Team Members

Jonathan Cox
William Heinig
Joshua Heansssler
Joshua Schroepfer

Advisors

Dr. Timothy Dewhurst
Dr. Gerry Brown

7 May 2018
I. EXECUTIVE SUMMARY

The two primary goals of the 2018 Solar Boat Team are to compete in Solar Sport One in the Netherlands with the Dutch boat, and to win Solar Splash 2018 with the Solar Splash boat. The goal to compete in the Netherlands carries with it associated goals of achieving stable flight on hydrofoils and maintaining an average speed of 10 m/s over the course of the race. In order to achieve these goals there are a number of objectives that the team must complete.

For the Dutch boat, a large part of the project was working with the electronics systems. A key objective here is to understand the boat’s sophisticated controls which include sensors, controllers, actuators, and a display and data logging unit (Andrew Nelson). Most of these components were in place at the beginning of the year, but not all were functioning as desired. Additionally, an inertial measurement unit (IMU) needed to be added to the boat this year for the purpose of providing the orientation of the boat at a given instant to the flight control system (Andrew Nelson). This is critical to achieving flight on hydrofoils, which greatly reduces drag on the boat. In order to achieve stable flight, we needed a flight control system as well (Andrew Nelson). This system is responsible for controlling the movement of the hydrofoils based on the orientation and height of the boat in order to maintain stable flight.

Being able to meet our target average speed is also dependent upon a well-designed energy management system (EMS) (Jonathan Cox). The purpose of such a system is to compute the optimum speed for the boat to run given the remaining stored energy in the batteries, estimated solar input for the remainder of the race, and the remaining distance to travel in the race.

A major component influencing the performance of the boat is the interaction of the hull and hydrofoil assemblies with the water, namely their drag. For efficient operation we needed to know what the drag was at a given speed for both hull-borne and hydrofoil flight conditions. While we do have some values from computer models and testing data from previous years, these values needed to be verified with experimental data (Josh Heanssler). We also needed an efficient and powerful propulsion system. This relates directly to Will Heinig’s responsibility of tuning our drive motor and motor controller and determining their peak efficiency operating points. It also involved Josh Schroepfer’s work in designing and manufacturing propellers that provide the necessary thrust and are efficient at the desired speed. This speed is determined primarily by the optimum speed of the motor, and the propellers will be designed for this speed.

For the Solar Splash boat, there are two main improvements that need to be made in order to stay ahead of the competition. Testing the existing solar cells determined we need newer, better performing solar panels (Jonathan Cox). We chose to replace the old panels with our new Solbian panels. Secondly, we aimed to design a new drivetrain capable of performing well for both the sprint and endurance portions of the Solar Splash race (Will Heinig). This will reduce the weight of the boat by eliminating the need for two separate drivetrains.

Additionally, one of the overarching accomplishments was the development of a data acquisition (DAQ) system capable of reliably recording data for each of the solar, drag, and thrust tests (Josh Heanssler). The new DAQ system is capable of recording more than fifty data points per second and now allows the team to record data while on or off the boat. Making the DAQ system mobile was one of our big specifications for it.

The team has made progress in each of these areas of focus. While flight on hydrofoils has not been achieved yet, an understanding of the electronics systems and programming has been gained, and the IMU was fully integrated with the rest of the sensors and now operates correctly and outputs accurate roll and pitch data. Codes have been written to parse the serial
data packets from the IMU to engineering values. A flight control system has been developed in Simulink. However, we have not tested the boat to fly on the system.

Numerous solar test have been performed and an energy management code has been written. This work has shown our Solbian solar panels output 99% of their rated value and justifying the decision of replacing the Solar Splash boat’s solar panels and building a new deck to hold the Solbian solar panels.

A test setup for drag testing was designed, built, and calibrated. It was used on the lake to measure the drag force on the hull at different speeds. The data collected read 12% less hull drag than the previous years’ tests and our drag force at design take off speed of 6.1 m/s was 350 N, which is low enough to achieve flight.

We made progress in understanding the operation of the dynamometer we use for motor testing. We made improvements to the software user interface, DYNOMax, to provide a clear representation of the torque and speed parameters. Additionally, we designed, implemented, and calibrated a test setup suitable for determining the thrust produced by forward facing contra-rotating propellers. Finally, we designed a new drivetrain for the Solar Splash boat and are in the process manufacturing it.
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III. PROJECT GOALS AND OBJECTIVES

The overall goal of the 2018 Cedarville University Solar Boat team is to fly the Dutch boat at an average speed of 10 m/s with stable flight and a functional Energy Management System in order to win the Solar Sport One races in the Netherlands and Monaco. Our other goal is to win the 2018 Solar Splash competition by making improvements to that boat.

All of our project specifications and constraints stem from our power budget. If the motor achieved three or four percent higher efficiency than anticipated, but the propeller was ten percent below its goal, the entire system will fail. Therefore, as we work towards our team’s overarching goal, our individual sections will have to be within specification.

These goals lead to the following team objectives:

- To implement a flight control system for the Dutch boat capable of sustaining stable flight on hydrofoils.
- To verify that the propellers can produce enough thrust to overcome the actual drag force on the boat by comparing its predicted drag to experimentally determined drag values.
- To make propellers that meet new performance parameters specified in the power budget.
- To design and build a new single drive train for the Solar Splash boat for both Sprint and Endurance races.
- To determine the most efficient operating conditions in the Joby electric motor and RoboteQ motor controller.
- To design and build a new data acquisition system that is portable, water and shock proof, and capable of acquiring analog, digital, and CAN signals as well as operational with other components external to the boat for the testing apparatus.
- To ensure the communication system is sufficient to provide data to the flight control system, energy management system, and data acquisition system. This means that height, IMU, GPS, BMS, and motor signals must be on the CAN bus.
- To create a functional Energy Management System for the Dutch solar boat.
- To know the solar power available at different times of day and different weather conditions for both the Solar Sport One and Solar Splash competitions.
- To know the state-of-charge of the batteries at any moment for optimal battery use in the races.
- To provide a pilot interface with mapping and GPS information.

IV. CURRENT DESIGN AND PROBLEM DEFINITION

A. Electrical System

1) Current Design: The electronics system on the boat consists of a network of sensors and controllers connected via a Controller Area Network (CAN) bus. The sensors load signals onto the bus, which can be displayed by the VeeCAN display and data logging unit. The main system controller, a Parker CM0711, can also interface with the CAN bus and is responsible for some of the control logic.

2) Analysis of Design Concepts: The system from last year was functional and worked well for competition, however, there are a few areas that should be improved or modified for the 2018 competition. First, the display screens on the VeeCAN display unit need to be updated. Also, we desire to display higher resolution on our battery voltage to provide better insight into our battery
status and draw down rates during competition. Finally, when the motor controller for the new drivetrain is implemented (discussed in sections F and G) the controller will need to be incorporated into the existing electrical system.

3) Design, Testing, and Evaluation: While most of this year’s electronics development has been for the Dutch boat, much of it is transferable to the Solar Splash boat. Some of the same display screens will be used for Solar Splash with only slight modifications. Also, the motor controller for the new Solar Splash drivetrain is the same controller we use in the Dutch boat. This means that the programming and control electronics can be directly transferred. Testing is still underway to determine whether an analog, PWM, or CAN signal is the most reliable way to run the motor controller.

B. Data Acquisition System

1) Current Design: Past years’ teams have used different electronic methods of data collection, depending on the application or test being performed. For on-board DAQ, last year’s team used a USB memory stick connected to the VeeCAN. Since the VeeCAN is connected to the CAN bus, it can take the CAN data and save it to a flash drive via its USB 2.0 port. The data is saved as a text file with each CAN message listed.

2) Analysis of Design Concepts: There is a need for a box that is well documented and can be used for all external tests we need to do on the boat that excludes internal systems already connected to the CANBus.
   - The DAQ must be portable, meaning it has its own power supply, does not need to be connected to a host computer, must have the quality to be transported easily, and can be implemented in any boat we need to test either in the shop or on the water.
   - The DAQ must be water and shock proof because it will be used for on-water testing.
   - The DAQ must be capable of collecting data in analog, digital, or CAN format and store it in a useable manner.

3) Design, Testing, and Evaluation: In the final schematic, Fig. 1, all the individual wires have been added as well as the terminal strips, to organize all the signals, and a CAN terminator was built to facilitate the return of information along the CANbus. The IMU, and a 12V battery, are all housed in the box, making it portable. Two DB9 connectors were added to connect the Yokogawa ScopeCorder to the DAQ box so that the VeeCAN can log the data on the CANbus and can program the Parker module easily. In addition, a GPS sensor was included that will send real time positioning and speed, through the CANbus to the VeeCAN. The final addition was that the box works with the Roboteq by adding a pull down resistor and had all the inputs and outputs going through the VeeCAN instead of the Parker for better signal resolution and accuracy.

   Accompanied with that box was the separate external testing schematics that needed to be created at the same time for the tests to work. These test schematics were designed to utilize the functionality of the aforementioned DAQ box. The difference between the tests is in the program that is running on the VeeCan display unit.
Figure 1. The Data Acquisition system electrical schematic (Final Version).
C. Solar System

1) Current Design: The primary goal of a solar panel test is to obtain the maximum power a panel can output and then compare that value to what should be its nominal value. We tested the current Solar Panel System to determine the efficiency of the panels. The Solar Splash Deck has three separate panels on it. Panels #1 and #2 didn’t have any obvious issues in the data. However, they were underperforming since they only output 200 W at one-sun-conditions when they should have output 300 W. In our testing we found out that a solar panel cell in Panel #3 was broken. If a single solar panel cell breaks, it begins limiting the current that can be produced by the entire panel. Bypass diodes are placed on groups of cells to prevent any further effects when a cell breaks. The diode will allow the current to bypass the broken group of cells. This allows the short circuit current of the solar panel to increase which restores some of the panel power, however due to the decreased number of cells, the panel outputs less power than its nominal rating.

2) Analysis of Design Concepts: The Solar Panel Array will be considered functional if it can output at least 95% of the 480 Watts limit in the Solar Splash rules. We conducted a solar test on one of our Solbian panels to see if it was performing correctly. The Solbian panel output 124 W in one-sun-conditions, which is extremely close to its 125 W rating. Since Solar Splash Deck had the problems with the bypass diode and our Solbian panels are functional, we concluded that we would retire the current Solar Splash Deck Panels and we would begin using our Solbian Solar Panels for the Solar Splash boat.

3) Design, Testing, and Evaluation: Since the Solbian panels are flexible and don’t fit on the current deck, we decided to design and build a new and lighter support for them.

First, we considered the layout for the panels. We concluded that we did not want a panel in front of the pilot because it would overhang too much due to its size and the location of the pilot. Therefore all four Solbian panels (three 125 W and one 100 W panels) needed to be placed on the back half of the boat. The layout with the least overhang was selected, as it best protects the panels and allows for a simple support system. The selected layout is shown in Fig. 2.

Figure 2. Final Layout for the Solbian Solar Panels on the Solar Splash Deck

Second, we considered the design of the support for the selected layout. We decided that a lightweight wooden frame with a one inch crown would be easy and quick to build, provide stiffness to the panels to prevent sagging, and still be lighter than the current deck. We created a support for a single panel to see how well it worked. After finishing, observing, and critiquing it, we slightly changed the design of the support, decided to create wooden I-beams for increased...
stiffness, and changed the kind of wood to decrease the weight of the support. This is shown in Fig. 3.

![Figure 3. Final Design for the Solar Splash Solar Panel Mounting System](image)

D. Battery System

1) Current Design: The setup for the battery test is similar to the solar panel setup. We use a load bank to draw variable battery current, and a data acquisition system. Most battery tests are conducted in order to know the battery’s Amp-hour rating. This varies a lot for each battery depending on the current drawn from the battery the minimum voltage is reached. For example, if ten amps are drawn from the battery for one hour and then it reaches \( V_{\text{min}} \), it has a 10 Ahr rating for a C1 test (C1 meaning it was an hour test). Similarly it could be a C5 test, which is five hours long, and the Amp value would be similar, but the overall energy output of the battery will be larger than the C1 test because batteries are more efficient outputting power slowly.

2) Analysis of Design Concepts: We will design a new Data Acquisition System to work for both the battery and solar panel testing (and other tests). The DAQ System needs to be able to draw up to 60 Amps and 12 Volts to model race conditions for the Solar Splash endurance race.

3) Design, Testing, and Evaluation: We needed a new way to perform current draw down tests on our batteries. Knowing that we needed to do various tests on several systems for both of our solar boats, we included battery tests in our design for the solar tests. The only difference is that the batteries are connected to the power and ground wires of the load bank instead of the solar panel. Detailed test procedure is given in Appendix F.

E. Energy Management System

1) Current Design: Currently to determine the speed required to utilize the power in the batteries, we relay information to the team on shore for them to calculate a change in speed to reserve more or less energy.

2) Analysis of Design Concepts: An Energy Management System (EMS) is a system that optimizes energy use of the solar boat. It does this in three steps. First, it evaluates how much total energy is available from the batteries and power from the solar panels. Second, it calculates how much energy will be used at different speeds (depending on drag forces, efficiencies in the solar boat system, and how much distance is left in the race). Finally, it outputs the speed at which the boat should operate at any given moment, in order to achieve the highest speed without depleting all of its energy prior to finishing the race.

We will consider the EMS to be successful if the boat has the desired amount of energy by the end of the race. For an endurance race we will give it the specification of using 98% of its
available energy. This may seem like a lot, but in a two hour race, drawing 95% instead of 100% of the energy means we could go another six minutes without running out of energy.

The overall concept for the EMS design is very simple. By knowing the distance remaining for a race \( D \) and the amount of drag corresponding to different speeds \( N \) we can calculate how much energy we will use at a constant speed to finish the race. Maintaining a constant speed throughout the entire race is the most efficient way to race and it is the quickest way to reach the finish line for a given amount of energy.

3) Design, Testing, and Evaluation: If the energy is within the specifications (2-5% or less of full battery capacity depending on the type of race), then our target speed is good and should be maintained. Fig. 4 shows a simple flowchart of this algorithm.

![Simple flowchart of the EMS program](image)

Fixed time races have the same process with just one added step. Since we know the duration of the race, we can assume a speed with which we calculate how far we will go during that time. Again, using our drag and speed we can calculate how much energy will be consumed during that time and the program will iterate to find the maximum speed we can go.

Right now, we are figuring out how to transfer the EMS code from MATLAB to C code so it can be put onto the Nexus 7 Tablet. Once the EMS is on the tablet and the Dutch boat is in the water, we will create different race scenarios and track our distance and energy remaining to test the EMS functionality on the Tablet. Once this is finished the specifications for a functional EMS will be complete.

F. Power Electronics

1) Current Design: On the software side, we are using Land & Sea’s DYNOmax software package. The Etek is a brushed DC Motor that previous Solar Boat Teams have used. The Etek is controlled by a Sevcon MillipaK DC motor controller. To control the Joby, we are using a RoboteQ motor controller that converts DC current and voltage into 3-phase AC power. This combination for motor/motor controller will yield a more tunable (and therefore potentially more powerful and efficient) drivetrain than systems in previous years for competition in the Netherlands/Monaco.

We need to properly program and tune the RoboteQ in order to maximize the possible motor efficiency. To program the motor controller, we must use RoboteQ’s proprietary programming language and software, MicroBasic and RoboRun+, respectively.
IV. CURRENT DESIGN AND PROBLEM DEFINITION

2) Analysis of Design Concepts: One challenge that faces us is getting the time-based data (torque, rotational speed, and 3 phase currents and voltages) measured on the same machine in the same It is imperative that we develop a method to do that to ensure that we can make the most accurate efficiency calculations as possible. Currently, we record torque and rotational speed with the dyno, and 3 phase currents and voltages must be measured with the Yokogawa ScopeCorder, as seen in Fig. 5.

![Figure 5. Power and Data Flow for Motor Efficiency Testing](image)

3) Design, Testing, and Evaluation: Last year’s team had to command the speed on the dyno and change the motor throttle input to make the motor work harder to get the desired torque. That method was an indirect method of getting the data needed for power calculations, so we decided to change the way we would control the motor and dyno for efficiency testing. This more direct method is to make the dynamometer control torque and make the input to the motor control speed.

Last year’s team had difficulties measuring the electrical power. The current sensor in the RoboteQ controller was not accurate and when used in efficiency calculations, gave values over 100%. They were also not able to measure three phase power supplied to the Joby BLDC motor from the RoboteQ motor controller because they did not have the necessary specialized instrumentation.

The results of these tests enable us to know what torque and speed to run the motor at, depending on the race event. We need to run the motor in a region of peak efficiency for the Sprint race, and we need to run the motor in a region of peak power for the Sprint race.

The torque and speed channels originate from an S-beam load cell and a Hall Effect speed sensor on the dynamometer, respectively.

The DYNO-Max PC software is unable to output real time signals for any channels, so we must pull the needed channels off in between the sensor harness and the data computer. To get the torque and speed channels into the Yokogawa, we designed what we call the “DAQ Hijack” box.
IV. CURRENT DESIGN AND PROBLEM DEFINITION

Fig. 6 (top waveform) and 7 (bottom waveform) show the load cell response (from the op-amp in the DAQ Hijack Box) to an applied positive and negative loading. The test in Fig. 6 was performed before changing the gains of the op-amp (resulting saturation or flat-lining) and before the Reference Voltage Offset Device was installed (resulting in only positive op-amp output). After making those changes, the output for the torque signal is representative of both positive and negative loads, and it does not saturate under load, as seen in Fig. 7. These results from the op-amp with the Reference Voltage Offset Device and smaller gain resistors show that these signals will be readable on the Yokogawa.

Figure 6. Top Trace: Op-amp Output Before the Use of the Reference Voltage Offset Device and Smaller Gain Resistors (thus only positive signal and saturation are present in this trace).
IV. CURRENT DESIGN AND PROBLEM DEFINITION

Figure 7. Bottom Trace: Op-amp Output After the Use of the Reference Voltage Offset Device and Smaller Gain Resistors (thus both signals correlating to positive/negative loads are present in this trace and no saturation).

G. Drivetrain and Steering

1) Current Design: Our current set up for Solar Splash consists of two separate drivetrains for the Sprint and Endurance events. The Sprint drivetrain consists of two Agni electric motors connected to the driveshaft via a speed-increasing belt drive with a rear facing, 4 blade, 11” diameter propeller. The Endurance drivetrain is a CU custom motor that is inside of a submerged pod attached to the down leg, with a front facing, 2 blade, 18” diameter propeller.

2) Analysis of Design Concepts: The reason we wanted to make a new drivetrain for the Solar Splash boat is to have a single drivetrain for both the Sprint and Endurance races. This allows us to not have to carry two drivetrains (Sprint and Endurance) for both races, thus saving approximately 70-90 lb. The drivetrain should be more efficient and lighter weight. The challenge here is that we need the single drivetrain to be efficient enough for the Endurance race, but still be powerful enough for the Sprint race.

3) Design, Testing, and Evaluation: The new drivetrain is a direct drive design, and should be more efficient than the previous belt drive design. To reduce drag on the submerged portion of the drivetrain, we designed the drivetrain in SolidWorks (Fig. 8) and performed SolidWorks Flow Simulator CFD Analysis on potential profiles that would be submerged in the water during a race. The results suggested that we chose the Yamato design for the outer shape of the down leg. We have started manufacturing some components and hope to use some existing components (transom swing arm mount, Yamato LGU, and Joby Motor).

To change drivetrain set-ups for Sprint/Endurance races, we will change the propeller and adjust the drivetrain depth in the water and angle from the transom.
IV. CURRENT DESIGN AND PROBLEM DEFINITION

Figure 8. SolidWorks Model – Solar Splash Drive Train – Section View (Omitting Drive Shaft for Clarity)

H. Propellers

1) Current Design: We use a computer program, Open Prop, to do a full analysis of a propeller; this includes a performance prediction at various operating conditions and a stress analysis. This design can be imported into Solid Works for modeling. This allows us to simulate a multitude of operating conditions the propeller will experience. Both boats are using propellers made using this software program.

2) Analysis of Design Concepts: The performance specifications for our propellers are as follows

1. Operate at the 85% efficiency or higher
2. Produce enough thrust at cruise speeds to fly the boat on hydrofoils. The Thrust requirement will be determined through drag testing of the DSC Hull and hydrofoil system
3. Run with no cavitation

To design a propeller we first need to know our motor’s operating power from the power budget. We will then look at our dyno data to determine the speed and torque range where the motor operates at peak efficiency for this power. This data will be inputs into Open Prop’s
parametric program. Once the data is recorded we run another analysis using a different speed and torque combination while still operating at the same motor output power as before.

3) **Design, Testing, and Evaluation:** After finding a range of propeller diameters that meet our efficiency specifications, we can take a propeller diameter and input it into Open Prop. This program contains inputs for the propeller diameter, input power, boat speed, and propeller geometry. The blade design values are used to generate geometries for both propellers. Open Prop then determines the thrust, efficiency and other performance characteristics of the propeller.

Once we have a propeller that meets the thrust requirements, we performed cavitation analysis to ensure the propeller will not experience cavitation.

Once we have a finalized design we need to determine how the propeller will perform at operating conditions different from its design specifications. This is important because we want the propeller to be efficient at a variety of operating points. Open Prop has an off design analysis feature which generates performance curves based on the advance coefficient Js.

These values are critical in that they allow us to determine the thrust and efficiency at different operating points for a propeller design. When evaluating a propellers performance at off design specifications we first need to determine the propellers operating speed and boat speed. This gives us the advance coefficient (Js). The advance coefficient determines the propellers thrust coefficient (Kt) and efficiency. Once we have the thrust coefficient we can determine if the specified operating point will produce the required thrust and the desired efficiency.

In order to evaluate our propeller designs we needed to find a way to determine the thrust on generated by the propellers and be able to compare this to the predicted performance specifications from Open Prop. To test our propellers we applied 8 strain gages to a contra-rotating drivetrain. The installation process of the strain gages is shown in Appendix J.1. The strain gage calibration procedures and data are shown in Appendix J.1.

**I. Hull Design**

1) **Current Design:** The existing design for the Solar Splash hull shape is very good and will not be modified. The current hull is designed to be a planing hull for the Sprint event, and a displacement hull for the Endurance Event. In 2014 the team manufactured a hull using a Kevlar shell and a honeycomb core. Analysis indicated that a 1 inch core was sufficient to meet the strength and stiffness requirements. Also, by using core we are able to meet the Solar Splash buoyancy requirements without using bulkheads or other means of buoyancy. Buoyancy calculations, showing that our hull meets Solar Splash regulations, are provided in Appendix C. Additionally, we used wooden gunnels for increased stiffness, aesthetics, and to provide a means of attaching the steering system and deck. The current hull weighs just under 70 lb (311 N). Two-phase flow Fluent analysis was completed for the 2014 hull. However, we had no real testing capabilities to measure actual drag on the hull during competition.

2) **Analysis of Design Concepts:** The existing design for the Solar Splash hull shape will not be modified this year. We did develop a new testing procedure that will allow for the hull drag verification. We built a mount for the bow that connects load cells to both the bow and a cable. The cable is then attached to another boat and pulled through the water at different speeds. The load cells will measure the tension in the cable. This cable tension is equal to the drag force on the hull as it moves through the water. This testing procedure has proven effective.

3) **Design, Testing, and Evaluation:** This past year we have been able to run several of these tests on one of our hulls. These tests can be used in the future for any new hull designs and
continued characterization of the current hulls used at Cedarville. Fig. 9 shows the results of testing the hull for our DSC boat. The same procedure can be used for future Solar Splash hulls.

Figure 9. 2018’s team Hull Drag Test (run 1, 2, 3) data after reduced (42 foot rope, balanced mass).
V. PROJECT MANAGEMENT

J. Team Organization
Cedarville University’s Solar Splash teams have primarily been composed of senior mechanical engineering students as part of their capstone courses, Mechanical Engineering Senior Design I and II. The team was split up into 11 sub teams focused on our work with the DSC boat that we will apply to the Solar Splash boat. Nine of those teams will contribute to changes in the Solar Splash boat.

- Electrical
  - Control Systems
  - Data Acquisition
  - Solar Testing
  - Solar Panel Mounting
  - Energy Management System
- Motors
  - Motor Testing
- Propulsion
  - Drive-Train Design
  - Contra-rotating Propellers
  - Hull Testing

The whole team met for two hours each week with the faculty advisors to discuss progress. Our team is advised by two faculty members: one mechanical engineer and one electrical engineer. In a paper written by our faculty advisors, Dewhurst and Brown (2013), they explain their approach to advising in light of three different educational models: the teacher-student model, the manager-engineer model, and the master-apprentice model. They attribute much of the solar boat team’s past success to the mentoring—which balances different aspects of each of these three types of relationships—that they have provided as faculty to students on the solar boat team.

K. Project Planning and Schedule
We organized this year’s team in August 2017 and each team member decided on measureable individual milestones to track their progress.

L. Financial and Fund-raising
The Cedarville University engineering department provides our team with a budget to complete some design work and fabricate and/or purchase components and parts. This year, very little money has been spent on the Solar Splash boat. The major purchases for the boat are aluminum stock for machining drivetrain components, a new VeeCan display, a new Parker programmable controller, and a Yokogawa ScopeCorder.

M. Continuity and Sustainability
Team continuity remains a challenge for Cedarville’s Solar Splash teams. Since the project is part of a capstone course, there are few underclassmen who remain involved in the project throughout the year. The most important means of project continuity has been the shared network drive that enables each team to access work completed by previous teams. It helps maintain research, contacts, part specifications, reports, and test data, passing all of the
information from team to team. The end-of-the-year reports are especially useful as a summary of work completed as well as the extensive appendices detailing specific work.

N. Self-Evaluation

This year, we have been able to meet most of our goals for both the DSC boat and the Solar Splash boats. Throughout the year our team focused on creating tutorials, maintaining the network drives to decrease clutter, and organizing our work in a concise and straightforward manner so that next year’s team can also have significant progress as they begin this project. We are satisfied with where our project is and believe we will do well against our competition again this year.
VI. CONCLUSIONS AND RECOMMENDATIONS

N. Conclusions
The following discussion addresses our overall project strengths and weaknesses from this year:

Strengths:
- We have added a new way to mount solar panels that will decrease weight and increase solar capture.
- The new manufacturing software cuts down propeller creation time by one-third.
- The new dynamometer allows us to develop motor curves for any of the many types of motors we use for the Cedarville Solar Boat Team.
- The new electronics and data acquisition system developed gives us reliability, control that can continue forward into future years and competitions.
- The switch to Solbian solar panels increase the efficiency of our solar array.

Weaknesses:
- Our work on the DSC boat has made it difficult to make many improvements to the Solar Splash boat, but much of the work done is applicable and can make significant improvements to the Solar Splash boat.

O. Summary of Goal Completion
Our goal is to win the 2018 Solar Splash Challenge and prepare next year’s team for the 2019 DSC. These objectives were used to set individual system goals.
- We have developed an electrical system which includes data logging, motor control, and a driver interface.
- We have improved the machining process for making designed propellers for competition.
- The new dynamometer testing setup allows for motor and drivetrain testing any type for future design.
- We can receive data for a number of tests.
- We have a functional energy management system.
- We can now measure the hull drag generated at a range of speeds.
- The drivetrain will be replaced with a lighter one that is multi-functional.

P. Where do we go from here?
Our team has made significant progress refining the 2017 boat. We are close to achieving stable flight on hydrofoils with our DSC boat. Once this is reliable, we plan to implement this technology on our Solar Splash boat

Q. Recommendations
- Future teams must continue to document and annotate their work: part design files, analysis work, test procedures, test data, and user guides for each process. Good documentation greatly helps future students understand the work already completed.
- At the beginning of the year, set goals that advisors think are realistic: teams may have to underestimate what they think they can complete. Once those deadlines are in place, resolve to follow them as closely as possible.
- Continue improvement of the electrical system
• Spend time understanding how the electrical systems work to come up with new improvement ideas.
• Ask questions immediately when relevant so that the ideation process begins sooner.
• Meet personally with each advisor throughout the week for advice.
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T:\Engineering Competitions\SOLAR BOAT\2015-2016\2. Solar Panels\Previous Years' Work\Joel Dewhurst
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Appendix A – Battery Documentation (Rule 7.10.2)

This year we will be utilizing one of each battery pack that has been used in the past. A set of three Genesis 42EP batteries weighting 32.9 lb (14.9 kg) each giving us a total weight of 98.34 lb (44.7 kg) for the first set. The second set we will use the Genesis 13EP batteries, each weighing 10.8 lb (4.9 kg); we will use 9 of these for the second set of batteries for a total weight of 97.2 lb (44.1 kg). This is in compliance with the new Solar Splash rule 7.4.1 having both of the battery sets under the 100 lb (45.5 kg) limit.

The specification and MSDS sheets for these two types of batteries, which were selected from the available batteries provided by Genesis as shown in Fig. A.1, are on the following pages in Fig. A.2.

<table>
<thead>
<tr>
<th>GENESIS PRODUCT FAMILY (All capacities at 10 hr. rate 25°C to 1.67 vpc)</th>
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</thead>
<tbody>
<tr>
<td><strong>GENESIS EP-</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Product (capacity)</th>
<th>Part Number</th>
<th>Internal res. of fully charged battery via 25°C</th>
<th>Nominal short circuit current for charged battery</th>
<th>Length in. (mm)</th>
<th>Widths in. (mm)</th>
<th>Weight in. (mm)</th>
<th>Weight Lb. (kg)</th>
<th>Brass Terminal (metric)</th>
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<td>G13EP</td>
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<td>G13EPX</td>
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<td>(165.15)</td>
<td>(176.02)</td>
<td>(25.4)</td>
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</table>

**Figure A.1. Genesis 13EP and Genesis 42EP Battery Specifications**
Section I - Product and Manufacturer Identity

Product identity:
Sealed Lead Battery
Cyclon®, Genesis®, SBS, SBS J, Hawker XE™ Odyssey® or Trolling Thunder™

Manufacturer's Name and Address:
EnerSys Energy Products Inc. (formerly Hawker Energy Products Inc.)
617 North Ridgeview Drive
Warrensburg, MO 64093-9301
Emergency Telephone Number: (660) 429-2165
Customer Service Telephone Number: 800-964-2837

Section II – Ingredients

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<th>Hazardous Components</th>
<th>CAS #</th>
<th>OSHA PEL-TWA</th>
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<tr>
<td>Lead</td>
<td>7439-92-1</td>
<td>50µg/m³</td>
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<td>Lead Dioxide</td>
<td>1309-60-0</td>
<td>50µg/m³</td>
<td>15 - 25 %</td>
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<tr>
<td>Sulfuric Acid Electrolyte</td>
<td>7664-93-9</td>
<td>1.0 mg/m³</td>
<td>15 - 20 %</td>
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<td>Non-Hazardous Materials</td>
<td>N/A</td>
<td>N/A</td>
<td>5 - 10 %</td>
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</table>

Section III - Physical/Chemical Characteristics

- Boiling Point - N/A
- Specific Gravity (H2O=1) - NA
- Vapor Pressure (mm Hg.) - N/A
- Melting Point - N/A
- Solubility in Water - N/A
- Appearance & Color - N/A

Section IV - Fire & Explosion Hazard Data

- Flash Point (Method Used): N/A
- Flammable Limits: N/A
- LEL: N/A
- UEL: N/A

Extinguishing Media:
Multipurpose Dry chemical, CO2 or water spray.

Special Fire Fighting Procedures:
Cool Battery exterior to prevent rupture. Acid mists and vapors in a fire are toxic and corrosive. Unusual Fire and Explosion Hazards: Hydrogen gas may be produced and may explode if ignited. Remove all sources of ignition.

Section V - Reactivity Data and Shipping/Handling Electrical Safety

Conditions to Avoid: Avoid shorting, high levels of short circuit current can be developed across the battery terminals. Do not rest tools or cables on the battery. Avoid over-charging. Use only approved charging methods. Do not charge in gas tight containers.

Requirements for Safe Shipping and Handling of Cyclon® Cells: Warning – Electrical Fire Hazard – Protect Against Shorting

- Terminals can short and cause a fire if not insulated during shipping.

Figure A.2. Enersys and Odyssey MSDS Sheets (1 of 3).
- Cyclon® product must be labeled “NONSPILLABLE” during shipping. Follow all federal shipping regulations. See section IX of this sheet and CFR 49 Parts 171 through 180, available anytime online at www.gpoaccess.gov.

Requirements for Shipping Cyclon® Product as Single Cells
- Protective caps or other durable inert material must be used to insulate each terminal of each cell unless cells are shipping in the original packaging from EnerSys, in full box quantities.
- Protective caps are available for all cell sizes by contacting EnerSys Customer Service at 1-800-964-2837.

Requirements for Shipping Cyclon® Product Assembled Into Multicell Batteries
- Assembled batteries must have short circuit protection during shipping.
- Exposed terminals, connectors, or lead wires must be insulated with a durable inert material to prevent exposure during shipping.

Section VI - Health Hazard Data
Routes of Entry: N/A

Health Hazards (Acute & Chronic): N/A

Emergency & First Aid Procedures:
Battery contains acid electrolyte which is absorbed in the separator material. If battery case is punctured, completely flush any released material from skin or eyes with water.

Proposition 65:
Warning: Battery posts, terminals and related accessories contain lead and lead compounds, chemicals known to the State of California to cause cancer and reproductive harm. Batteries also contain other chemicals known to the State of California to cause cancer. Wash hands after handling.

Section VII - Product and Manufacturer Identity
Steps to be taken in case material is released or spilled:
Avoid contact with acid materials. Use soda ash or lime to neutralize. Flush with water.

Waste Disposal Method:
Dispose of in accordance with Federal, State, & Local Regulations. Do not incinerate. Batteries should be shipped to a reclamation facility for recovery of the metal and plastic components as the proper method of waste management. Contact distributor for appropriate product return procedures.

Section VIII - Control Measures - Not Applicable

Section IX - Transportation, Shipping and Handling
EnerSys Energy Products Inc. batteries are starved electrolyte batteries which means the electrolyte is absorbed in the separator material. The batteries are also sealed. As of September 30, 1995, EnerSys Energy Products Inc. batteries were classified as "nonspillable batteries", and as such are not subject to the full requirements of 49 CFR § 173.159. The previous exempt classification, "Dry Batteries, Not Restricted" was discontinued effective September 30, 1995. "Nonspillable" batteries are excepted from the regulation's

Figure A.2 (cont.). Enersys and Odyssey MSDS Sheets (2 of 3).
comprehensive packaging requirements if the following conditions are satisfied: (1) The battery is protected against short circuits and is securely packaged. (2) For batteries manufactured after September 30, 1995, the battery and outer packaging must be plainly and durably marked "NONSPIILLABLE" or "NONSPIILLABLE BATTERY". (3) The battery is capable of withstanding vibration and pressure differential tests specified in 49 CFR § 173.159(d). (4) At a temperature of 55 °C (131°F), the battery must not contain any unabsorbed free-flowing liquids, and is designed so that electrolyte will not flow from a ruptured or cracked case.

EnerSys Energy Products Inc. batteries have been tested by WYLE Scientific Services & Systems Laboratories Group and determined to be in compliance with the vibration and pressure differential tests contained in 49 CFR § 173.159(d), and therefore as of September 30, 1995, excepted from the DOT requirements set forth in 49 CFR § 173.159, other than paragraph (d).

Battery shipments from EnerSys Energy Products Inc. Warrentsburg location, will be properly labeled in accordance with applicable DOT regulations.

**Packaging changes performed at other locations may require additional labeling, since in addition to the battery itself containing the required marking, the outer packaging of the battery must also contain the required marking: "NONSPIILLABLE" OR "NONSPIILLABLE BATTERY".** Because the batteries are classified as "Nonspillable" and meet the three conditions above, [from § 173.159(d)] they do not have an assigned UN number nor do they require additional DOT hazard labeling.

The regulation change effective September, 1995, was to clarify and distinguish to shippers and transporters, all batteries that have been tested and determined to be in compliance with the DOT Hazardous Material Regulations, the International Civil Aeronautics Organization (ICAO), and the International Air Transport Association (IATA) Packing Instruction 806 and Special Provision A67, and therefore excepted from all other requirements of the regulations and classified as a "nonspillable battery".

Per 42 USC Section 14322 (US Code Title 42 – The Public Health and Welfare), packaging must be marked with the following: "Contains Sealed Lead Battery" and "Battery Must Be Recycled".

**Section X - Additional Information**

The EnerSys Energy Products Inc. sealed lead acid battery is determined to be an "article" according to the OSHA Hazard Communication Standard and is thereby excluded from any requirements of the standard. The Material Safety Data Sheet is therefore supplied for informational purposes only.

The information and recommendations contained herein have been compiled from sources believed to be reliable and represent current opinion on the subject. No warranty, guarantee, or representation is made by EnerSys Energy Products Inc., as to the absolute correctness or sufficiency of any representation contained herein and EnerSys Energy Products Inc. assumes no responsibility in connection therewith, nor can it be assumed that all acceptable safety measures are contained herein, or that additional measures may not be required under particular or exceptional conditions or circumstances.

N/A or Not Applicable - Not applicable for finished product used in normal conditions.

Informational MSDS Part Number 2602-0043 Rev. 2 (09/07/06)

**Figure A.2 (cont.).** Enersys and Odyssey MSDS Sheets (3 of 3).
Appendix B – Flotation Calculations (Rule 7.14.2)

The surface area of the new hull which utilizes 1 layer of 1.25 inch of Nomex honeycomb is 65.0 ft$^2$ and the surface area which utilizes 2 layers of 0.472 inches of Nomex honeycomb is 7.1 ft$^2$. Thus, the buoyant force provided by the hull alone, neglecting the Kevlar skins is given by the following.

$$B_H = \left( \sum_{i=1}^{n} A_i t_i \right) \rho_{water}$$

$$= \left( 65.0 \text{ ft}^2 \times 1.25 \text{ in} \times \frac{\text{ft}}{12 \text{ in}} + 7.1 \text{ ft}^2 \times 2 \times 0.472 \text{ in} \times \frac{\text{ft}}{12 \text{ in}} \right) \frac{62.4 \text{ lb}}{\text{ft}^3}$$

$$= 468 \text{ lb}$$

Where $B_H$ is the buoyant force on the hull when submerged, $A_i$ is the surface area covered by a given core thickness, $t_i$ is thickness of the core in a given region, and $\rho_{water}$ is the density of water. Because the batteries are secured to the hull, their buoyant force also contributes the overall buoyant force on the boat. The volume of 3, 42 EP batteries is less than that of 12, 13 EP batteries, and will therefore be used for our calculations.

$$B_B = 3V_{42EP} \rho_{water}$$

$$= 3 \times 0.175 \text{ ft}^3 \times 62.4 \frac{\text{lb}}{\text{ft}^3}$$

$$= 33 \text{ lb}$$

Where $B_B$ is the buoyant force of the batteries and $V_{42EP}$ is the volume of the Genesis 42EP batteries. Therefore, the maximum possible buoyant force exerted on the hull is given by the following.

$$B_{tot} = B_H + B_B$$

$$= 468 \text{ lb} + 33 \text{ lb}$$

$$= 501 \text{ lb}$$

Also, the weight of the hull, as given by the power budget is shown in Table B.1. Based on our calculations, our new hull can easily support its own weight plus a 20% safety factor as the buoyant force of 501 lb is much greater than the required buoyant force of 370 lb.
### Table B.1. Weight Budget for 2018 Solar Splash Boat

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<tr>
<th>Components</th>
<th>2014 Sprint</th>
<th>2014 Endurance</th>
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<tr>
<td>Batteries</td>
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<td>100</td>
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<tr>
<td>Sprint Drivetrain &amp; Controllers</td>
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<td><strong>370</strong></td>
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### Certificate of Liability Insurance

**Certificate of Liability Insurance**

This certificate is issued as a matter of information only and confers no rights upon the certificate holder. This certificate does not constitute a contract between the issuing insurer(s), authorized representative or producer, and the certificate holder.

**Important:** If the certificate holder is an additional insured, the policy(ies) must be endorsed. If subrogation is waived, subject to the terms and conditions of the policy, certain policies may require an endorsement. A statement on this certificate does not confer rights to the certificate holder in lieu of such endorsement.

**Producer:**

Wallace & Turner, Inc.
P.O. Box 209
39 Warder Street #209
Springfield, OH 45501-0209
Patrick E. Field

**Contact:**

Patrick E. Field

**Insured:**

Cedarville University
251 North Main Street
Cedarville, OH 45314

**Insurer:**

Cincinnati Insurance Company

**Certification Number:**

ACORD31

**Carrier:**

Mixon

**Date:**

05/31/2018

**Cedar3**

**OP ID:**

CW

**Coverages**

**Certificate Number:**

SIP003158

**Revision Number:**

This is to certify that the policies of insurance listed below have been issued to the insured named above for the policy period indicated. Notwithstanding any requirement, term or condition of any contract or other document with respect to which this certificate may be issued or may pertain, the insurance afforded by the policies described herein is subject to all the terms, conditions and exclusions of policies in such contracts.

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**Description of Operations/Locations/Vehicles**

ACORD 101 (Additional Remarks Schedule, may be attached if more space is required)

Event: Solar Splash 2018 held June 5-9, 2018 at lake adjoining Clark County Fairgrounds, 4401 S. Charleston Pike, Springfield, Ohio 45505

**Certificate Holder:**

SOLAR SPLASH Headquarters
c/o Jeffrey Morehouse, PhD, PE
Mechanical Engineering Dept
309 Newbridge Rd
Lexington, CA 92072

**Cancellation:**

SOLARSP

Should any of the above described policies be cancelled before the expiration date thereof, notice will be delivered in accordance with the policy provisions.

**Authorized Representative:**

Patrick E. Field

**ACORD 25 (2014/01)**

The ACORD name and logo are registered marks of ACORD.
### Appendix D – Team Roster

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<th>Name</th>
<th>Degree/Program</th>
<th>Year</th>
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<tr>
<td>Jonathan Cox</td>
<td>BSME</td>
<td>Senior</td>
<td>Battery and Solar Testing, Solar Panel Mounting, and Energy Management System</td>
</tr>
<tr>
<td>Joshua Heanssler</td>
<td>BSME</td>
<td>Senior</td>
<td>Drag Testing and Data Acquisition</td>
</tr>
<tr>
<td>William Heinig</td>
<td>BSME</td>
<td>Senior</td>
<td>Motor and Controller Testing and Drivetrain Design</td>
</tr>
<tr>
<td>Andrew Nelson</td>
<td>BSME</td>
<td>Senior</td>
<td>Electronics System and Flight Control System</td>
</tr>
<tr>
<td>Joshua Schroepfer</td>
<td>BSME</td>
<td>Senior</td>
<td>Propeller Testing and Manufacturing</td>
</tr>
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</table>
Appendix E - Solar Panel System

Figure E.1. Solar test setup 04-05-18
Solar Test Procedure:

1. Obtain necessary equipment and wiring (box that says ‘Solar Test Wiring’) from the EPL. Refer to the solar test schematic in Appendix N for the necessary equipment and electrical connections for each different test (with or without MPPTs).
   - Necessary Equipment
     - Solar Panel, Load Bank, DAQ Box, Pyranometer, and Fluke 80T-IR
     - Wiring setup dependent on test, all the configurations are in the Solar Panel and Battery Test schematic
2. Confirm the solar test program is flashed onto the VeeCAN. If not, refer to Appendix G.2.
3. Make sure you have a USB flash drive that is empty.
4. Attach desired Solar Panel to the Solar Panel stand. Point panel directly at the sun if you want the most power out of the panel. Otherwise, measure the angle of the sun and then lie the panel stand flat on the ground.
5. Connect all the wires.
6. Turn on the DAQ system, navigate to the solar test option, then plug the USB into the back of the VeeCAN.
7. Turn the knob on the Transistor load bank to ensure the VeeCAN is reading the changing values of voltage and current.
8. If you are ready to begin your test, click start on the VeeCAN.
9. Sweep the current as high as you can (CW) and then sweep it back to zero (CCW). Conduct a complete sweep in approximately 5-10 seconds.
10. Click ‘stop’ on the VeeCAN.
11. If you want to conduct more tests, repeat steps 8-10. Once you are finished with your final test go to step 12.
12. Click ‘eject’ on the VeeCAN.
13. Remove the USB from the VeeCAN.
14. Plug the USB into the blue cart computer.
16. Select the DBC file and click the green arrow in the middle of the screen.
17. Load your solar test.
18. Click ‘convert to CSV file’
Appendix F - Battery System
Battery Test Procedure:
1. Obtain necessary equipment and wiring (box that says ‘Solar Test Wiring’) from the EPL. Refer to the solar test schematic in Appendix N for the electrical connection for the Battery test.
   a. Necessary Equipment
      i. Battery, Load Bank, and the DAQ Box.
      ii. Wiring setup dependent on test, all the configurations are in the Solar Panel and Battery Test schematic
2. Confirm the solar test program is flashed onto the VeeCAN. If not, refer to Appendix G.2.
3. Make sure you have a USB flash drive that is empty.
4. MAKE SURE THE TRANSISTOR LOAD BANK SWITCH IS TURNED TO BATTERY MODE not solar mode.
5. TURN THE KNOB ON THE TRANSISTOR LOAD BANK ALL THE WAY COUNTER-CLOCKWISE PRIOR TO CONNECTING THE BATTERY.
6. Connect all the wires.
7. Turn on the DAQ system, navigate to the solar test option, then plug the USB into the back of the VeeCAN.
8. Turn the knob on the Transistor load bank to ensure the VeeCAN is reading the changing values of voltage and current.
9. Click ‘start’ on the VeeCAN.
10. Turn the knob on the Transistor load bank to draw the desired current.
11. When the test is finished click ‘stop’ on the VeeCAN.
12. If you want to conduct more tests, repeat steps 4-11. Once you are finished with your final test go to step 13.
13. Click ‘eject’ on the VeeCAN.
14. Plug the USB into the blue cart computer.
16. Select the DBC file and click the green arrow in the middle of the screen.
17. Load your solar test.
18. Click ‘convert to CSV file’
Appendix G - Energy Management System

Energy Management System Flowchart:

User Inputs: Number of races for the day, time each race begins, estimated weather conditions and corresponding time of day (cloudy, hazy, sunny), distance for each race

Speed Loop Prediction Calculation: Assumed initial speed (10 m/s), calculate energy consumed (distance) x (drag @ current speed),
- If energy consumed > energy available → decrease speed and reiterate → drag and energy consumed decrease
- If energy consumed < energy available → increase speed and reiterate → drag and energy consumed increase
- If energy consumed (approx.) = energy available → maintain current target speed

Live energy percentage and distance remaining values from the CAN bus

In Race Speed Loop: Known initial speed
- If actual energy remaining > predicted energy remaining → decrease speed and reiterate
  → drag and energy consumed decrease
- If actual energy remaining < predicted energy remaining → increase speed and reiterate
  → drag and energy consumed increase
- If actual energy remaining (approx.) = energy available → maintain current target speed

If last race is finished → End program
Else return to Live readings

User Manual to convert from MATLAB to C code:
1. Will be filled out when first successful transfer is complete.
Appendix H - Electronics System

Appendix H.1 - Programming the Parker CM0711

20. Create a new Simulink model for the controller or modify an existing model. Use regular Simulink blocks as well as the custom Raptor blocks in the Raptor Library to program the desired functionality. Ensure there is a Hardware Definition block as well as an XCP Protocol Definition block in the top level of the model with the settings shown Fig. H.1 and H.2.

![Figure H.1. Parker ECU Definition block and settings](image-url)
Also make sure that the Matlab directory is the same as the directory which contains the Simulink model

21. Perform a Model Update (Ctrl+D). Simulink automatically performs a Model Update before simulating or building the model, but it can also be done independently. It is quicker than building the model and often reveals many modeling mistakes or oversights, such as incorrect data types, unconnected blocks, algebraic loops, etc.

22. Build the model (Ctrl+B). This compiles the Simulink model into code suitable for the target hardware. The process may take a while depending on the size of the model. This should create a .rpg file as well as an rtw folder. You only need the .rpg file.

23. Connect the Parker to the PC via the Kvaser USB-to-CAN cable. Make sure you connect to the Parker CAN1 (CAN1 is for programming, you cannot program over CAN2). Turn on the Parker.

24. Open RaptorCAL and click “Flash” (Fig.H.3). The RaptorCAL software should search for a hardware module and find the Parker as shown in Fig. H.4.
25. Click “Select” and browse for the .rpg file you just created. Click “Open” and the RaptorCAL software will begin reprogramming the Parker. It will first erase the old program and then flash it with the new one. A window will pop up letting you know when the reprogramming is complete.

**Figure H.3.** Flashing module with Raptor-Cal Tool

**Figure H.4.** Raptor-Cal discovering Parker module
Appendix H.2 - Programming the VeeCAN 320

1. Create a new Simulink model for the controller or modify an existing model. Use regular Simulink blocks as well as the custom Raptor blocks in the Raptor Library to program the desired functionality. Ensure there is a Hardware Definition block in the top level of the model with the settings shown in Fig. H.5.

![ECU Definition](image.png)

**Figure H.5. VeeCAN 320 ECU Definition and settings**

Also make sure that the Matlab directory is the same as the directory which contains the Simulink model.

2. Perform a Model Update (Ctrl+D). Simulink automatically performs a Model Update before simulating or building the model, but it can also be done independently. It is quicker than building the model and often reveals many modeling mistakes or oversights, such as incorrect data types, unconnected blocks, algebraic loops, etc.

3. Build the model (Ctrl+B). This compiles the Simulink model into code suitable for the target hardware. The process may take a while depending on the size of the model. This should create an rtw folder containing the build.

4. Open the rtw folder that was just created. If the model name has not changed since the last update, it will overwrite the existing build folder.

5. Open the folder with the build number (see Fig. H.6)
Appendix H - Programming the Pololu Jrk 21v3 Motor Controllers

This guide explains how to program the Pololu Motor Controllers (PMCs) for use with the Firgelli linear actuators. The Pololu documentation is quite comprehensive and in general the Pololu Jrk Configuration Utility software is straightforward to use. However, there are a couple aspects that took some time to figure out, and this guide should help clarify.

1. Input. The input signal is mapped to a target signal using the scaling set in the configuration. For PWM mode, the input is in units of 2/3 us, meaning the pulse width in microseconds is multiplied by 3/2 (1.5) to get the input value. For a pulse range of 1 to 2 ms, this corresponds to input of 1500 to 3000. To get the best resolution in control, these values should map to target values of 0 and 4095 respectively. It is advisable for the Absolute Min and Absolute Max to be a little outside the pulse width range expected so that there is room for small deviation in the PWM signal without triggering a fault in the controller. A small Dead Zone is also useful so the control signal can vary some before the actuator starts to move. This can help eliminate a constant pulsing of the motor.

2. Feedback. For our Firgelli linear actuators, the feedback signal is an analog voltage from a potentiometer in the actuator. The Pololu reads this voltage and interprets it as a raw feedback value. The raw feedback is then converted to a scaled feedback value to
compare to the target value (and determine which way to drive the actuator). To appropriately scale the feedback, follow this process:

a. Set the input scaling to full range (0 – 4095)
b. Set the feedback scaling to full range
c. Put the controller in serial mode and manually adjust the target until the actuator reaches the cutoff switch on either end or the target value reaches a maximum/minimum. Ensure the range of motion needed for hydrofoil movement does not reach either cutoff switch. If it does, reposition the actuator such that the necessary range of motion occurs in an area of travel that does not come near the cutoff switches.
d. Now adjust the position of the actuator to the minimum desired position (most retracted). Record the target value needed to get it to this position, and convert it to the raw value using the equation:

\[ \text{Raw} = -\text{Scaled} + 4095 \]
e. Adjust the position to the maximum desired position. Again record the target value and convert it to a raw value.
f. Command a target value about halfway between the first and second recorded target value to move the actuator between the min and max positions.
g. On the feedback tab, set the minimum to be the smaller of the two calculated raw values, and the max to the larger of the calculated raw values.
h. Click “Apply settings to device”
i. Now the scaled FB of 0 and 4095 correspond to the minimum and maximum positions. The only way the Pololu will try to drive the actuator beyond these positions is if the potentiometer slips or the feedback signal becomes corrupt some other way.
j. On the PID tab, there is a parameter called “Feedback dead zone”. This could also be called “maximum error”. The smaller this is, the closer the Pololu will try to get the feedback to the target, but too small of a value may cause the actuator to always be hunting around, trying to hit the target exactly.

Appendix H.4 - Modifying and Using DBC Files

DBC (DataBase Container) files are used to define the CAN messages and signals. They can be created and edited in the Kvaser Database Editor software. These definitions are critical for proper communication on the bus as well as interpreting and logging the data. Because the Kvaser software does not lend to copying or printing, we also keep an Excel document with these definitions. (T:\Engineering Competitions\SOLAR BOAT\2017-2018\4. Electronics\DBC files\Most Recent\Master CAN Bus Signal List xx-xx-18.xlsx) This same folder contains the latest DBC files for the Dutch boat (DSC_FullSystem.dbc) and data acquisition box (DAQ_prop_drag_solar.dbc).

It is very important that the NAMES OR LOCATIONS OF THE DBC FILES DO NOT CHANGE! You may change them, but be prepared to re-select the correct file for every instance of a CAN read or write block in the Parker and VeeCAN codes. This is tedious and time consuming.
Appendix H.5 – Overview of RS-232 Protocol

RS-232 is a form of asynchronous serial communication with each message containing a start bit, 8 data bits, a parity bit, and a stop bit. The start bit triggers the local oscillator on the receiving end so that the sending/receiving “clocks” are synchronized. The 8 data bits are then sent. A longer packet of data cannot typically be sent because this increases the risk of the oscillators in the receiver/transmitter drifting apart and skewing which bit is which. The parity bit checks the accuracy of the signal using the “even number of 1’s” standard. When the message is sent, the parity bit is assigned such that the total number of 1’s in both the data and parity bit is an even number. For example, if the data has three 1’s, the parity bit will also be assigned to “1” so that there are four (an even number) of 1’s. That way, the receiver can check the message and if there is not an even number of 1’s it automatically knows there is an error. Single bit errors (or any odd number of bit errors) will then be flagged, and multibit errors are far more unlikely. Finally, the stop bit allows time for the receiver to re-initialize. Fig. H.8 shows a diagram of the typical RS232 message format.

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<tr>
<td>9600</td>
<td>104 μs</td>
</tr>
<tr>
<td>19200</td>
<td>52 μs</td>
</tr>
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**Figure H.8. Typical RS-232 Message Format**
Appendix I - Motor and Motor Controller System

![Diagram of DAQ Hijack Box Connector Layout]
This box goes in between the sensor harness and the data computer. It allows all the analog channels to pass through the connectors and PCB (printed circuit board, see Figure I.2) in the box while being able to pick some off to use ourselves, without changing what the data computer sees.

![Figure I.2](image_url)

**Figure I.2.** Printed Circuit Board Schematic for the DAQ Hijack Box. Created using PCB Artist Software.

The header pins on the PCB enable one to look at any channel with an oscilloscope. The DAQ Hijack box connects to the sensor harness and data computer using 36-pin Centronics micro ribbon connectors (IEEE 1284 Type B). It outputs its data via a ribbon cable that is attached to a frequency input (speed) and 16-channel scanner box (torque) for the Yokogawa. Up to three additional channels can be sent to the output ribbon cable if desired, by jumping a wire from the desired channel to the “To Ribbon: pad in the upper right hand side of the board. The 3”x4” PCB is attached to a project enclosure box via a 3D printed screw hole adapter.

In the box, the “torque channel” is actually 4 separate analog channels from the load cell’s full bridge strain gage array: Bridge Excitation Power/Ground and Signal +/- . To actually get the torque channel from those four wires on the PCB, I used an op-amp (LTC2053 chip, Fig. I.3) to pick off and amplify the difference of the Signal +/- channels (mV range).
The gain for the op-amp is determined by the resistors in the integrated component holder \((\text{Gain} = 1 + \frac{R_2}{R_1})\). The output of the op-amp is on the scale of 0-5V as determined by the gain. In order to measure both tension/compression loads of the load cell (positive/negative signal), a tunable Reference Voltage Offset Device was employed, which shifts the zero-point from 0 V to 2.5 V, so that loads of both types can be measured and recorded. This amplified 0-5V signal from the op-amp is then put onto pin 29, which is a 0-5V channel. That is the pin number that goes to the DYNO-Max software and is logged there as “0-5V Load Cell”. (Note: The DYNO-Max software does not take negative torque commands. If you want to apply a load to the motor while spinning the opposite direction of calibration, simply change the sign of the gain in the DYNO-Max software).

Obtaining the speed data is a much easier process. There are only two wires: Signal and Ground for the Hall Effect speed sensor. The signal waveform is a square wave pulse with 4 pulses per revolution of the motor shaft. These two channels are put onto the output ribbon and sent to the Yokogawa via the frequency input channel on the Yokogawa.
Appendix J - Propellers

Appendix J.1 - Installation of Strain Gages

In order to measure the thrust and the torque differential on a Contra-Rotating Propeller (CRP) drivetrain, we decided to apply strain gages on Steven Smith’s 2009 CRP drivetrain. We choose to use omega’s 120 ohm SGD-6/120-LY13 strain gages. Fig. J.1 shows the specifications for the gages applied on the CRP drivetrain.

![Omega SGD-6/120-LY13 Strain Gage Specifications](image)

Figure J.1. Omega SGD-6/120-LY13 Strain Gage Specifications

Once the gages were selected we needed to decide how we wanted to arrange the gages on the CRP downleg. In order to get the most sensitive reading we used two full bridges of four strain gages each. One bridge would measure torque and the other bridge would measure thrust. The torque gages are applied equidistant from the neutral axis of the drivetrain. This is intended to make them insensitive to the bending moment produced by the propellers’ thrust. The thrust gages are applied as close to the leading and trailing edges of the drivetrain. This exposes them to the most strain due to a thrust load while still allowing the gages to be installed a precise distance from the drivetrain’s neutral axis. Fig. J.2 shows the layout of the strain gages on the drivetrain that I worked with Dr. Zavodney to develop.
This is the layout design for the Solar Splash drivetrain to measure thrust and any torque from the counter-rotating props. The circle is a hole on the tubing through which eight color-coded wires will pass through the drivetrain tubing past the supports that hold the drivetrain to the boat. The gages are to be installed on the airfoil section of the drivetrain.

Joshua Schroepfer & Dr. Zavodney v.7 11 April 2018

Figure J.2. Strain Gage Layout on the CRP Drivetrain
Once the layout was finalized, the installation area was prepared according to Strain Gage installation manual found in the pressure vessel lab. We used M-Bond AE-10 to adhere the strain gages to the aluminum surface. M-Bond AE-10 is an epoxy adhesive, which is used for long-term applications. Solder pads were laid out along with the strain gages in order to position them precisely. More details about using M-Bond AE-10 to apply strain gages is available on Vishay Precision Group’s website.

We allowed the epoxy to cure for 24 hours then removed the tape used to position and install the gages. The lead wires of the gages were stuck to the down leg because of excess epoxy that squeezed out during the application process. These lead wires had to be carefully freed from the epoxy and the solder pads had to be cleaned of any excess epoxy that stuck on the solder area. After this, the lead wires were soldered to the appropriate solder pads and the gages were connected into two full bridges according to the strain gage layout diagram shown above. In Fig. J.3. In Fig. J.4, the gages are shown after they had been wired into the bridges on the drivetrain.

Figures J.3 and J.4. Strain Gages Wired into Two Full Bridges on CRP Drivetrain

Once the Gages had been wired in the full bridges, 8 wire ribbon cable was routed inside the drivetrain past the lower bushing. This allowed the ribbon cable to be undisturbed by the drivetrain bushings which prevents it from getting caught on the drivetrain mount and possible ripped off in a turn. The hole that the ribbon cable was routed through was sealed with silicon and zip tied to the drivetrain. This keeps the ribbon cable from contacting the driveshaft inside the drivetrain. The ribbon cable was soldered to the appropriate solder-pads and the other end was inserted into an 8 pin Deutsch plug.

In order to make the strain gage installation waterproof, we needed Vishay Precision group’s M-Coat F and A kits along with polyurethane. We followed the procedure outlined in the kits’ manuals but a brief overview of the general process is outlined below.
Strain Gage Waterproofing Procedure using Vishay’s M-Coat F, A, and polyurethane kits.
1. Embed ribbon wires from gages in Butyl rubber (Fig. J.5)
2. Seal installation area with polyurethane
3. Test Bridges to ensure they function
4. Apply butyl rubber to installation area to seal gages. This should expand past the polyurethane to provide another water barrier.
5. Pinch the layers of the butyl rubber to ensure a tight seal at the seams
6. Install aluminum tape over butyl rubber.
7. Seal the seams of the aluminum tape installation using the included Nitrile rubber (Fig. J.6.)

Figure J.5. Embedded Ribbon Cable in Butyl Rubber & Polyurethane Coating over Strain Gage Installation

Figure J.6. Aluminum Tape and Nitrile Rubber
Appendix J.2 - Calibration Procedure for Strain Gages

After applying the strain gages to the drivetrain, we needed to calibrate the gages for thrust and torsional loads. The following is a guide on the calibration procedures we followed. The wires running from the strain gages represent two bridges, one for thrust and one for torque. Each bridges set of wires was put into a Deutsch plug according to the Propeller and Drag Testing Box schematic. This plug is then connected to the propeller and drag test box. The test box contains two strain gage amplifiers (SGA boards). These amplifiers take the bridge output and amplify it by 995. We are using this gain value because it gives sufficient resolution on the analog inputs to our DAQ system. The SGA boards then output this analog voltage to the DAQ. The schematic for the Propeller and Drag Testing Box is shown below in Fig. J.7

![Propeller and Drag Testing Box Schematic](image)

To calibrate the bridges for a thrust load we used increments of 10-pound weights up to 30 pounds. The propellers we will be testing are designed to produce 123 N of thrust with at 600 rpm with a torque input of 4 N-m.

Figure J.7. Propeller and Drag Testing Box Schematic

When calibrating the strain gages we applied loads to simulate positive and negative thrust loads. Fig. J.8 shows the calibration setup for a positive thrust load and Fig. J.9 shows the calibration for a negative thrust load. We assigned the positive thrust load to propel the boat forward. While applying the loads, we placed the wooden supports where the bushing supports attach the drivetrain to the transom of the boat. The drivetrain was secured to the table using a ratchet strap and the drivetrain was checked to be level before applying the weights.
To read the output of the bridges we connected a digital multimeter to the DAQ’s ground pin and analog outputs 1 and 3 of the DAQ box. Channel 1 is the amplified output of the thrust bridge and channel 3 is the amplified output of the torque bridge. At zero applied torque, the bridges will read a non-zero voltage. This voltage represents the offset of the bridge. This value needs to be subtracted from the other reading to determine how the amplified outputs change with different thrust loads. A plot showing the response of the two bridges is shown in Fig. J.10.
The thrust gages responded to thrust loads linearly and the torque gages were mostly insensitive to thrust. A least squares linear regression was applied to the data and the trend line equations are recorded on the plot above.

To calibrate the torque gages we applied a pure torque using the setup shown in Fig. J.11. The setup consisted of a ratchet, 6 inch extension, two U-joints, and a 1/2 inch socket. The socket was attached to nut threaded onto the smaller output shaft of the drivetrain. The U joints transmit a torque to the output shaft but prevent any axial loads from affecting the calibrations. The jack stand in the figure below supports the end of the ratchet and ensures the moment arm remains level during the thrust calibration.
The output of the bridges was read in the same method as the thrust gages. Fig. J.12 shows the response of the two bridge to a torsional load.

**Figure J.11. Method Used to Apply a Simulated Torque**

**Figure J.12. Response of Thrust and Torque Gages to a Pure Torsional Load.**
Using the trend lines for the thrust and torque bridges in each of the calibration tests we are able to use superposition to back out the thrust and torque that each of the bridges read. Equation K.1 shows the superposition of the readings for the thrust and torque gages.

\[
V_{\text{Thrust}} = (M_{\text{thrust}} \cdot T_{\text{thrust}} + B_{\text{thrust}}) + (M_{\text{Torque}} \cdot T_{\text{Torque}} + B_{\text{Torque}})
\]

\[
V_{\text{Torque}} = (N_{\text{thrust}} \cdot T_{\text{thrust}} + C_{\text{thrust}}) + (N_{\text{Torque}} \cdot T_{\text{Torque}} + C_{\text{Torque}})
\]  \hspace{1cm} (J.1)

This process was implemented in a TK code and was tested to see if it would output the correct thrust and torque loads for various combinations. We found that it did not give accurate results. As a result of this we decided to use Equation K.2 to determine the thrust and torque responsible for outputting the recorded \(V_{\text{thrust}}\) and \(V_{\text{torque}}\). We used the equation below because it output more accurate results when applying thrust and torque loads simultaneously.

\[
V_{\text{Thrust}} = (M_{\text{thrust}} \cdot T_{\text{thrust}} + B_{\text{thrust}} + \text{Bias}_{\text{Torque}})
\]

\[
V_{\text{Torque}} = (N_{\text{thrust}} \cdot T_{\text{thrust}} + C_{\text{thrust}}) + (N_{\text{Torque}} \cdot T_{\text{Torque}} + C_{\text{Torque}})
\]  \hspace{1cm} (J.2)

Attached is the TK code I wrote to take the measured values and calculate the thrust and torque that produced those readings.

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<th>Comment</th>
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<td>-0.005599</td>
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<td>Slope of the Thrust curve from Thrust calibration test</td>
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<td>0.000113</td>
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<td>Slope of the Torque curve from Thrust calibration test</td>
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<tr>
<td>0</td>
<td>Bth</td>
<td></td>
<td></td>
<td>y-intercept of the Thrust curve from Thrust calibration test</td>
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<tr>
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<td>Cth</td>
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<td>y-intercept of the Torque curve from Thrust calibration test</td>
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<td>Bq</td>
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<td>y-intercept of the Thrust curve from Torque calibration test</td>
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<tr>
<td>0</td>
<td>Cq</td>
<td></td>
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<tr>
<td>-0.014</td>
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<td></td>
<td>Offset voltage from thrust gages in torque calibration.</td>
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<table>
<thead>
<tr>
<th>Vth</th>
<th>.213</th>
<th>Voltage difference of Thrust gages (full-bridge) from zero point</th>
</tr>
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<tbody>
<tr>
<td>Vq</td>
<td>.004</td>
<td>Voltage difference of Torque gages (full-bridge) from zero point</td>
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### Appendix J - Propellers

<table>
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<tr>
<th>T</th>
<th>2.488</th>
<th>0.36</th>
<th>2.275</th>
<th>0.356</th>
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<tr>
<td>Q</td>
<td>-40.543678</td>
<td>-19.935285</td>
<td>-9.114624</td>
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<tr>
<td>T_lb</td>
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<table>
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<td>Vth = Vth_recorded - V_zero_T</td>
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<tr>
<td>Vq = Vq_recorded - V_zero_Q</td>
</tr>
<tr>
<td>Vth = (Mth * T + Bth) + Tq_offset</td>
</tr>
<tr>
<td>Vq = (Nq * Q + Cq) + (Nth * T + Cth)</td>
</tr>
</tbody>
</table>

This program was given to Andrew Nelson, to be programmed into the Data Acquisition System. Fig. J.13 shows the compares the unadjusted DAQ Thrust output when a known, combined thrust and torque load is applied. The second curve shows the data that has been adjusted for the consistent error in the thrust readings. To find the correct value to adjust the data we took the found the average percent difference in the reported DAQ thrust data from the thrust we applied and increased each of the thrust reading by this percentage.
Figure J.13. *DAQ Thrust Output for Combined Thrust and Torque Loads*

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Thrust Values Recorded by DAQ

- **Series 1**: y = 0.887x - 2.3442, R² = 0.9997
- **Series 2**: y = 0.9809x - 0.0503, R² = 0.9995

<table>
<thead>
<tr>
<th>DAQ Output Thrust Load (N)</th>
<th>Applied Thrust Load (N)</th>
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<tr>
<td>-200, -150, -100, -50, 0, 50, 100, 150, 200</td>
<td>-200, -150, -100, -50, 0, 50, 100, 150</td>
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Fig. J.14 shows the method by which we applied the combined Thrust and Torque loads. The thrust load is applied using the same method used in the thrust calibration test. When we wish to apply a torque, we use vice grips clamped to the coupler at the input end of the drivetrain. Additional weights can be hung off the end of the vice grips to increase the applied torque. A ratchet is attached to the output shaft of the drivetrain and a counter torque is applied to the drivetrain. We ensure the vice grips attached to the coupler are horizontal and allow the reading to get to a steady value before recording the thrust and torque from the DAQ.

**Figure J.14. Combined Thrust and Torque Loads on the CRP Drivetrain**

For detailed schematics of the DAQ box and propeller test box see Appendix N.

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**Appendix J.3 - Motor Tachometer Calibration**

In order to determine the efficiency of our propellers we need to know the power input to them along with the propellers power output. Equation J.3 shows the motor power and Equation J.4 shows the propeller power.

**Variables**

N – motor speed (rpm)
Q- motor Torque (N-m)
\[ T = \text{Thrust (N)} \]
\[ V_s = \text{Ship speed (m/s)} \]
\[ P_{\text{motor}} = \frac{2 \times \pi \times N}{60} \times Q \quad (J.3) \]
\[ P_{\text{propeller}} = T \times V_s \quad (J.4) \]

We got a small DC motor mounted to a bracket. The DC motor has a socket for an Allen key, which is inserted into a socket head cap screw in the non-drive end of an Etek motor.

Because this is a DC motor, we know that the voltage and speed are linearly related by the motor’s speed constant. To attain this motor speed constant, we needed to determine the motor speed and armature voltage at several points. We used a stroboscope to determine the motor speed and an electric drill to spin the motor. Fig. J.15 shows the instrument we used to determine the motor’s speed constant. Fig. J.16 shows a plot of the motor’s armature voltage vs the speed.

Figure J.15. Measuring Motor Speed and Armature Voltage
The slope is the motor’s speed constant. We attained a value of 0.00256 V/Rpm for the motor speed constant. The voltage from the tachometer is then sent into a voltage divider in the propeller test box and on to the VeeCan for recording during the propeller test. This voltage is converted into the Etek Motor’s speed using Equation J.5

**Variables**

\[ N = \frac{V*(R1+R2)}{k*R1} \]  \hspace{1cm} (J.5)

- \( N \) – Motor Speed (rpm)
- \( k \) – Tachometer Motor’s Speed Constant (V/rpm)
- \( V \) – Tachometer Output Voltage
- \( R1 \sim 1\Omega \) resistor in voltage divider
- \( R2 \sim 9\Omega \) resistor in voltage divider

**Figure J.16. Plot of Motor Armature Voltage vs Speed**

![Tachometer Calibration](image)

\[ y = 0.00256x + 0.00592 \]
\[ R^2 = 0.99970 \]
Appendix J.4 - Comparison of CAMWorks and HSMworks

Below is a pros and cons list of CAMWorks and HSMworks. Both programs are available as add-ins for Solid works.

CAMWorks
- **Pros**
  - Well documented method for machining propellers
  - Cedarville already has the licenses for CAMWorks
- **Cons**
  - The process for doing simple task such as drilling a hole is made difficult due to CAMworks defaulting to the wrong setting and crashing into your part.
  - Toolpath generation times are very long for complex processes.
  - Post Processing of Complex toolpaths is also very long
    This is due to the fact that CAMWorks has to feed its toolpaths through a program that is linked to a specific mill. The post processing happens in another program. This makes the process take up a lot of computing power
  - Confusing user interface that has multiple windows.
  - Tool path setup is split between two tabs Operations and Features
  - Online support is somewhat minimal. YouTube has some tutorials.

HSMworks
- **Pros**
  - Streamlined toolpath step process.
  - Well documented explanations of what the options in the toolpath setup do
  - Adaptive feature is easy to setup
    (This is perhaps the most attractive aspect of HSMworks. The program will keep the tool engaged with the cutting area for the most amount of time. This reduces time spent cutting air. The adaptive feature also take a deeper cut with a smaller step over. This is improves tool life because the more of the tool’s cutting surface is engaged. Typically, in CAMworks we take a shallow cut with a wide step over. This wears out only the first 1/10th of the end mill and shortens tool life)
- **Cons**
  - New program so there is a learning curve to it
  - Guides will have to be made if we do decide to switch to HSMWorks as our CAM program
  - Licenses will have to be switched over.
  - Old CAMworks programs will not be available as guide to help users make a new propeller

The team did look into another CAM program called Fusion 360. Fusion 360 is a standalone CAD/CAM software package. Fusion 360’s CAM package is the same as HSMworks, as they are made by the same company, Autodesk. The team felt that introducing users to a new CAD program would steepen the learning curve as they would have to navigate through a new CAD program to define avoid areas and contain areas. While this would not be hard to learn, it would add one more obstacle to overcome and master. Thus we opted not to further investigate Fusion 360 as a potential CAM program.
Appendix K - Drag Force Testing

Figure K.1. The Drag and Propeller Testing SGA board testing box manufactured final product 4”x8”x4.
Figure K.2. The Drag and Propeller Testing SGA board testing box manufactured final product 4”x8”x4(annotated).
Figure K.3. Load Cell Calibration Setup graphic (2017).
Figure K.4. The load cell calibration test data results for the Drag Force Test.
Figure L.1. *The Data Acquisition System and test schematics flow chart.*
Figure L.2. The Data Acquisition System and test schematics overlay (latest version).
Figure L.3. The Battery and Solar Panel testing electrical schematic (latest version).
Figure L.4. The Hull Drag and Propeller testing electrical schematic (latest version).
Figure L.5. The Data Acquisition system electrical schematic (latest version)
Figure L.6. The Data Acquisition system manufactured final product.
# Appendix M - Contact Information

<table>
<thead>
<tr>
<th>Name</th>
<th>Contact Information</th>
<th>Position/Role</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jarkko Ahlqvist</td>
<td>Direct +358 3 4124 4356 Cell +358 50 5401760 <a href="mailto:jarkko.ahlqvist@parker.com">jarkko.ahlqvist@parker.com</a></td>
<td>Senior Project Manager at Parker Hannifin, Finland</td>
</tr>
<tr>
<td>Jesse Avery</td>
<td>800-223-1236</td>
<td>Works at LADD industries, provider of Deutsch Connectors</td>
</tr>
<tr>
<td>Jonathan Cox</td>
<td><a href="mailto:jcox@cedarville.edu">jcox@cedarville.edu</a></td>
<td>Battery and Solar Panel Testing</td>
</tr>
<tr>
<td>David Duquesnel</td>
<td>+1-734-272-0210 <a href="mailto:dduquesnel@neweagle.net">dduquesnel@neweagle.net</a></td>
<td>Sales and Support Representative at New Eagle</td>
</tr>
<tr>
<td>Joshua Heanssler</td>
<td><a href="mailto:joshuaheanssler@cedarville.edu">joshuaheanssler@cedarville.edu</a></td>
<td>Drag Force Testing/Data Acquisition System</td>
</tr>
<tr>
<td>William Heinig</td>
<td><a href="mailto:willheinig@cedarville.edu">willheinig@cedarville.edu</a> (614) 586-3146</td>
<td>Solar Splash Drivetrain/Motor and Motor Controller</td>
</tr>
<tr>
<td>Kirk Lola</td>
<td>Office 847 258 6278 Mobile +1 828-980-2217 <a href="mailto:klola@parker.com">klola@parker.com</a></td>
<td>Product Manager at Parker Hannifin</td>
</tr>
<tr>
<td>Andrew Nelson</td>
<td><a href="mailto:anelson119@cedarville.edu">anelson119@cedarville.edu</a> 269-612-7452</td>
<td>Electronics System/Flight Control System</td>
</tr>
<tr>
<td>Cosma Pabouctsidis</td>
<td><a href="mailto:cosma@roboteq.com">cosma@roboteq.com</a></td>
<td>Tech support at RoboteQ</td>
</tr>
<tr>
<td>Joshua Schroepfer</td>
<td><a href="mailto:jschroepfer@cedarville.edu">jschroepfer@cedarville.edu</a> (757) 971-8252</td>
<td>Propeller Testing and Manufacturing</td>
</tr>
<tr>
<td>RoboteQ Support</td>
<td><a href="mailto:techsupport@roboteq.com">techsupport@roboteq.com</a></td>
<td></td>
</tr>
<tr>
<td>Blake Wilson</td>
<td>+1-480-664-6660 <a href="mailto:blake@roboteq.com">blake@roboteq.com</a></td>
<td>Business Development Manager &amp; Field Applications Engineer at RoboteQ</td>
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