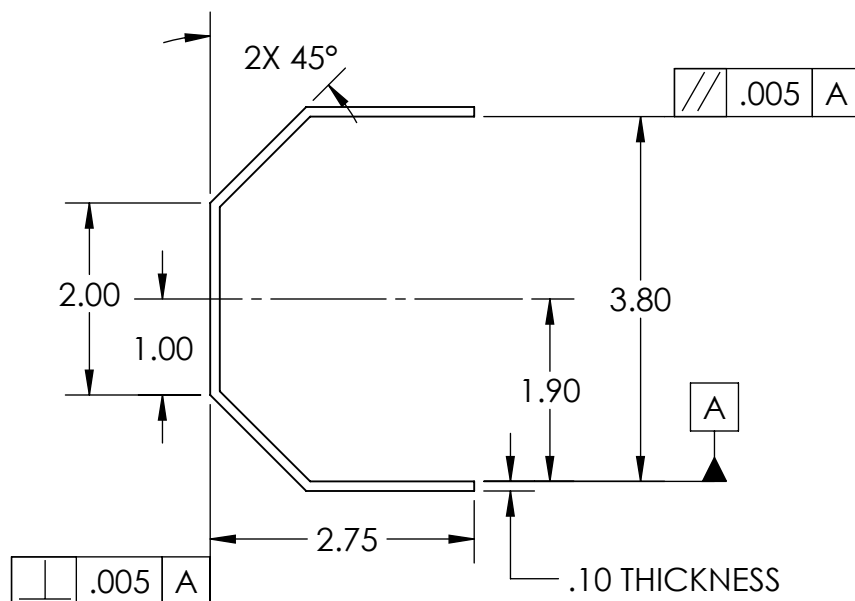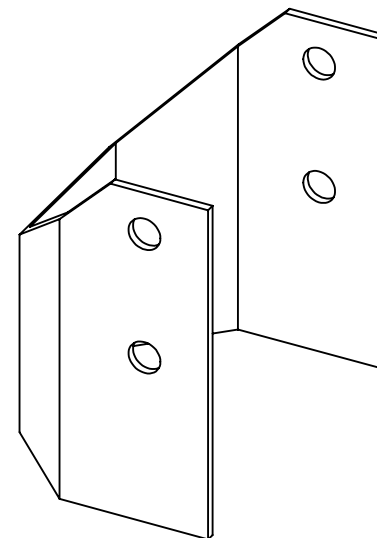
4.0

40°

2X R.15
BEND RADIUS
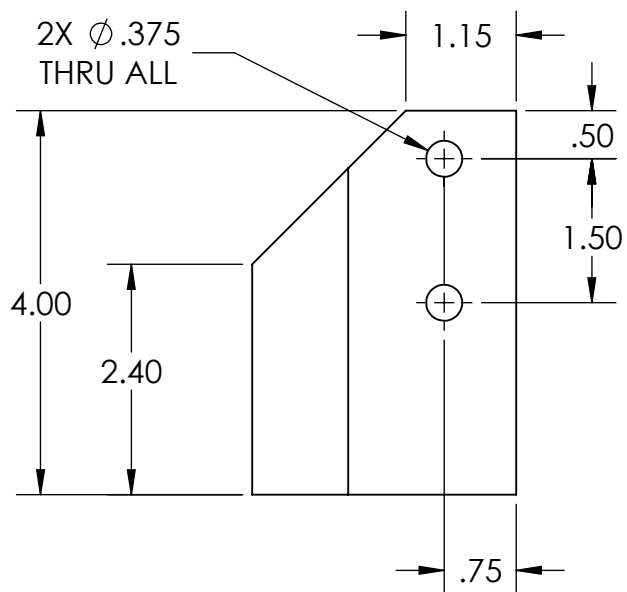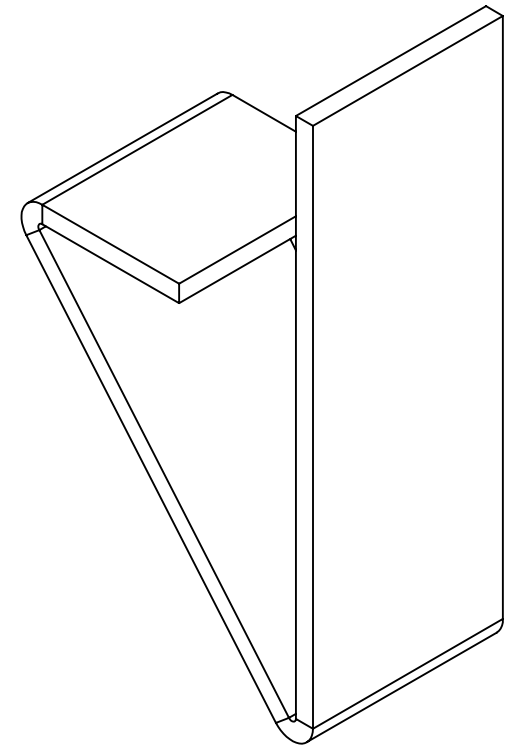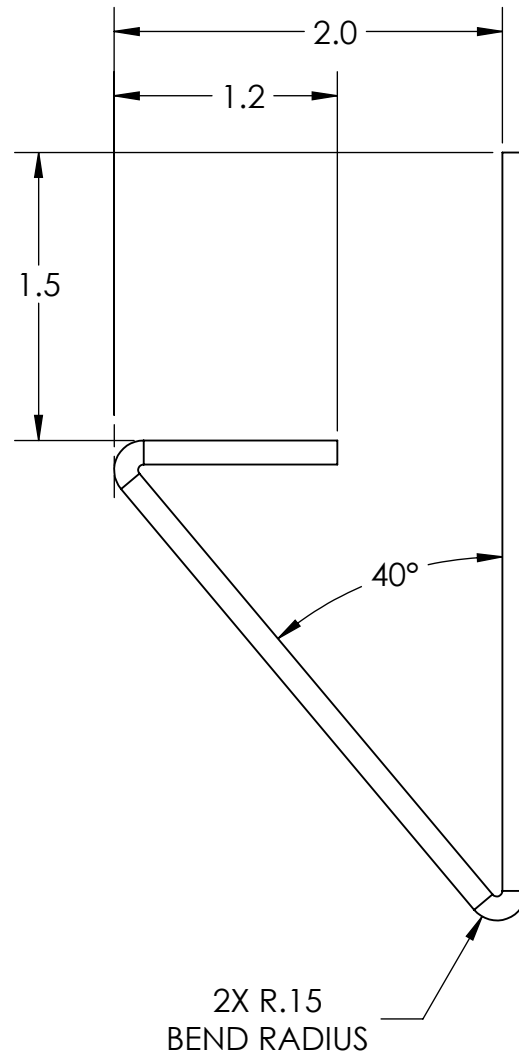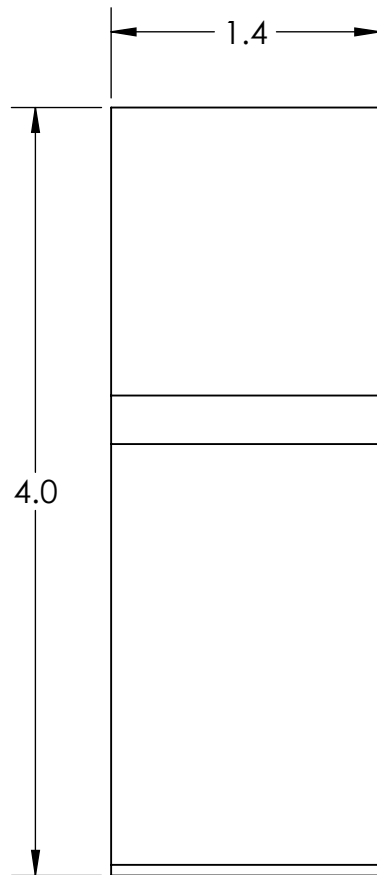
UNLESS OTHERWISE SPECIFIED:
1.   ALL DIMENSIONS IN INCHES
2.   TOLERANCES:
        X.X = ±0.1
        X.XX = ±0.05
        ANGLES = ±1°
3.   INSIDE TOOL RADIUS 0.05 MAX
4.   BREAK SHARP EDGES 0.05 MAX
5.   MATERIAL: Al 6061-T6, 0.125 IN
     THICKNESS

UNLESS OTHERWISE SPECIFIED:
1.   ALL DIMENSIONS IN INCHES
2.   TOLERANCES:
         X.XX = ±0.01
         X.XXX = ±.005
         ANGLES = ±1°
3.   INSIDE TOOL RADIUS 0.05 MAX
4.   BREAK SHARP EDGES 0.05 MAX
5.   MATERIAL: MDF
6.   SEE CAD FILE FOR DETAILS

Ø.76

Ø.25

NACA0018
  AIRFOIL

1.95

3.91

.25
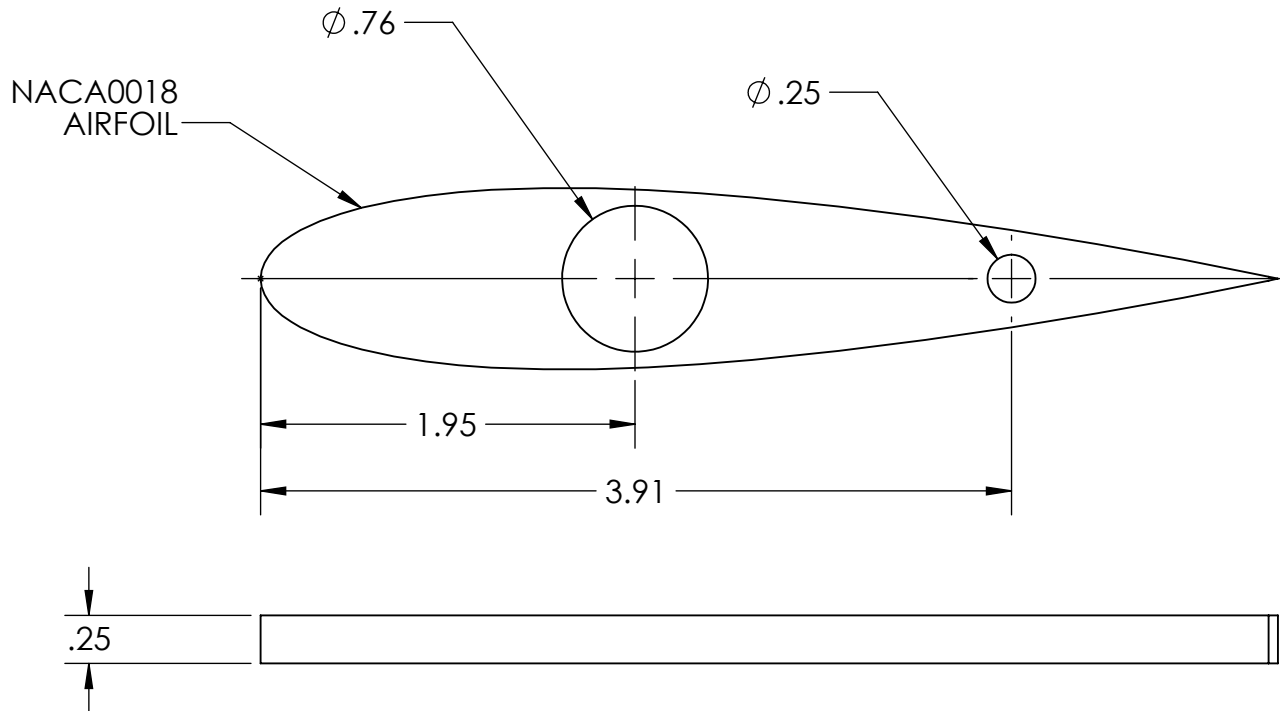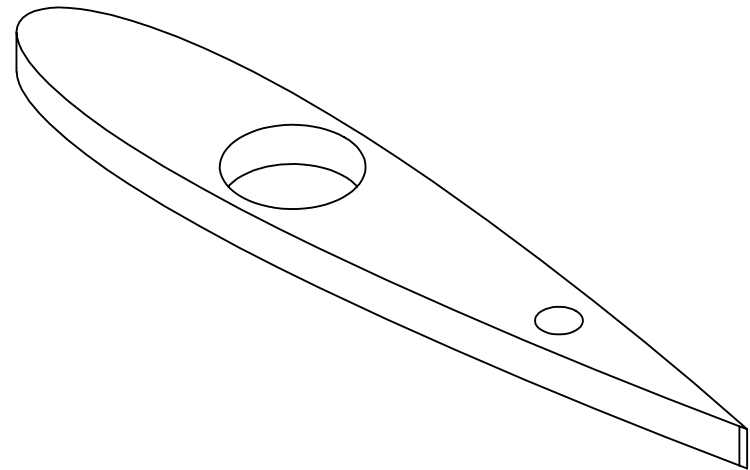
MULTIPLE OF THESE PARTS
WILL BE STACKED TO CREATE
THE INTERNAL RUDDER BODY
(17 IN TALL)

Ø9.00

Ø1.01

3X R.25
ALL AROUND

Ø8.50 MM

(3.25)

2.00

1.00

19°

R.20

Ø4.50 MM

R1.25

UNLESS OTHERWISE SPECIFIED:
1. ALL DIMENSIONS IN INCHES
2. TOLERANCES:
   X.XX = ±0.01
   X.XXX = ±.005
   ANGLES = ±1°
3. INSIDE TOOL RADIUS 0.05 MAX
4. BREAK SHARP EDGES 0.05 MAX
5. MATERIAL: PLA
   16
   √ FAO
6.
7. SEE CAD FILE FOR DETAILS OF
   BLADE CONTOURS

6.44

1.25

$\varnothing$ 2.06

$\varnothing$ .60
THRU ALL

2X .05 X 45°

$\varnothing$ .886 ⍌ 0.30

Cal Poly Mechanical Engineering		PN: 102014	Title: TAIL CONE		Drwn. By: NIKO BANKS
ME SENIOR PROJECT	Dwg. #: 12	Nxt Asb:	Date: 6/2/2020	Scale: 1:2	Team: WITHOUT A PADDLE

UNLESS OTHERWISE SPECIFIED:
1. ALL DIMENSIONS IN INCHES
2. TOLERANCES:
   X.XX = ±0.01
   X.XXX = ±.005
   ANGLES = ±1°
3. INSIDE TOOL RADIUS 0.05 MAX
4. BREAK SHARP EDGES 0.05 MAX
5. MATERIAL: 304 SS

M4x0.7 Tapped Hole

Ø 8.00 MM

.45

9.14

Appendix N. Budget

BUDGET

|	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Total	Average
Starting Balance	1,000												Total	Average
Total Income	0	0	0	0	0	1,645	0	200	100	0	0	0	1,945	162
Total Expenses	0	0	0	0	0	905	1,245	40	0	0	0	0	2,190	182
NET (Income - Expenses)	0	0	0	0	0	741	-1,245	160	100	0	0	0	-245	-20
Projected End Balance	1,000	1,000	1,000	1,000	1,000	1,741	496	656	756	756	756	756		

	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Total	Average
INCOME CATEGORIES														
MESFAC						1,645							1,645	137
Company donations													0	0
Competition Funds								200	100				300	25
													0	0
													0	0
													0	0
													0	0
													0	0
													0	0
													0	0
Total Income	0	0	0	0	0	1,645	0	200	100	0	0	0	1,945	162

	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Total	Average
EXPENSE CATEGORIES														
Gas (Transportation)													0	0
Car miles (Transportation)													0	0
Boat trailer (Transportation)													0	0
Electric Motors						320	1,065						1,385	115
Solar Electronics													0	0
Battery						95							95	8
Motor Controllers						80	180						260	22
Wiring								40					40	3
Propellers													0	0
Billet (for machining)													0	0
Controls - Throttle/Steering						30							30	3
Test Electronics						40							40	3
COTS (rods, hinges, pins)						30							30	3
Gears						50							50	4
Bearings						40							40	3
Carbon Tubes						120							120	10
Enclosure - WT						100							100	8
													0	0
Total Expenses	0	0	0	0	0	905	1,245	40	0	0	0	0	2,190	182

Appendix O. Purchased Part Website Links

Part	Link
10 Gauge Wiring	https://hobbyking.com/en_us/turnigy-high-quality-10awg-silicone-wire-5m-black.html?queryID=&objectID=60264&indexName=hbk_live_magento_en_us_products
T-Motor U8II	https://www.foxtechfpv.com/t-motor-u8-ii.html
T-Motor T 60A ESC	https://www.foxtechfpv.com/t-motor-t-60a-esc.html
Lift-off Hinge	https://www.mcmaster.com/catalog/126/3127
Bearings	https://www.mcmaster.com/standard-ball-and-roller-bearings
Solar MPPT Optimizer	https://www.solar-electric.com/solaredge-p700-solar-optimizer.html
Eyebolts	https://www.mcmaster.com/eyebolts
Threaded stud with cotter pin	https://www.mcmaster.com/threaded-pins
CNHL 8000MAH 22.2V 6S 30C LIPO BATTERY	https://chinahobbyline.com/index.php?route=product/product&product_id=87

Appendix P. Solar Module Specifications

Module provided by SMUD: JKM235P-60

JKM245P-60

POLY CRYSTALLINE MODULE
225-245 Watt

Jinko Solar introduces a brand-new line of high performance modules in wide application.

KEY FEATURES

Our solar cells offer high conversion efficiency to ensure the highest quality

Our high performing modules have an industry low tolerance of +/- 3%

The modules can withstand high wind-pressure, snow loads and extreme temperatures

Passed IEC 5400 Pa mechanical loading test

QUALITY & SAFETY

Industry leading power output warranty (12 years/90%, 25 years/80%)

5-year warranty on product materials and processing technology

ISO 9001:2008 (Quality Management System) certified factory

IEC61215、IEC61730 certified products

APPLICATIONS

On-grid residential roof-tops | On-grid commercial/industrial roof-tops | Solar power plants | Off-grid systems
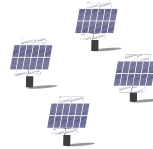
www.jinkosolar.com | sales@jinkosolar.com

Engineering Drawings

Front   Side   Back

NOTE: Dims to oval holes are measured to the top of each hole

Electrical Performance & Temperature Dependence

Current-Voltage & Power-Voltage Curves (240W)

1000 W/m²   600 W/m²   800 W/m²   100 W/m²
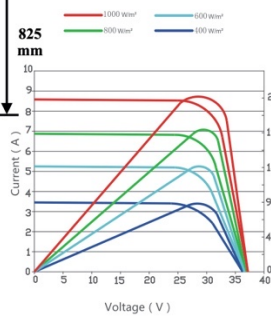
Temperature Dependence of Isc,Voc,Pmax
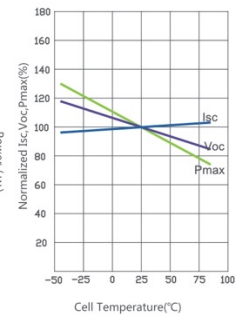
Mechanical Characteristics

Cell Type	Poly-crystalline 156×156mm (6 inch)
No.of cells	60 (6×10)
Dimensions	1650×992×45mm (64.97×39.06×1.77 inch)
Weight	19.0kg (41.9 lbs.)
Front Glass	3.2mm, High Transmission, Low Iron, Tempered Glass
Frame	Anodized Aluminium Alloy
Junction Box	IP65 Rated
Output Cables	TÜV 1×4.0mm²/ UL 12AWG, Length:900mm

Packaging Configuration

(Two boxes + 4pcs addition module = One pallet)

23 pcs/box, 50 pcs/pallet, 700 pcs/40'HQ Container

SPECIFICATIONS

Module Type	JKM225P	JKM230P	JKM235P	JKM240P	JKM245P
Maximum Power at STC(Pmax)	225Wp	230Wp	235Wp	240Wp	245Wp
Maximum Power Voltage (Vmp)	29.4V	29.6V	29.8V	30V	30.2V
Maximum Power Current (Imp)	7.65A	7.78A	7.89A	8.01A	8.12A
Open-circuit Voltage (Voc)	36.7V	36.8V	36.9V	37.2V	37.4V
Short-circuit Current (Isc)	8.25A	8.35A	8.47A	8.56A	8.69A
Cell Efficiency(%)	15.75%	16.00%	16.50%	17.00%	17.25%
Module Efficiency(%)	13.74%	14.05%	14.35%	14.66%	14.97%
Operating Temperature(°C)	-40°C~+85°C				
Maximum system voltage	600V (UL) /1000V (IEC) DC				
Maximum series fuse rating	15A				
Power tolerance	±3%				
Temperature coefficients of Pmax	-0.45%/°C				
Temperature coefficients of Voc	-0.27%/°C				
Temperature coefficients of Isc	0.05%/°C				
Nominal operating cell temperature (NOCT)	45±2°C				

STC: Irradiance 1000W/m²   Module Temperature 25°C   AM=1.5

The company reserves the final right for explanation on any of the information presented hereby.

Appendix Q. Motor Specifications

T-Motor U8II-KV150

Product Drawing-U8II
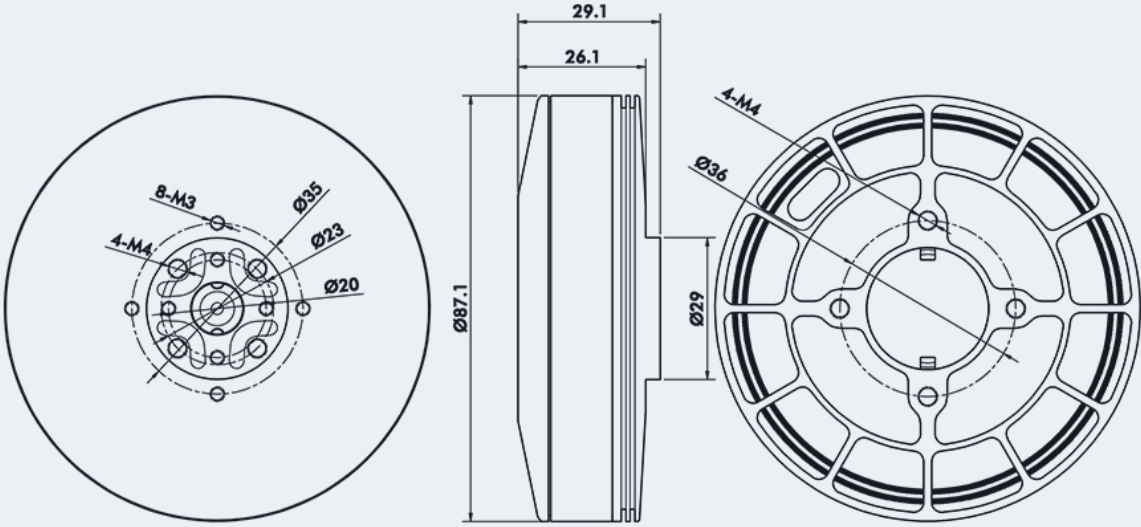
Specifications-U8II

Diameter	87.1mm
Height	29.1mm
Shaft Diameter	15mm
Configuration	36N42P
Lead Spec	90mm
Ingress Protection Level	IP55
Packing Size	130*111*50.6mm
Accessories	Φ32*10*3mm CPC*1、M3*12mm Screw for propeller installation*4、Φ11*14.5 locating pin*1、M4*12mm Screw for motor installation*4

KV	150	Rated Voltage（Lipo)	6S / 12S
Motor Weight (Incl. Cable)	273g	Propeller Recommendation	28-30" / 22"
Idle Current（18V)	1A	ESC Recommendation	AIR 40A、ALPHA 60A LV FLAME 60A HV
Internal Resistance	85±5mΩ	Quadcopter（28CF)	8kg
Peak Current（180s)	29.7 / 26.5A	Hexacopter（28CF)	12kg
Max. Power（180s)	712.8 / 1272W	Octocopter（28CF)	16kg

Additional specifications, including test data under different temperature conditions with standard T-motor propellers attached, can be found here.

Appendix R. Battery Specifications

CNHL 8000MAH 22.2V 6S 30C LIPO BATTERY

Stock Number	800306
Capacity	8000mAh
Voltage	22.2V / 6-Cell / 6S1P
Discharge Rate	30C Continual / 60C Burst
Charge Rate	5C Max
Size	47X62X170mm
Weight	1113g (Including wire and connector)
Output Connector	XT90
Balance Connector	JST / XH
Remarks	N/A

More information about the battery can be found here.

Appendix S. Test Procedures

The specifications for each test can be found in Table 3.2.

> *BULLET POINT KEY:*
> - General Procedures
> + Safety Related Procedures

Test #1: Top speed of the boat

Description of Test:

There will be one test to determine the top speed of the boat in operation.

> When the boat has the solar panels attached there will be a maximum speed that the boat can achieve and when the boat is hooked up to the battery there will be a max speed the boat can go. The max speed will determine how the boat does in competition.

Acceptance Criteria:

Target top speed is 7 mph.

Required Materials:

- Boat with propulsion system
- Two solar panels
- Battery
- GPS tracking app
  - Phone to run app

Testing Protocol:

- Put boat in water
- Have boat captain get on boat
- Turn on GPS tracking app
+ Place GPS device in wire component box
- Run boat at full throttle
- Record position data over time to determine top speed

Data:

Panel		Battery	
Time	Position	Time	Position
Top Speed:		Top Speed:	

Test #2: Maximum acceleration of the boat

Description of Test:

Run full boat and measure the acceleration from 0 to max speed (time measurement).

> Test will be conducted for the boat with solar panels and with battery to get a measurement for both systems. Acceleration will be measured with the same GPS tracking setup as in the top speed test.

Acceptance Criteria:

Target time for 0 to max speed in less than 10 seconds.

Required Materials:
- Boat with propulsion system
- Two solar panels
- Battery
- GPS tracking app
  - Phone to run app

Testing Protocol:
- Put boat in water
- Pilot boards boat
- Turn on GPS tracking app
- + Place GPS device in wire component box
- Start boat from rest and accelerate to max speed at full throttle
- Record position data over time to determine acceleration

Data:

Panel		Battery	
Time	Position	Time	Position
Acceleration Time:		Acceleration Time:	

Test #3: Steering capability tests for shaft rotation and turning radius

Description of Test:

There will be two tests to see how the steering apparatus operates:

A) How much the steering column has to rotate
- To ensure the driver can easily turn the boat

B) How well the boat turns under maximum turning input
- To ensure the boat will be able to run in the slalom race

Acceptance Criteria:

- Full rotation of propulsion systems achievable in two full rotations of steering wheel
- Turning radius is less than 15 ft

Required Materials:

- Boat fully assembled
- Rope
- Stake or buoy
- Protractor
- Sawhorses (4)
- Drone?

Testing Protocol:

Rotation of steering column:

- Have boat resting on sawhorses
- Rotate steering column full rotation
- Measure angle change of rudder

Turning radius of boat

- Put boat in water
- Have buoy or stake in lake with rope attached
    - Another person in the water can also operate
- Attach other side of rope to center of boat
- Run boat with turning apparatus to the extreme point
- After length of rope between boat and buoy stops changing measure length of rope
- Record turning radius

Data:

Number or column rotations	Degrees of turning

Number or column rotations	Turning Radius

Test #4: Water Channel Flow Visualization

Description of Test:

Spin prototype propellers while in water channel to get a flow visualization

Required Materials:

- Water Channel
- Propellers
- Propeller mount
- Dye
- High-Speed Camera

Acceptance Criteria:
Propeller design is acceptable if no flow separation or cavitation is observed.
Testing Protocol:

Setup:

+ Clear space around the Water Channel
- Fill Channel with water
+ Check for leaks and fix if present, check the area for water where it shouldn't be
- Check safety equipment around/on Channel
- Turn on Channel pump
- Insert propeller system
+ Check filter to ensure that it is clean and that water can pass through it without obstruction

Performance Test:

- Activate motor to spin propeller and observe, take notes on behavior (quick sketch too)
+ Wear hearing protection if pump is too loud
- Use a high-speed camera to take slow-motion video to capture footage of the water flowing around the propeller
- Repeat flow visualization with different propeller designs

Clean up:

- Power down and remove propeller system from channel
- Turn off Channel pump
+ Check safety equipment around/on Channel
+ Check for leaks/stray water
- Drain and stow channel

Data:

No quantitative data will be produced from this test. The only results will be the flow visualization videos that will be used for better understanding of the propeller and for our Final Design Review report.

Test #5: Battery life at max draw

Description of Test:

Battery life test to ensure that batteries will deplete completely in 25 minutes, and produce the rated energy (180 Watt-hours)

Required Materials:

- Balance charger
- 180 Watt-hour Batteries (2)
- 24V halogen light bulb

Acceptance Criteria:

Battery produces rated energy (180 Watt-hours) and depletes completely in 25 minutes

Testing Protocol:

+ Put up tape around area so no-one touches the hot lights
+ Keep cables on table to avoid trip hazards
- Attach XT90 and balance leads between battery and smart charger
- Charge battery fully and record voltage
- Attach the battery to five 100-watt lights in parallel.
- Discharge battery with five 100-watt lights until it reaches a voltage of 18V.
- Recharge the battery slowly to the starting voltage. Record from the smart charger screen, the amount of mAh transferred into the battery.
- Repeat test 2 times for continuity check

Data:

Total battery capacity when discharged at 500 watts, duration of discharge at 500 watts

Test No	Battery Capacity (W-h)	Batter Life Time (min)
1		
2		

Test #6: PV Panel Energy Conversion Test
Description of Test:

This is a test of the solar panels provided by SMUD to ensure that they are producing the power that they are rated for.

Required Materials:

- Solar Panels (2)
- EE solar panel measuring kit (From Dr. Dale Dolan, EE professor)
- Supports to hold solar panels at different angles
- Sunlight

Acceptance Criteria:

Panels produce rated max power under specified conditions
Testing Protocol:

- Connect solar panels to measuring devices from solar measuring kit
- Set solar panel angle to desired position
+ Ensure that panels are stable and will not fall over if blown by wind
- Run measurement and record power at different voltage and current
- Export data into .csv
- Save .csv file of data for future use
- Test at multiple angles, shading %

Data:

Full output data will be saved to .csv file. Record test conditions and max power here.

Test Specifications	Max Power

Test #7: Electrical power transfer (wires)

Description of Test:

There will be one test to determine the power loss per unit length in the wires used to transfer power.

Required Materials:

- Multimeter
- Power source
- Wire
- Tape measure

Acceptance Criteria:

Power loss must be less than 3% of the total passing through wires.

Testing Protocol:
- Measure length of wire being tested
- Hook wire up to power source with load on opposite end
- + Ensure wire does not reach excessive temperatures and does not break
- Measure voltage and current at beginning and end of wire length
- Difference in above measurements will determine power loss

Data:

Length of wire	Power at start	Power at end

Test #8: Motor Power and Efficiency Testing

Description of Test:

This test is to check efficiency of the motor under conditions that it will experience during operation. Multiple tests will be run to determine optimal throttle for efficient operation. An uncertainty analysis will be conducted with data from this test as well.

Required Materials:

- Dynamometer (inside EE power laboratory)
- Yokogawa wattmeter (EE power lab)
- Motor
- Battery/power source

Acceptance Criteria:

Motor efficiency under design conditions must be greater than 80%.

Testing Protocol:

- + Wear safety glasses near spinning components
- + Keep cables/wires on table to avoid trip hazards
- Connect motor to support fixture
- Connect motor adaptor part to dynamometer shaft
  - + Spin shaft by hand a few times to ensure that all components are concentric
- Connect motor to power source
- Connect leads from battery to Yokogawa to record voltage, current, and power
- Power up system at no load and record power, voltage, current, and speed
- Check to make sure motor does not overheat after each test
- Repeat test three times for each torque load to get statistical data
- Repeat test for multiple torque loads
- Shut off power to motor
- Compile and analyze data

Data:

Torque (lbf•in)	Speed (RPM)	Power (W)	Voltage (V)	Current (A)

Test #9: Shaft and Gearset Efficiency Test
Description of Test:

This test is to check the mechanical efficiency of the gearbox and shaft systems. The motor efficiency must already have been determined so the effects of loading on the motor can be accounted for.

Required Materials:

- Dynamometer (inside EE power laboratory)
- Yokogawa wattmeter (EE power lab)
- Motor
- Battery/power source
- Gearbox

Acceptance Criteria:

Shaft and gearbox efficiency must be greater than 90%.

Testing Protocol:

+ Wear safety glasses near spinning components
+ Keep cables/wires on table to avoid trip hazards
- Attach gearbox output to dynamometer
  + Spin shaft by hand a few times to ensure that all components are concentric
- Connect motor to power source
- Connect leads from battery to Yokogawa to record voltage, current, and power
- Power up system at no load and record power, voltage, current, and speed
- Check to make sure motor does not overheat after each test
- Repeat test for multiple torque loads
- Shut off power to motor
- Compile and compare data to motor data without gearbox attached

Data:

Torque (lbf•in)	Speed (RPM)	Power (W)	Voltage (V)	Current (A)

Test #10: Weight test of full propulsion system
Description of Test:

This is a weigh test of the entire propulsion system to get an accurate measurement of its weight. The test will likely be conducted in the Mustang 60 machine shop.

Required Materials:

- Scale
- Propulsion System

Acceptance Criteria:

One full propulsion system must weigh less than 30 lbs.

Testing Protocol:

+ Wear close-toed shoes
+ Put on Safety glasses (due to environment)
- Place scale on ground
- Turn on scale
- Tare scale
- Have a person stand on scale
- Record weight of person
- Hand fully assembled propulsion system to person standing on scale
- Record weight of person and propulsion system
- Repeat test three times for continuity
- Step off scale carefully and safely
- Turn off scale
- Record weight in in Excel data sheet
- Take "behind the scenes" photos, record findings in logbook and keep data in Excel file

Data:

Propulsion System	Weight (lbf)

# Solar Regatta Propulsion Operators Manual: Set-up of Propulsion system on Boat

Mounting Propulsion Units to the Hull

Follow these directions to integrate two Propulsion Units with the Hull:

1. Slide square tubing from propulsion unit over the smaller square tube protruding from the hull. Secure with two bolts.
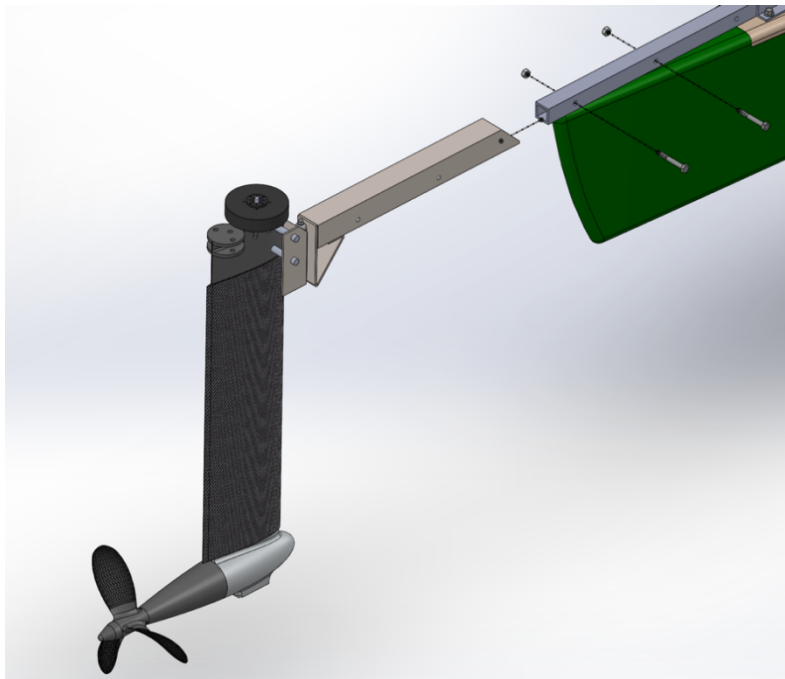
2. Use bolts to attach each propulsion unit to the steering-rod.
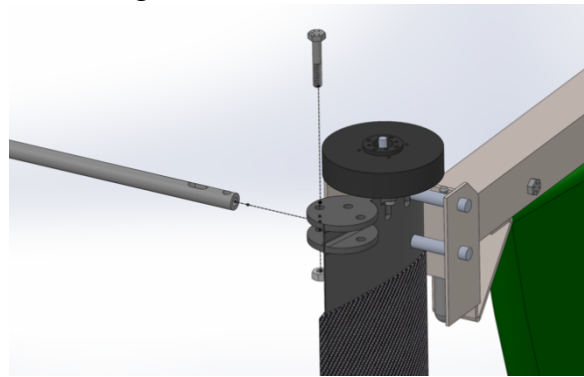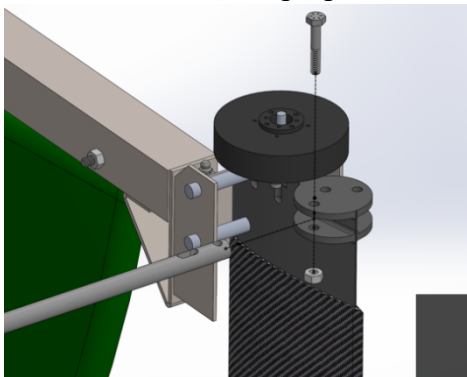
3. Congrats! The propulsion units are secured to the hull and connected to each other. They are now ready to be connected to the steering system and the motors are ready to be wired.
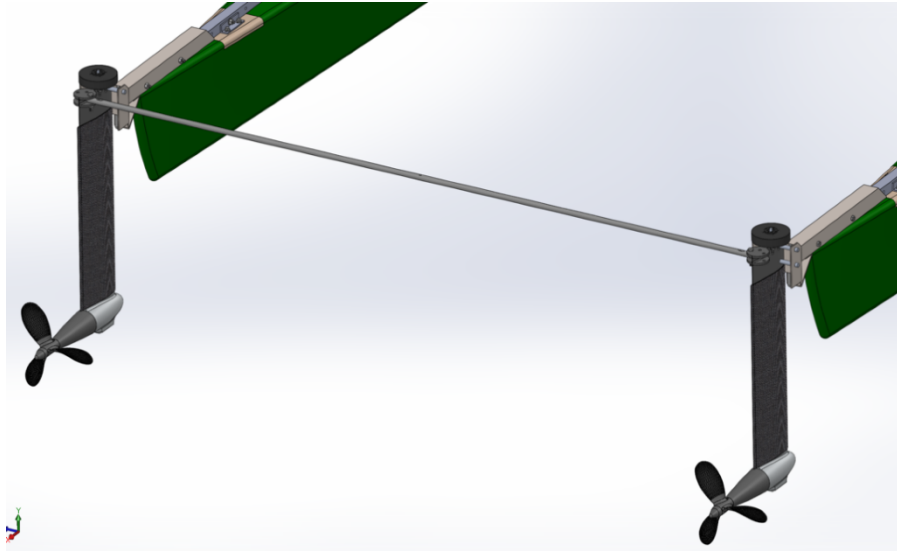
After the propulsion units have been mounted on the boat

Align and fix the distance between the two units by attaching the alignment rod:

1. Set rod width to match with width of the boat by putting a bolt through the solid and sleeve rods
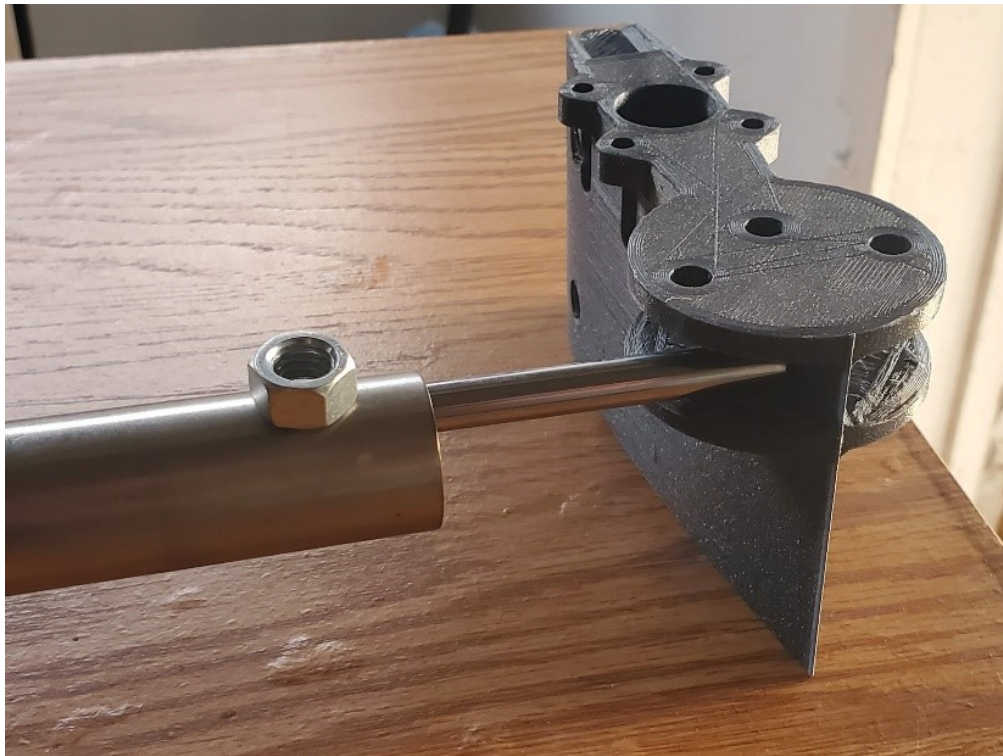
2. Attach rod to each unit on the motor mount with U-pin and lock to itself

Attach hardware for steering system

    1.   Attach adjustment panels to motor mounts with bolts (panel is metal plate with holes equally spaced to attach eyebolts)

    2.   Attach cable tightening mounts to the eyebolts on the adjustment panels

    3.   Attach eyebolts to desired location, ensuring distance from mount is the same for each side by winding two nuts in opposite directions to ensure proper height

    4.   Attach eyebolts to boat frame in mirrored locations through the center of the boat (CAD image with circles showing where to mount) by winding two nuts in opposite directions to ensure proper height

    5.   Mount steering column guide: Two wooden boards with 6-12in between and holes in both for the column to go through both at the same downward angle

<u>Running the cable through the system</u>
1. Mark center of the cable with marker
2. Run cable through the hole in the steering column with equal distance on each side of the hole

3. Rotate one side the cable 8 times around the column in a clockwise direction below the hole and the other side 8 times counterclockwise above the hole

    a. Use vice-grips to keep the one side from unwinding when you wind the other
4. Run the cable coming from the bottom of the hole to the starboard side of the boat and the cable from the top of the hole to the port side of the boat and through the respective eyebolts on each side
5. Run the cable through the eyebolts along the boat until it reaches the eyebolt on the adjustment panel
6. Run the cable around the cable tightening mounts through the eyebolts on the adjustment panel
    a. Use vice-grips to keep cable tight through eyebolts
7. Tighten provided cable fasteners to each cable attaching it to itself
8. Use zip ties to attach excess cable to itself