NAU
SOLAR FLYERS

EE Solar Flyers

Design Document II — November 11th, 2022

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Project Partners: ME 476C Team

<u>Subject Description:</u> This document outlines all elements to the construction of a solar-powered unmanned aerial vehicle (Solar UAV).

NOTES:
- The deliverable lead editor is **Gabriel Martin**
- Substantial, numerical values, and measurements in the **Design** section are in **bold.**

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Introduction

The goal of the project is to construct an unmanned aerial vehicle (UAV), whose flight time can be extended by at least 50% from solar power. This is achieved by recharging a lithium polymer battery that powers the drone with solar technology to increase its capacity. This project is funded by W.L. Gore & Associates and the CEIAS department at Northern Arizona University. The client for the product is David Willy, the senior lecturer of Mechanical Engineering at Northern Arizona University. Our team will be working closely with the Sol Avem mechanical engineering team to construct the solar-powered UAV. The initial budget to construct the device is a total of $1500.00, split between the two teams. Since then, we have asked for and received additional funds in the amount of $900.00, making the total budget $2400.00. Our team of electrical engineers will attempt to operate within $700.00 to $900.00 of that budget. This solar-powered UAV is categorized as a multidisciplinary project. The construction of the UAV and ensuring its flight from a battery can be identified under a mechanical engineering skillset. Understanding the characteristics of a renewable power source like solar energy, and using it to prolong the life of a mechanism can be identified under an electrical engineering skillset. Both teams will be using the knowledge, resources, and skillsets learned within the scope of their undergraduate program to build this device. UAVs (drones) are mainly built for military security and surveillance operations, or recreational use. The dreadful impact of global warming has raised a time-sensitive demand for alternative, renewable, and clean energy sources. Solar technology aims to be one of the more practical and efficient options. There have been efforts to use solar energy as an indefinite supply of energy for numerous appliances. A traditional UAV will usually run on some type of battery to power the motor and is operated by a transmitter with a sensor of some sort. The battery type commonly used for UAVs is lithium polymer (Li-Po) batteries. The solar technology will lie on top of the mechanism to draw power. The main issue for achieving prolonged flight of a UAV is energy management while it is airborne. A challenge for us will be delivering the right amount of power from solar technology, which will correspond with the rate of power the motor is consuming from the battery. The irradiance of the sun, temperature, battery discharge rate, and the weight of the plane, will all play a role in assembling our PV system. However, the solar energy harvested cannot directly be delivered to the battery. The charge might exceed its capacity and destroy it. A charge controller will be used to regulate the charge from the solar panels to the battery. The client has an established background in avionics. When outlining his requirements for the product, he gave our team insight into the bigger picture of the project. To summarize, UAVs are an underappreciated tool. You will often see companies produce goods of such under contract for the government. UAVs are used for top-level surveillance and can be weaponized as well. A substantial point to consider is that the construction of a military-grade UAV, depending on size and function, costs anywhere from $500,000 to $100,000,000. However, the total costs of the lives you are replacing with a UAV will exceed those amounts. On top of that, achieving prolonged or even indefinite flight from solar power could save companies lots of money on batteries, and could inspire other technologies to be run or supported by solar energy. The document will outline every detail of the project reached so far, and provide insight into what will be achieved over the duration of the project.

Previous Work

Batteries and fuels stood as the primary sources of energy for years (as they are for most technologies). In recent years, the demand for renewable and sustainable energy sources has prompted an increased demand for their applications. The sun is an everlasting source of energy, so the idea of maximum power harvest has driven companies in the solar industry into competition. Maximum power point tracking allows solar technologies to produce the maximum power output by using power conditioning methodologies and supporting electrical components to make up for any variance in the process. We have reviewed a few previous works on these concepts to gauge how our project can be achieved.

In 2019, a mechanical engineering team from Northern Arizona University (Solis Fur) attempted to design a solar-powered aircraft capable of sustaining indefinite flight for their capstone project [1]. The plane they assembled held a wingspan of 4 meters, a weight of 7.6 lbs, and an operating voltage of 17.2 V from C-60 solar cells. Their Bill of Materials is sectioned by the elements of their design and the procedures for the construction of all the aircraft's parts [1]. It should be noted that the aircraft did not meet the advanced objectives/requirements asked by the client. The plane failed to run off of its solar array. Although the direct reasoning for their failures cannot be found, a few speculations can be made. The team consists of 5 mechanical engineers. Photovoltaic energy is covered under an advanced elective course held in the electrical engineering undergraduate course requirements, so it can be assumed that the team probably had little-to-no prior knowledge of solar energy systems. To add, the team did not use a charge controller of any sort, so only estimations of the PV array's energy output could have been made to know what could adequately charge the battery. Nevertheless, the team's endeavor to build the UAV is remarkable in its procedure, and they have provided some great sources to reference for building a functional device.

A helpful guide was provided to our team at the beginning of the project: "Photovoltaics: Design and Installation Manual". Photovoltaics (as mentioned earlier) is not a subject often touched on during our undergraduate program. A manual can only go so far depending on its content and relatability, but we have found it to be helpful in understanding the basic concepts to build any sort of solar system. To add, a standard manual itself holds the validation and accreditation of experts in the field of photovoltaics. This design and installation manual covers topics from system sizing, system assembly, radiation fundamentals, orientation to the sun, magnetic declination, climate considerations, how to gather isolation data, and more [2]. To summarize, this manual has helped us fill in gaps in knowledge, verify our thought processes, and will likely play a major role in troubleshooting.

Our team came across an article reviewing a similar project developed in Thailand. This team aimed for a 6+ hour flight time using SunPower C60 mono-crystalline silicon PV cells [3]. These cells are the same ones that the NAU 2019 Solis Fur team used. The main difference between this UAV and our design is the lack of a charge controller. A critical issue discussed in the paper concerns the relationship between the energy the limited PV cells could produce on the device failing to account for the power requirement. Additionally, when their team was building the model, they were accounting for projected insolation levels during one season of the year in Thailand. The testing took part during another season of the year, where insolation levels showed minor spectrum changes from the preceding season. Usually, calculations and testing are simulated at STC (1000 W/m^2 and 25° C), but their actual test conditions deviated far from this. This will remind our team to execute a proper environmental analysis and prepare accordingly for our final testing.

Our team came across an article discussing the specifications and behaviors of a solar module, and how an improved Perturb & Observe algorithm may improve the efficiency of that standalone PV system [4]. A PV system's voltage, current, and power outputs under ideal conditions can be modeled as an IV and PV curve, shown in Figure 4. The article reviews the derivation and importance of a solar cell's open-circuit voltage (Voc), short circuit current (ISC), series resistance (Rs), and shunt resistance (Rsh) under partial shading conditions.

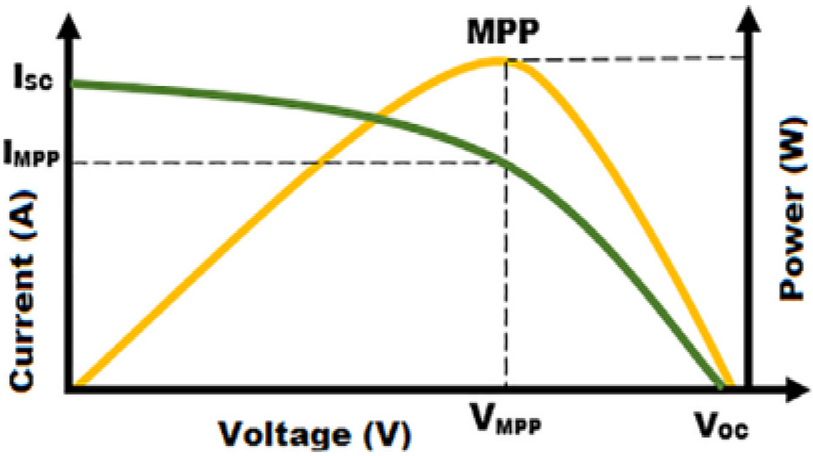

Figure 1: I-V and P-V model curve of a solar cell

One of the last sources our team came across was an article detailing the implementation of a solar MPPT charge controller, for the purposes of battery protection and energy metering [5]. A charge controller is a major functional component for an independent PV system and will maintain an appropriate charging voltage for the battery. On top of that, it accepts a voltage from the PV array and conditions it to its maximum power output. In this article, a DC-to-DC controller is programmed via Arduino to implement a Perturb and Observe algorithm. This methodology is proven effective. However, to preserve time and materials, there are off-the-shelf MPPT charge controllers you can buy for your PV system. They operate in the interest of adequately charging the battery you are using, but it will be up to us to determine the size of the PV array and which MPPT charge controller can do the job.

Design

System Architecture

See Figure 2 for a diagram of the Solar UAV system architecture. The C60 solar cells have commonly been used to build an array size of any choice. Our system will deliver an estimated 15 volts and 6 amps to our MPT-7210 charge controller. The charge controller chosen was due to a redesign of our system.

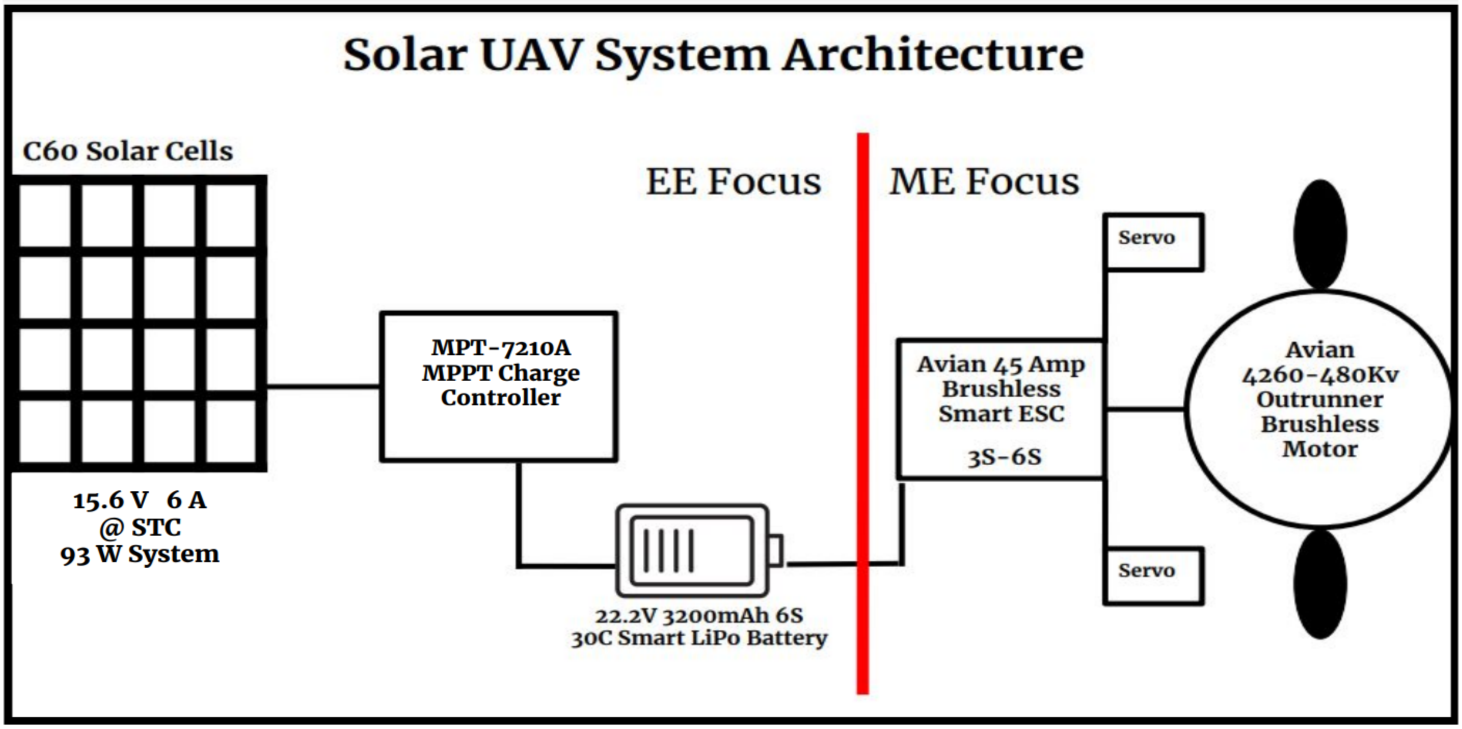

Figure 2: System Architecture of the Solar Powered Unmanned Aerial Vehicle (UAV)

Functional Decomposition

1) **Load Specification**

The brushless motor, transmitter, receiver, servos, and electronic speed controller (ESC) were all chosen by the mechanical engineering team. The main factor in their motor choice was its ability to support our total estimated weight of the plane: **9lbs.** The motor was manufactured by a company called Spektrum, which specializes in RC assembly products. After the motor was selected, the company suggested the ESC, servo motors, transmitter, and receiver be purchased with the device, because of their direct compatibility with the motor. As of now, the mechanical team has successfully gotten the UAV to fly, using their 3rd iteration of the product. See the brushless motor's specifications in Table 1, the electronic speed controller's specifications in Table 2, and a diagram of the system in Figure 5.

<u>**Avian 4260-480Kv Brushless Motor**</u>	
- Voltage Input Range	18.5-22.2V (5-6S LiPo)
- Propeller Range	13x10 to 15x8 Electric
- Max Cont. Power / Current	810 W / 36.5 A
- Max Burst. Power / Current	1350 W / 60.8 A
- RPM/Volt	480 Kv
- Weight	268 g
- Connector	4mm Bullet

Table 1: Brushless Motor Specifications

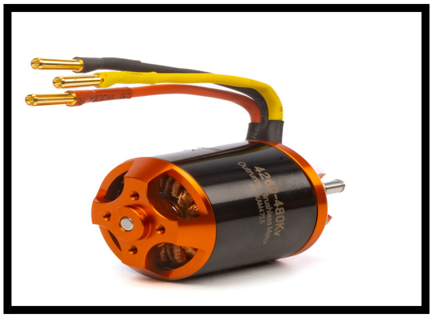

Figure 3: 4260-480Kv Brushless Motor

<u>**Avian 45 Amp Brushless Smart ESC**</u>	
- Voltage Input Range	11.1-22.2V (3-6S LiPo)
- Max Cont./ Burst Current	45 A / 60A
- Weight	50 g
- Dimensions (LxWxH) (mm)	62 x 38 x 13
- Key Features	Programmable, BEC, Auto Cut Off

Table 2: Electronic Speed Control Specifications

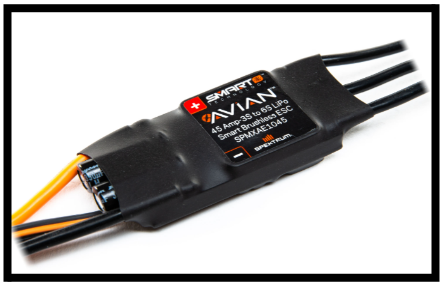

Figure 4: 4260-480Kv Brushless Motor

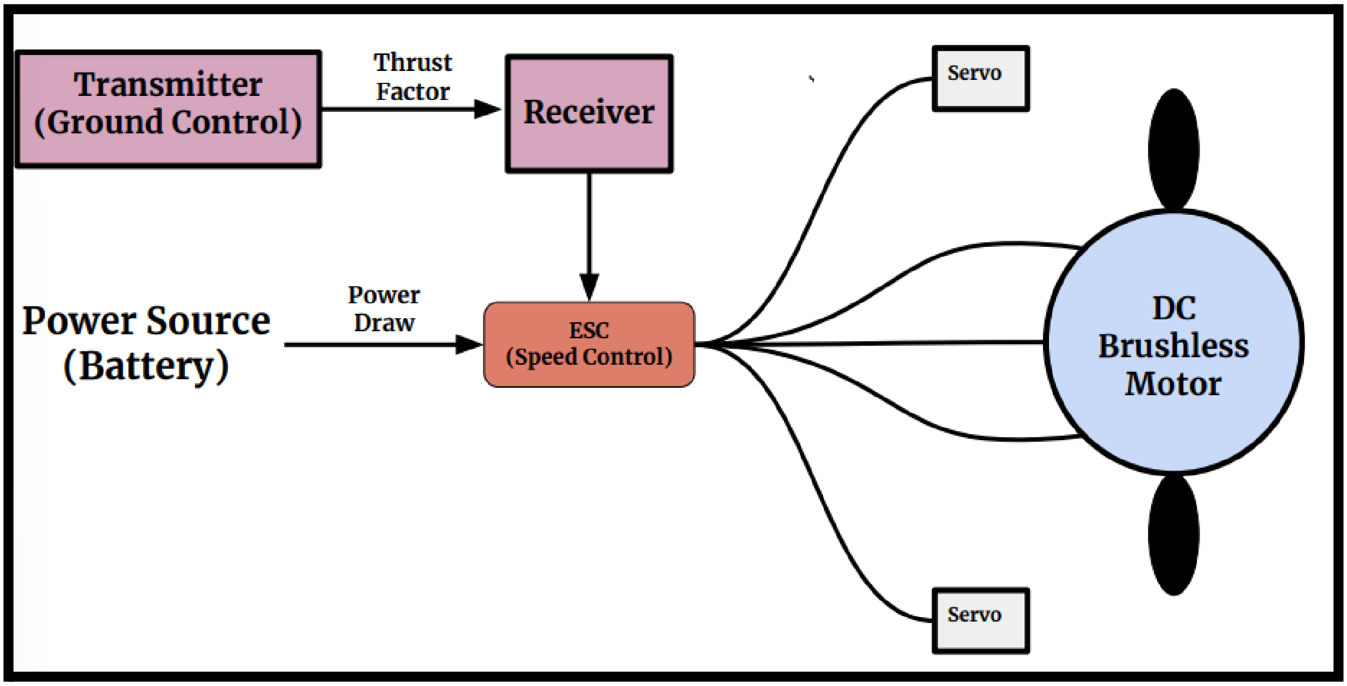

Figure 5: Setup of Motor System

2) PV Array

The solar panels used for this project will be C60 monocrystalline cells. As mentioned before, these cells are commonly used for UAVs because of their weight of 7 **grams** each and their choice of array sizing. A schematic of the C60 cell can be seen below in Figure 6 and the C60 cell's specifications can be seen in Table 3.

C60 Monocrystalline Silicon Solar Cell	
- Pmpp at STC	3.4 W
- Vmpp at STC	.582 V
- Impp at STC	5.93 A
- Voc at STC	.687 V
- Isc at STC	6.28 A
- Efficiency	22.5 %
- Dimensions (LxWxH) (mm)	125 x 125 x 1.65
- Weight	7 g

Table 3: C60 Solar Cell Specifications

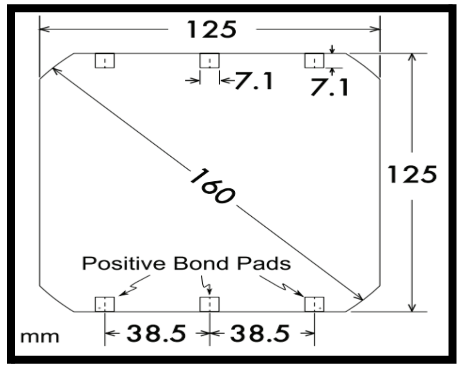

Figure 6: Schematic of Solar Cell

The decision to use the C-60 technology was an easy decision, and the decision matrix we created supported it. The next issue was figuring out the adequate amount of solar power required to feed into our charge controller and ultimately charge our Li-Po battery. Our PV sizing depends on the motor's thrust factor and its relationship with the battery's capacity. After a series of preliminary calculations (Appendix I), we determined that our solar system needs to output a minimum of **97 W** to adequately charge the battery. The surface area (topside) of the UAV is slightly curved, but shouldn't pose any issue to the array's attachability. The best setup we could build off of the surface area allotted is a configuration of 26, C-60 panels spread across the plane, connected in series. These connections will be made with a couple of feet of tabbing wire, several dogbone connectors, solder flux, solder rosin, electrical tape, and a welding tool. The cumulative weight of the panels is **.404 lbs / 182 g**. The total weight of the tabbing wire, dogbones, and solder is estimated to be .**2 lbs / 91 g.** These weights and cell configurations meet our project requirements. A schematic of this setup can be seen in Figure 7 and the expected output of our PV array can be seen in Table 4.

PV Array for Solar UAV	
- Ppv(max)	77.5 W
- Vpv(max)	13.6 V
- Ipv(max)	5.7 A
- # of cells	24
- Weight	273 g

Table 4: PV Array Specifications

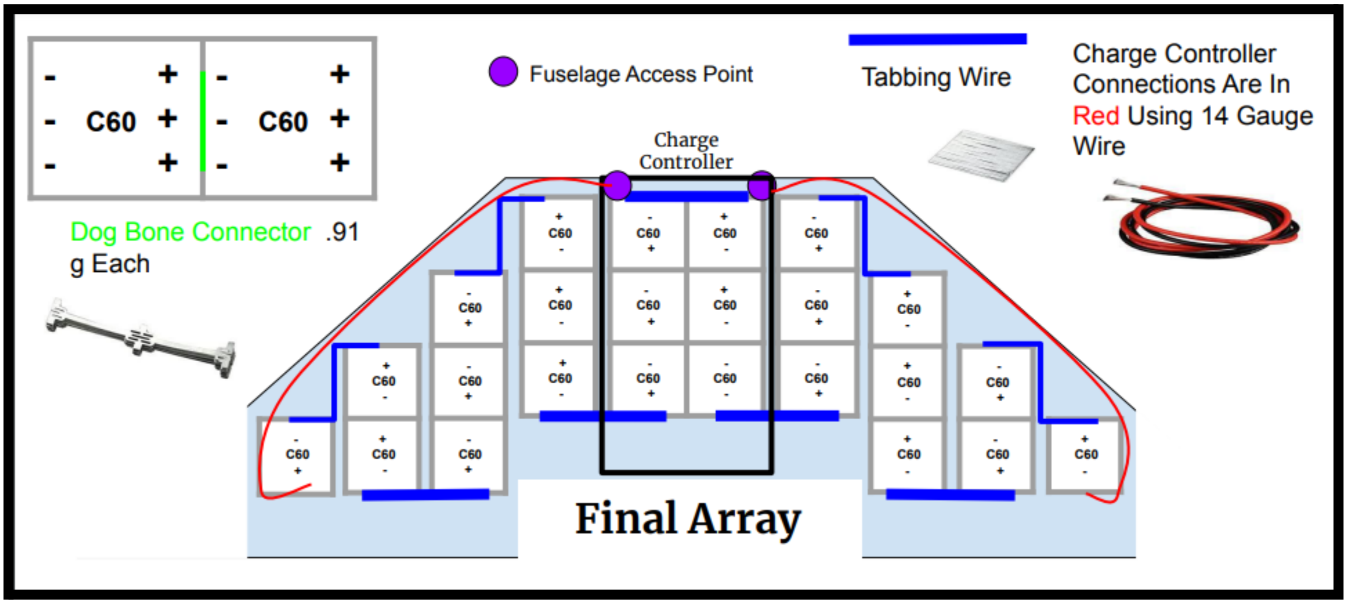

Figure 7: Schematic of Solar Panels on UAV (3rd Iteration)

Prior to assembling the array, each cell needs to be tested. They are extremely delicate, so the slightest mishandling of them can result in a crack in the surface, and an overall fault in their performance. If a faulty cell is used in an array, then the whole array is useless. With every individual Voc and Isc test, it was critical that each cell gave a read of at least **.6 volts** and **4 amps.** If a cell met these requirements, then they were eligible to be soldered into our array. The mechanical engineering team had 3 total iterations of the UAV, each with different surface areas, which forced our team to alter our design. We built our first array for the UAV's second iteration, which included 14 panels to be soldered for a wing. The dogbone connectors provided an easy connection for the cells that were stacked on top of each other, but the tabbing wire would run horizontally across each column to sustain the series connection. We were able to successfully assemble an array of 14 panels together and get a reading. However, we received a voltage output reading of 2.4 volts, when we were shooting for at least 7 volts. The voltage loss of the array was significant, and could not be used. We speculated three probable causes for this voltage loss.

1) A faulty cell may have shorted the entire array.
2) One or multiple solder joints may have been a "cold" joint. After a meeting with our advisors, our team committed to a more careful and precise soldering approach.
3) The resistance of tabbing wire or dogbone connectors significantly affects the overall efficiency of the array.

The 2nd time we complied an array for the mechanical engineering team's 3rd iteration of the UAV, we made sure to test every cell and make sure our solder joints were minimal and smooth. At first, we were placing solder directly on top of the connectors and tabbing wire. While this method worked for the dogbones, we found the voltage drop was due to the tabbing wire. We then tried placing a small amount of rosin onto the leads, then pressing the wire on top of the solder, in an attempt to melt it on. The method proved efficient, as it eliminated the voltage loss we were receiving.

3) Solar Encapsulation

The team has plans to encapsulate the solar array by laminating them for protection while they are on top of the UAV. We used self-sealing laminating material, scissors, a blade, and a ruler for this process and the result was satisfactory. The panels were tested afterward and showed no loss.

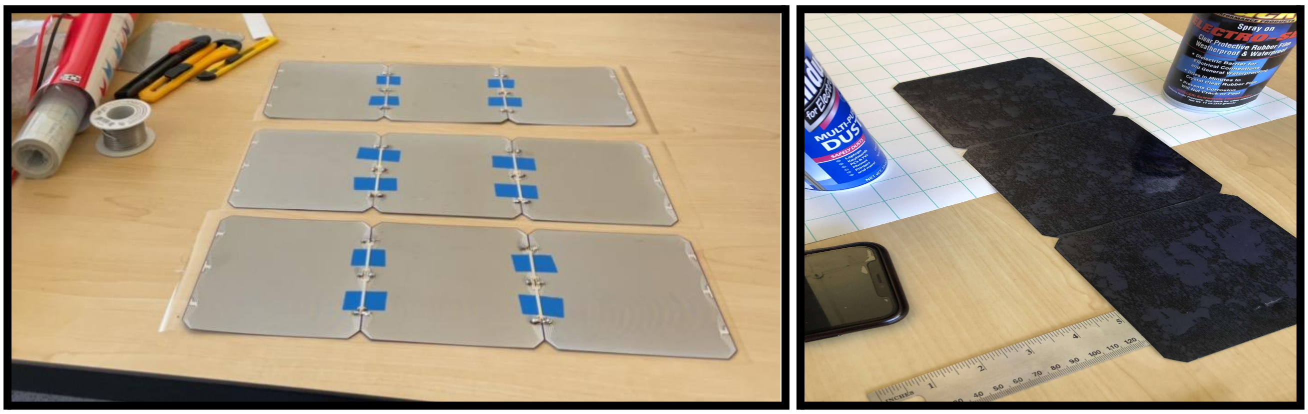

Figure 8: Solar encapsulation (Front and Backside)

4) Battery

A lithium-ion polymer (Li-po) battery is a lightweight, rechargeable battery. Li-po batteries are suitable for robust and high-power use. These batteries are rated by their cell count. Each cell included in a battery pack carries a rated voltage of 3.7 volts. Our battery specifically has 6 cells (6S), which adds up to a 22.2 V, rating of our battery. Li-Po battery cells should be protected by an electronic circuit in order to prevent them from overcharging or over-discharge [8]. This is where a charge controller comes in handy. This battery was selected by the mechanical engineering team to get the motor running, so our system is based on this battery choice. See Table 8 for battery specifications.

<u>22.2V 3200mAh 6S 30C Smart LiPo Battery</u>	
- Capacity	3200 Ah
- Battery Voltage	22.2V
- Maximum Continuous Discharge Rate	30C
- Number of Cells	6
- Battery Type	LiPo (3.7V per cell)
- Connector Type	IC5
- Dimensions (L x W x H) (mm)	142 x 42 x 38
- Weight	484g

Table 6: Specifications for 22.2V 3200mAh Smart LiPo Battery

Figure 9: Li-Po Battery

5) Charge Controller

The charge controller that we are using for this project is the MPT-7210A charge controller. Our team struggled to find the right charge controller for our system. In most scenarios, they were either too heavy or exceeded the specifications for our PV input and battery output. The team was under the assumption that this charge controller would track the maximum power point of a photovoltaic panel module voltage quickly and precisely, as it was advertised. Before our team hooked the charge controller up to our solar array, we made sure to develop safety procedures. The connectivity of electrical components, especially with a battery, can be quite dangerous. Once everything was hooked up, it took us a couple of weeks to find the appropriate charging voltage and current. The charge controller is more of a configurable boost converter, rather than a self-acting MPPT tracking mechanism. We ended up finding the maximum power point ourselves. With each configuration we attempted, it would either charge or not charge. We reached a maximum charging current of 3.4 amps and 24 V. The charge controller could be set higher, but would not charge our battery past these specifications. The charge controller charging specifications can be seen in Table 8.

MPT-7210A Charge Controller	MPT-7210A
• Input Voltage	DC 12-60V
• Output Current	0-10A Adjustable
• Output Power	20-600W
• Working Modes	MPPT and DC-DC
• Item Size(approx)	131*96*54mm
• Tracking Efficiency	98%
• Output Voltage	DC 15-90V adjustable
• Weight With Casing	0.45 lbs
• Weight Without Casing	0.23 lbs

Table 7: Charge Controller Specifications

Figure 10: MPT-7210A Charge Controller

Charge Controller Application	
- Solar Input Voltage	10.90 - 13.60 V
- Charging Voltage	24 V
- Charging Current	3 - 3.4 A
- Charging Power	70 - 80 W
- Wire Size Connection	Solar - 14 | Battery - 12AWG
- Charging Performance	The charge controller over the course of 30 minutes charged the battery 8% in capacity. Against 45% throttle on the ground, 1%.

Table 8: Charge Controller Charging Specifications

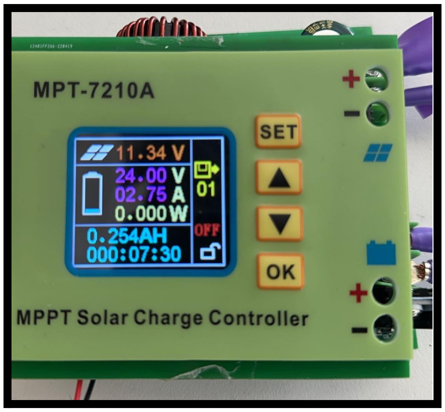

Figure 11: MPT-7210A

6) Component selection and Construction

Aside from the product's functionality, weight plays the most significant role in our component selection. Our motor is suited to support 9 lbs of weight maximum, so all of the elements of the UAV must be weighed prior to ensure we are within our bounds. Between the solar array, charge controller, battery, and connection tools, we are looking to stay under **40%** of the plane's total weight. **40%** of the plane's total weight is 3.6 lbs / 1633 g. The electrical components size up to under **2 lbs / 907g**, so our weight requirement is met. The surface area of our UAV permits less space for our solar panels than we would have hoped for. The delta shape of the UAV also permits challenges. We were able to manage 26 C60 monocrystalline solar panels within the UAV's surface area, based on the mechanical engineering team's 3rd iteration. Each of the panels has an area of 125mm x 125mm. Refer to Figure 6 for details. We must ensure all onboard components can fit within the volume of the fuselage. Below is a list of tools we will be used to assemble our components together.

- Soldering Tool and Machine
- Soldering Rosin
- Soldering Flux
- Electrical Tape
- Power-Free Gloves
- Glass Plating
- Wire Strippers & Cutters
- Digital Multimeter
- Super Glue
- Tabbing Wire
- Dogbone Connectors
- 14 Gauge Wire
- Materials listed within the solar encapsulation process

Project Results

Aircraft:
Weight: 5.7 lbs. (2600g)
Thrust to Weight Ratio: 0.81
Wingspan: 5 ft
Chord Length (Max): 19.5"
Chord Length (Min): 8"
Surface Area: 6.8 ft^2
Max Speed: 50 mph
Max Duration without solar: **6 minutes**

Photovoltaic System:
24 solar panels (series)
Total Array Voltage (VOC): 13.7 V
Total Array Amperage (ISC): 5.7 AMPS
Max Power Output: 77 Watts
MPPT Charge Controller Voltage Output: 24 Volts
MPPT Charge Controller Amperage: 3.3 AMPS
Flight Duration with solar panels: **7 minutes and 8 seconds**

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Our PV input never exceeded 5 Amps, which meant we were never going to be able to charge the battery efficiency enough to meet our goal. Flight without solar was 6 minutes, and flight with solar is just over 7 minutes. Our flight time was only extended by 17 %. Our shortcomings can be traced back to not having enough solar. An increase in overall PV output allows a higher charging current. A higher charging current allows the allowance of a better charge controller. A better charge controller allows a faster charge to our battery. This is where we fall short of our goal. There are MPPT charge controllers that are used for residential PV systems, but most of them are rated over 100 watts of power, 15 Amps of current, etc. These charge controllers will adequately read PV voltage and overall battery capacity and output the most efficient charging current. However, they are too heavy or they exceed our PV's compatibility. There is a heavy restriction for our PV system size because of the amount of surface area we were allotted, and the weight we had to stay within bounds of. We were still able to recharge the battery, which is the essence of our project. If we can extend the flight time of the UAV even a little, we can develop a new plan to ultimately meet our goal. We assembled a functional product at most, with all the elements of our system architecture working, separately. We built a working PV array, chose the right charge controller, and installed the entire system on the UAV with everything working as intended.

Conclusion

The concept behind UAV aircraft is quite simple: solar panels are installed on the wings of the aircraft. These solar panels help in capturing the solar-oriented energy from the sun and helping to convert it into electric energy that can help in moving the system and controlling devices, with any extra energy being stored in batteries. It is possible to use the energy stored in the batteries at night and in locations where there is a deficiency of the sun's solar energy. The conclusion that can be drawn from a thorough assessment and analysis of the benefits and drawbacks of solar-powered aircraft is that the energy produced by solar panels is significantly less than the energy produced by generators and batteries, and there is also some energy loss. The main reason for including a sun-based control system in a UAV is to extend the run by providing an additional control source while in flight. The solar control system requires the greatest control point tracker (MPPT) and PV cells. The MPPT records the PV cells' most extreme control point and extracts the most extreme control Point Tracker (MPPT) necessary for the solar control framework. The PV cells capture solar energy and convert it to electric energy. The MPPT locates the PV cells' greatest control point and releases the most extreme control from the PV cell. Although we faced many problems with a couple of things in our project such as choosing which charge controller that we will be using that meets our requirements for example if it does have MPPT, is it light weighted, or can it be adjustable by taking the case off and decreasing the weight. Also, if it's easy to use and smart. So, the previous ones didn’t really meet our requirements but we ended up finding the charge controller(MPT-7210A) that does have MPPT, also can be lightly weighted by taking the whole case off, and meets all our requirements. The second problem that we faced in our project was soldering the solar panels which cause some energy loss and not giving a good reading, so we manage to do the right way of soldering after a couple of tries which start to give us good reading. So our planning ahead will be doing full assembly and integration of the solar system, official flight testing, and analysis. After that, we will start to install the solar panels on top of the UAV. Finally, we will be doing the final testing and analysis. Then, test our solar system to charge the battery during flying and extend the flight duration by 150%.

Appendices

I. PV Sizing Calculations

Our PV sizing depends on the motor's thrust factor (X_T) and its relationship with the battery's capacity. A new battery capacity is used to consider a 10% loss factor: **2.88Ah**. Thrust is a factor of motor speed, and we will rate it as a percent value from 0% to 100%.

- X_T(Initial) = **75%** **Thrust estimated to lift UAV off-ground (30-45 sec)**
- X_T(New) = **30%** **Cont. thrust estimated to maintain flight**

Practically, we can use both thrust factors to get a range of PV output by taking the power of the motor and multiplying it by the thrust factor. Then we can divide that by the battery's nominal voltage of **22.2V** to get the current draw by the ESC. Taking the battery's capacity, and dividing it by the current will give us an estimate of flight time. We calculated flight time for both thrust factors, which resulted in 9 ½ and 23 ½ minutes. We want to add 50% more capacity to the battery during the flight:

- 2.88 Ah / 2 = 1.44 Ah more capacity within 9 ½ and 23 ½ minutes.
  - 1.44 Ah / 9.45 min = **9.14 A**
  - 1.44 Ah / 23.55 min = **3.67 A**

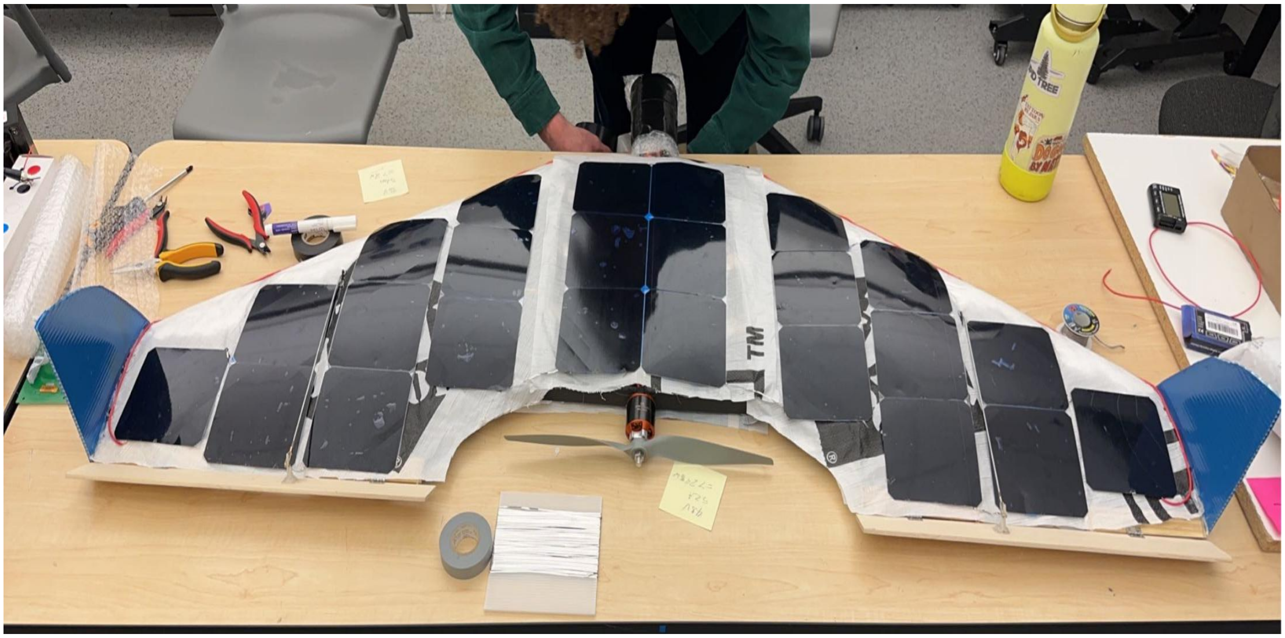
Our power output range can now be calculated using the currents above:

- P_{max} = I * V = (9.14) (22.2) = **202.9 W**
- P_{min} = I * V = (3.67) (22.2) = **81.5 W**

Our solar output should be in the range of **80 and 200 W.** To narrow down our output, we can take another approach. Generally, a PV output should be 20% higher than the battery's voltage. The minimum current we should output is **3.64 A.** Power output can now be calculated, and we can check if it fits within the range of 80 and 200W.

- 22.2 * 1.2 = 26.64 V
  - 26.64 V * 3.64 A = **96.96 W** (minimum power from solar)

II. Final Iteration of UAV



III. Gantt Chart (Updated 11.11.22)

Solar UAV

EE (NAU) Solar Flyers

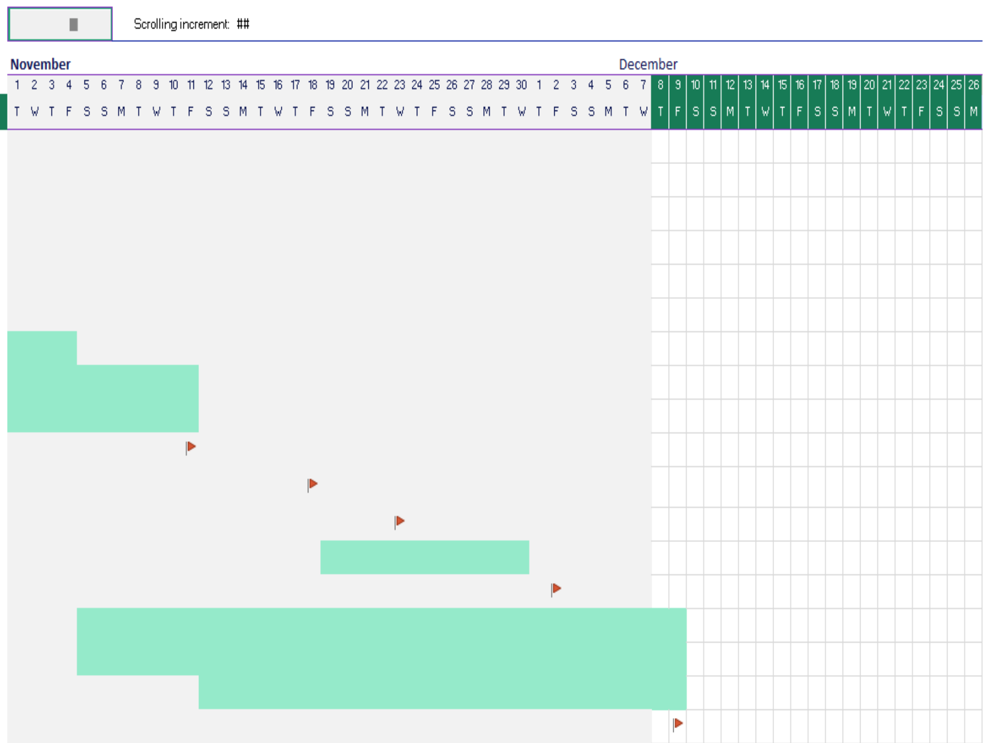
Gabriel Martin & Sultan Alhazawbar

Project start date: 1/10/2022

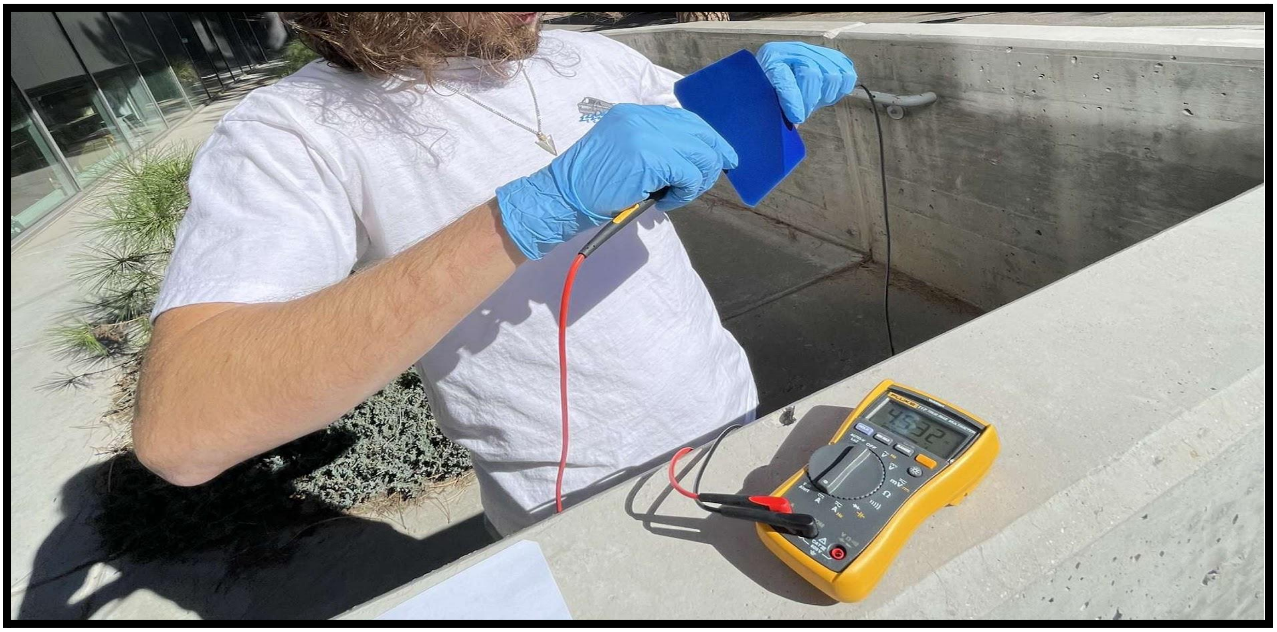
Milestone marker: 1

Milestones

Milestone description	Assigned to	Progress	Start	Duration (# Days)	Finish
EE476C					
EE486C					
Recap Assessment	G.M	100%	8/29/2022	10	9/9/2022
1/3 Build Assessment	G.M & S.A	100%	9/9/2022	37	10/14/2022
Individual Contribution Assessment	G.M & S.A	100%	10/14/2022	16	10/28/2022
Website Check I	S.A	100%	10/14/2022	16	10/28/2022
2/3 Build Assessment	G.M & S.A	100%	10/14/2022	23	11/4/2022
Team Design Document II	G.M & S.A	100%	10/14/2022	30	11/11/2022
Website Check II	S.A	100%	10/28/2022	16	11/11/2022
Prototyping Phase A: Array Assembly	G.M	100%	11/11/2022	1	11/11/2022
Prototyping Phase B: Charge Controller Configuration / Connection	G.M & S.A	100%	11/18/2022	1	11/18/2022
Prototyping Phase C: Full Integration	G.M & S.A	100%	11/23/2022	1	11/23/2022
UGRAD Poster	G.M	100%	11/18/2022	14	12/2/2022
UGRAD Symposium	G.M & S.A	100%	12/2/2022	1	12/2/2022
3/3 Build Assessment	G.M & S.A	100%	11/4/2022	37	12/9/2022
Team Design Document III	G.M & S.A	100%	11/4/2022	37	12/9/2022
Website Check III	S.A	100%	11/11/2022	30	12/9/2022
Project Completion	G.M & S.A	100%	12/9/2022	1	12/9/2022



IV. Individual Cell Testing



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