MRE 480 Design Report

Solar-Powered RC Plane “Sunrunner”

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Abstract

While the use of renewable energy sources such as solar power has become increasingly used over the years including projects that focus on extended flight time for unmanned aerial vehicles that can span across several days, there is little implementation of this technology in remote controlled (RC) aircraft. RC aircraft including fixed-wing planes and multirotor drones have commonly lacked extended flight time due to various constraints that include areas such as the difficulty of increasing battery capacity without affecting the overall weight of a vehicle and therefore the end goal, flight time. With this short flight time comes a much more extended recharge time that can only be compensated for with extra battery packs or more conservative flying in order to preserve energy. The aim of this project is to develop a solar powered RC aircraft that can exceed the flight time of common types of RC aircraft of similar size and cost while not heavily changing the overall weight or performance of the aircraft. We will focus on the previous projects we have found through our research in order to determine how their designs succeeded or failed in order to determine the best path forward for a design that will meet our desired performance parameters. While there has been almost no commercially available products similar to our goal, the existence of personal projects and research papers covering these areas gives us confidence that we will be able to turn this aim into a success.

There are many areas of technical analysis to consider with a project like this to get off the ground. Since we proposed this project we have done a deeper dive into the bigger aspects of this project that will allow our plane to take to the skys. Our main area of technical analysis will be the electrical analysis which will allow our plane to charge while under normal flight conditions. Our second area of analysis was the aerodynamic analysis which aimed at looking at different airfoils and designs to determine best flight characteristics for steady flight. We also wanted to make sure our design isn't going to cost a large sum of money so we analyzed our bill of materials based on bulk pricing to make sure this is a financially viable product to produce.

1 Introduction and Problem Statement

The reason we are proposing to build and manufacture a commercial RC solar plane is because there is currently no commercial RC aircrafts out on the market with this type of power delivery system. The other issue we are seeing with what products that are out on the market now is that for the price of these planes there isn't a compelling product with large flight times stretching past an hour or two or even longer. While there have been successful attempts at making larger scale unmanned aircraft fly for extended periods of time on solar energy, there is a lack of commercially available systems. Instead, there is a larger group of individuals forced to design and build their own solar powered vehicles from scratch due to the lack of availability.

1.1 Introduction

With the shift in society from fossil fuels to renewable energy resources, the world is looking to put these potentially limitless supplies of power to the task of replacing the current technology that utilizes substances such as oil and gasoline. With the ever increasing concern of global warming making this all the more relevant, the usage of energies such as solar or hydroelectric energy has skyrocketed in the past few decades. As it stands, the uses for solar power have gained popularity and use not only amongst large businesses and energy companies, but also on the level of the individual consumer. Solar panels can be seen in a variety of uses by individual consumers from being able to produce enough power from panels attached directly to their home that they are receiving money from the power utility companies. In fact, there are even tested aircraft that utilize solar energy to remain in the air for days at a time. However, these are large scale aircraft that are not available to the average consumer or even to many companies, but that might not be that case forever. In the market of Remote-Controlled (RC) aircraft, there is very little usage of solar power, to the point where there are little to no existing products that utilize solar energy for remote controlled aircraft. Many available examples of solar powered RC Aircraft are either research projects by schools and companies, or hobbyists developing their own system due to the lack of products available on the market. With RC Aircraft, your performance and duration of flight is limited heavily on the capacity of our battery system. However, as you increase in capacity you often increase in weight resulting in a lessening gain and lower maneuverability as your plane must now continue to carry the weight of the increased battery size throughout runtime. With the application of solar energy, a user would possibly be able to maintain the same size battery they were using before, but gain the ability to fly for an extended length of time or even be able to fly indefinitely as long as the sunlight provided was high enough to charge the battery while flying.

1.2 Problem Statement

RC aircrafts have always been limited in their flight times by the size of the battery. While batteries have decreased in size and weight over recent years, long-lasting RC aircrafts have yet to see similar improvements. Average RC planes are currently seeing flight times of 10 to 30 minutes, while it often takes over an hour to charge that same battery once used up. While the concept of using solar panels on an aircraft is not unheard of, from larger unmanned aircraft with wing spans reaching over 100 feet to smaller DIY projects across the internet, there is a lack of these kinds of aircraft available for purchase at the hobbyist level. Our aim is to develop a Solar Powered RC Aircraft capable of flight times exceeding those of battery-powered equivalent aircraft with the ability to charge while in flight.

With the proper components, it should become viable to not only increase our flight time through the use of solar panels, but also allow for the possibility for indefinite flight times with the right solar conditions and with the right solar panels equipped. With the proof of concept to extended flight times of an RC plane through the use of solar cells is proven, the use of future solar cells on our RC plane design could lead to all day and night flight times in the future.

1.3 Preliminary Design Goals

To help solve our problem, we are going to break the project down into two main categories: Electrical analysis, and aerodynamic analysis. The electrical analysis will ensure that we address the electrical concerns that will power the plane and charge the batteries. The aerodynamic analysis will ensure that our plane will be able to get off of the ground, be relatively stable for flight, and give us some flight characteristics of flight before we build the plane.

In order to solve this problem we will first start by trying to model our systems or by doing simulations with our design criteria considered. Once we obtain favorable results from these simulations we will move forward with our first functioning prototype. We will start our first prototype in three sections. The first will be the solar circuit to make sure the solar cells are able to push adequate power to the plane's electrical components while simultaneously charging our batteries. The second area to prototype will be the communications between the radio transmitter and receiver to make sure our control surfaces are receiving the correct signals and performing as expected. The third area for prototyping will be the layout of the solar cells on the wings of the plane and the overall design of the plane and airfoil.

Once we have a functioning prototype of these three areas we can move forward with testing our flying wing with everything equipped except the solar cells. We want to take this design into the sky first without the solar cells so we can figure out what the average flight time will be with no cells. Once we have this information we will then move forward with installing the solar cells onto the top area of the wing and then fly it again to hopefully see the plane able to operate for a longer duration than without the solar.

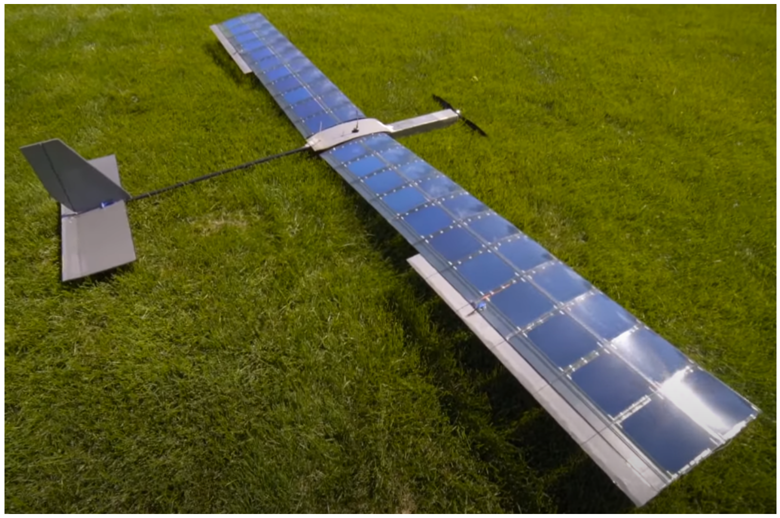
We will know if our project is successful or not by first flying the plane without the solar cells until the batteries die as a benchmark flight time, and then once again with the solar cells to prove that equipping an RC plane with solar cells has the ability to at least double the flight time.

2 Background Research and Literature Review

2.1 Detail Background and Market Research

Upon searching the internet for solar powered RC planes we were only able to find cheap toys that used solar as a direct drive system with no batteries. These small toys are not comparable to what we are aiming to build for our solar powered RC plane. For this reason our group started doing research on normal battery powered RC planes to figure out common design features and overall electrical components used. Fortunately we were able to find a couple enthusiast projects that accomplished the same thing our group is trying to accomplish, attaching solar cells to the wings of an RC plane as supplementary power. These RC solar plane enthusiast projects helped our group envision how we would build our own design and solve our problems.

Two enthusiast projects that our group examined are shown in Figure 1 and Figure 2 below. We examined these two completed solar planes to determine what architecture and electronics worked well or not to then use as a bases for our project.



[1]Figure 1: Enthusiast V3 Solar Plane

[2]Figure 2: Enthusiast V4 Solar Plane

[3]We were also able to find another scholarly project where they went through a similar design process that we are going through. In this article they also used FoilSim- a simulator that shows the performance characteristics for different aerofoil designs. Our group will be following a similar design strategy outlined in this scientific project along with selecting similar parts that are required in order to fly.

For the reason there are no commercially available solar planes on the market and we are fabricating and hand selecting all of our parts and materials there is no reason to fear stealing a patented idea or design.

2.2 Customer Needs

Our potential customers are RC plane enthusiasts, surveyors, farmers, and any other individual or group that would benefit from the use of a long-duration aircraft capable of flying throughout the day to complete the desired objective with little to no downtime.. These customers need a plane that can stay in the air for extended periods of time with a long communication range. The plane also needs to be light with the ability to have parts changed. It also needs to be stable while flying. Currently, there are no solutions on the market. The only solar planes are the ones built by hobbyists or by research groups and companies looking at developing solutions suited to their specific design goals, making this one of the few products available on the market..

The major customer needs are longer flight time. This is achieved with a solar system. Convenience, durability, and an autonomous system are the next important needs for the customer. The plane needs to be small enough for transport, while large enough to have enough panels on the plane to charge the batteries at a good rate. The plane must be durable enough for a mildly rough landing. The autonomous system should be in place for a fairly soft landing so the systems don't break. The range, price, and weight will be determined by the other needs.

Customer Needs

Customer Focus	**Parameters**
Purpose of Plane	Longer Flight time, Surveying/Photography and Hobby Flying
Solar Powered	Bypass Diodes, MPPT, net positive charging, 45min+ flight time
Convenience	Modular wings/solar panels, Landing Gear/skids, Replaceable body/wings
Durability/Weather Resistance/Material	Splash Proof and Land-Resistance
Autonomous Flying System	Waypoint, Emergency Return
Radio Transmission Range	Greater than 400ft
Price	Final cost less than $500
Weight	Less than 10 lbs
Max Size	2000mm wingspan, 1500mm length

3 Design

Most of the design work we did revolved around two areas: electrical and aerodynamic characteristics of our RC plane. For the electrical systems, we started by finding out what other RC planes use to fly and compared it to our needs with a focus on the available thrust provided along with the power consumption of the motor and control surfaces. After we found this required information, we could move forward with the design of the airplane body. For the body of the plane, we looked at different types of designs that would provide us with the desired lift along with enough available surface area to which we can mount solar cells in order to generate enough power from our solar array to match or exceed the expected consumption of our electrical system. With these two key areas complete we will still have several other sections to finalize to ensure our design succeeds. This includes designing the internal space of the plane to allow us to store our system components with a focus on how it affects our overall performance in areas such as heat management and making sure our weight is distributed correctly. Overall, we have confidence in our project's success given our research has shown that the concept is possible to not only researchers and companies, but also to hobbyist individuals who have shown physical proof of the designs success.

3.1 Preliminary Design Ideas and Trade Study

In our search for inspiration, we found little that closely followed our goals for a solar-powered, long-flight UAV, limited to either small-scale hobby projects or multimillion-dollar research efforts, with little in between. The glider-style was provided by the Swiss-designed Solar Impulse, a solar plane that flew for 26 hours straight, but also had a $170M budget.

Out of the small scale hobbyist solar powered RC plane projects that we found online, these gave us the conceptual knowledge that this idea has been proven and can work. These hobbyist projects didn’t resemble any known large scale plane, fighter jet, or bomber so the marketability of these hobby planes would be even harder to appeal to RC plane pilots. We wanted interesting designs that would appeal to an RC enthusiast; give them something to look at with all that extra flight time. An initial idea was to use the design of the SR-71 Blackbird, but we decided it did not have the appropriate wing-surface/size ratio we thought would be effective, so we turned to the B-2 Spirit instead – a plane with far more wing area and angular design that would better fit the square solar cells we envisioned using.

Another one of our favorite plane designs was the C-130 Hercules, which has an iconic look. Based on our market research we also found meny RC planes that resembled this planes style. This style plane also had some of the longest flight times but we believe that's because it can carry a much larger payload and generally is equipped with a much larger battery. Some downsides of this plane is that it's wing surface area isn't as large as what we would get out of the B-2 bomber for instance. Another downside of this plane is that it has a complicated construction method, and has 4 separate drive motors that will possibly drain our batteries faster than one drive motor.

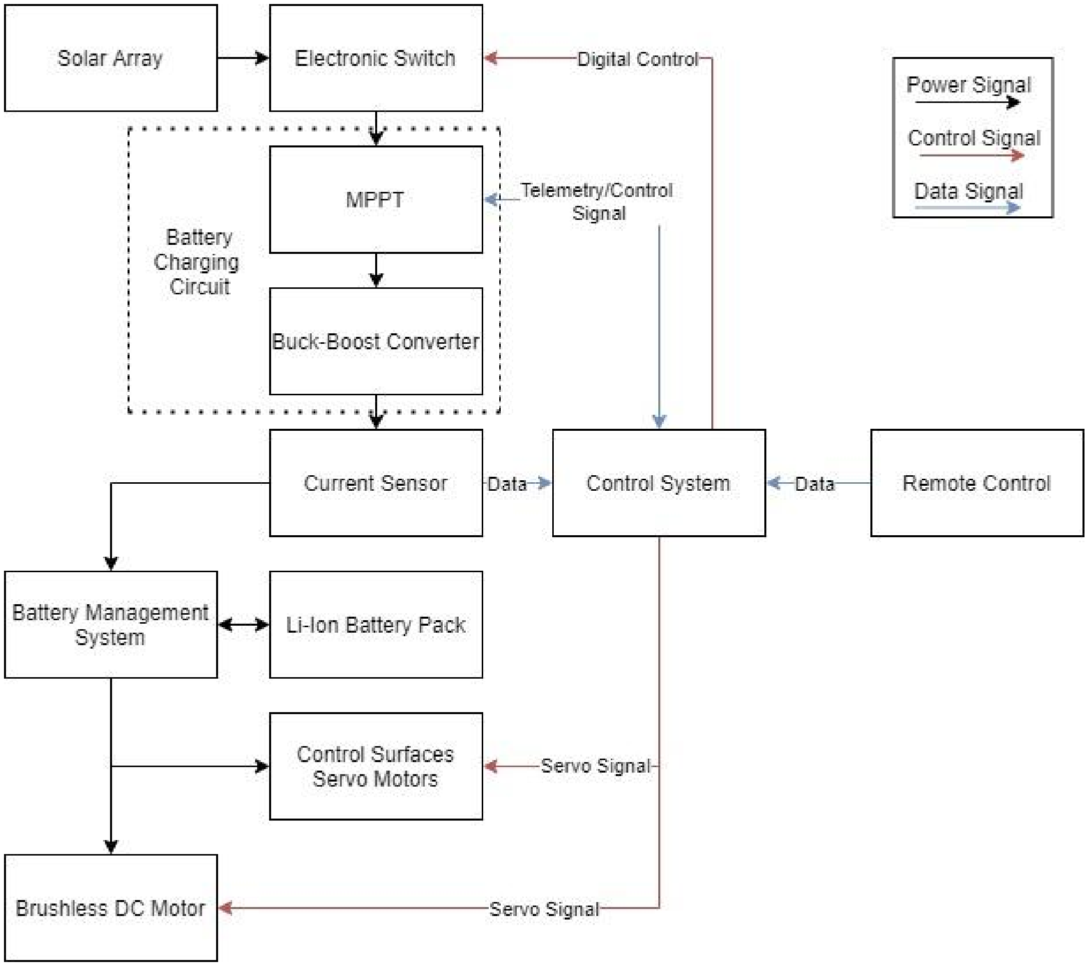
3.2 Target/Final Specifications

For our final design, we are looking to create a solar powered remote controlled aircraft capable of flight times greater than standard RC aircraft of the same size and battery capacity. Our main areas to consider for our final target specifications are the overall wingspan of the plane, the solar panel usage in watts, and the overall weight of the plane. We have found through our research that increasing the wingspan any further for commercially available RC Planes heavily increases the price and structural complexity of our designs. Considering this we decided to have a wingspan less than 2000mm. For our solar panel usage we estimated that we would need to produce at least 100W of power during proper weather conditions, this amount of power is adequate to power our electronics and provide a positive charging current. The rest of our target specifications are shown in the proposed vs analyzed specifications table below.

Proposed vs. Analyzed Specifications				
Metric Number	**Metric**	**Unit**	**Objective**	**Analyzed**
1	Wingspan	mm	<2000	2000
2	Solar Panel Usage	watts	>100	107
3	Weight	Pounds	<10	N/A
4	Battery Size	volt	11.1	11.1
5	Battery Capacity	mAh	3000	3000
6	Flight Duration	minutes	>45	>100
7	Turn Radius	deg/sec	6	N/A
8	Appearance	N/A	B2 Bomber	B2 Bomber
9	Durability	N/A	Splash Proof and Land-Resistance	N/A
10	Cost to Produce	USD	<500.00	$586.27

3.3 Product Architecture

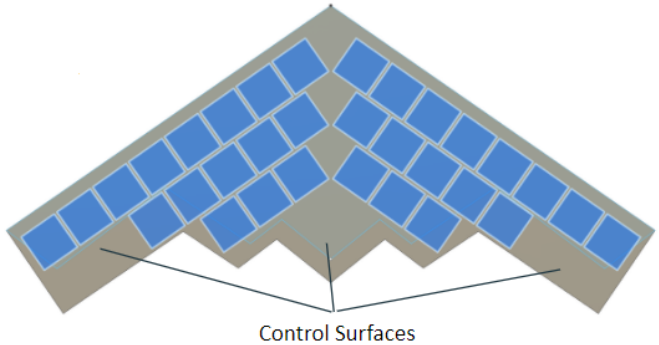
The electrical system can be divided into the solar system, battery system, control system, and the motors. The solar panels will be connected to an electronic switch which will shut off the solar array when the batteries are fully charged. The electronic switch will be connected to the MPPT which will track the maximum power point and will decide how much the buck-boost converter should boost. Then once the voltage is optimal it is sent to a current sensor which is connected to the battery management system. The battery management system will make sure that the batteries are not getting too high of an input current, not getting too hot, and not pulling too much current. The battery management system then goes to the battery pack, servo motors, and the brushless DC motor. The servo motor is used to turn the plane, while the DC motor is used to fly.



Electrical *System Architecture*

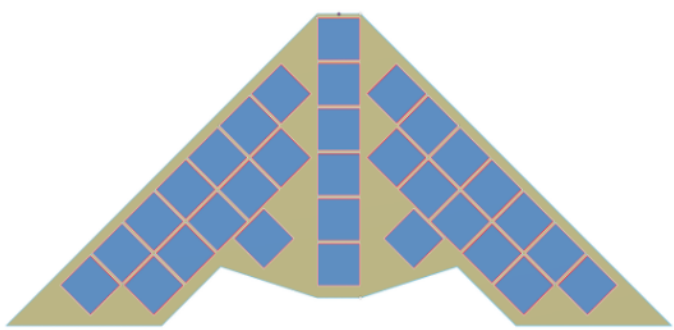
3.4 Overall Design

We had two main constraints when deciding on a final design that we first had to consider. The first being from the information gathered from the electrical analysis, this informed us that we needed at least 32 solar cells in order to power or electronics and charge the batteries. The second piece of information being our design criteria wanting the appearance of our solar plane to resemble a B-2 bomber. In order to account for both of these constraints we started by modeling a scaled version of the B-2 in Fusion 360. From the original layout of the B-2 bomber we quickly realized 32 cells were not going to fit on the main outline of the B-2 so we increased the length and changed the angles on the back wings, this allowed for the cells to fit.



Adjusted B-2 Design

For our second A1 design we had to consider both of these constraints again but this design was inspired by an existing solar RC plane. This A1 design, shown below, has a better aspect ratio which helps the stability of the plane, and we believe it could also be made more modular if taken to production.


A1 Design

Overall the A1 design has larger issues with where to put the control surfaces that will allow for steering of the plane. This design also has a problem with the allowed space in between the solar cells. Solar cells can become less efficient and possibly even short circuit if the panels terminals touch or are not at a proper spacing between the cells. The adjusted B-2 design also more closely resembles a B-2 bomber with it’s jagged edged tail fins. For these design reasons we will be moving forward with the Adjusted B-2 design.

3.5 Discussion of Constraints, Risks and Back-up Plans

Our constraints are surface area, structural integrity, weight, turn radius, and cost. The surface area needs to be large enough to have enough solar panels to power the plane while being small enough to fit in a car. The plane must be able to handle a mildly rough land. 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 plane must be similar in price to other RC planes of the same price to be competitive.

The major risks of our system are the battery pack and aerodynamics. If the battery pack receives too much current, over-heats, or pulls too much current, the battery pack can become volatile. If our aerodynamics are wrong, then we either won't get in the air, we will flip over, or we could come crashing down. We could be set back if our test plane crashes, because a lot of resources will be ruined, and we will have to start all over. The solar panels are the safest portion of the plane. However, even though it is one of the safest portions, if it fails, there could be some bad consequences. The panels could not work. They could fall off if not secured properly. The worst case scenario for the panels is if there is a smashed panel. If this happens, then the current will continue circling in that cell which can create enough heat to start a small fire. Overall, all parts of the plane need to function properly, or the plane could either not work or crash mid-flight.

4 Analysis

In order to move forward, we must determine if our design can meet or exceed the specifications we have decided on. If the design does not meet our desired characteristics, we must either change our design or lower our specifications. For a RC Solar Powered Plane, there are several areas we must analyze in detail that will make or break our design: Power Consumption versus Generation, Aerodynamics and Flight Characteristics, and Manufacturer Suggested Retail Price (MSRP). These are the main sections of our analysis that we had to do in order to determine whether our design and product was feasible and economically viable for us to develop. In order to perform analysis we used already existing software and systems made to simulate the real-world aspects of our designs. For example, in order to simulate the expected output of our solar array compared to the power usage of our aircraft we used an already developed Matlab model of a solar maximum power point tracking charge controller that could simulate our array operating characteristics as well as our battery and load characteristics. We are confident that our analysis is correct from our multi-source approach. We not only performed our own individual research and simulation, but we also sought advice and help from those more knowledgeable such as professors at SIUE who had done similar analysis for areas such as aerodynamic analysis. With these three main areas of analysis complete, we still have several sections we must investigate that are necessary but not as important as the three previously listed which includes parts of our design such as the design of our solar charge controller, electrical wiring characteristics, control system and communication,

4.1 Analysis Plan

For our design we have a number of areas of technical analysis that would aid us in the understanding and implementation of our design. For our main areas of analysis which include the electrical analysis of the power generation of our solar array compared to the power consumption of our RC plane, the aerodynamics of our plane, and MSRP of our total product. These are areas where we must understand and see that they succeed as they will largely dictate the success or failure of our design. If our system can not provide more power than it consumes during our normal cruising conditions, then we will not be able to charge our battery during flight and are simply extending the flight time of our battery. However, if our design can produce more power than it consumes, it means that our system can fly indefinitely as long as conditions are met that result in that net positive charging capability. This analysis goes together with our aerodynamic analysis as well. We want our design to be efficient, if the aerodynamics of our system are poor, it would mean that our electrical system must work that much harder in order to keep our plane in the air. Therefore, the better our aerodynamic designs are, the better our electrical system will perform by having less work for it to take care of to ensure proper flight.

Along with the main areas of technical analysis that we are looking at for this design, we also have other relevant analysis that must be accomplished so that we can ensure the success of our design. As part of our electrical analysis we must look at the proper design of our solar charging circuit. In our current prototypes we are using a pre-built MPPT solar charge controller rated for a medium amperage and made for a 3-cell li-ion battery. However, there is no method to control the charge controller or regulate any of its functions. If there were a danger we would need to rely on our battery management system that would shut down the connection to the battery pack but that would also shut-off our plane. We have looked as part of our charging system will be the implementation of a physical control switch between the solar array and battery pack so that if the system becomes dangerous we are able to turn off the solar array while still powering our electronics and maintaining control of our plane in order to continue flying or safely landing. With the implementation of a solar charge controller that we can monitor and control through some sort of controller we provide ourselves the ability to mitigate or eliminate possible problems before they become catastrophic failures.

As another section of electrical analysis we must also ensure that the physical components of our system are adequate for the required performance. A major area of this is heat dissipation and current ratings. Given the larger amounts of current our system could draw we must ensure that our system will not overheat to the point of failure and a part of this is ensuring that our connections do not produce a large amount of heat. By looking at the maximum current draw of our system and including a safety factor we can determine the sizing of our wiring and circuit board paths to ensure that we are not generating an unnecessary amount of heat through small wires that could heat up and cause problems including setting our plane on fire.

Another area we must observe and analyze is the control system and communication of our plane. We are looking at using a standard RC controller however we must ensure our choice in equipment will match our design characteristics. We expect a certain range from our system so based on the position of our receiver and the strength of our signal we could fall short of our desired range which produces the chance of the plane going rogue during flight with the pilot losing control and possibly resulting in a disastrous crash that could completely total the system.

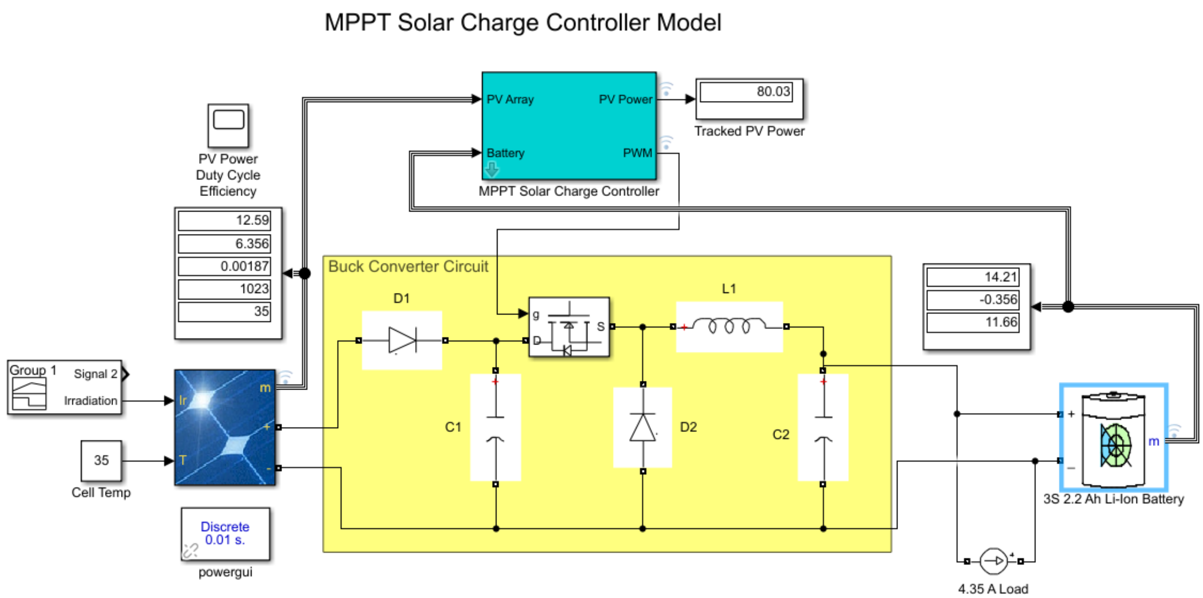
As another part of the control system we must find the correct method of translating user input to system movement. Given our research about the flying wing model of a B2 Bomber we know that there is a possibility that we will need some system assistance in maintaining flight beyond the user input due to the aerodynamics and control surfaces of the design. This means we must analyze the added complexity of our design if we are required to source our signals through an on-board controller that would change the control surfaces of our system to match our user desired movement. If it is required to have a controller on-board we must continue our analysis into the desired method of control in order to produce the desired movements. Will we require a set of sensors that will provide the controller the necessary information to perform a control loop like a PID control to correct for changes in desired and actual movement or will there be more efficient methods available to us. In case of added components, we will also need to look at our electrical and aerodynamic performance to ensure that we are not negatively impacting the performance of our system to the point where it does not meet our desired performance.

4.2 Electrical Analysis

When looking at the performance of our design, one of the key elements we must analyze is the output of our solar panel compared with the expected consumption of our RC Plane. To determine whether this will occur, we must analyze the performance of our design without having to build it to decide whether our current design is actually feasible or if it would require modifications to the design in order to fulfill our goal of being able to fly the RC plane while being able to also charge the batteries during conditions available to the average pilot. What we know is that in order to produce more power than we consume our planes available surface area must be converted to mostly solar cells, which develops a required minimum surface area for solar cells to be able to produce the required power. However, even with converting the entirety of our available surface area, it is possible that the power consumption of our plane will be more than we can supply from the solar array alone. This would result in a system that can not charge while flying and can only extend the flight without providing a possibility of theoretically infinite flight time while solar conditions remained above a certain threshold.

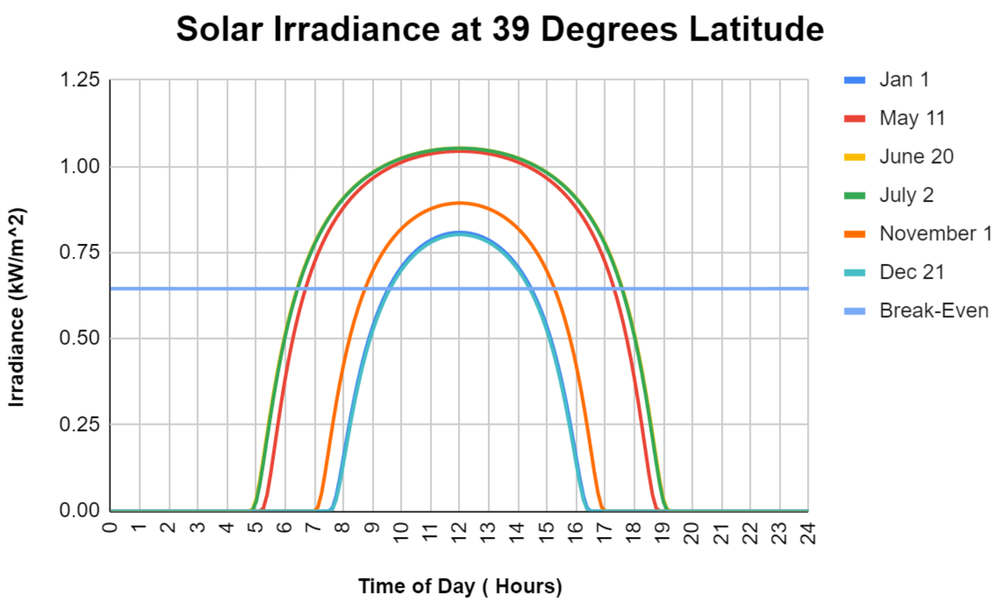
In order to develop a system for testing the performance of our power consumption, we must define the operating characteristics and environment in a manner similar to expected normal use. For the flight environment, we make the assumption that we will be flying the plane on a day without cloud cover, allowing us to use available data regarding the solar irradiance levels at our location throughout the day for any given day of the year. While it is possible for the user to fly during overcast days, our goal is to show that there exists an environment throughout the year that would allow us to achieve mid-flight charging. Our expectation is that for most overcast days it is likely that the solar array would not produce enough power to charge the battery, but still provide enough power to extend the flight time beyond what is available for planes of similar scope that lack an on-board solar array. With this environment we also assume a constant temperature for the weather and the solar cells, as the solar cells heat up, there is a decrease in efficiency, resulting in a lower maximum available power. For our system we assume that the solar cells will be operating at 35ºC which corresponds to 95ºF. Another assumption we make is the operating conditions of our aircraft. While during flight our plane will be consuming a variable amount of power, for the sake of our analysis we assume that the plane's power consumption is a constant value during a stable cruising condition where our motor and control systems require a constant power to keep the plane in its current movement and altitude. For our plane, we are making the assumption that we are using a 3S 11.1 volt lithium ion battery pack with a rated capacity of 3000 mAh. While during actual design we might look at different capacities or possibly even different battery configurations we will use this as the basis for our simulation. From there we have the voltage of our system and we can begin to find the power draw of our individual components based on the results of our aerodynamic analysis to find the operating point for our main motor. Using the results of our aerodynamic analysis and the information regarding our electrical components, we found that the power draw of our system for our system would be roughly 50 watts or 4 amps discharge. With this information we can begin our simulation using the specifications of our design.

While in our research we found an available Matlab Simulink model of a Maximum Power Point Tracking (MPPT) Solar Charge Controller. With this model we are able to adjust the operating characteristics of a solar array to match the expected performance of our solar array. Next we also have the capability to adjust the characteristics of our battery model, matching the performance of a li-ion battery pack of our expected battery system. The last portion of our model is the attached current source that will act as our load. We use this current source to act as a constant 4 amp discharge from the battery that will simulate a constant load and allow us to see what conditions and irradiance level will produce a net charging on the battery terminals. For our test we will be varying the irradiance level across the solar array and plot the current across the battery for a given range of 0 to 1000 W/m^2. With this performance for a given irradiance value we can find at what irradiance value and above we will provide a charging current to the battery rather than discharge which will allow us to find the range during a given day we would expect net charging as well as the theoretical flight duration of the RC Plane for a given constant irradiance.



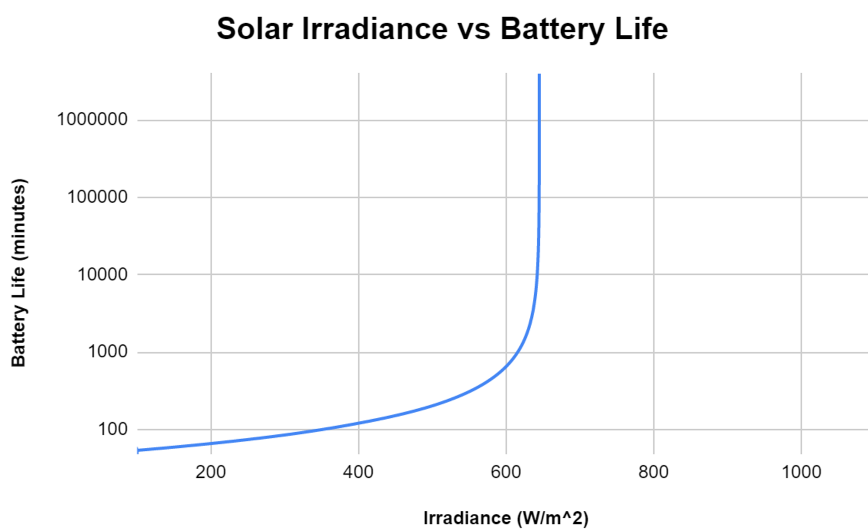
Matlab Simulink Model of an MPPT Solar Charge Controller

Based on the results of our simulation we are able to find that for a range of irradiance from 0 to 1000 W/m^2 we are able to generate a maximum current of roughly 6.8 Amps to charge our system. This means that given our constant discharge of 4 amps we are left with 2.8 A charging capability of our system at stable flight. Along with this maximum possible charging current we also were able to define the break-even point of our system where an irradiance value higher than 645 W/m^2 would produce a charging current in excess to the consumption of our load, allowing us to fly continuously without draining our system. Using solar irradiance data for our latitude, we were also able to plot the break-even point in comparison to the irradiance level throughout an entire day. What this shows is that throughout the year we are able to experience weather where our system will have a range of over 4 hours of potentially infinite flight time where our system will charge the battery rather than draining it. This shows that our system does not only work for the seasons where there is a high duration of sunlight, but even on days like the winter solstice, December 21, we still have a much greater length of flight with the solar array system than planes of similar design.



Graph of Solar Irradiance

Using our current and irradiance data from our simulations we were also able to construct a graph showing how the flight time of our system changes as we approach the break-even irradiance level. The goal of this is that even during potentially overcast days we will still improve upon the available flight time of our battery pack. With the graph shown below in a logarithmic scale, we see several key features. The first is the vertical asymptote that exists at the irradiance level 645 W/m^2. As we approach this point, the discharge current of the battery approaches zero, resulting in an infinite flight time as shown as the graph's y-axis of Battery life climbs past 1,000,000 minutes, or 278 days, of flight time. While this is not the true flight time of the system considering we will not maintain a constant irradiance level in most places of the world for this extended period of time, we can see that even on days of potentially cloudy or overcast weather with irradiance levels below 600 W/m^2 our flight time is over twice that of with the battery alone. For example, at an irradiance level of only 400 W/m^2 , which occurs during the summer between 5 and 6 AM, we still see a flight time almost equal to 2 hours compared to a non-solar flight time of just 30 minutes. As a counter to the previous comment where we will not see a constant irradiance level for extended time, this is also true for a low level irradiance such as this. If a pilot began flying in the early hours of the morning, it would be possible that the plane could continue flying on battery life until the point the irradiance level reaches the break-even point. At this point, the battery charge consumed during the earlier hours will be recuperated for the entire range of time above this break-even point, allowing for possibly day-long flights greater than 12 hours and onward. In fact, if all other factors were held constant, given potential increases of battery capacity with little changes in overall system weight could allow models of these designs to eventually reach a point that they could fly through the night and recharge during the day.



Irradiance Versus Battery Life

4.3 Aerodynamic Analysis

What Defines Flight

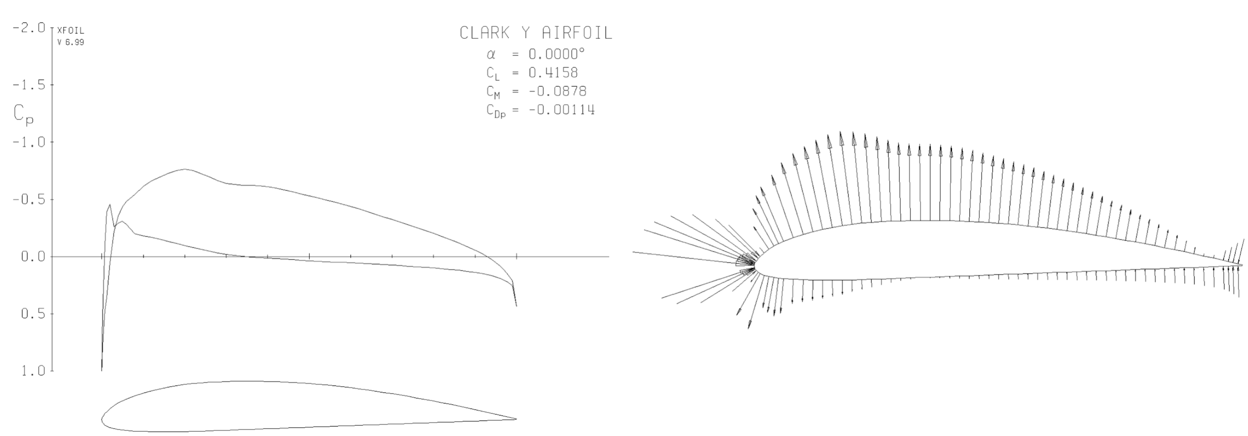
The goal of our aerodynamic analysis was to understand the feasibility of getting a plane flight-capable with the added weight and aerodynamic instability of an array of solar panels atop it. To this end, we needed to discern what parameters we needed to meet to produce flight, how to determine those 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.

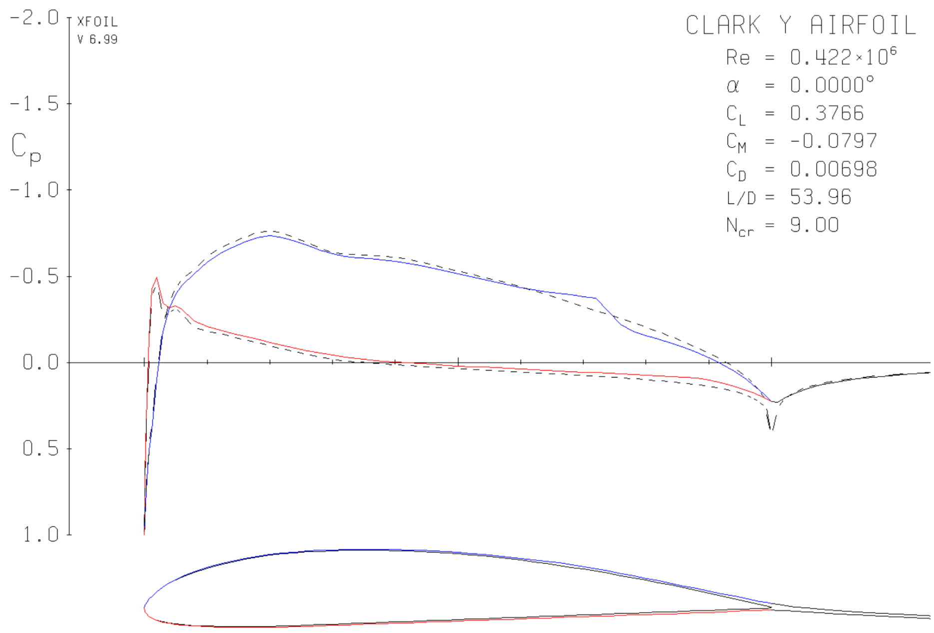


[3] Figure 3 *Here are two representations of the initial Xfoil analysis. The left shows the magnitude of aerodynamic forces, and the right illustrates the directionality as well*

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.



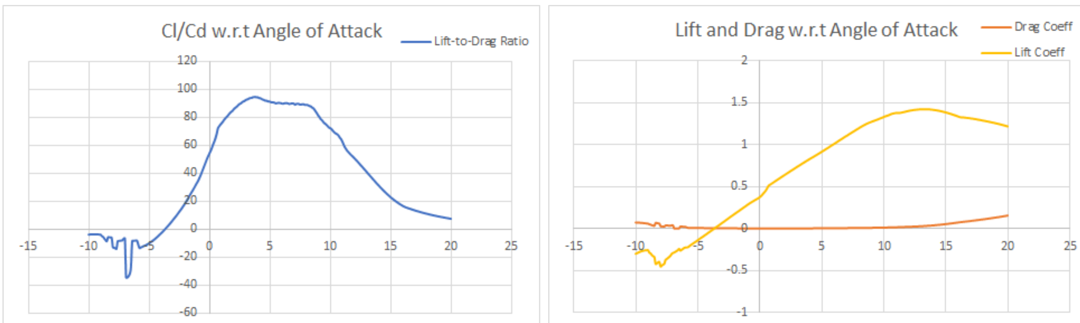
[4] Figure 4 *An adjusted Xfoil analysis accounting for viscous airflow.*

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.



[5] Figure 5 *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.

We additionally hope to implement a variation to the Clark-Y design called a Kline-Fogleman airfoil. This shape cuts a great deal of the material out of the back of the wing, but at sufficiently low Reynolds number will not negatively impact the lift the wing produces. The benefits provided are twofold, as the reduction in weight at the back of the plane will shift our center of gravity to a stably-favorable position, and lighter plane producing the same amount of lift requires less power to keep moving, meaning our plane can be both more stable and efficient from one change. This is the aspect for which we needed to keep the Reynolds number under 5e5, because at speeds that generate larger values, the turbulence generated by the uneven upper surface begins to reduce the plane's aerodynamics and become a detractor instead. If this is implemented, our plane will be regulated to never reach a speed for this threshold to be met.

If we consider getting in the air to be a trivial matter, as our research suggests, in order to consider this part of the project successful, we must increase the stability of our plane as much as is possible. We will be reaching out to several new flight-knowledgeable contacts and hobbyist sources to find suggestions on how best to approach this quickly and efficiently. The goal is to have a functional PID controller ready for adjustment and tuning in place by the time we build our first physical prototype of the plane, to ensure we have the most time possible to optimize our flight characteristics.

4.4 MSRP 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.

5 Timeline and Budget Estimation

5.1 Timeline

In our analysis portion, we still need to calculate our weight analysis, how much energy loss we would have for different solar encapsulation methods, and a more accurate aerodynamics analysis. This should hopefully be done by the end of january. We have already tested some solar panel set-ups. We are wanting to test out our plane without solar panels, our communications, and our entire solar set-up before we put it all together. If we start mid-January, we would be able to finish all of this pre-testing by the end of February. We can test our electrical system in a working plane, communications, and then we can test our aerodynamics by putting our working electrical system in a foam test plane. The solar panels should be the last thing we build as to save the panels from damage. So we can build each part after doing the appropriate test. Programming should start when we are doing communications, so this should be around the beginning of February. Then we should be testing, reviewing, and fixing our build multiple times. This should start around the beginning of March and end around April 19. Then we should be finishing our project presentation around april 26. We are following the old time line very well. We should be able to stick to this schedule if we work throughout January. We will make a more in depth timeline when we have finished our analysis.

Timeline for Project Development		
	Start Date	**End Date**
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

5.2 Budget

Our MSRP analysis and budget for this project are actually two different topics we have to discuss further. For the reason our group isn't actually buying bulk quantities of the components comprising our Sunrunner plane, we have to develop an expected budget for ourselves. Below is our *Bill of Materials* that reflects the components our group still needs to buy, at normal retail pricing, in order to successfully build a single Sunrunner plane.

1. MATERIAL	Quantity	Cost	Total
Aero-modelling Foam Board	1	$24.50	$24.50
ABS Half Rod Rod	1	$1.80	$1.80
Hot Glue	1	$6.99	$6.99
Mounting Bracket	1	$10.49	$10.49
		MATERIAL	$43.78
2. Electronics	Quantity	Cost	Total
Motor	1	$26.78	$26.78
Propeller	1	$6.08	$6.08
Servos	3	$3.79	$11.37
Flight Controller	1	$14.99	$14.99
Battery	3	$3.43	$10.29
Solar Cells	32	$4.05	$129.68
GPS Module	1	$15.90	$15.90
9 DOF IMU	1	$7.95	$7.95
Radio Receiver	1	$16.99	$16.99
Radio Transmitter	1	$9.99	$9.99
ESC	1	$16.50	$16.50
		Electronics	$266.52
Total (Material and Electronics)			$310.30

5.3 Learning Plan for Acquiring and Applying New Knowledge

There are several areas that we must learn more about in order to make our design a success. One major area of knowledge we must improve upon is designing and building circuit elements. With our desired performance we have been looking at available integrated circuits to act as our solar charge controller for our system. However, because we are still uncertain on the exact parameters of our system or even the possibility of being able to handle multiple configurations we must design our own circuit. In order to do this we must know how to not only pick our required components, but also design our circuit board in an efficient and safe manner. If our circuit board traces are too thin, there is a chance of our board and components overheating, however if we continue to increase the size of our board too far we will make it an inconvenient circuit that creates a hassle with finding a correct place within our aircraft.

Another area we must learn is creating a plane frame depending on our material. We are currently looking at using foam which requires us to learn how to cut out our design from foam blocks as well as connecting pieces of foam together so the plane can handle its weight throughout movements including taking off and landing on different surfaces. There are several different methods we can go about creating our foam frame, one of which includes the process of hot-wire cutting. This is one of the more common methods and likely the simplest to complete without complex equipment.

5.4 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

Most of our codes are basic electrical and mechanical codes. There are codes for flying an unmanned aerial system and codes are also included if we want to possibly use our system for taking videos. The main electrical standards are 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 system that will likely exceed 250 grams, we will need to have our aircraft registered with the FAA before conducting any flight tests.

6 Conclusions

Due to our analysis and what hobbyists have been able to do, we believe our project will be successful. We were able to calculate that we should be able to generate enough power from our solar systems, at solar noon, to charge our batteries while in flight, allowing us to fly continuously without draining our system, resulting in non-stop flight while we are at or close to solar noon. Our aerodynamic analysis proved that we should be able to get the plane in the air, and we have the thrust required to keep it in the air. We also have the tools to be able to build the plane at our disposal. This is a good mechatronics design because we have to design both the electrical and mechanical systems to work together in order to get the plane off of the ground. We will know that our project was successful when we can fly the plane with solar panels at least twice as long as flying the plane without the solar panels. This will benefit surveyors and farmers the most, but also provide an exciting platform for others who require an unmanned aerial system with the goal of extended flight. They will be able to get a good view of the land or whatever they are observing without having to return to the pilot in order to refuel or change batteries. This will save both time and therefore money for the users. We also have a secondary goal of designing our system with the ability to hold a payload, this could allow for an increase in potential uses not only to surveying and video, but also to the possible role of package delivery or research by applying sensor and data collection systems to the aircraft.

Appendix

	Count	Price each	Cost for each part for 300 planes	Cost for each part per single plane
Motor and ESC combo (6 Pack)	50	$112.79	$5,639.70	$18.80
Propeller	300	$3.65	$1,094.40	$3.65
Servos	900	$0.62	$557.23	$1.86
Flight Controller	300	$8.99	$2,698.20	$8.99
Battery	900	$1.68	$1,512.00	$5.04
Solar Cells	9600	$1.63	$15,667.20	$52.22
GPS Module	300	$9.54	$2,862.00	$9.54
9 DOF IMU	300	$4.77	$1,431.00	$4.77
Radio Receiver	300	$10.19	$3,058.20	$10.19
Radio Transmitter	300	$5.99	$1,798.20	$5.99
		Total	$36,318.13	$121.06

References

[1] https://youtu.be/xS2iCj-HSqY

[2] https://youtu.be/SwbJJoe09DI

[3] Mehta, Alpesh, et al. *Design and Fabrication of Solar R/C Model aircraft*. 2013, citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.300.9990&rep=rep1&type=pdf.