MRE 480 Design Report

Solar-Powered RC Plane "Sunrunner"

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Abstract

The goal of our project is to extend the flight time of a standard sized remote control (RC) plane through the implementation of a solar array charging system. Currently, many RC planes are limited by the size, weight, and capacity of our battery system on remote aircraft. As we look for a longer range, the size of a battery increases and therefore weight also increases. However, with the implementation of a solar charging system, we can maintain the same weight and size battery but greatly extend our flight time. We ended up deciding on a flying wing style plane in the form of the B2 Stealth Bomber to provide a large space for our solar array along with the space for potential payloads and lift characteristics. During our construction we focused our Alpha prototype on proving the feasibility of solar generation where we could determine that the solar charging system and flight control system was properly functioning without needing to test the systems complete performance. In our Beta prototype we focused on proving the feasibility of our entire electrical system as well as performing flight testing. We found that our solar array was capable of providing the required power entirely from our solar array and was able to charge both during sunny and cloudy weather during cruising conditions. Despite these successes our plane was not capable of flight due to various factors including launch speed, inadequate control surface sizes, and insufficient protection for landing and take-off. However, given a different plane body, our system proved that it was possible to power an RC plane on solar to greatly extend the flight time of our system which was our main goal in this project.

1 Introduction and Problem Statement

1.1 Introduction

The world is currently accepting the fact that global warming is currently endangering the entire planet. To deal with this, most countries have been turning away from fossil fuels and have switched to renewable resources like nuclear, wind, and solar power. Due to solar power being relatively safe and easy to implement, solar energy has taken off in popularity. However, as we have done more research, the RC plane industry in America has not taken advantage of solar energy. The few solar RC planes that we have found were created by schools for research projects or hobbyists. How long an RC plane can stay in the air is heavily impacted by the battery system. A common way to increase the flight time is to simply add more batteries.

However, if you add more batteries then you also add to the weight of the plane. The weight of the plane affects the aerodynamics of the plane as well as how much current needs to be drawn to get the plane off of the ground. So essentially, the usefulness of increasing the amount of batteries is proportional to the weight of the plane. Therefore, if you could charge the batteries while flying without adding a lot of weight to the system, you could stay in the air much longer.

1.2 Problem Statement

Over the past few decades, battery capacity has improved very little. RC plane batteries are affected even more due the size and weight limitation of the aircraft. The average RC plane can only stay in the air for around 10-30 minutes at a time before needing a fully charged battery. Charging an RC battery takes at least an hour. This is an issue if you are taking videos, surveying, or delivering items. Even though there are many people that have used solar panels on RC planes, the projects are either 100 foot planes or much smaller DIY projects. For hobbyists or companies who either don't have the money or space for a 100 foot plane, there is a lack of aircrafts for purchase.

It is viable for solar panels to increase the flight time for a plane or even allow an RC plane to fly all day if the conditions are ideal. Since there is proof of increased flight time, the use of solar cells could increase the flight time of our project to all day.

1.3 Design Goals

To solve the problem for RC plane flight time, we are attempting to add an efficient solar power charging system to a lightweight plane. To do this, the solar system needs to be created to be light, efficient, and tough enough to last several uses. This means that the panels will have to be created by us, the system will need an MPPT to track the power and boost the voltage to maximize the power that is generated by the panels. The plane also needs to be designed to be lightweight, aerodynamic enough for flight, and large enough surface area for solar panels. We will know that the project was successful after we fly the plane with panels and significantly increase the flight time from flight time without panels.

1.4 Constraints

Our constraints are surface area, structural integrity, weight, turn radius, battery capacity, and cost. The surface area needs to be large enough to have enough solar panels to power the plane while being small enough for easy storage and travel. The plane must be able to handle a mildly rough landing. The plane needs to be as light as possible so the plane can be efficient. The plane must be able to turn without flipping. The batteries need to have enough capacity to power the plane when solar isn't an option, yet it shouldn't be too large of a battery that would defeat the purpose of using solar. The plane must be similar in price to other RC planes of the same price to be competitive.

We first wanted to start with deciding the appropriate capacity of the battery needed to fly an RC plane. To do this, we used the electronics that most RC planes use as well as their weight. Once we decided that, we had to calculate the amount of solar cells that would be needed to also power the plane. From there, we then needed to decide what plane form would be able to accommodate those solar cells. We would then have to check over our design by calculating the weight to make sure that everything will work.

2 Design

2.1 Discussion of Design process

Our design first centered on the different types of planes we could develop into solar powered aircraft systems. We looked at models specifically for gliders, the C130 Hercules, and B2 Stealth Bomber as inspiration for our frames. From there we began to look at the strengths and weaknesses for each design by taking visual interpretations of the systems. For example, we looked at the expected number of motors we would use on each design along with the number of control surface servos and how this would affect our net power consumption. From there we also looked at the amount of space available to each design, as a larger surface area would increase the total amount of solar energy available to our system.

After picking the B2 Bomber, we began to look at adjustments we would need to make in order to make our design feasible. We found that given the size of our surface area and the design of our airfoil, we would be able to maintain flight while being able to charge. We did need to make some changes on where our motors would be given that the B2 does not have electric propeller motors and therefore we had to design a placement for them. Some of the comments we noted were a focus on the specific market we would take this project in along with the aerodynamic analysis for the final design. We looked to refine the potential uses for this project through interactions with other outside sources to look at areas this craft would excel in compared to quadcopter systems that are more stable and efficient in short duration projects.

In our Alpha prototype, we were able to gain insight on the performance of our solar array system when compared to a very limited thrust-current relationship of our main motor system. We determined that at our 50 % throttle position which marked our cruising speed, we would likely be producing a net positive charging current but we needed to test the entire system in order to fully determine the result. That is why in our Beta prototype we were able to place all of our components within the plane and finalize the full design. We then were able to begin extensive ground testing that proved that during both cloudy and sunny weather we generated enough power from our solar system to run all of the electrical components while still providing enough energy to charge the battery for our cruising throttle. Our setback came when we attempted to fly the plane where it quickly crashed to the ground which we feel was caused by a few factors including insufficient launch speed as well as inadequate control surfaces. We know that should we perform this project again we would likely go for a much more stable aircraft and accept some less surface area for our solar array given we had a decent amount of excess energy that could have been shaved off if required and still produced a continuous flight system.

2.2 Final Design

For our final design we have a fuselage mounted underneath the plane, this compartment gives us a place to store all of our electronics. We also utilized wind fences underneath the plane to help with streamlining the air moving under the plane. Our servos are mounted to aileron flaps that will steer the plane and help gain and decrease in altitude. Solar cells will be mounted to the top of the plane on each of the steps to our stare step airfoil design.

The final design also meets our wingspan criteria of 2000mm. Our solar panel array is rated for a theoretical 100 Watts of power but we measured this to actually be 97 Watts. The final weight of the plane weighed in at 3.538Kg which was under our allowed 4.5Kg weight. We used an 11.1V battery pack rated for 5000mAh.

Our biggest strength in our final design is the ability to more than double the original flight time with the same size battery in both cloudy and sunny weather conditions. Some of the weaknesses of the final design are the ailerons were too small to provide enough change in forces acting on the plane to change the direction and altitude of the plane. Another weakness of the final plane design is that the plane weighed too much at the far extremes of the wings causing the wings to sag when picked up. This extra weight located in the wings changed the plane's aerodynamics and ultimately helped lead to the plane crashing.

2.3 Back-up Plans

We had a few backup plans if anything went wrong. If we couldn't get the solar charger we designed to work, we were going to try to use a cheap solar charger we found on Amazon. If we were having issues getting the plane itself to work, we were going to buy an RC plane, and change the electrical circuit to work with our solar charger.

In the end, we ended up having to use the Amazon charger because our custom designed solar charger had a factory defect that we couldn't fix. When we finally figured out that the custom designed solar charger had a factory defect, it had pushed back our plans quite a bit. Because our plans were pushed back so much, there was no time for us to find and get a functional RC plane. This meant that we had to gather as much data as we could to prove our solar design works, before actually testing flying.

3 Analysis

3.1 Aerodynamic Analysis

3.1.1 First Semester Analyses

What Defines Flight

The goal of our aerodynamic analysis was to understand the feasibility of getting a plane flight-capable with the added weight and aerodynamic instability of an array of solar panels atop it. To this end, we needed to discern what parameters we needed to meet to produce flight, how to determine those parameters from the size and shape of our plane, and to learn how to properly model our plane to correctly analyze it. This was our area of least expertise, since none of our team has studied aerodynamics before the design of this plane. A large portion of our initial efforts were iterative and overlapping, adding new information to older attempts as we learned its significance in ensuring accuracy.

The flight of an airplane is most strongly characterized by the shape of the wing's cross-section, or 'airfoil', and by the slant of the front of the airfoil relative to the direction of the wind flowing over it, or 'angle of attack (AoA)'. As a plane with a well-designed airfoil moves through the air, at a proper AoA much more air will be hitting the underside of the wing than the top. This apparent greater density of air under the wing generates a buoyant lifting force on the wing; but so too does the apparent greater density of air at the nose of the wing generate a secondary drag force counter to the plane's direction of flight. These forces are not actually separate, but it is helpful to separate them as such to better understand how the useful, perpendicular lift portion of the aerodynamic force changes with respect to the parallel drag portion.

To model this, we first wanted to directly use the actual airfoil of the B-2 bomber, but it proved too difficult to find or usefully create our own model of the wing. We turned to common airfoils used by hobbyists and store bought RC planes, as these were already proven to work well with planes of similar speed and size to our own. Our analysis to this point has been performed on the popular Clark-Y airfoil, which has a simple and easy-to-manufacture design.

Modeling the Wing

We used a program called Xfoil for the analysis of the aerodynamics on this airfoil. Xfoil uses a panel method approximation to provide the net forces acting normal to the surface of small, discrete sections along the surface of the airfoil. The summation of these forces across the entire wing can be thought of as some net aerodynamic force that acts upon the plane at some interior point described as the center of pressure. This net force can be broken into vertical and horizontal components that are termed the lift coefficient and drag coefficient, respectively.

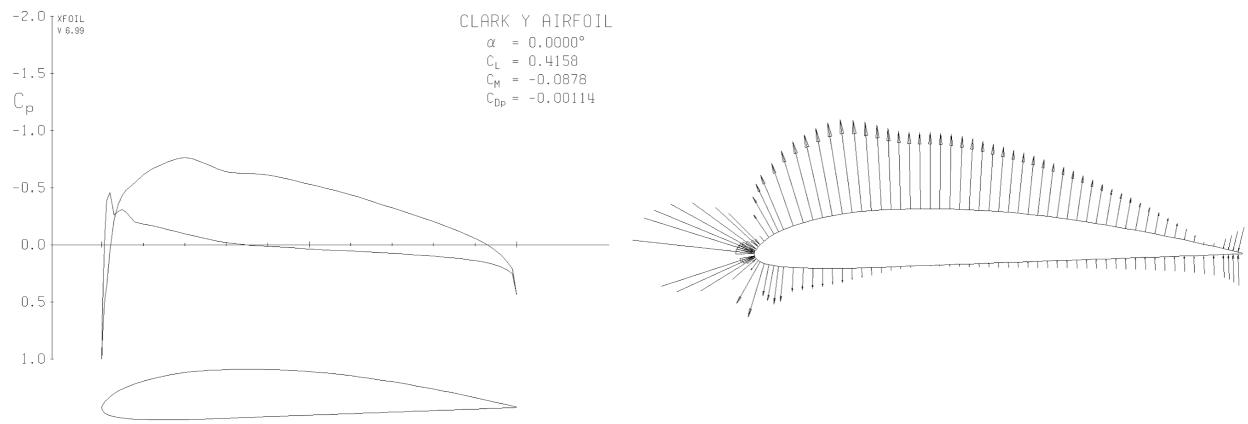

Figure 3.1: Here are two representations of the initial Xfoil analysis. The left shows the magnitude of aerodynamic forces, and the right illustrates the directionality as well

This has been the foundation for our analysis, but it is not a complete representation of the interaction between the wing and air. Additionally, the aerodynamic force is associated with a Reynold's number (Re) that describes the ratio of viscous and inertial forces acting on the surface of the wing. This value plays a substantial role in the generation of turbulence by a plane in flight, which will increase the magnitude of created drag forces and decrease lift forces. At higher speeds, the flow of air directly at the boundary layer of the airfoil's surface becomes more and more turbulent and unstable, diluting our increased lift with respect to our increased speed.

As air in the real world is viscous and will produce effects and forces not predicted by our current model, this inviscid analysis is not complete, but it is also not without use. The Reynolds number is a function of our airfoil's airspeed and horizontal chord length, and of the density and viscosity of the air, which change with altitude, temperature, etc. Our analysis uses values associated with an air temperature of 20°C, at an altitude of 400'. Our chord length was geometrically ascribed as a function of our plane's wingspan and its surface area. The velocity value can be any positive number though, theoretically, so we turned to our inviscid study to give us a better starting range to inspect.

Using methods we will develop and discuss further below, we found that upper and lower bounds for a good cruising speed should be between 5-20 m/s. Further, some studies into features we hope to add to enhance the wing are only useful under a Reynolds number of 5e5. Our study of this has not been exhaustive, but we opted to use the speed 12.5 m/s, as it fits in our range and produces a suitable Re = 4.22e5. That is not to say that will end up being our plane's actual speed, but it approximates the airflow conditions close to the speed our plane should be going. We can redo our analysis with viscous flow accounted for and see how it changes our data.

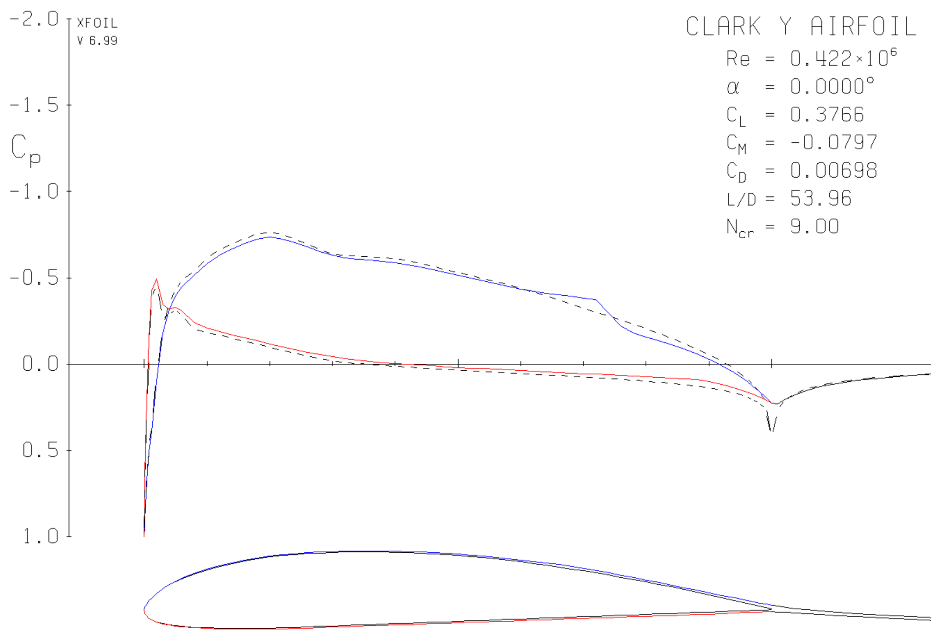

Figure 3.2: An adjusted Xfoil analysis accounting for viscous airflow.

The illustration above is useful for understanding the turbulent phenomena we discussed previously. In the bottom form, we can see the original airfoil now outlined by two separate blue and red lines on the top and bottom of the surface, respectively. These represent the boundary layer between the airfoil and overall airflow introduced by turbulence. In the upper form, they show the adjusted aerodynamic forces generated, which are imposed over the original plot, now seen as a dotted line. The net results of this are the reduction of the lift coefficient and increase of the drag coefficient, which was a negative number previously and is positive now.

Additionally, towards the trailing right edge of the airfoil, the boundary fully separates from the surface of the plane. This can have a great impact on the plane's dynamics and stability, and on the macro scale, this turbulence can result in entire lengths of the wing not producing meaningful lift. One of our two main focuses before next semester is to perform 3D fluid analysis of our plane to see how this will affect our design, and see what changes and stabilizing features we might implement to counter it if necessary. For now though, we shall still limit our focus to the 2D Clark-Y airfoil analysis.

Collecting and Analyzing Data

If we perform this analysis over a wide range of AoA, we can chart and plot this data to create a more complete look at our airfoil's dynamics across its potential range of use. Xfoil produces its own set of graphs for this analysis, but they are too cluttered and have data that is extraneous to our needs. While we have all of this data saved, we will plot the lift and drag coefficients, as well as the lift-to-drag ratio also provided in Figure 4 as L/D.

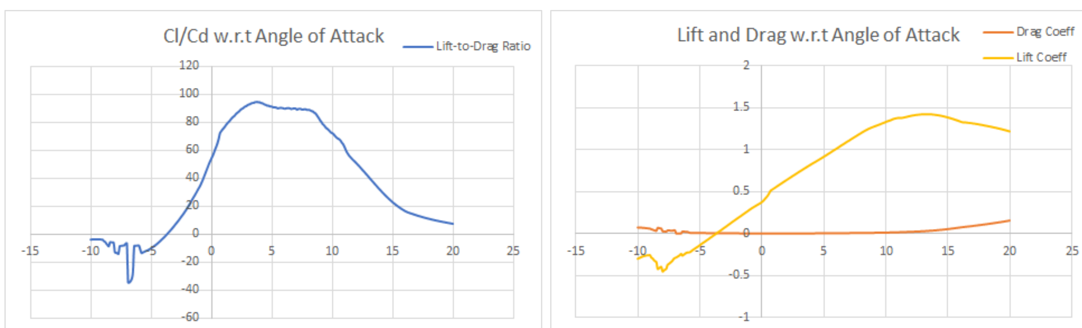

Figure 3.3: The illustration on the left plots the lift-to-drag ratio with respect to the airfoil's angle of attack and the right plots lift and drag coefficients with respect to the same

The data charted in Figure 5 is finally that crucial information we sought to define our plane's boundary conditions for safe flight, under conditions similar to those expected during routine operation of the plane. Of particular interest are local extrema in the data, namely the maximum lift coefficient and LtD ratios, and the minimum drag coefficient.

We said before that lift is generated when more air is hitting and pushing the underside of the wing than the top. Angling the wing upward, which increases the AoA, will increase that proportion and thereby increase the lift. That tilts the aerodynamic force backwards similarly, meaning that it will produce more lift *and* more drag. The maximum of the lift coefficient signifies the angle at which tilting the wing back won't produce any extra lift - more and more of the net force is being directed backwards as drag. You can see that when this occurs, the drag coefficient starts increasing dramatically. This angle is known as the stall angle for the plane, and the plane should never be allowed to angle this high, lest it stall and crash. Additionally, this can be reconfigured to provide the slowest speed the plane can go without falling is the stall speed. Likewise, the lowest drag coefficient possible can provide the fastest speed the plane can reach.

In general, we do not want our plane to go close to *any* of these boundary conditions. A plane that wants to maintain steady flight at a constant speed will have no net forces acting on it. That means that it must produce a lift that fully counters its weight, and to do so it needs to fly at a speed to generate that lift. That also generates a drag force that will slow the plane down in isolation, so you must also provide a forward thrust to counter that as well. Since there is a direct, known relation between the lift and drag, there is the same direct relation between the weight of our plane and the thrust needed to maintain its speed, i.e. W/T = L/D.

A plane with a LtD ratio of 50 requires 1/50th of its weight in thrust in order to keep it moving. Since thrust translates directly to power consumption by the plane, a high ratio results in a more energy-efficient AoA for steady flight. The maxima of that graph represents the most efficient angles for flight, which will be useful for general flight and for determining the best angles for gaining altitude. Our plane reaches a maximum ratio of 94, suggesting our plane, in the ideal condition, would only need 1.06% of its weight provided by the propeller to maintain speed.

To avoid assuming ideal conditions for lift, we opted to model our plane's steady flight being at the Y-intercept of the graph, at 0 angle of attack, with a LtD ratio of 54. Though we do not know the official weight of our plane yet, estimating a weight of 30 N allows for us to say that, at the upper bound for our plane's weight, we could produce the same flight characteristics and power requirements by shifting to the more efficient angle of attack. We are looking to keep the plane light, however, and the bigger point of using a reduced value as such is to provide a good cushion for when real world effects lower our plane's aerodynamics, which we definitely expect to occur. We can effectively lose 40% of our expected flight power and still adjust for it.

With our assumptions in place, we are left with a 30 N plane that must move faster than 6.2 m/s to stay airborne, and will comfortably glide at 12.1 m/s (sufficiently close to our value assumed for the Reynolds number) requiring 7.94 W of power to maintain flight. With an expected generation of 107 W from our solar panels, this is a wonderful thing to hear. Even if those requirements double due to currently unsimulated aerodynamic constraints, our plane will still have certain windows of the day capable of net-positive charging, and will regardless be able to drastically increase flight time over non-solar alternatives.

Goals on Improving Stability

As it stands, we no longer have any question as to whether the plane *can* fly. What we had merely taken as assumption from other RC planes, and the few hobbyist solar planes, has been cemented by our studies. That is a great and encouraging relief, but it still only qualifies the 'flight' aspect of steady flight. Beyond the issues of getting the plane airborne, it became increasingly obvious that an even larger problem would be keeping it airborne; the design we have chosen is a flying-wing plane modeled after a real-world aircraft with a complex computer control system to allow it to fly without crashing in a stiff breeze.

This is due to a lack of physical features like a tail and tail fin that provide passive stabilization to counter the plane's wobbling in the air. Without these corrective forces, our plane would actually have negative stability, and any perturbations would not only shift the plane, but continue shifting the plane further and further, becoming stronger as the plane shifts. The control surfaces on a plane that help it change directions in roll, pitch, and yaw now become crucial to keeping the plane from tumbling out of the sky at all times.

This is why our second and most important point of order in aerodynamic analysis before next semester is to make progress into either designing a PID controller to maintain stability, or find one that already exists that we could alter to fit our plane's needs. With a sufficiently tuned PID, even our relatively unstable plane will be capable of maintaining flight, though it is still uncertain that we can tune it sufficiently to keep it completely steady. A lot of flying wing RC planes on the market today have a characteristic 'wobble' as the structure rolls and yaws in a steady loop. This would severely impact our hopes for potential market expansion in terms of surveying, photography and videography, and other observational tasks that would be better suited by some competitor's steadier product.

For the purpose of ensuring the best, smoothest flight we can for our customers, it is imperative to begin studying this soon and beginning our designs/modifications for the PID controller. Additional to it though, there are several design elements we are looking to add that will passively act to stabilize our plane in place of the aspects a flying wing has lost. We are looking to install wing fences on the bottom surface of the plane, which will help properly direct airflow and counter crosswinds and airflow along the swept edge of our wing, which is undesirable as we want it to instead flow directly over the front of the wing and off the back. Wing fences directly at the tip of the wing can also help with something we mentioned earlier, where portions of the wing, usually near the end, will lose their ability to meaningfully generate lift due to turbulence. Tip fences can steady those vortices near the end and restore lift to some or all of that wing surface. They have the additional benefit of acting as skid plates to protect our plane's underside if we make them out of a hard foam, as planned.

3.1.2 Second Semester Analyses

In order to design a controller for the plane, we set out to design a state space parameterization of the plane's flight dynamics. This state space would represent the desired flight state of the plane, with input from the user going towards modifying this desired state, rather than directly affect any control surface on the plane. In this way, we could create the desired fly-by-wire system for the Sunrunner and have the best chance to maintain flying equilibrium.

To this end, we established a state space model consisting of nine variables, three each for the linear velocity, angular velocity, and Euler-rotated orientation of the plane. The control for the plane had four components, one for the motor and three for the intended control surfaces. These could be combined to create a control system that would be designed and implemented through Simulink, or potentially migrated to our Ardupilot system. These three are illustrated below, with the equations for dx/dt following the same order as x, just in a vectorized form.

$$\overline{x} = \begin{pmatrix} u \\ v \\ w \\ p \\ q \\ r \\ \phi \\ \theta \\ \psi \end{pmatrix} = \begin{pmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \\ x_6 \\ x_7 \\ x_8 \\ x_9 \end{pmatrix} = \begin{pmatrix} \text{velocity in body } x \text{ axis} \\ \text{velocity in body } y \text{ axis} \\ \text{velocity in body } z \text{ axis} \\ \text{angular rate about body } x \text{ axis} \\ \text{angular rate about body } y \text{ axis} \\ \text{angular rate about body } z \text{ axis} \\ \text{bank Euler angle} \\ \text{pitch Euler angle} \\ \text{yaw Euler angle} \end{pmatrix} \qquad \overline{u} = \begin{pmatrix} \delta_{A1} \\ \delta_{A2} \\ \delta_{e} \\ \delta_{th} \end{pmatrix} = \begin{pmatrix} u_1 \\ u_2 \\ u_3 \\ u_4 \end{pmatrix} = \begin{pmatrix} \text{aileron} \\ \text{aileron} \\ \text{elevon} \\ \text{throttle} \end{pmatrix}$$

Figure 3.4: Parameterizations of the plane's current physical state and the input of the plane's controls. These fly-by-wire controls would be provided by our plane's in-board computer, as determined by changes to a feedback system altered by the user's remote control inputs

$$\dot{\overline{x}} = f(\overline{x}, \overline{u}) = \begin{pmatrix} \frac{1}{m} \overline{F}^b - \overline{\omega}_{b/e}{}^b \times \overline{V}^b \\ I_b{}^{-1}\left(\overline{M}^b - \overline{\omega}_{b/e}{}^b \times I_b \, \overline{\omega}_{b/e}{}^b\right) \\ H(\Phi) \, \overline{\omega}_{b/e}{}^b \end{pmatrix}$$

Figure 3.5: The equations of motion for the above system, where the vectors represent: F as force, w as angular velocity, V as linear velocity, I as inertial moment, M as torque, and H(Phi) as an Euler rotation.

This is the basic parameterization required to represent the plane in flight, and further characterization would be necessary to provide useful data. In order to understand this system, we must understand - or at least approximately simulate – the forces acting upon the plane under different operating conditions. After extensive searches for information on any flight dynamics pertaining to the B2 failed to provide results (not surprising, in relation to its status as a top-secret government spy plane), it was our intention to operate with a series of control ranges for each input, and systematically run through these ranges for each to catalogue and describe how each altered the flight of the plane. For the control surfaces, this range represented the angles over which their servos could be rotated. For the propeller, this would represent the percentage at which the throttle was running.

This is similar in concept to our work with Xfoil in the first semester, when we took a common airfoil and ran it through tests at varying angles of attack. This work could be marginally continued in the same way, though our final plane design necessitated a more comprehensive approach. With so many independent variables, this system would need to be linearized to allow for any form of real-time analysis and adjustment with an ODE. Our intention was to do this via Taylor Series approximations to create a linear time-invariant system, which would require us to have a full understanding of the flight dynamics of our plane. Once we have this linearized system, we could implement a solver in Simulink to fully model our control system. There could be further issues from here, but it is my understanding that this would have been sufficient to allow for initial flight testing and potential trimming of the system.

Xfoil is great for analyzing a singular 2D airfoil, but after the changes to our plane design brought on by manufacturing constraints, our plane had non-uniform and tapering wings with an atypical fuselage, all problems not easily accounted for in this software. It would be necessary, then, to create a new full 3D model of our redesigned plane and run it through more extensive computer simulations. This aerodynamic simulation would allow us to model and predict the forces acting upon the plane over its entire range of speeds and motions, thereby allowing us to vectorize the net action upon the plane's aerodynamic center, as well as watch for issues that could arise under certain conditions. These issues included large areas of dead air or excessive turbulence, vortices created by the swept wings, or angles at which the plane became too unstable to control.

This would also let us know just to what extent we could control and maneuver our plane, based on the size and placement of our control surfaces; how fast this design would need to go to maintain flight, and what operating speeds were safe to reach; and would highlight any flaws in our design that might need to be changed before reaching the manufacturing stage. It is frustrating that these are the questions that ultimately arose after our plane's crash, as we were unable to model the plane this way. Online searches suggested the use of another Autodesk program, their fluid dynamics program 'CFD'.

Were we able to get this program, we could have imported the design from Fusion360 directly and could have generated a script to run it through a few thousand simulations over a weekend to fully outline our operating space. Unfortunately, our budget did not have room for the $6,000 price tag they quoted us to license the software, even after they were sure to note they understood our plight and were offering a near-50% discount. My position as a student offered no help, and SIUE did not offer a license for the software either. Searches for competitor's services produced similar costly results.

I genuinely believe that we could have gotten this plane flying well - or at the very least known that we absolutely had to change features of the plane to allow for flight - if we could have gotten access to this or a similar program. I did dozens of hours of study and research on how to do all of this, what information we would need to collect from it, and how to implement the data in matrix form to be easily used in MATLAB, only to fall short because I could not get access to the necessary tools to do it. In light of this depressing and insurmountable monetary roadblock, we elected to use a pre-built fly-by-wire system already programmed into the Ardupilot, with the intention of doing a full re-tuning of its parameters to fit our plane after assembly had been completed.

As an additional note, we were introduced to methods of numerical linearization that might have allowed us to experimentally calculate the partial derivatives for our full state space without the need to fully model our plane. This would potentially let us bypass the roadblocks that kept us from properly tuning our controller. Unfortunately, this information was not made available in our drone dynamics class until after the Sunrunner had already crashed. Further study into this would be beneficial, and preferable to the price tag of the analytical tools required otherwise.

3.2 Solar Power Analysis

In order to first determine whether our project would be feasible, we had to determine the approximate power generation of our system compared with the expected consumption. To do so, we used a simulink model for a solar array with a battery and load connection shown in figure 3.6. The point of this was to simulate the solar array as part of our plane during flight where we estimated a 4.35 Amp load. This is a high estimate that took into account a lower performance motor that would require a higher power consumption to maintain cruising speed conditions along with the rest of the components of our design including control surfaces, flight controller, and communication. We then can also input the specifications of our solar array into the system and set the desired characteristics of our charger and battery. In this case, we had a 32 cell array capable of a maximum power of 107 Watts that would be connected to a 11.1 V Li-Ion battery with a maximum capacity of 2200 mAh. With these parameters we are able to run the simulation while varying two main parameters: cell temperature and solar irradiation. What we know from the performance sheet of our cells is that we want to maintain a lower temperature due to a constant decrease in power performance per degree celsius. We decided we would test our system at 35 degrees celsius which was the high end of our expected cell temperatures. We then created a test input for irradiation that would go through an average day's irradiance cycle in different parts of the year to measure at what irradiance level for our location we would go from net discharge to net charging for our system.

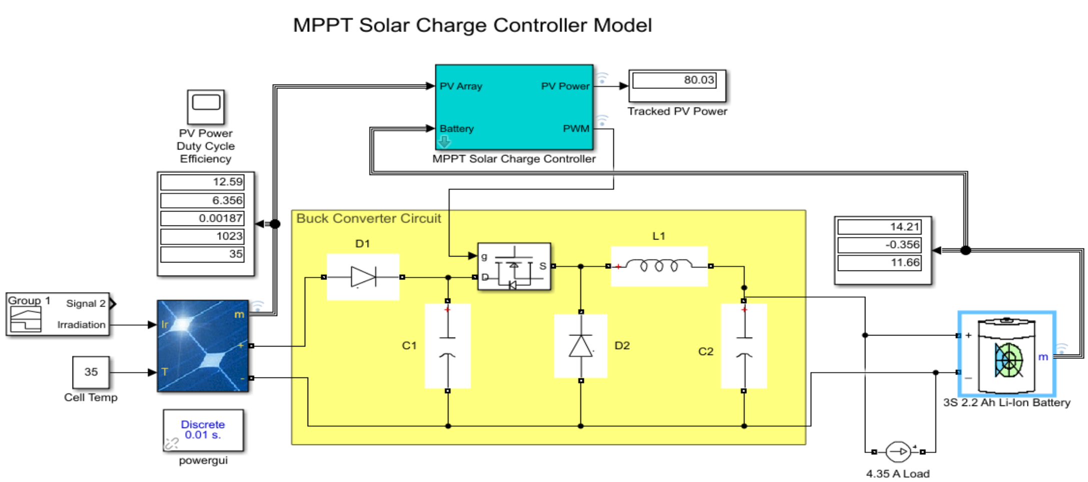

Figure 3.6: Simulink model of MPPT Solar Charging System with Load.

What we found was that given only irradiance data, our system required an irradiance level of 706 W/m^2 to break-even. This means that any irradiance level above this value would result in a charging battery system given a continuous load of 4.35 Amps. We then found the solar irradiance data for our location for several days of the year including the major dates such as the Summer/Winter Solstice and Spring/Fall Equinox. This would show us the best, worst, and average irradiance we could see throughout the year for a given day. With this can then can plot all of the irradiance levels of these dates against our break even irradiance level to determine on which days, if any, we would be able to achieve a net charging system. The results of this research is shown in figure 3.7 below.

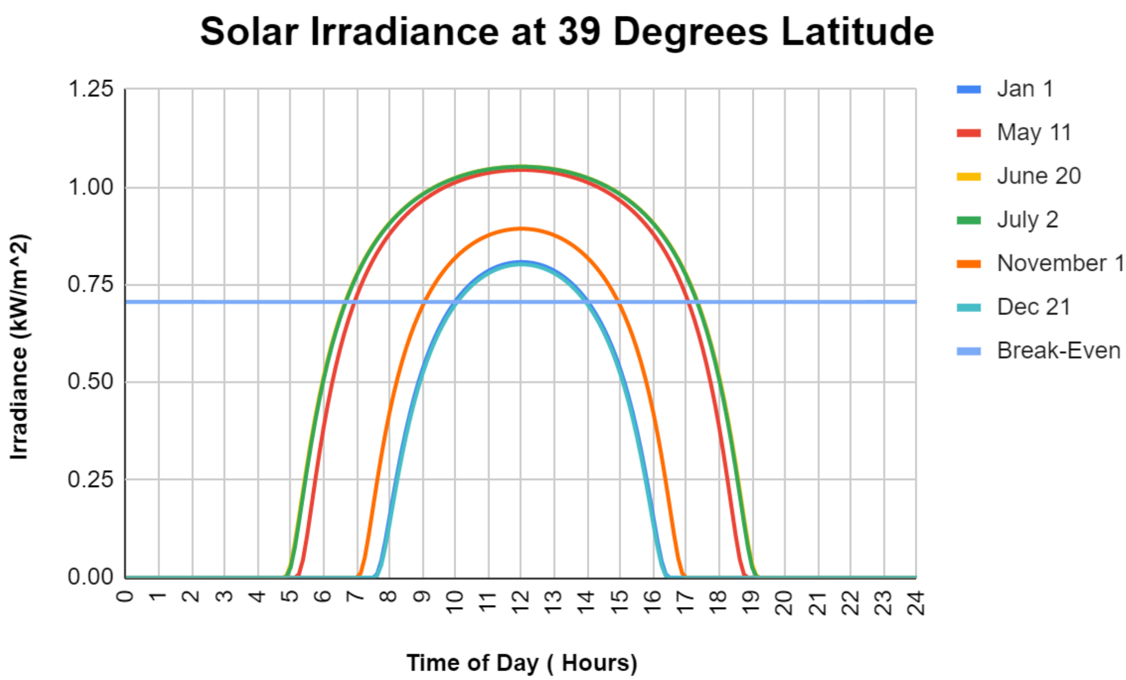

Figure 3.7: Solar Irradiance at our Latitude with break-even mark at 706 W/m^2.

What we found was that even during our worst expected day, the Winter Solstice where the nights would be the longest, that we still had a time of roughly 4 hours where we would be net charging. For the Summer Solstice we can see an even greater length of net charging time of almost 11 hours. This means that for at least 4 hours on any given sunny day in the year we would have a plane capable of non stop flight. This is not including potential flight time before and after we pass below the break even line where our flight time is still greatly extended.

We looked at the current generation produced by a given irradiance level, we were able to calculate the expected battery life in minutes for the system up to the point where it reached the break-even irradiance level. Shown in figure 3.8, we can see that even before reaching the break-even point our flight time is still many times greater with the array than without. Without solar, our normal battery life is only roughly 30 minutes. However, even at an irradiance level of

500 W/m^2 we have over three times the flight time compared to non-solar flight. This was an excellent sign for us that our system would be able to produce continuous flight situations in more than a single case. Given the maximum potential irradiance we saw of over 1000 W/m^2, having a break-even point of 706 gives us a large room for potential operation both above and below our break-even point. Even in cloudy weather or short days, we would still greatly extend our flight times during less than greater environments.

Given these results, we are very confident that our current design will produce a plane capable of charging during flight. In order to confirm this in our final design, we will have to actually test the power generation of our solar array and compare it with the actual power consumption of our system. Our theoretical values might be close, but there is potential for changes to our electrical components that could increase our required break-even irradiance level.

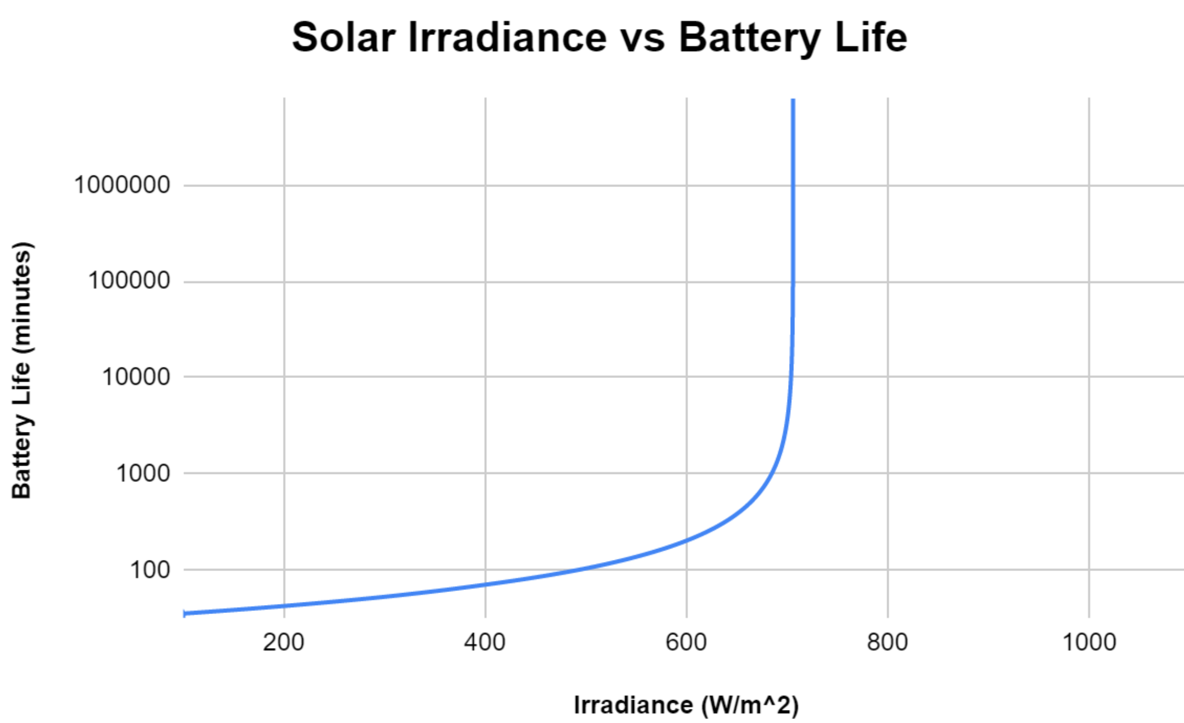

Figure 3.8: Battery Life with Respect to Solar Irradiance.

3.3 MSRP Analysis

Small Manufacturer's Bulk Pricing Sheet				
1. MATERIAL	Quantity	Cost	Total	
Aero-modelling Foam Board	7.5	$10.00	$75	
ABS Half Rod Rod	4	$0.36	$1.44	
Hot Glue	50	$0.06	$2.89	
Mounting Bracket	10	$0.52	$5.25	
Electronics	1	$121	$121	
MATERIAL			$205.64	
2. LABOR	Set Up (# of Min)	Run (# of Min)	Cost/Hour	Total
Cutting/Trimming/Gluing	20	20	$25	$17
CNC	20	30	$5	$4
Assembly	20	60	$50	$67
Labor				$88
3. OVERHEAD			100%	$293
			Subtotal	$586.27
			50% Profit	1.5
			4. Sale Price	$879.41

Due to our MSRP analysis, we ended up not using carbon fiber, because it was far too costly for what we wanted to do. Our estimation for the electrical parts was a little low. Custom solar panel prices were hard to come by. If we had a better understanding of what this is, our electronics section would be much higher.

4 Alpha Prototype

4.1 Alpha Prototype Construction

During the Alpha construction of our project we were mainly focused on two main areas, the electrical construction and the aerodynamic characteristics of the plane. The main area of focus was on our electrical components. We started by finding what other RC planes use to fly and compared those needs to the needs of our project. We focused on the available thrust provided by the motor along with the power consumption of the motor and control surfaces, and power draw from the other electronics. Once we were able to find this vital information we could move forward with the design of the airplane body.

For the design of the airplane body we looked at different types of wing design that would provide the adequate lift and also have enough surface area for the mounting of the solar panels. Having enough surface area for the solar panels is crucial in order to generate enough power to at least double our flight time. To satisfy both of these design criteria for the airfoil design we decided to go with a KFm3 airfoil design. This airfoil design can be seen in the example below, *Figure 4.1*. This resembles a very common airfoil design known as the Clark-Y airfoil, this design has ideal lift characteristics but is missing the flat available area to mount solar panels. The KFm3 design gives our plane 3 different levels to mount our solar panels too, satisfying our design criteria.

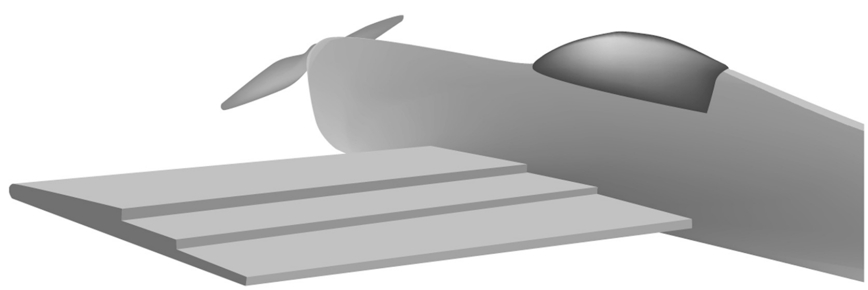

Figure 4.1: KFm3 airfoil design

To help with the manufacturing process in Beta testing we first built the scaled version of the plane out of cardboard. The alpha plane can be seen below in *Figure 4.2*, you can also see the style of KFm3 airfoil in *Figure 4.3*.

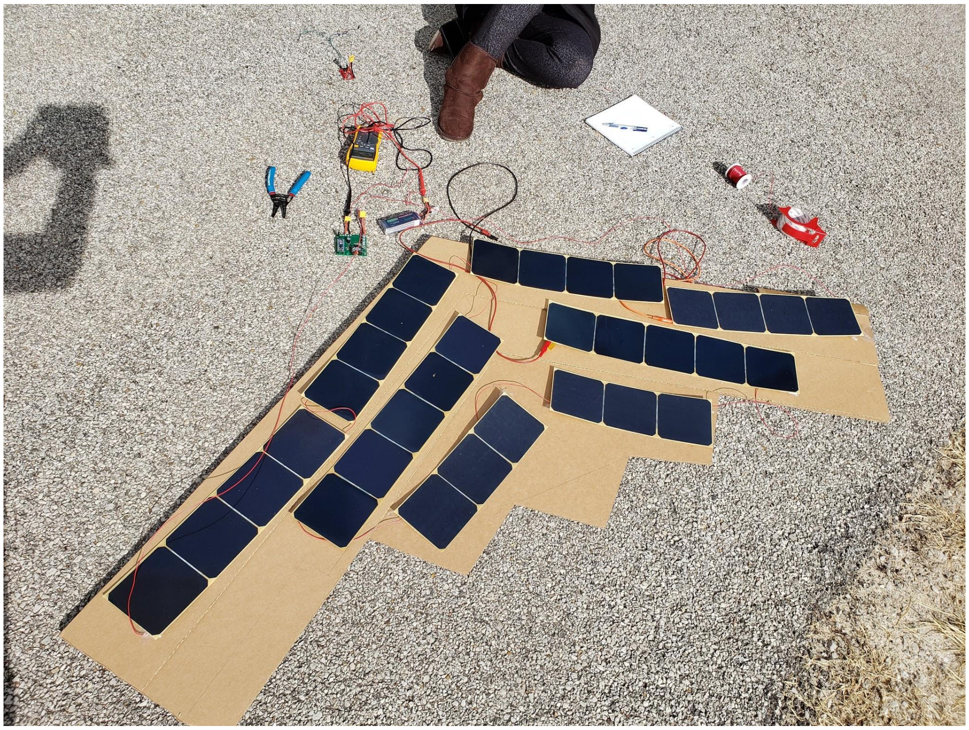

Figure 4.2: Alpha testing solar on prototype plane

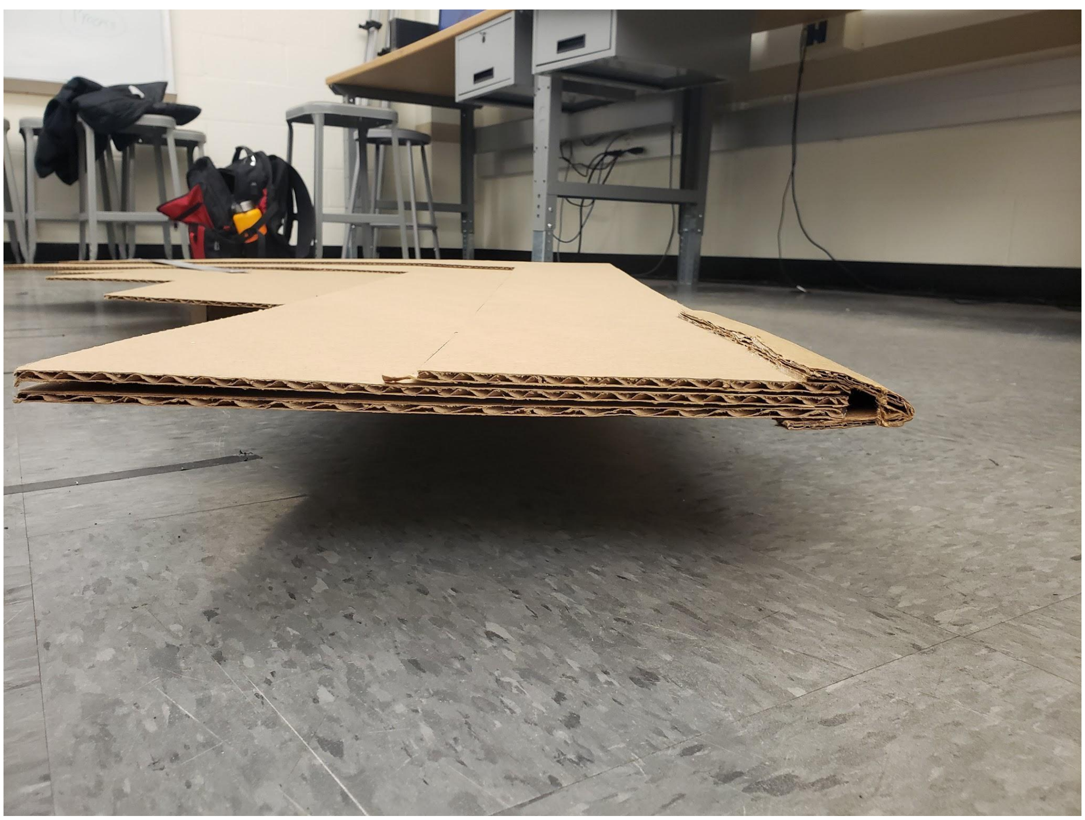

Figure 4.3: KFm3 Airfoil design of Alpha plane.

While conducting testing in the Alpha stage of this project we figured out our MPPT solar charger wasn't producing power as we designed. We first ran into an issue with the ground traces not being large enough to carry the multiple amps of current through the wires. This led to a few of the wires getting very hot and actually breaking the wire traces on the PCB board. Upon making larger ground traces for the redesigned PCB board we also noticed that 2 of the resistors that are used to control output current were the wrong size also so we updated these resistors before sending the board off to get printed again.

4.2 Alpha Prototype Testing

4.2.1 Power Generation Testing

For our Alpha Prototype, the most important testing was on the functionality of our electrical system and the power draw of our plane versus the expected power generation of our array. In order for our design to be considered feasible, we had to test whether our solar array would provide enough power on average to charge a battery while providing the necessary power for our system draw. Since our goal was to design a product that would be able to charge during flight, we have to produce more power during our cruising conditions then we used, resulting in a net positive current applied to the battery.

We know based on our simulation that our expected cruising speed conditions should be achieved using a throttle of 50%. We are also aware that the maximum potential power generation our solar array is capable of is no more than 97 Watts based on our current setup but not including any potential power losses. This leaves us with the desire to find the power draw curve of our plane given a varying throttle position to determine if we produce more power than used at 50% throttle and at what throttle would we expect to break even given a 97 Watt supply from the solar array.

In order to test this, we assembled all components required of our plane including the following: two control servos, our main motor, the flight controller, radio receiver, and GPS receiver. Since we did not have our plane yet fully created, we used mounting clamps to hold the motor in place. With the motor locked in place, we attached the propeller to the motor. Without the propeller, the current measurements would be inaccurate as there is no load on the motor, resulting in a highly underestimated current measurement.

Using a fully charged 11.1 V (3S1P) Lithium Polymer (Li-Po) battery, we connected a multimeter in current measurement mode in series between the battery and our plane electrical system. Once we have confirmed the correct responses from the flight controller, we can turn on the remote control. In this test, we simply used the markings on the remote control which indicated 6 settings for the throttle control. This allowed us to note the throttle position in terms of 1/6 or 16.67% throttle per tick. Starting from 0 % throttle, we began to move up the throttle position to each tick and measured the current draw of the system at that moment and recorded the data.

After testing throttle, we would test the systems power draw for other components such as the servos connected to our control surfaces as well as our flight controller and communication modules. We measured the idle current when the throttle was not running and the servos were resting in their starting configuration as the constant current draw of our system. We then measured the servos through a range of motions to max out their possible load to find the highest current value for a given servo position. This would tell us the maximum potential power required to move the servos. Using this we can then combine with the motor draw to find the maximum possible current draw of our system as well as the current draw during cruising conditions.

4.2.2 Testing Results

Using the testing data of throttle to current draw, we were able to construct a plot of the throttle versus power draw given as nominal 12 V battery supply. We then also constructed a table indicating the power consumption of our cruising conditions, take-off conditions, max servo power, and flight controller power compared to the power generation of our solar array. At cruising conditions we assume our servos are running minimally and our throttle remains at 50%. Also, at take-off conditions we assume the motor is running at 100 % throttle and our servos are maxed out to achieve maximum lift.

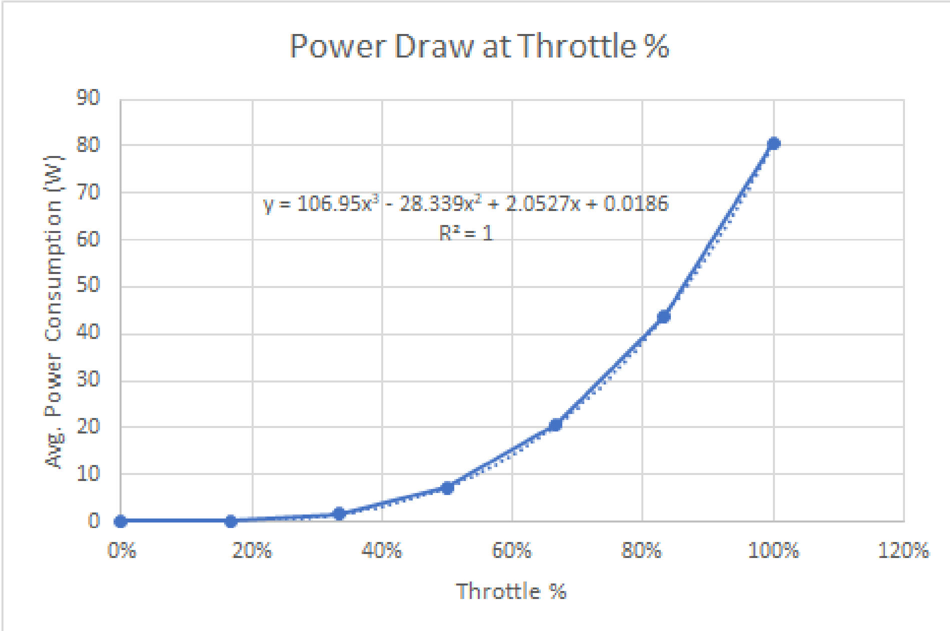

Figure 4.4: Power Draw vs. Motor Throttle

Power Consumption of Electrical Components	
Cruising Throttle	7.25 Watts
Take-off Throttle	80.7 Watts
3 Control Servos	15 Watts
Flight Controller (radio/telemetry)	2.5 Watts
Power Generation of Solar Array	
20.2 V x 4.8 A = 97 Watts	

Table 4.1: Power Consumption of Electrical Components.

What we found from this testing was that our design is feasible. Given a maximum potential power generation of 97 Watts, even during take-off conditions we would only see a power draw of 98.2 Watts. This would only occur during the start of flight, meaning that at cruising conditions, our power draw is only around 10 Watts, resulting in a definite surplus of power that could be used to power the battery.

While this is an extremely positive result in terms of proving the feasibility of our product, we have not yet begun testing on the actual solar power generation. Currently we were assuming 100% efficiency from the solar array, but depending on the result of our MPPT Solar Charging Circuit design, we might hit a lower max potential in terms of solar power which can lead to us not reaching our goal of charging during flight. We will have to confirm the results of the solar charging itself as well as the flight capability of our plane before making the final determination on feasibility.

5 Beta Prototype

5.1 Beta Prototype Construction

For the Beta prototype construction, our group was mainly focused on building the final form of the plane. We started by ordering sheets of 10mm aero-modelling foam board as the main construction material for the plane. In order to build the KFm3 airfoil design we had to cut the foam to the shape of the wings and then glue the boards together in order to span the whole wingspan. Once we had the individual layers of the foam cut out we were then able to stack and glue the different layers together in order to get the desired thickness of the plane. At this point the plane was in three different pieces and ready to be fully assembled, this product can be seen below in *Figure 5.1*.

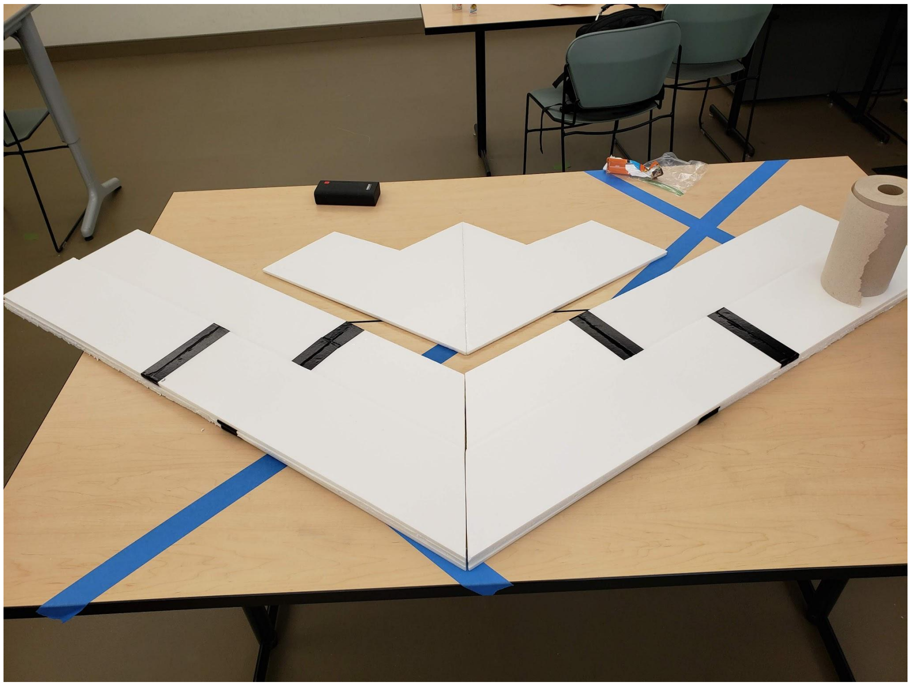

Figure 5.1: The plane in 3 pieces ready to come together

At this point in the construction process we needed to connect these three pieces together through the use of mounting brackets, doll rods embedded into the foam, and lots of glue. The final product of this being put together can be seen below in *Figure 5.2*, the red lines that are drawn on the picture help illustrate where we have the doll rods located in order to give the plane extra support on these seams. You are also able to see in this image where we have the silver mounting brackets holding the two halves of the wing together. In *Figure 5.2* you are also able to see that we have the aileron flaps cut out of the plane as well. We were able to cut these flaps out of the plane through the use of a hot knife. The hot knife we used was a home built one that you plugged into the wall and it would put a current across a taut wire causing it to heat up and be able to cut through the foam.

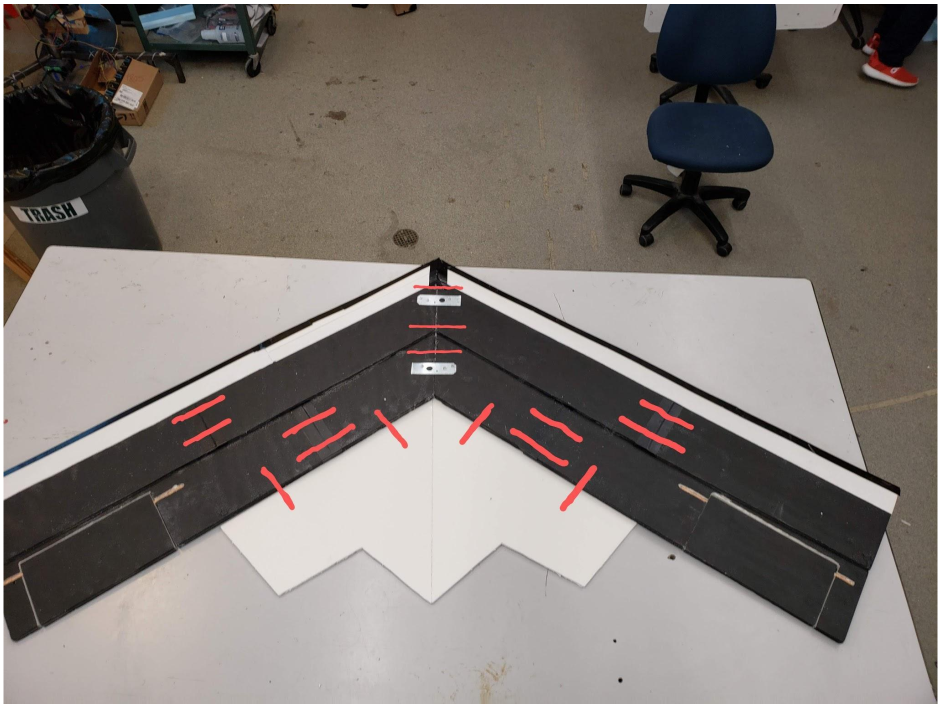

Figure 5.2: Construction of the beta prototype

From the point of having a flying wing, as shown above, we then needed to build the fuselage, wind fences, motor mount, and mounting position and canals for the servo controls. The servo wires are shown by the green trace shown in *Figure 5.3*. In order to build the channels for the servo wires we used a dremel to remove material. The fuselage and wind fences were all made out of foam as well.

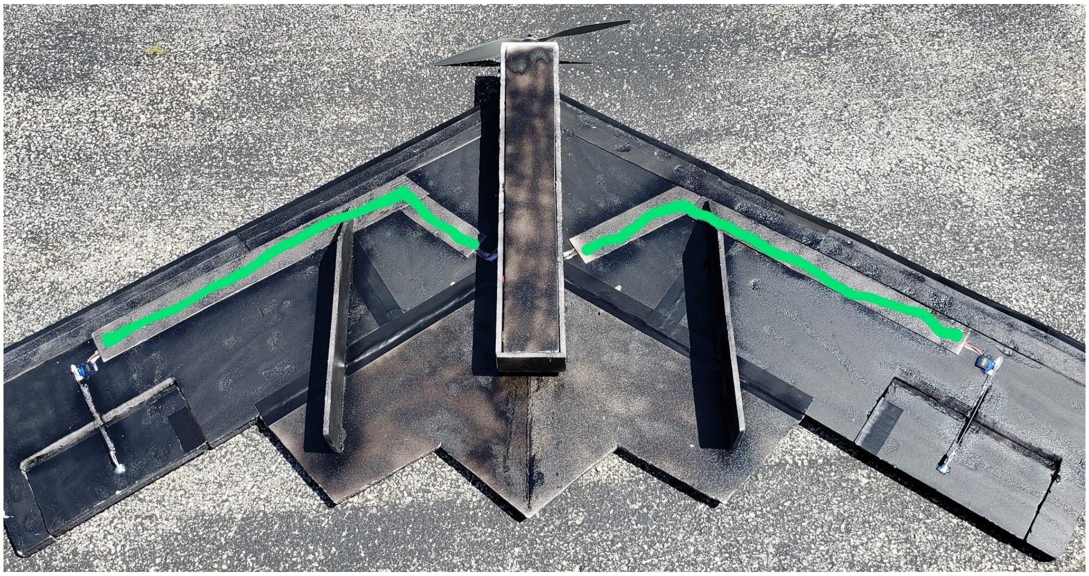

Figure 5.3: Green lines shows the rout of the servo wires

The location of the motor mount and how it would connect to the plane was something we still needed to figure out. We couldn't just attach the motor to the foam because it would rip out of place due to the forces. In order to securely mount the motor to the plane we had to first build some type of mounting bracket that would secure to the plane. This was done through the use of two pieces of aluminum sandwiched between the top layer of the fuselage, and then a large bolt was secured through the metal to hold everything in place. This mounting bracket can be seen below in *Figure 5.4*. You can also see one of the hendge mechanisms in *Figure 5.4*, this was so we can open up the fuselage to service all the electronics.

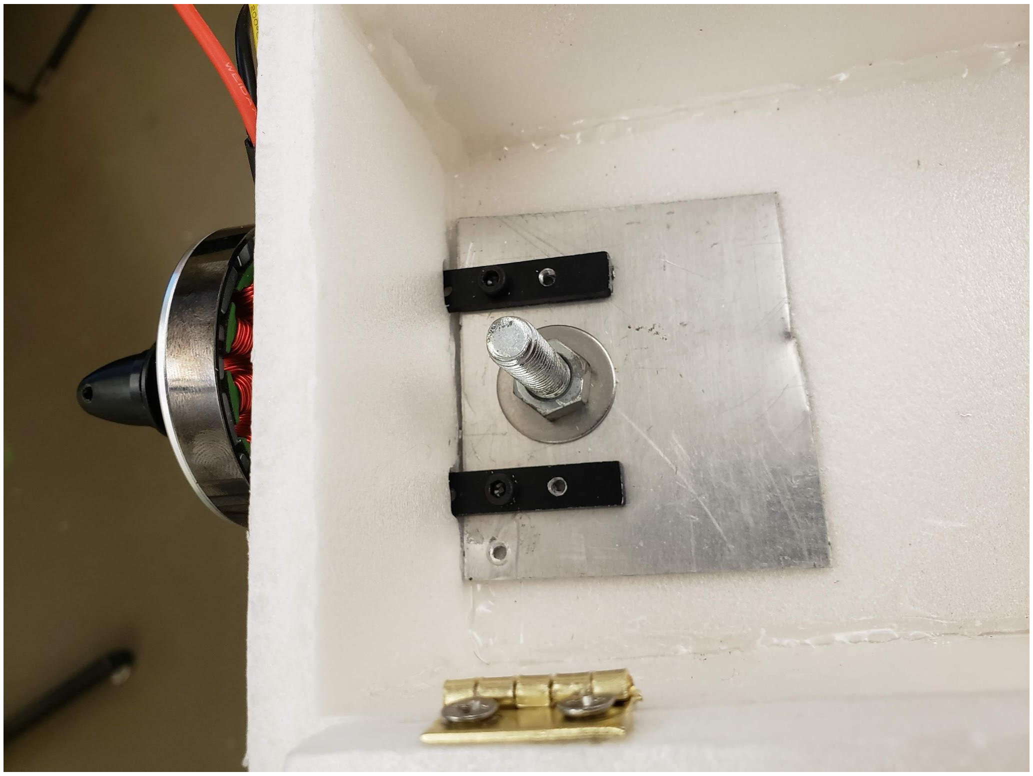

Figure 5.4: The mounting bracket for the drive motor

At the same time we were building the plane we were still troubleshooting the MPPT solar charger. The MPPT charger was stuck in a setup procedure where you set the startup configuration through the use of I^2C communication bus. We were passing all the correct information to the IC and we were able to read back this information correctly, but the charger was still having an issue passing any current to charge the battery. We ended up reaching out to Texas Instruments to help with this error. For the rest of our solar charge testing we used a pre bought MPPT charge that ended up being less efficient by doing a max current of 5A instead of the 10A we tried to design for. Even with this last minute design change we were still able to prove positive net charging, we will talk more about the solar testing in the next section of the report.

5.2 Beta Prototype Testing

5.2.1 Power Generation vs. Consumption Testing

When looking at the feasibility of our design, one of the most important factors was whether we are able to generate more power from our solar array than we use in our plane electronics. In order to do this we used an ammeter connected in series between our Li-Po battery pack and the rest of our electrical system. With this we are able to measure the bi-directional current traveling to or from the battery depending on the conditions of our solar charger and our flight system. If our solar charging is non-existent or very low, we expect to see a positive current value which indicates that the battery is being discharged. If the measured current is negative it means we are generating more power than our system is using and excess is being used to charge the battery pack.

For our testing we are able to alter our motor thrust from 0% to 100% throttle and able to observe the exact throttle position from our flight control software. With both throttle position and current draw, we are able to move from 0 % to 100% throttle while measuring the current across the ammeter. For the sake of proving our design, we tested in three cases. Our first case is with no solar charging attached. This could simulate any situation where we would not be able to generate power from our array, be it from damage to the array or low light and nighttime flying. Second case is solar charging during overcast conditions. It is possible the plane would fly in cloudy weather and our hope is that we are either able to charge during overcast weather, or it will extend the flight time of our system to at least twice the normal flight time expected from our battery capacity. Our last case is solar charging during sunny weather. This is the main area we want to show the feasibility for. If we are unable to charge during sunny weather, that means that in no other condition will we be able to charge our system. By showing it charges in sunny weather, we can at least validate the plane's capabilities in a specific environment it could be useful in.

5.2.1 Power Generation vs. Consumption Results

With the results of each case, we used a polynomial best fit line to the fourth power to model our system performance with respect to throttle position. With each case we can see the current consumption of the battery and specifically focus on the current consumption at our 50% throttle point we defined as our throttle at cruising speed.

For our first case, we can see the current draw for our flight system at 50% throttle is roughly 1.75 Amps. At a battery capacity of 5500 mAh this leads to flight time of roughly 3.15 hours. We can use this as an assumption for our maximum possible flight time without any solar charging and use the current value as an indication of what the system should normally demand from our battery. At maximum throttle we have a current draw of around 6.5 amps, which would result in a battery lifetime of 0.85 hours if the plane ran full throttle till it died.

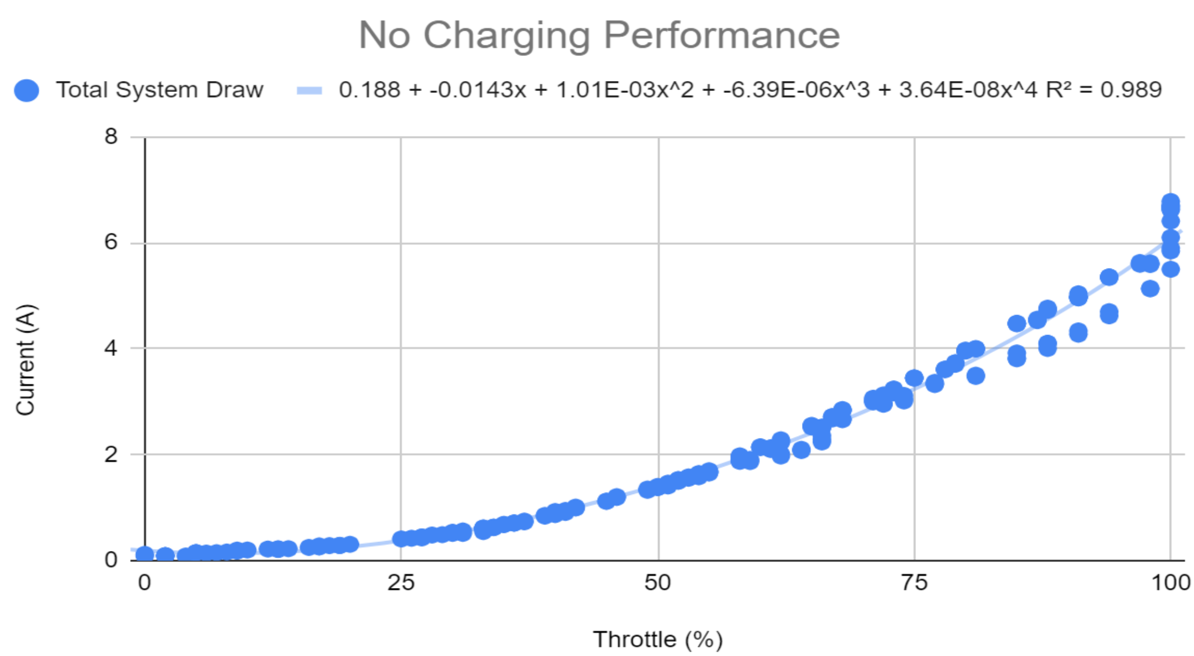

Figure 5.5: Plane current consumption with no charging.

For our cloudy weather data, we are able to see that we achieve a negative current value till around 56% throttle. This means that for any throttle position below 56% we are charging our battery pack and providing all the necessary power demands from the solar array alone. At 50% throttle, we have a negative current which means that we are capable of sustained flight for as long as we maintain our throttle at 50% and at any value below 56% throttle. At 100% throttle we see a current draw of roughly 4.25 Amps which would result in a battery capacity of 1.3 hours if the plane ran full throttle till it died, this is an increase of roughly 1.89 times longer in terms of battery life.

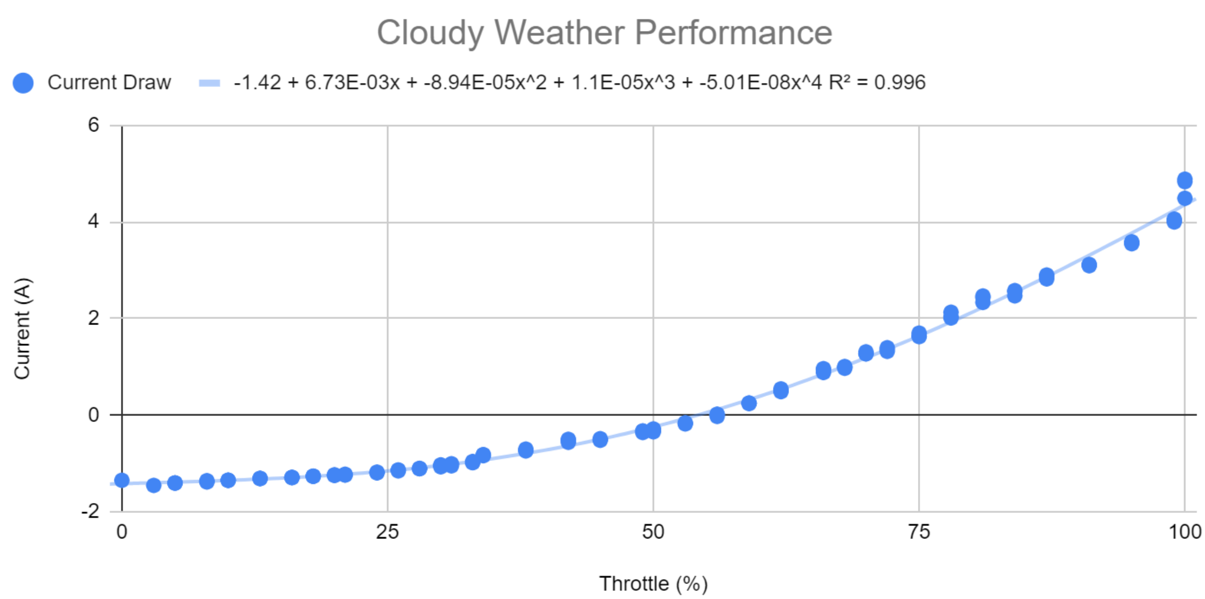

Figure 5.6: Plane current consumption with charging during cloudy weather.

For our sunny weather performance , we are able to see the best possible performance of our solar array. During sunny weather we see that we are able achieve a charging current all the way till roughly 76% throttle. This means that at our conservative estimate cruising throttle of 50% we are able to charge while flying, with a charging current of roughly 1 amp while providing power to the rest of the system. At 100% throttle, our maximum current measurement is only 3.5 Amps, resulting in a flight time of 1.57 hours, which is 1.2 times longer than our cloudy weather performance and almost twice as long as our plane's performance without any solar charging whatsoever.

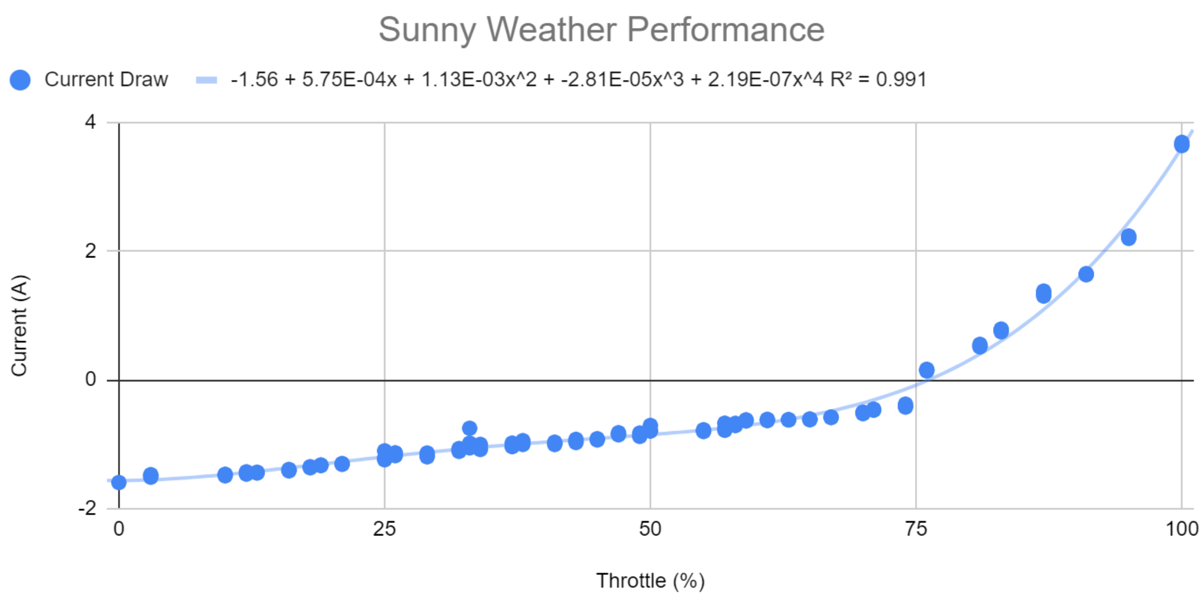

Figure 5.7: Plane current consumption with charging during sunny weather.

Overall, our testing results were very promising. Not only were we able to prove that during sunny weather we would be able to charge the battery at our cruising throttle of 50%, we were also able to show that even during overcast weather, which heavily reduces our available power output, with the ability to still charge (albeit a very slow charging current) the battery pack while supplying power to the rest of our electrical system. This is in line with what we had calculated last semester with our Simulink model that showed we would be able to power all of our electrical systems and charge our battery system. In fact, if we had to make downsizes to our system, we could still provide net charging ability during sunny weather for a large margin given our break-even point during sunny weather is around 76% throttle compared to our cruising throttle of 50%. This means that if our design required changes that would increase our required throttle position we could still handle the increased demand while maintaining our performance.

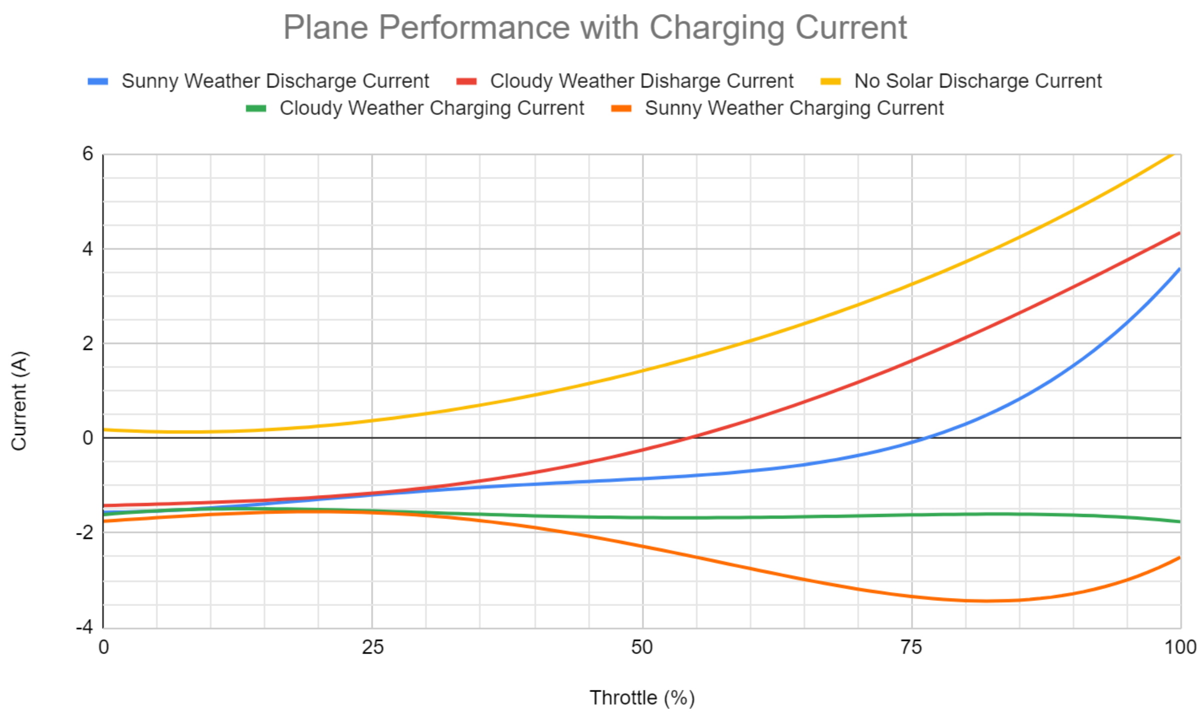

Figure 5.8: Plane Performance at with all conditions.

5.2.2 Flight Controller Tuning

We ran into significant troubles while attempting pre-flight calibration of the flight controller, most of which came down to time constraints to learn and implement a new technology in the plane. The fly-by-wire controls pre-programmed in Ardupilot allotted controls for two flaps, which gave priority to the ailerons for turning and lateral control. It proved too tall a task to alter their code to provide control for a rear elevon, as there was little documentation available on how this could best be done. Our plan was to try with two, and if absolutely necessary go back and find a way to add the third to their software.

Shipping delays and scheduling issues between the team really brought this effort to its knees. This resulted in the plane itself not being fully constructed until the week of our first flight test, leaving little time to work with and tune the controller. The size of the plane, likewise, led to difficulties testing: the massive wingspan made it difficult to rig up and test in the lab, and made transport to a separate location difficult. As the wind tunnel on campus was too small for testing our aircraft, we had to find another way to simulate flight at ground level.

To do this, our team harnessed the plane with twine over its center of mass, elevated a few feet off the ground. Two large fans were placed in front of the plane, one in front of each wing, and turned on. The hope was to perturb the plane in different ways inside this airstream, and adjust the controller tunings accordingly to reach our desired stability/settling constraints. This effort proved largely ineffective due to the controller's heavy reliance on GPS and gyroscopic data for feedback. Since our plane had zero surface velocity, ground-test tuning seemed to offer no added control to the plane. There was frustratingly little information online in regards to tuning a controller for a plane without well-known flight dynamics, which left us with the option to attempt tuning during an actual flight.

5.2.3 Flight Testing and Results

For our flight testing, our main goal was to achieve any level of steady airborne flight. In order to do so, we planned to launch the plane by hand after allowing the motor to achieve maximum throttle to give the best chance for the plane to get clear of our stall speed, and set the flaps to achieve maximum upward lift. We would then move forward and launch the plane to give it some starting velocity to begin producing enough lift to maintain altitude while accelerating up to cruising speed. Either in flight or after our first flight, we would tune the controller to better stabilize the plane, based on our observations from the ground.

Unfortunately, our plane did not achieve the requirements to maintain altitude and fly and instead crashed to the ground. We found that there are likely several factors that played into the crash, including poor control tuning, insufficient control surface size in comparison to our weight, insufficient take-off speed, and inadequate landing and take-off equipment, which as stated previously we were unable to account for pre-flight without better understanding of our plane's aerodynamic characteristics via fluid flow analyses.

With less-than-stellar control surface tuning, our system - which, as a flying wing-style plane, is unstable by nature - could not correct itself to maintain altitude and with the combination of small control surfaces, at our starting speed we could not generate enough lift to continue to move the plane upward. It is possible with the implementation of large control surfaces that we could take-off at a much lower launch speed along with the ability to correct enough to stay airborne as it accelerates.

The implementation of landing gear would also have greatly improved the survivability of our design. With landing gear we could have started from the ground and using the propeller we can accelerate forward and allow our plant to naturally reach the speed required for take off. If we had accelerated fully and still not been able to take off from the ground we would have been able to discover our plane did not possess the correct characteristics to fly without us needing to let the plane smash into the ground. Another benefit of the landing gear is the ability to land more safely, our plane could have used the landing gear to protect the plane body and allowed the wheels to take more of the damage first to provide the additional strength of our design and repeatability.

6 Final Product Design

Between the Alpha and Beta construction phase we didn't change much in terms of the design of the plane, we were mainly focused on the electrical side of this project to make changes. We did it this way because if the plane wasn't able to fly then we could always rely on a store bought plane to then "hack" with all of our electronics in order to have it run on solar power. Below in *Figure 6.1* is the final 2D model of our plane.

From the Alpha construction phase we had issues with the MPPT solar charger that we designed, so in order to have a more reliable charging system for the Beta prototype we went with a store bought MPPT charger. Even though this store bought charger was less efficient we were still able to prove we were able to at least double the flight time of the plane.

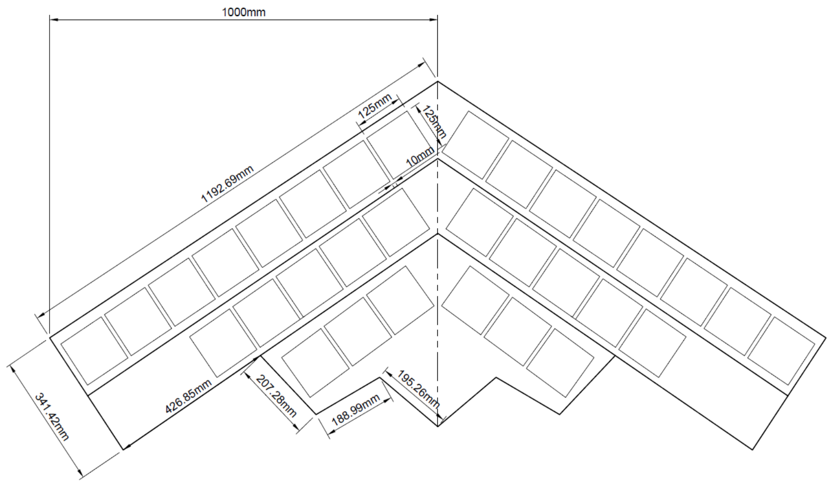

Figure 6.1: Adjusted B-2 Design

7 Miscellaneous

7.1 Cost Analysis

For our first year of manufacturing the Sunrunner RC solar planes we projected 300 units to be produced and sold. To account for this number of planes we researched bulk prices for all the components and materials needed to build 300 planes. For the reason our group is purchasing consumer level electronics we were unable to find available bulk pricing for these electronics so we took an average of 40% off our electronics pricing sheet. Based on our design goals we are wanting to be able to produce the Sunrunner plane for less than $500 each so getting bulk pricing discounts is imperative.

To figure out how much foam we are needing to order for the body of the plane we first started by modeling our design in Fusion 360. This allowed us to separate the plane into different sections so we were able to calculate the total surface area of the plane that is requiring foam building material. For the rest of the building material we discussed how many and where we would be attaching mounting brackets on the plane, how much of the ABS half rod's we would be using for wind finches, and how much foam glue or hot glue would be needed to attach everything together. All this pricing information can be found in the *Small Manufacturer's Bulk Pricing Sheet* shown below.

For the labor costs to produce the Sunrunner we are pricing in that it will cost $25/hr for cutting, trimming, and gluing sections of the plane to get ready for the CNC machine. The CNC machine will only cost $5/hr to run. Our largest labor cost comes in from the assembly of the plane and electronics like attaching the solar cells. The assembly labor costs are shown to be $50/hr.

Small Manufacturer's Bulk Pricing Sheet				
1. MATERIAL	Quantity	Cost	Total	
Aero-modelling Foam Board	7.5	$10.00	$75	
ABS Half Rod Rod	4	$0.36	$1.44	
Hot Glue	50	$0.06	$2.89	
Mounting Bracket	10	$0.52	$5.25	
Electronics	1	$121	$121	
MATERIAL			$205.64	
2. LABOR	Set Up (# of Min)	Run (# of Min)	Cost/Hour	Total
Cutting/Trimming/Gluing	20	20	$25	$17
CNC	20	30	$5	$4
Assembly	20	60	$50	$67
Labor				$88
3. OVERHEAD			100%	$293
			Subtotal	$586.27
			50% Profit	1.5
			4. Sale Price	$879.41

Our overhead is 100% of the cost of our materials and our labor costs. This overhead category is setting money aside to cover all the costs for human resources, accounting, sales team, marketing, capital costs, and taxes. Considering all of these above categories our team is able to produce one Sunrunner plane for $586.27. We are planning on taking 50% profits from this plane so we will be marking up our plane to a sale price of $879.41.

7.2 Timeline

	Start Date	End Date
Ethics Research	19-October	8-November
Societal Research	19-October	8-November
Final Presentation Draft	22-November	22-November
Final Presentation Video	16-November	4-December
Final Presentation	22-November	8-December
Design Paper	31-December	11-December
Design	1-December	31-December
Analysis	1-January	31-January
Pre-Testing	11-January	28-February
Build	22-January	28-February
Program	1-February	28-February
(Test, Review, Fix) X3	1-March	19-April
Project Presentation	10-April	26-April

Actual Timeline	Start Date	End Date
Analysis	1-January	31-January
Pre-Testing	23-February	6-March
Build	23-February	13-April

Program	1-March	13-April
(Test, Review, Fix)	13-April	18-April
Project Presentation	18-April	26-April

We started off having to do some redesigning since the solar charger wasn't working. Since we did this redesign, we didn't order our parts until February which made our schedule completely off. So we did not have time to do more than one flight test.

7.3 Learning Plans and New Knowledges Acquired

During our research into solar chargers, we learned about the characteristics of solar cells, batteries, and the differences between PWM solar chargers and a MPPT charger. To design a solar charging system, we learned how to use Simulink to simulate the solar system and improve our design. We used Eagle to design our electrical systems and to test out our ideas.

We learned a lot about aerodynamics and how to calculate thrust, lift, and drag. Using Fusion 360 we designed our airfoil, modeling its aerodynamic characteristics in Xfoil. We researched control systems and surfaces such as ailerons, elevators, and rudders to best understand how to stabilize our plane. With this new knowledge, we decided to add wind fences to the bottom of the plane as a passive stabilization method. Though not used in our final construction, we designed a flight controller in MATLAB that brought together the very highest concepts we've learned in control theory here at SIUE, fusing them with our new understanding of what forces act on our plane and how.

We would have been able to test our design even easier if we were able to get access to the windtunnel, but that fell through. However, we were able to use the Solar Racing Team's lamination machine to make the panels. By doing this, we were able to make our panels handleable as well as light. We also found some information saying that you can use kevlar instead of tedlar for a backing of the solar panels, to make them lighter and more flexible.

7.4 Codes and Standards

Codes and Standards	
Targeted Area of Our Design	**Source**
Batteries	https://www.cpsc.gov/
Unmanned Aircraft Systems	https://www.faa.gov/uas/
Camera Mounting	https://flightflix.net/faa-camera-mount-guide/
Aircraft Registration	https://www.faa.gov/uas/getting_started/register_drone/
Mechanical Design	https://www.faa.gov/mechanics/regs_policy/
Recreational Flyers	https://www.faa.gov/uas/recreational_fliers/
Electrical Regulations	https://www.ecfr.gov/cgi-bin/text-idx?c=ecfr&tpl=/ecfrbrowse/Title14/14tab_02.tpl

There was only one code that we ended up not using, which was the camera mounting standard. We ended up not having time to put a camera on the plane.The main code that we used was the electrical standards for batteries which talk about the required safety features for unmanned aerial systems and their battery systems which include battery management and protection systems. Based on the weight of our plane, we far exceed 250 grams, so we had to register our plane with the FAA.

8 Next Steps

There are a great deal of things to take away from our initial testing data that can go towards redefining the design of our aircraft. First and foremost is the overall size of the plane and ratio of panels to surface area. Due to initial misunderstandings about the power required by the Sunrunner's digital systems, we anticipated needing at least 30 solar panels. This necessitated changing our plane's design, extending the depth of the wings and fuselage, which might have contributed significantly to our difficulties in stabilizing the plane; and also limited the space we had available within the B2 frame shape to create control surfaces, which definitely contributed to stability issues.

Our ground testing data suggested that the solar panels were generating net positive power at well over 50% throttle, which was already our most conservative estimate required for sustained flight. In fact, at 50% throttle on a good early spring day, the plane was generating twice the power needed by all systems combined. This suggests that we could cut the number of cells on the plane in half. This opens a lot of doors for positive changes to the design, the most obvious of which are significant reductions in weight and cost, two *major* limiters to the design of the plane and its overall marketability. This ability to improve efficiency only increases if we can get our design for the MPPT to function properly or find a pre-designed one on the market if the price is right.

Additionally, this means that several of our other plane designs become far more feasible from the solar standpoint. Aside from aesthetic purposes, a large factor driving our choice of the B2 was the large surface area of the plane for solar panel application, a factor that we apparently weighted too heavily in our selection process. If something like the Hercules or the twin-boom design allows for much greater stability control and easier forms of modularization, while also providing a large enough surface area on just the upper wing surface for net-positive or net-zero solar charging in flight, then it is an easy choice to select another design. This would have the added benefit of being a category of planes with more available aerodynamic documentation, with common control methodologies and well-modeled designs.

Were we to continue with the B2 design, however, there are several steps we would want to take to ensure we could get better results. We understand now that we did not provide enough measures to guarantee the plane could reach its desired state for steady flight, and we need to address those issues. Cutting down on panels would allow us to redesign the wing, with greater available area in back for larger ailerons, and give us space at the front edge of the wing to create a better aerodynamic shape to carry wind over the back of the wing. We would additionally include wheeled landing gear, which would allow us to safely take off and land without requiring a person to ever throw or catch what is arguably a delicate and less-stable plane. The money saved on solar panels would have made this more feasible to do this past semester.

To make a more viable product for the hobbyist consumer market, we needed to create a more rigid and sturdy product. This could potentially be achieved by reducing the wingspan, to generate less bend on the wings, but would ideally be solved with a sturdier build material or a resin coating to the plane, if weight tolerances allowed. This would much better protect the plane from the elements, as well as provide safer places to grab and hold the plane. We also found that this level of cover would not likely cause any insular problems, as heat management was surprisingly easy for our solar system, even on the ground, without 20-30 mph winds blowing over the elements.

The product is likewise viable for surveying industries and companies that desire long-term flight capabilities. Changing to one of the other body designs would make it far more reasonable to equip the plane with some form of camera or other data-capture devices or carry some form of payload. Provided there is sunlight, these planes could travel all day, either in a small area or over vast distances – potentially several hundred miles a day. This could allow for fast transport of goods and information through areas with difficult terrain too large to cover on the single battery of a non-solar drone or plane. Moreover, it can provide *continuous* coverage for an extended period of time, which is something that no non-solar product can offer. While this might be a niche area of performance, there is the chance that it could be vital to some research effort or other, making this a viable and desirable product worthy of continued efforts.

9 Conclusions

Our plane might have crashed, but our concept flies higher than ever in its own regard. We took great risks this year in our efforts – we wanted our product to stand as its own statement piece in the marketplace, and to do so we took efforts to create something unique. We underestimated the troubles we would face due to these decisions, or at the least expected to be able to better solve them. It is unfortunate that the plane could not fly, but that is not to say there is no pride and value to take away from our efforts.

Over the course of this year, our team of engineers with little to no aerodynamics experience learned an entire new field of study in order to understand, design, model, and control an airplane. We went from learning the basics of lift and drag to linearizing the flight dynamics of a famous stealth bomber, and only came short, in our belief, due to a hurdle that seemed mostly out of our control. We could not get the software required to properly analyze our plane. Even this, though, provides a learning opportunity for the team. Never again will I let myself be left powerless against a problem like this – it is *crucial* for good design to account for and plan around what we think are the largest potential hurdles to our progress. We did not have a good alternative in place when we discovered this issue, and so rather than alter our plane's design to something more easily modeled or stabilized, we just took palliative measures to make slight aerodynamic improvements, hoping they would collectively be enough to overcome a problem we never addressed in its own right.

As for what did go right in our initial designs, we proved not only that we can improve flight times drastically using solar panels, but also that we do not need an exorbitant number of cells to do so. It was shocking how small the power requirements for a well-flying plane could be, which in turn opened several different plane styles and markets for us. While this still has potential as a product for the general hobbyist market, there exists a very real niche we could carve out with surveyors, researchers, and remote providers of all kinds. The improvements to flight time and battery efficiency genuinely cannot be understated, thereby creating a unique sustainability in the Sunrunner's ability to remain airborne doing something for the customer.

A drone or plane without self-charging capabilities loses twice the potential time and distance it can operate if it must return before it can land or get a new battery. In a scenario like this, if you have a drone with 40 minutes of battery life and it takes 5 minutes to get it into position for whatever you wish to observe, you have roughly 30 minutes of viable data-collection time before you must return. Additionally, there are 10 minutes of time where you are missing out on collecting data, equating to 25% coverage loss. With our plane, that viable time increases to several hours – operation times potentially more than an order of magnitude greater than non-solar alternatives, with no down-time during that time span. In terms of a surveyor's work, our plane could sweep entire forests, fields, or farms without direct operation. You could plot a full day's path for it to sweep through and launch it in the morning and come back for it in the evening. This provides an easy and hands-off method for long-term and intensive monitoring of large swaths of land, all customizable to the customer's requirements.

What started as a potential hobbyist gimmick has evolved into something with real market possibility. This is something we would like to continue, provided the right time and funding. This is certainly something worth exploring further overall, and we should gauge the interests and needs of these new potential markets to start our next round of designs. In a secondary aspect, we would like to take another go at making *this* current design successful after getting or learning the right analytical tools for the job. In an ideal world, the Sunrunner will rise and mark the dawn of a new age in commercial remote flying technology.

References

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10 Appendices

10.1 Solar Plane Power Draw with Charging During Sunny Weather

Throttle (%)	Plane Current w/ Solar (SUNNY)
0	-1.593
3	-1.51
3	-1.471
3	-1.483
10	-1.469
10	-1.489
10	-1.466
12	-1.462
12	-1.427
12	-1.45
13	-1.433
13	-1.445
13	-1.44
16	-1.412
16	-1.402
16	-1.39
18	-1.364
18	-1.352
18	-1.349
19	-1.33
19	-1.325
19	-1.321
21	-1.31
21	-1.305
21	-1.298

25	-1.24
25	-1.21
25	-1.101
26	-1.134
26	-1.176
26	-1.134
29	-1.194
29	-1.135
29	-1.172
32	-1.088
32	-1.109
32	-1.066
33	-0.982
33	-1.055
33	-0.751
34	-1.067
34	-1.08
34	-1.001
37	-0.981
37	-1.036
37	-1.023
38	-1.002
38	-0.962
38	-0.943
41	-0.986
41	-1.003
41	-0.967
43	-0.972
43	-0.923
43	-0.95
45	-0.913
45	-0.923
45	-0.932
47	-0.852
47	-0.82

47	-0.841
49	-0.825
49	-0.865
49	-0.877
50	-0.707
50	-0.794
50	-0.787
55	-0.801
55	-0.774
55	-0.791
57	-0.672
57	-0.782
57	-0.754
58	-0.707
58	-1
58	-0.705
59	-0.621
59	-0.624
59	-0.638
61	-0.632
61	-0.617
61	-0.613
63	-0.619
63	-0.618
63	-0.62
65	-0.619
65	-0.609
65	-0.608
67	-0.584
67	-0.581
67	-0.576
70	-0.524
70	-0.508
70	-0.501
71	-0.47

71	-0.465
71	-0.454
74	-0.422
74	-0.41
74	-0.376
76	0.139
76	0.165
76	0.153
81	0.513
81	0.524
81	0.552
83	0.747
83	0.779
83	0.789
87	1.379
87	1.343
87	1.302
91	1.65
91	1.639
91	1.632
95	2.234
95	2.222
95	2.197
100	3.638
100	3.655
100	3.688

10.2 Solar Plane Power Draw with Charging During Cloudy Weather

Throttle (%)	Plane Current w/ Solar (OVERCAST)
0	-1.349
3	-1.455
5	-1.406
5	-1.405

5	-1.404
8	-1.384
8	-1.375
8	-1.357
10	-1.348
10	-1.349
10	-1.35
13	-1.314
13	-1.309
13	-1.311
16	-1.289
16	-1.29
16	-1.294
18	-1.266
18	-1.265
18	-1.264
20	-1.248
20	-1.235
20	-1.245
21	-1.24
21	-1.237
21	-1.224
24	-1.189
24	-1.18
24	-1.195
26	-1.135
26	-1.141
26	-1.154
28	-1.102
28	-1.108
28	-1.109
30	-1.07
30	-1.04
30	-1.03
31	-1.05

31	-1.007
31	-1.016
33	-0.96
33	-0.984
33	-0.981
34	-0.822
34	-0.818
34	-0.84
38	-0.727
38	-0.741
38	-0.703
42	-0.563
42	-0.515
42	-0.501
45	-0.509
45	-0.521
45	-0.488
49	-0.327
49	-0.331
49	-0.36
50	-0.3
50	-0.345
50	-0.286
53	-0.158
53	-0.182
53	-0.172
56	0.015
56	-0.027
56	0.018
59	0.239
59	0.25
59	0.248
62	0.503
62	0.486
62	0.543

68	0.969
68	0.996
68	1.006
66	0.882
66	0.962
66	0.943
70	1.31
70	1.268
70	1.272
72	1.32
72	1.36
72	1.395
75	1.625
75	1.635
75	1.698
78	2.13
78	2.011
78	2.038
81	2.433
81	2.466
81	2.333
84	2.469
84	2.555
84	2.578
87	2.9
87	2.82
87	2.88
91	3.11
91	3.119
91	3.092
95	3.548
95	3.588
95	3.564
99	3.998
99	4.058

99	4.025
100	4.488
100	4.884
100	4.832

10.3 Solar Plane Power Draw without Charging

Throttle	Total System Draw
0	0.086
2	0.086
4	0.087
6	0.142
7	0.15
8	0.162
9	0.199
10	0.2
12	0.218
13	0.224
14	0.225
16	0.249
18	0.283
20	0.308
25	0.409
26	0.422
28	0.483
29	0.49
30	0.535
30	0.528
30	0.514
31	0.56
31	0.514
33	0.606
33	0.614
33	0.617
34	0.627
34	0.632
35	0.685

35	0.679
37	0.732
37	0.746
39	0.84
39	0.853
40	0.897
40	0.903
41	0.947
41	0.909
42	0.998
42	1.01
42	0.995
45	1.123
45	1.118
46	1.208
46	1.193
49	1.351
49	1.327
50	1.393
50	1.401
52	1.53
52	1.527
54	1.634
54	1.643
55	1.697
55	1.682
58	1.916
58	1.913
59	1.911
59	1.87
62	2.012
62	1.974
64	2.078
64	2.101
66	2.361
66	2.291
66	2.24
68	2.671

68	2.66
72	2.965
72	2.952
74	3.118
74	3.014
74	3.055
77	3.337
77	3.365
77	3.324
81	3.477
81	3.501
85	3.81
85	3.92
85	3.82
88	4.101
88	4.103
88	4.005
91	4.274
91	4.336
94	4.621
94	4.7
98	5.14
98	5.13
100	5.5
100	6.1
100	5.9
100	5.845
0	0.119
51	1.462
51	1.409
51	1.452
53	1.555
53	1.58
53	1.57
55	1.678
55	1.654
55	1.661
58	1.966

58	1.949
58	1.978
60	2.142
60	2.149
60	2.133
62	2.233
62	2.281
62	2.256
65	2.553
65	2.543
65	2.521
67	2.716
67	2.718
67	2.674
68	2.852
68	2.843
68	2.833
71	3.065
71	2.995
71	3.021
73	3.24
73	3.231
73	3.166
75	3.447
75	3.45
75	3.445
79	3.735
79	3.706
79	3.734
80	3.955
80	3.974
80	3.962
85	4.477
85	4.47
85	4.48
88	4.747
88	4.766
88	4.723

91	4.975
91	4.964
91	4.959
94	5.356
94	5.355
94	5.345
97	5.605
97	5.595
97	5.628
100	6.78
100	6.71
100	6.69
100	6.41
100	6.62
100	6.64
100	6.67
98	5.62
98	5.6
98	5.59
91	4.978
91	4.981
91	5.037
87	4.543
87	4.558
87	4.53
81	3.996
81	4.004
81	3.997
78	3.614
78	3.613
78	3.603
72	3.128
72	3.096
72	3.083
66	2.521
66	2.507
66	2.512
61	2.127

61	2.128
61	2.098
58	1.885
58	1.874
58	1.904
54	1.606
54	1.624
54	1.583
52	1.502
52	1.518
52	1.497
50	1.383
50	1.386
50	1.378
40	0.927
40	0.898
40	0.869
36	0.706
36	0.711
36	0.71
34	0.631
34	0.627
34	0.622
33	0.548
33	0.6
33	0.595
27	0.428
27	0.446
27	0.447
19	0.286
19	0.288
19	0.285
17	0.263
17	0.278
17	0.258
13	0.216
13	0.213
13	0.211

9	0.18
9	0.184
9	0.181
5	0.147
5	0.15
5	0.152
2	0.095
2	0.094
2	0.093