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DESIGN, CONSTRUCTION, AND TESTING OF A SOLAR-POWERED, MULTIROTOR, UNMANNED AERIAL VEHICLE

by

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December 2018

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13. ABSTRACT (maximum 200 words)

A ground force commander (GFC) is in a constant fight to maintain complete situational awareness of his or her respective area of operations (AO). This means being aware of all friendly and enemy movement in his AO, and being able to quickly identify new threats and neutralize them efficiently. One of the greatest tools at an AO's disposal for achieving these objectives is the utilization of intelligence, surveillance, and reconnaissance (ISR) aerial platforms. While these platforms are incredible assets, they are often remotely controlled by a higher headquarters, and sensor coverage time is usually shared between multiple ground units spread across numerous AOs. This means that the GFC rarely has access to the sensor as often and for as long as desired.

Therefore, the impetus of this thesis is to design, build, and test an ISR platform, controlled by a team on the battlefield, which is capable of virtually uninterrupted sensor coverage due to utilization of a photovoltaic solar array as a power supply. This study includes computer-assisted design, 3D printing, multirotor technology, solar energy absorption, maximum power point tracking, energy storage, and full-motion video relays to achieve the objective.

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DESIGN, CONSTRUCTION, AND TESTING OF A SOLAR-POWERED, MULTIROTOR, UNMANNED AERIAL VEHICLE

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ABSTRACT

A ground force commander (GFC) is in a constant fight to maintain complete situational awareness of his or her respective area of operations (AO). This means being aware of all friendly and enemy movement in his AO, and being able to quickly identify new threats and neutralize them efficiently. One of the greatest tools at an AO's disposal for achieving these objectives is the utilization of intelligence, surveillance, and reconnaissance (ISR) aerial platforms. While these platforms are incredible assets, they are often remotely controlled by a higher headquarters, and sensor coverage time is usually shared between multiple ground units spread across numerous AOs. This means that the GFC rarely has access to the sensor as often and for as long as desired.

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LIST OF ACRONYMS AND ABBREVIATIONS

AM0	Air Mass Zero
AO	Area of Operation
BTJM	Best Triple Junction with Monolithic Diode
CAD	Computer Assisted Design
COTS	Commercial Off-The-Shelf
EO	Electro-Optical
GFC	Ground Force Commander
GHI	Global Horizontal Irradiance
IED	Improvised Explosive Device
I_{MAXP}	Amperage at Maximum Power
I_{SC}	Short Circuit Amperage
IVO	In Vicinity Of
Li-Po	Lithium Polymer
MPPT	Maximum Power Point Tracking
P_{MAX}	Maximum Power
PV	Photo-Voltaic
SVTOL	Short Vehicle Takeoff and Landing
TIC	Troops In Contact
VDC	Direct-Current Voltage
V_{MAXP}	Voltage at Maximum Power
V_{OC}	Open Circuit Voltage
VTOL	Vertical Takeoff and Landing
UAV	Unmanned Aerial Vehicle
Wh	Watt-Hour

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I. INTRODUCTION

A. BACKGROUND

Over the past decade, unmanned aerial vehicles (UAVs) have become a favored tool of United States ground combat leaders, known colloquially throughout the service as ground force commanders (GFCs). These GFCs leverage the electro-optical sensor payloads on these aerial platforms to surreptitiously watch the enemy or collect battlefield atmospherics, to monitor potential persons of interest, to conduct persistent overwatch of a friendly patrol or route reconnaissance before an operation, and to enhance understanding of friendly and enemy positions during a troops-in-contact (TIC) situation where friendly forces are engaged in an active firefight with the enemy. Ultimately, the UAV serves to increase the GFC's overall knowledge of the battlefield environment, so that they can be better informed when making important tactical and strategic decisions.

In certain areas of operation, such as Afghanistan, where "military operations are planned and executed in an extremely challenging environment," UAVs have continued to prove their value [1]. Aside from the obvious intelligence advantages a UAV provides, it also greatly reduces the risk factor that would normally be incurred by utilizing a manned aerial platform or a soldier in the field. Pilots of manned aerial platforms could be shot down or their life could be put into jeopardy due to equipment malfunction in the aircraft. A soldier in the field may be great at gathering intelligence, but is inherently exposed to both active and passive threats, such as fatal interactions with the enemy or the possibility of triggering an improvised explosive device (IED), respectively.

While the United States currently maintains a large inventory of UAVs, not all of these are available to a particular GFC at any one time. Most UAVs in a combat theater are referred to as "theater assets." Essentially, this means that most of these assets are controlled, remotely, by a joint higher headquarters and are tasked to certain missions based on varying priority levels. According to the

Department of Defense, most of these theater assets fall in Categories 2, 3, 4, and 5, as seen in Figure 1 [1]. However, the UAVs in Category 1 are usually organic to a specific unit and can be controlled and employed by that unit when and how it sees fit. The UAVs in Category 1 are usually smaller and do not require as much maintenance and infrastructure support (such as launching platforms or large runways) as the other four categories.

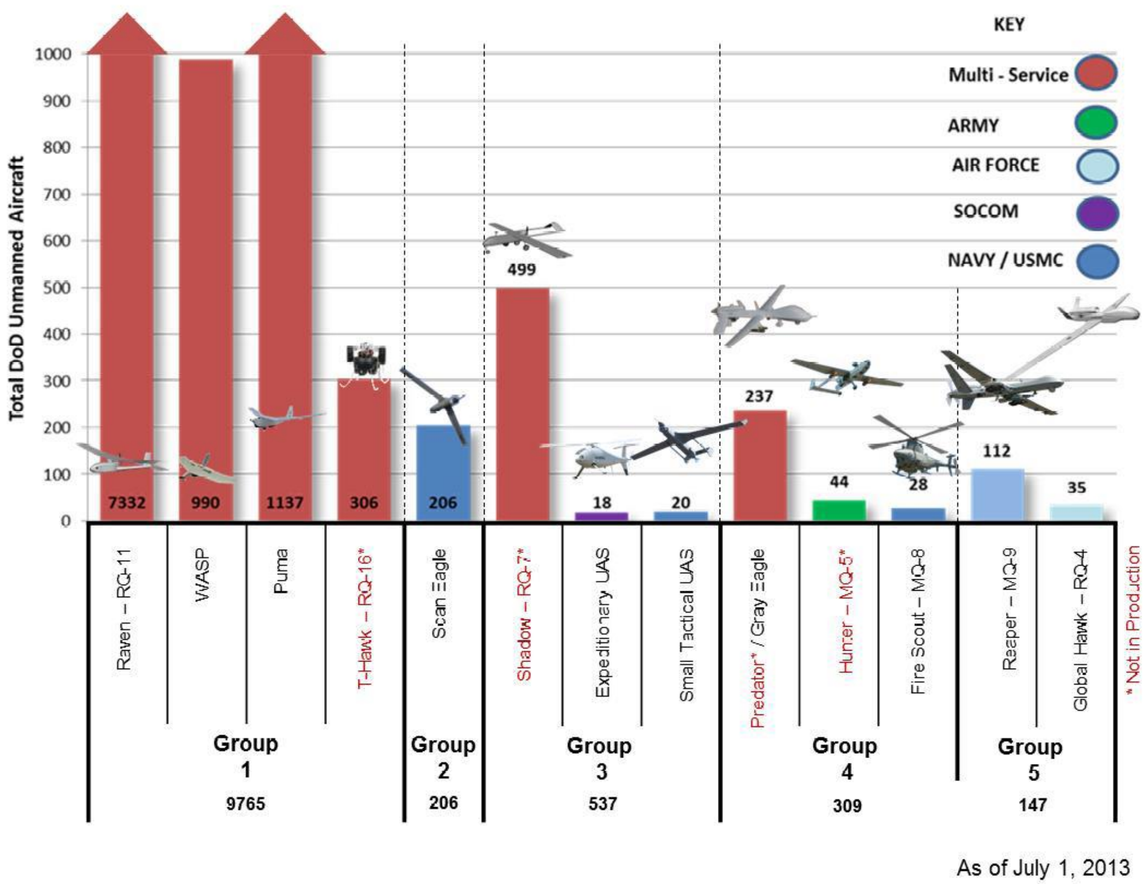

Figure 1. United States UAV Inventory, 2013. Source: [1].

The Category 1 UAVs all possess specific advantages and disadvantages. The main advantage they share is that they are usually man-portable and can be controlled remotely by the same ground team that plans to benefit from their intelligence collection. This autonomy positively influences the pace of battle and intelligence collection and dissemination. The GFC is able to employ the asset's sensors exactly where they need them relatively quickly without having to go through a middleman and without having to compete with the needs of other ground units around the area. However, one enormous disadvantage that most all of the assets in Category 1 share is that they are greatly limited by the endurance of their on-board power sources and are usually restricted to operating only in ideal weather conditions. This thesis intends on developing a UAV that is not limited by these factors.

B. OBJECTIVE

The objective of this research is to identify the ideal UAV which is available for Intelligence, Surveillance, and Reconnaissance (ISR) support, utilizing an electro-optical (EO) payload, for a small tactical team operating out of a combat outpost; a much-desired capability for United States Special Operations Forces currently operating overseas. To further refine this requirement, it has become necessary to develop a hypothetical scenario that accurately represents the typical environmental parameters and tactical situation that such a team might encounter. For the purpose of this thesis, the following scenario will be explored:

- **Who**: A 18 man platoon of Navy SEALs
- **What:** Conducting sustained combat operations out of a small, remote combat outpost in a semi-permissive mixed urban/rural environment
- **Where:** A 50 km^2 AO In Vicinity Of (IVO) Kabul, Afghanistan
- **When**: Typical Afghanistan fighting season (May-October) 2016
- **Why**: In order to help promote governance, stability, and development throughout the area of operations
- **Operational Requirement:** A small UAV capable of user control, launch, and recovery, which is available to remain on station and

stream imagery 24/7 via an EO payload, in order to provide persistent overwatch, route reconnaissance, and/or target identification throughout the AO

Because the platoon is operating out of a remote combat outpost in a mixed urban/rural environment, it is essential that the UAV be able to be launched and recovered without a runway or bulky launch/recovery devices. It also means that the UAV would need to be controlled organically by a member of the platoon at the outpost or collocated in the field with the combat team. There are a number of small tactical Group 1 UAV's in the Department of Defense inventory that satisfy these requirements [1]. The RQ-11B Raven [2], the RQ-20B Puma AE [3], the Wasp AE RQ-12A [4], the Snipe [5], the Aeryon SkyRanger [6], and the Honeywell RQ-16 T-hawk [7] (which was terminated in 2011) [7] will not be considered as part of this research. All are short/vertical takeoff and landing (SVTOL) or vertical takeoff and landing (VTOL) capable and do notvrequire the use of a runway or launch/recovery equipment.

All of the aforementioned UAVs also have EO sensors with live video streaming capability. Moreover, save for the Snipe (due to its relatively short endurance of 15 minutes [5]), all platforms could surveil a decent good portion of the proposed 50 km^2 AO. The Raven, Puma, and Wasp all have advertised endurances of 180 [2], 90 [3], and 50 [4] minutes, respectively. The greatest limiting factor here, where all the listed Category 1 UAVs seem to fall short, is the requirement to provide streaming video around-the-clock in order to support the platoon's mission. All of the UAVs being considered in this scenario are powered by some form of a battery, with a limited storage capacity, that cannot sustain a continual operation of the camera payload without the periodic refueling of the vehicles power stores. In order to "refuel," each UAV must be recovered and the batteries must either be swapped or recharged, before the platform and its sensor can be redeployed to continue its mission; hardly the persistent coverage that the operational requirements of this scenario demand.

With no known UAV platform in existence that could aptly satisfy the operational requirements of this scenario, it quickly became obvious that one would need to be designed from the ground up. The design process, which ultimately resulted in the creation and construction of such a UAV, known from here on out as the Condor, will now be discussed in detail.

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II. DESIGN

In this chapter, the focus is on identifying the steps that went into the creation of the Condor. Time, cost, and availability of parts and resources were constraining factors that heavily influenced the direction and scope of research. The power system of the Condor will be the main focus of the design.

A. REQUIREMENT IDENTIFICATION

The first step in the design process of the Condor was to identify an appropriate power source. As seen with the Raven, Wasp, Puma, Snipe, and SkyRanger, the endurance of the platforms in the field was directly correlated to both the rate of energy consumption of the platform, as well as the amount of energy stored onboard in the form of batteries. As is evident in Figure 2, save for very few special circumstances, energy efficiency is commonly greater for fixed wing aircraft than it is for rotary wing aircraft.

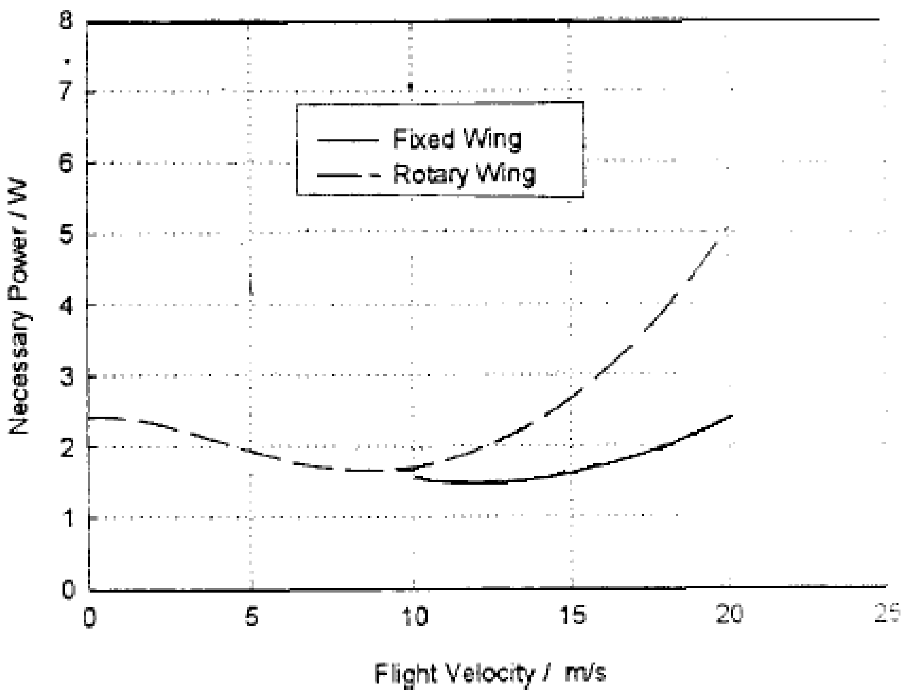

Figure 2. Comparison of Power Efficiency in Fixed and Rotary Wing Aircraft. Adapted from [8].

Even though a fixed wing aircraft design would require less energy to stay airborne than would a rotary aircraft, theoretically providing greater endurance and time on station to support the mission, it became necessary to take into account some other operational constraints as well. Given that the platoon in this scenario is operating in a semi-urban environment, buildings and other large structures would have a significant presence in the UAV's area of operation. The VTOL characteristics of a rotary UAV provide a greater margin of safety when it comes to launch and recovery in an urban environment than those of a fixed wing UAV, even one with SVTOL capabilities. Also, with only a small contingent of 18 men, virtual around-the-clock control of an aircraft actively flying around could quickly become a daunting and time consuming task. Obviously, some sort of autopilot or waypoint navigation system could help alleviate some of the pressure of constant human control, but that would likely put the UAV in a precarious situation if it was flying on autopilot and inclement weather were to move into the AO unexpectedly.

Moreover, the operational requirements state that the UAV does not actually have to be airborne at all times, just available to stream imagery. Essentially, this means that the UAV could land in a certain location and, using a controllable camera system, image or stare at the target. As it so happens, this virtual "downtime," where the UAV is not drawing power to stay airborne, but only to stream imagery, would be a perfect opportunity to also recharge its batteries.

Given that the UAV could potentially be located at a great distance from its controller during this "downtime," a physical battery swap or conventional recharging methods (where the power system is plugged into a standalone power source) would be simply out of the realm of possibilities. Instead, the UAV would have to rely on an unconventional method, such as solar energy, to sufficiently recharge its batteries.

B. REQUIREMENTS ANALYSIS

When designing any battery operated device that relies on solar energy as its sole means of recharging its power stores a number of important factors need to be considered. First, the exact amount of solar energy that will be available to the device in its given operating environment must be determined. Second, there needs to be an efficient means of capturing this solar energy. This is often accomplished through the use of numerous multi-junction solar cells joined together as part of a larger photo-voltaic (PV) array. Next there must be a method for storing this captured energy onboard the device which the device can draw off of during times of minimal or non-existent solar insolation.

In the UAV environment, the choice of what batteries to use is tied directly to the energy needs of both the vehicles motors as well as the vehicle's payload, in this case an EO camera. The final factor that must be considered is an unavoidable consequence of utilizing PV arrays in a non-controlled environment. Because the electrical output of the solar cells is directly proportional to the constantly varying amount of solar insolation available to them at any given point in time, the electrical output of the solar cells will, in turn, vary constantly. In order to capture whatever output from the solar cells is available at that instant and convert this energy to the correct voltage and amperage needed to recharge the device's batteries a method known as Maximum Power Point Tracking (MPPT) will need to be utilized.

1. Solar Energy Availability

Broken down into the simplest of criteria, the effectiveness of solar energy recharging is determined by two factors, the amount of solar energy available at a location and the efficiency of the solar cells, or collective photo-volatic (PV) array, at capturing that solar energy and converting it to electrical power. The question of how much solar energy would be available at the AO during the May-October operational timeframe was determined by consulting the National Solar Radiation Database (NSRDB), "a serially complete collection of hourly and half-hourly values of the three most common measurements of solar radiation—global horizontal, direct normal, and diffuse horizontal irradiance—and meteorological data" [9]. The NSRDB data is so vast that it is considered an accurate representation of a specific area's solar climate and can be used as a predictive tool to measure how much solar energy will be available in any one area at a specific time of year. NSRDB data from the geostationary satellite, Meteostat 7, will be utilized in this scenario.

The specific NSRDB data that is of interest is the measure of Global Horizontal Irradiance (GHI). A GHI value is obtained by combining the measured Direct Normal Irradiance (DNI) with the measured Diffuse Horizontal Irradiation (DHI). DNI is defined as "the amount of solar radiation received per unit area by a surface that is always held perpendicular to the rays that come in a straight line from the direction of the sun at its current position in the sky" [10]. While DHI is defined as

> the amount of radiation received per unit area by a surface (no subject to any shade or shadow) that does not arrive on a direct path from the sun, but has been scattered by molecules and particles in the atmosphere and comes equally from all directions. [10]

Using both measured DNI and DHI values, GHI is then calculated via the following equation:

$$GHI = DHI + DNI * \cos(\theta)$$

where Ө represents the solar zenith angle. A visual representation of GHI is best exhibited in Figure 3.

In this figure, straight lines represent DNI, while squiggly lines represent DH.

Figure 3. A Visual Representation of GHI. Source: [10].

INSDRB calculates GHI based on what is referred to as a Typical Meteorological Year (TMY). A TMY is defined as “one year of hourly data that best represent weather conditions over a multiyear period” [9]. Using a multiyear data set and averaging out the results helps account for a broad array of meteorological influences on solar insolation at ground level such as cloud cover and particulate or moisture in the air. Figure 4 indicates that the NSDRB has calculated that in a TMY the GHI for Kabul, Afghanistan is approximately 5.59 kWh/sq.m/day.

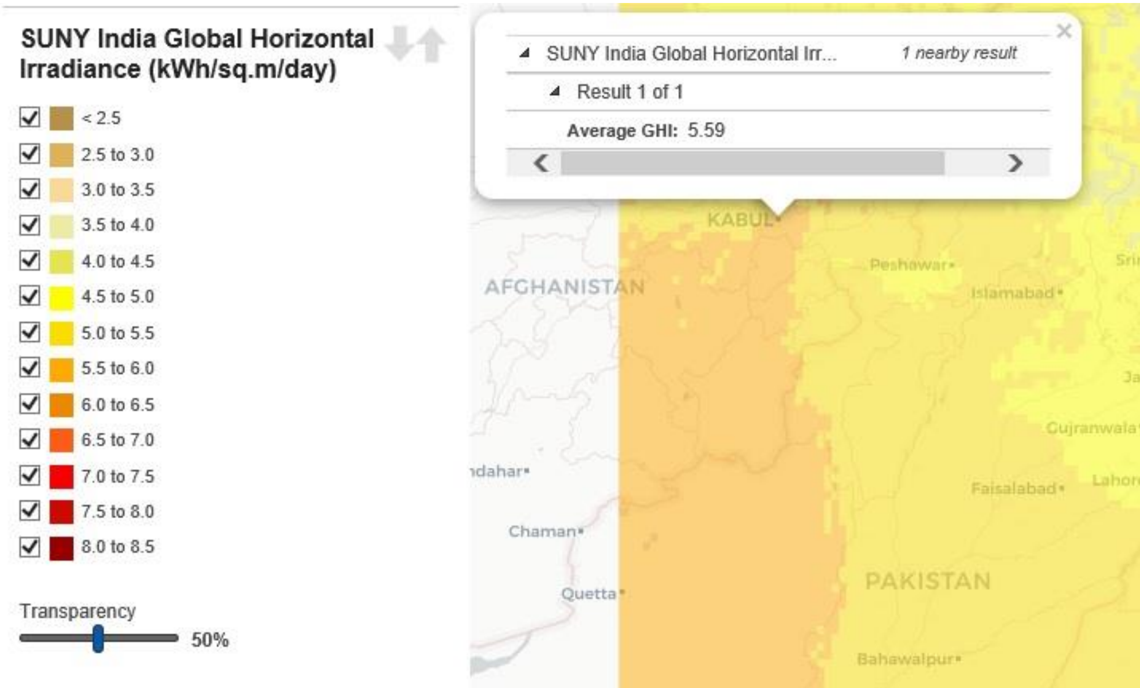

Figure 4. Average GHI for Kabul, Afghanistan during a TMY. Source: [11].

Given the Earth's tilt of 23.5 degrees and Kabul's latitude of approximately 34 degrees North, it becomes obvious that during summer months, Kabul would experience longer daily periods of solar insolation (more daylight hours) and a greater GHI value than it would in the winter months. Recalling the hypothesized scenario presented earlier this thesis is only concerned with the time period of May through October in Kabul. It can be surmised that the GHI during this period can actually be expected to be quite a bit greater than the average GHI indicated for an entire TMY. In fact, average GHI in Kabul in July has been as high as 8.2 kWh/sq.m/day, while average GHI in December has been as low as 3.5 kWh/sq.m/day. However, for the sake of erring on the conservative side of the amount solar energy available to the Condor, we will assume a GHI of only 5.6 kWh/sq.m/day is available. This value will be taken into account, along with a few other factors, to help determine the size of PV array needed to keep the Condor and its camera system operating indefinitely.

2. Solar Cell Efficiency

During the design of Condor, one important consideration was the size of the PV array that would need to be utilized. A larger array would inherently weigh more than a smaller array and decrease the performance and, ultimately, the flight endurance of the UAV. Moreover, a larger array would induce more parasitic drag and provide more surface area for wind to catch, causing increased instability in the UAV. In order to minimize the size of the PV array that would be needed on Condor, it became critical to utilize a solar cell that was extremely efficient at converting available solar energy into usable electrical energy.

A typical single junction silicon solar cell usually exhibits an efficiency of anywhere in the range of 15–24%, depending on the manufacturer. Fortunately, enormous strides have been made in the past twenty years to greatly increase the efficiency of solar cells. One such development has been to combine multiple layers of distinct compounds in series within a single solar cell. Each layer is optimized to collect energy from a distinct part of the solar spectrum. These multi-junction solar cells are remarkably more efficient than their single layer brethren. For Condor's PV array, a total of 64 EMCORE Best Triple Junction with Monolithic Diode (BTJM) solar cells, marketed at a 28% efficiency, were utilized [13]. The layered construction of these BTJM cells is broken down in Figure 5.

Figure 5. Molecular Makeup of an EMCORE BTJM Solar Cell. Source [12].

In order to determine the actual output characteristics of the BTJM cells, they were tested in a controlled environment on the Solar Test Bench using an artificial illumination source as seen in Figure 6.

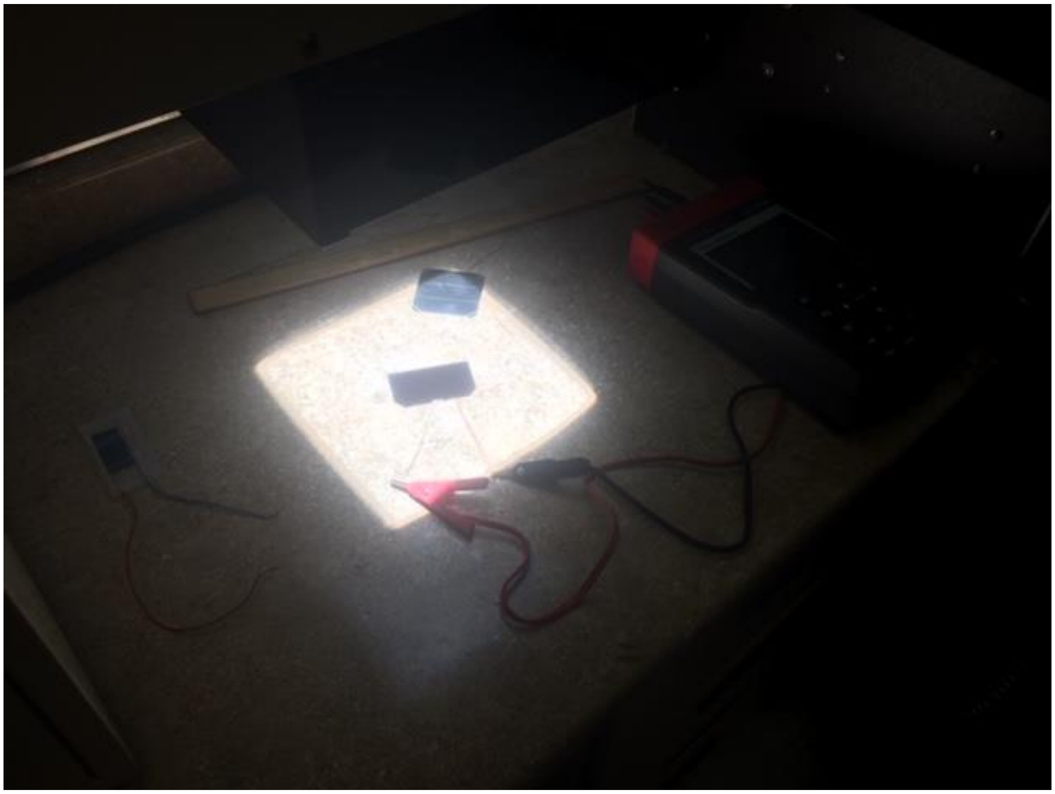

Figure 6. Testing of the EMCORE BTJM Solar Cell on the Solar Test Bench

By utilizing a solar analyzer during the test bench analysis, as seen in Figure 7, an I-V curve for the solar cell was plotted and various operational characteristics of the solar cell, such as open circuit voltage (V_{OC}), short circuit amperage (I_{SC}), maximum power (P_{MAX}), voltage at P_{MAX} (V_{MAXP}), and amperage at P_{MAX} (I_{MAXP}), were able to be extracted.

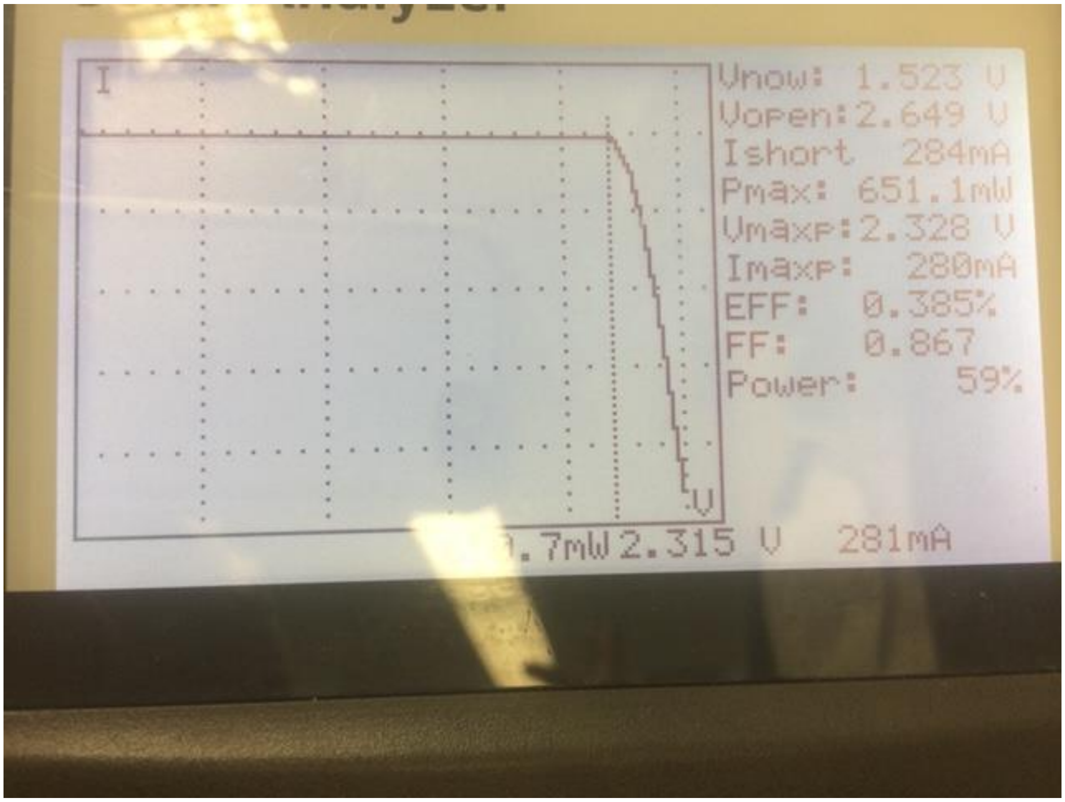

Figure 7. Solar Analyzer Analysis of a Single EMCORE BTJM 28% Solar Cell

All operating characteristics, save for the I_{SC} and I_{MAXP}, obtained during the test bench correlated extremely well with the I-V curve obtained from the EMCORE datasheet seen in Figure 8, indicating that the cells were performing as advertised.

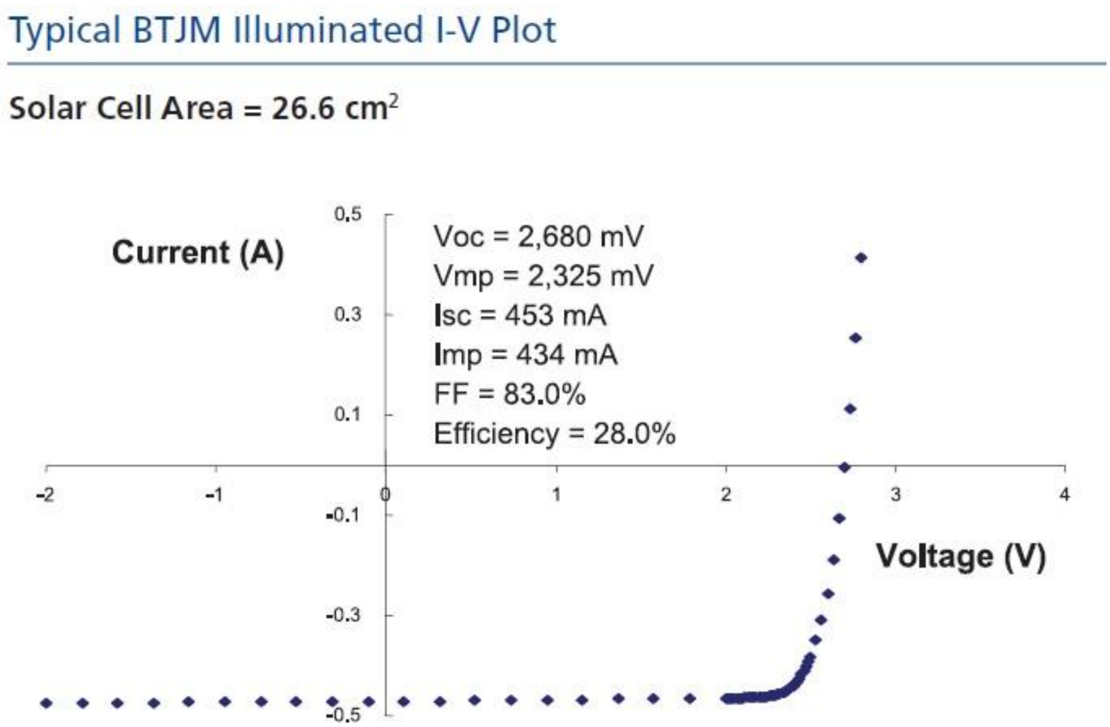

Figure 8. I-V Curve from EMCORE Datasheet. Source: [12].

The main reason for the difference in I_{SC} and $I_{MAX}P$ is that the illumination source of the test bench was not calibrated to AM0 as was the illumination source used in the production of the EMCORE datasheet tests. Air Mass Zero (AM0) is the intensity of light that can be expected in space outside of the earth's atmosphere and is measured at approximately 136mW/cm^2, depending on the time of year. At sea level on earth, AM1.5 is the commonly accepted value of solar intensity. The AM measurement in this case is 1.5 vice 1 because, on average, the Sun's incident light rays usually have to travel through greater than 1 air mass length depending on the latitude the measurement was taking at as well as the time of year the measurement was taken. In Kabul, a mountainous desert region with an altitude of 2000m above sea level, AM1 would be the appropriate value of solar intensity and can be approximated to 100 mW/cm^2, during daylight hours with no cloud coverage. The relevant takeaway from this is that the illumination intensity setting of the test apparatus has the greatest effect on the total output power of the solar cell. Because the light intensity at AM0 is approximately 26% greater than the light intensity at AM1, in Kabul, and with voltage being held constant, it can be assumed that the BTJM solar cells will produce approximately 317mA of current at AM1.

Obtaining these various operating characteristics of the solar cells used in Condor was a crucial step to conducting the design calculations that were needed to determine the size of PV array that needed to provide sufficient power to the UAV, enough to operate the payload indefinitely while also recharging the batteries enough to provide additional daily flight time. The next step was to determine how the solar energy captured via the solar cells would be stored onboard Condor.

3. Battery Selection

Battery selection for Condor was extremely limited by the availability of parts. The four motors on the quadcopter required a voltage that could only be supplied by a 4S battery. The only 4S batteries readily available in the lab were 4S3P (4-series, 3-parallel) lithium polymer (Li-Po) batteries with an 88.8 Watt-hour (Wh) storage capacity as seen in Figure 9.

Figure 9. Li-Po 4S3P Batteries Used on Condor

In order to effectively charge any particular architecture of Li-Po batteries, the amount of direct current voltage (V_{DC}) input from the charger must effectively match the current state-of-charge of the battery so as to prevent any excessive heating; heating which transpires in the form of a catastrophic fire. This range of voltages can be found in Figure 10.

State Of Charge vs. Lipoly Pack Voltage

% Capacity	1S Cell	2S Pack	3S Pack	4S Pack	5S Pack	6S Pack
100	4.20	8.40	12.60	16.80	21.00	25.20
95	4.15	8.30	12.45	16.60	20.75	24.90
90	4.11	8.22	12.33	16.45	20.56	24.67
85	4.08	8.16	12.25	16.33	20.41	24.49
80	4.02	8.05	12.07	16.09	20.11	24.14
75	3.98	7.97	11.95	15.93	19.92	23.90
70	3.95	7.91	11.86	15.81	19.77	23.72
65	3.91	7.83	11.74	15.66	19.57	23.48
60	3.87	7.75	11.62	15.50	19.37	23.25
55	3.85	7.71	11.56	15.42	19.27	23.13
50	3.84	7.67	11.51	15.34	19.18	23.01
45	3.82	7.63	11.45	15.26	19.08	22.89
40	3.80	7.59	11.39	15.18	18.98	22.77
35	3.79	7.57	11.36	15.14	18.93	22.72
30	3.77	7.53	11.30	15.06	18.83	22.60
25	3.75	7.49	11.24	14.99	18.73	22.48
20	3.73	7.45	11.18	14.91	18.63	22.36
15	3.71	7.41	11.12	14.83	18.54	22.24
10	3.69	7.37	11.06	14.75	18.44	22.12
5	3.61	7.22	10.83	14.43	18.04	21.65
0	3.27	6.55	9.82	13.09	16.37	19.64

Figure 10. State of Charge of Li-Po Battery versus the Battery's Voltage. Source [14].

Because the VDC output of Condor's PV array would almost certainly never be able to mimic the necessary voltage required to charge the battery, electrical power could not simply be directly dumped into the batteries when charging. Instead, it is necessary to implement another device into the electrical chain which would be responsible for regulating the electrical output of the array and ensuring that the charging voltage applied to the battery would effectively match its current state of charge.

4. Maximum Power Point Tracking Efficiency

When dealing with solar energy, MPPT is a commonly used method for ensuring the maximum amount of energy is harnessed by a battery system despite changing input conditions or output requirements [15]. Since it has already been stated that in its operational environment, Condor's PV array can expect to encounter varying angles of incidence with the sun as well as varying states of charge of the battery, MPPT will play a vital role in electrical energy management.

In 2015, a former Naval Postgraduate School (NPS) student, Robert Fauci, worked with a commercially available MPPT device as part of his master's thesis research [16]. The MPPT device, also commonly referred to as a boost controller, Fauci modified was the ISV009v1 with the SPV1020 onboard processor, sold by STMicroelectronics, as seen in Figure 11. One of Fauci's endeavors was to modify both the input and output voltages of the module, through experimentation with input and output voltage dividers (four resistors), in order to allow the module to operate within the same parameters required to charge a 4S Li-Po battery that were used on a fixed wing UAV; the same battery to be utilized by Condor. Through skillful modification of the ISV009v1, Fauci was successful in achieving functionality with the 4S batteries.

Figure 11. STMicroelectronics ISV009v1 MPPT as Manufactured. Source: [16].

Fortunately, one of Fauci's modified MPPT's was still available to be utilized in Condor. As an added bonus, the MPPT weighed in at only 25 grams. In the realm of UAVs, especially quadcopters, weight is a precious commodity and each component of a vehicle has to be carefully scrutinized to ensure that the benefit of its addition does not outweigh its strain on the overall performance of the vehicle. The equation commonly utilized to calculate the power required by a multirotor UAV is:

$$Power\ Required = Weight^{3/2} - Disc\ Area^{1/2}$$

where Disc Area is the total area swept by all rotors.

In the case of Condor, the MPPT was an absolutely necessary component and would only contribute a small amount to its overall weight.

One of the major drawbacks of needing some type of charge controller, in this case an MPPT, is that they are never 100% efficient at transferring all of the collected energy from the PV array to the onboard batteries. In fact, the ISV009v1 MPPT has an overall efficiency of around 90%. This value will be taken into account along with other important values discussed earlier, such as daily solar GHI available in the AO, solar cell efficiency, and battery storage capacity, when determining the size of the PV array that must be constructed to indefinitely power Condor's payload.

C. VEHICLE CONSTRUCTION

To say that quadcopter UAVs have become popular in the last few years is a tremendous understatement. Because of this rising popularity, there are numerous commercial off-the-shelf (COTS) quadcopters readily available for open purchase. However, because Condor was going to have a very unique and possibly very large PV array attached to it, it was determined that the best course of action was to design the quadcopter from the ground up using a 3D computer assisted design (CAD) program called Solidworks. The parts designed in Solidworks would then be either 3D printed in-house or cut using the CNC machine at the NPS Machine Shop. Having this autonomy and flexibility of not having to adhere to a preexisting form factor for Condor meant that the quadcopter could be effectively designed around the PV array. This allowed Condor to be designed as small as possible in order to meet the objective.

1. Payload

In order to keep costs low, an effort was made to utilize and repurpose as many quadcopter parts as possible that happened to be laying around the lab from previous thesis and research work.

The payload of Condor consists of all of the components that would need to be in operation at all times, even when not flying, in order to meet the objective criteria of uninterrupted and indefinite video surveillance. Those particular components are a GoPro4 camera, a two-axis camera gimbal, a Pixhawk flight controller with GPS, and a video transmitter. Each component was tested to determine its individual power draw. This data would directly influence the size of the PV array that would be needed on Condor. Results of these tests are depicted in Table 1.

Table 1. Power Consumption of Condor Payload Components

Component	Power Draw (Watts)
Camera	1.5
Gimbal	2.5
Video Transmitter	3
Pixhawk Controller	2
Total Payload	***9***

In order to continuously power the payload and meet Condor's operational requirements, the batteries would need to supply a continuous 9W to the payload, at all times.

2. PV Array

Before construction of the PV array could take place, it was imperative to first determine the size of the solar array that would be needed based on the known power draw of the payload and the daily solar energy availability in the operating environment.

a. *PV Array Design Calculations*

The first step in PV array design was to lay out all of the given data and parameters and then use back of the envelope calculations to determine how many solar cells would be needed to meet the operational criteria. All of the given data used in this first step are outlined in Table 2.

Table 2. Given Data for Calculation of PV Array Size

Given	Value	Units
GHI for Kabul over TMY	**5.6**	**kWh/m^2/day**
Power Draw of Payload	**9**	**W**
Camera (GoPro 4)	*1.5*	W
Gimbal (Two-axis)	*2.5*	W
Video Transmitter (3DR)	*3*	W
Flight Controller (Pixhawk)	*2*	W
Solar Cell Efficiency (Emcore BTJM)	**28**	**%**
MPPT Efficiency (ISV009v1)	**90**	**%**
Individual Solar Cell Size (Measured)	**0.00266**	**m^2**
Length	0.0395	m
Width	0.0689	m

Using this data, a number of calculations were then made to determine how many solar cells would be needed to power only the payload for an entire 24-hour period. These calculations are seen in Table 3.

Table 3. Calculations Made to Determine the Number of Solar Cells Needed

Criteria	Value	Units	Calculation
Payload Power Draw Per 24 hour Day	216	Wh	*9W x 24h*
Useable GHI Per Day	1411.2	$Wh/m^2/day$	$5.6kWh/m^2/day$ x 1000 x 0.28 x 0.9
Array Size To Power Payload For 24hr Day	0.1531	m^2	$216Wh / 1411.2Wh/m^2/day$
Number Of Cells Needed In The Array	57.5	cells	$0.1531m^2 / .00266m^2/cell$

Even though only 57.5 cells would be needed in the array, this number will be rounded up to 58 as the solar cells used cannot be divided in half.

It was decided at this point that even though only 58 solar cells would be needed to supply the 216Wh of energy necessary to power the payload throughout the day, there should be some margin for error in the event that Condor happened to land in a position which partially shaded part of the PV array as well as to make up for days with partial cloud cover. Instead of 58 solar cells, Condor would end up utilizing 64 solar cells in its PV array, making the array $0.17m^2$.

Another important design constraint that became evident here is that using only one of the 4S3P 88.8Whr batteries for Condor would simply not be enough energy storage capacity, especially given the fact that the LiPo cells should not be drained to below 15% of their total charge capacity due to an increased risk of damaging the cells below this threshold. Instead, it was determined that two of these batteries would be used, bringing the total energy storage capacity of the UAV to 177.6Wh.

In order to conduct any further calculations with regard to how much time would be required for Condor's 64 cell PV array to recharge the batteries and to power the payload, the given GHI value had to be dissected further. As noted previously in this thesis, the GHI value given is simply an average for a TMY and would vary greatly depending on how many hours of daylight occur in a given period of time. The data obtained from NREL and the NSRDB database was broken down further and the average number of daylight hours per month was calculated for the six-month (May-October) operational timeframe, as seen in Table 4.

Table 4. Monthly Average Number of Sunlight Hours Each Day. Adapted from [11].

Month	Hours of Measureable Solar Insolation
May	12
June	14
July	14
August	14
September	12
October	11
Average	**12.8**

As can be seen from the table, an average of 12.8 hours of daily measurable solar insolation can be expected during the six month operational timeframe being considered. Again, to err on the side of caution and provide an added safety margin, this average was truncated down to 12 hours to give a more conservative estimate.

Finally, all relevant criteria and data was taken into account in order to determine the number of daylight hours that would be required to recharge the Condor's batteries, to run Condor's surveillance payload for 24 hours a day, and to run the surveillance payload constantly and recharge the batteries at the same time. The results from these calculations are found in Table 5, below.

Table 5. Theoretical Power Performance of Condor's PV Array

Criteria	Value	Units	Calculation
Total Battery Capacity (2x 4S3P)	**177.6**	Wh	88.8Wh x 2
Battery Capacity	12	Ah	
Battery Voltage	14.8	V	
Number of Solar Cells in Condor Array	**64**	cells	
Total Size of Solar Array	**0.17**	m^2	$0.0027m^2$ x 64
Number of Hours of Solar Insolation Per Day	**12**	hours	From Table 4
Usable GHI Expected For Each Hour of Sunlight	117.6	$Wh/m^2/h$	1411.2 $Wh/m^2/day$ / 12
Energy Required To Run Payload For 24 Hours	**216**	Wh	From Table 3
Energy Required To Charge Batteries And Run Payload	**393.6**	Wh	216 Wh + 177.6 Wh
Sun Needed to Recharge Batteries (Payload Off)	**8.9**	hours	177.6Wh / ($0.17m^2$ x $117.6Wh/m^2/h$)
Sun Needed to Run Payload for 24hrs (No battery recharging)	**10.8**	hours	216Wh / ($0.17m^2$ x $117.6Wh/m^2/h$)
Sun Needed to Run Payload and Fully Recharge Batteries	**19.7**	hours	393.6Wh / ($0.17m^2$ x $117.6Wh/m^2/h$)

The important takeaway from all of these calculations is that with 64 EMCORE BTJM solar cells in the proposed operational environment, Condor will theoretically be able to successfully capture and stream video surveillance continuously if its PV array is exposed to at least 10.8 hours of sunlight every day. Moreover, Condor will be able to recharge its batteries even quicker, with only 8.9 hours of sunlight, so that it will be able to remain mobile. It becomes obvious here that from a theoretical standpoint, taking into account that very conservative estimates were instituted at every juncture of the design considerations to account for the proverbial "worst-case scenario," in order to sufficiently charge the batteries for any extended flight, it would be prudent to institute an operational duty cycle; whereby the payload would be turned off for a certain length of time and all power production would be focused towards recharging the batteries. Such an arrangement would allow Condor to both be prepared to fly for an extended period of time, while also remaining ready to stream video surveillance as needed.

b. PV Array Assembly

In order to build the PV array, a number of 3D models were created in Solidworks to explore different form factors. The initial hasty design of Condor's PV array can be seen in Figure 12 and the final design can be seen in Figure 13.

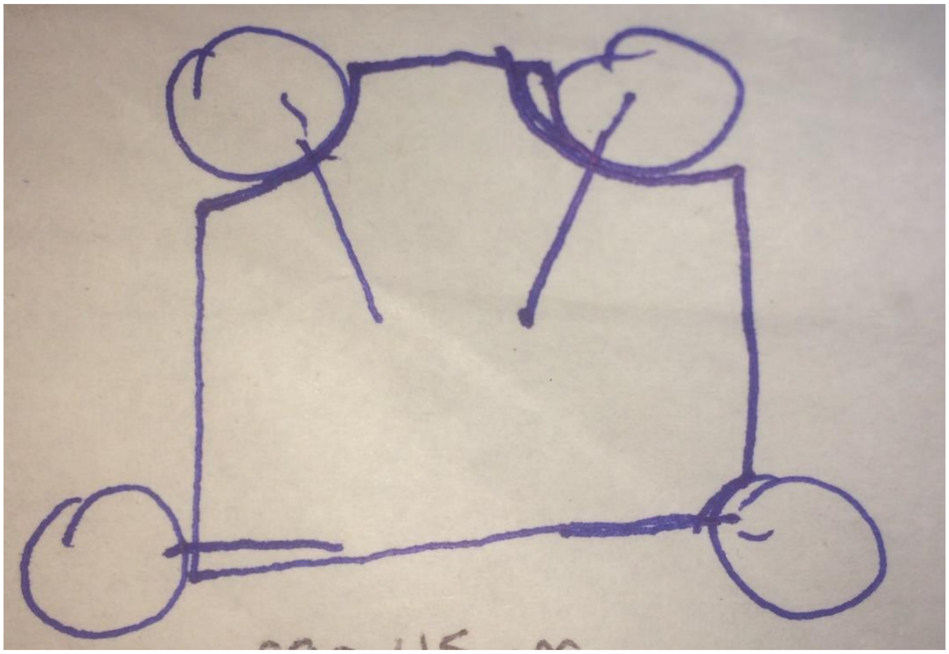

Figure 12. Condor PV Array Initial Sketch

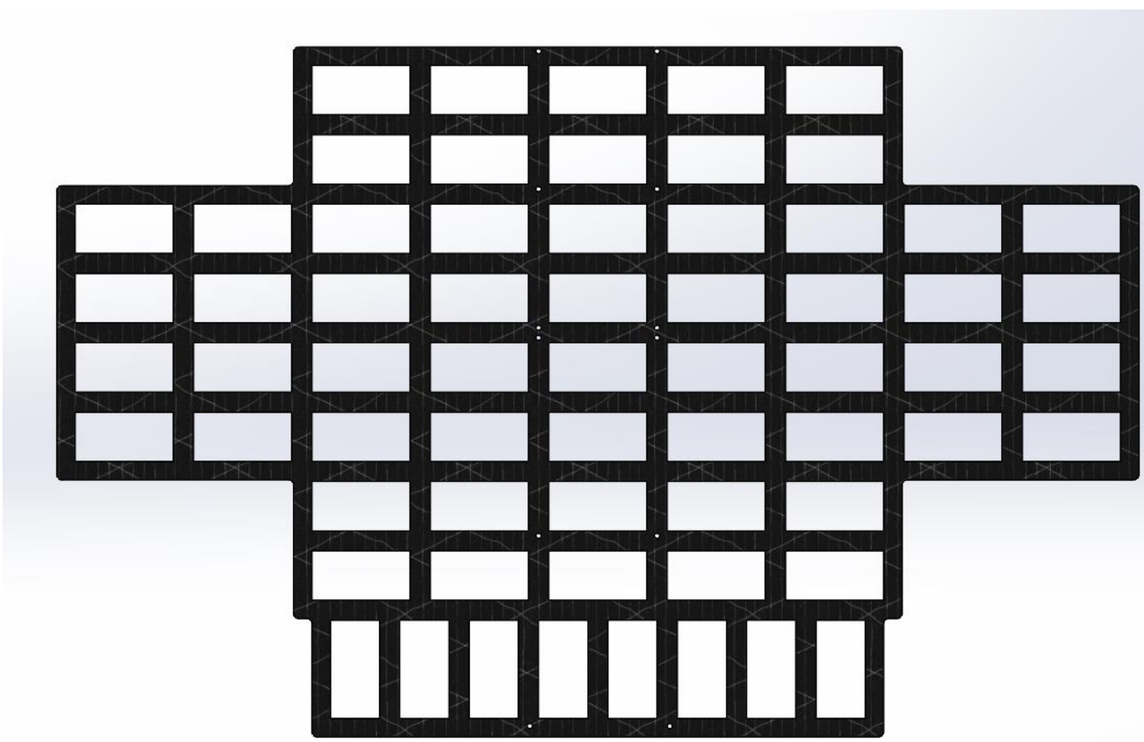

Figure 13. Condor PV Array Final Design

This design would allow for 16 strings of 4 solar cells per string. Each string of solar cells, in theory, would provide a VMP of 9.2V and an IMP of 0.43A at AM0, according to the EMCORE datasheets. The MPPT would try to capture the voltage and current at this MP location on the solar cell I-V curve. Once all 16 strings were connected in parallel, they should also provide a V_{MP} of 9.8V and an IMP of 6.88A. The actual amperage output of the array would turn out to be much less than this due to the fact that it was not operating at AM0.

The PV array design was then transferred from Solidworks to the NPS Machine Shop where it was cut out of a CNC router machine from 1/4” foam sandwiched by 3 layers of carbon fiber on each side, as seen in Figure 14. While the material used was already relatively lightweight, the back of the array was also routed out as much as possible in order to save extra weight. A slot was also routed above where each solar cell would eventually be emplaced in order to allow for wiring to pass through from the bottom of the array up to each solar cell connection tab. All told, the resulting array was both lightweight and rigid enough as to not bend or break during the stresses of flight.

Figure 14. Condor PV Array Being Cut on a CNC Machine

Because each solar cell is made of conductive material, it was necessary to insulate them from the carbon fiber PV array frame. This was accomplished by laying down strips of non-conductive Kapton tape along the entire top of the array, as seen in Figure 15.

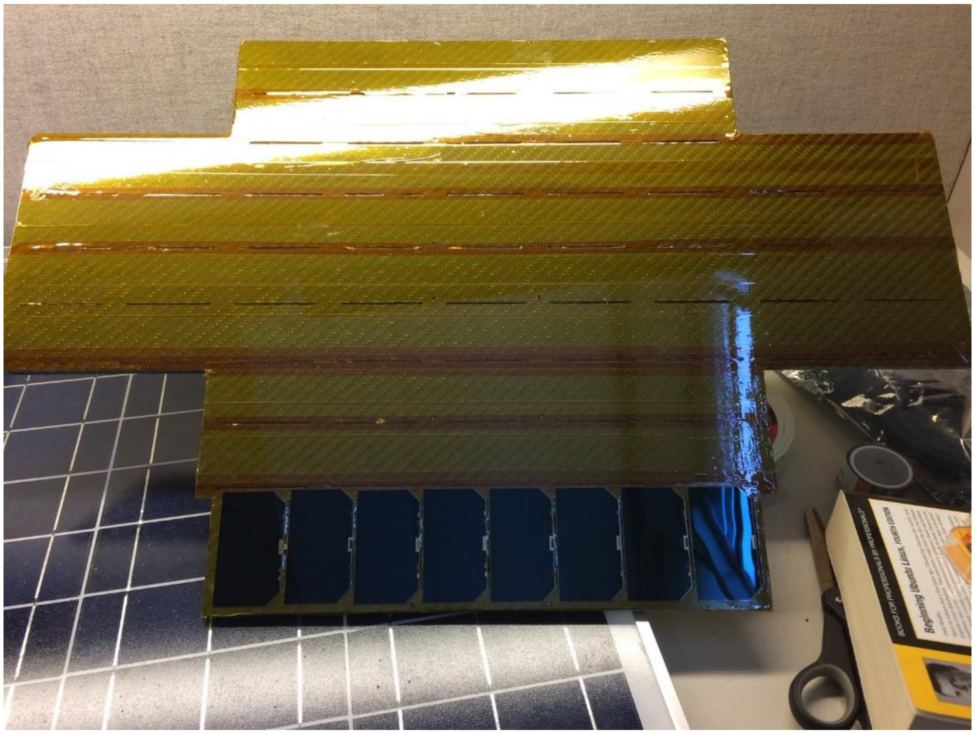

Figure 15. Insulating Kapton Tape Covering the Surface of Condor's PV Array

After applying the Kapton tape, each solar cell was then laid down in place, by hand, using a thin layer of welders cement brushed onto the array. The resulting array with all solar cells installed can be seen in Figure 16.

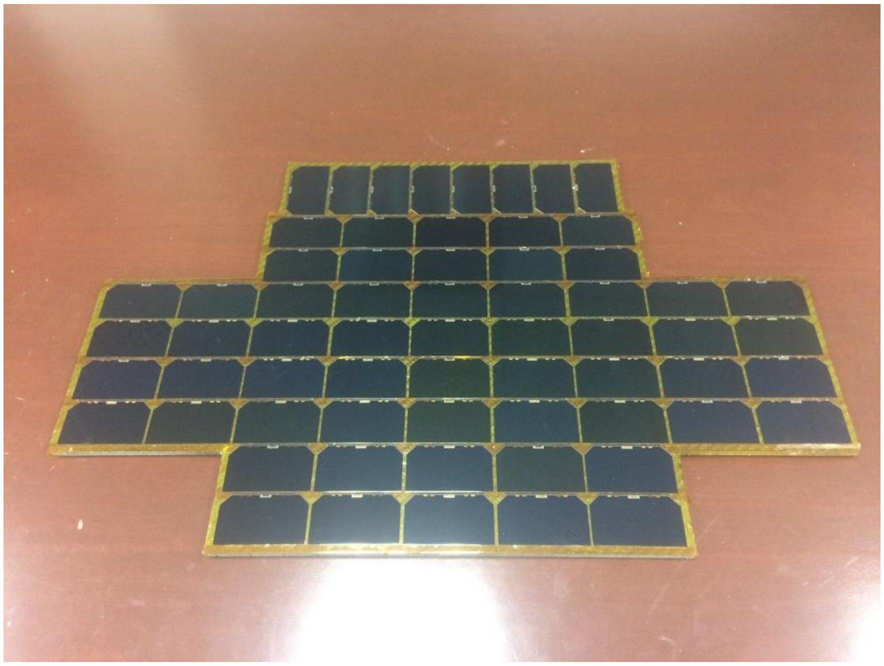

Figure 16. 64 Solar Cells Hand-Mounted on the Condor PV Array

The solar array was then wired together in the previously discussed fashion, 16 strings of solar cells connected in parallel, with each string consisting of 4 cells connected in series. A blocking diode was wired in between each string to prevent any backflow of electricity from any high output string to any low output string. The solar array would eventually be connected directly to the MPPT which would optimize the voltage and current output heading to the battery.

3. Vehicle Frame and Support Components

In order to provide torsional rigidity to the vehicle and prevent any warping during flight, it was decided that Condor should be designed with a two-layer sandwich construction. The upper and lower frames were each meticulously designed in Solidworks from scratch, as seen in Figures 17 and 18, and important considerations were given to the locations of all of the necessary electrical components, such as MPPT, GPS, gimbal, Pixhawk flight controller, and battery compartments as well as all the structural components such as motor mounts, frame supports, and screw holes.

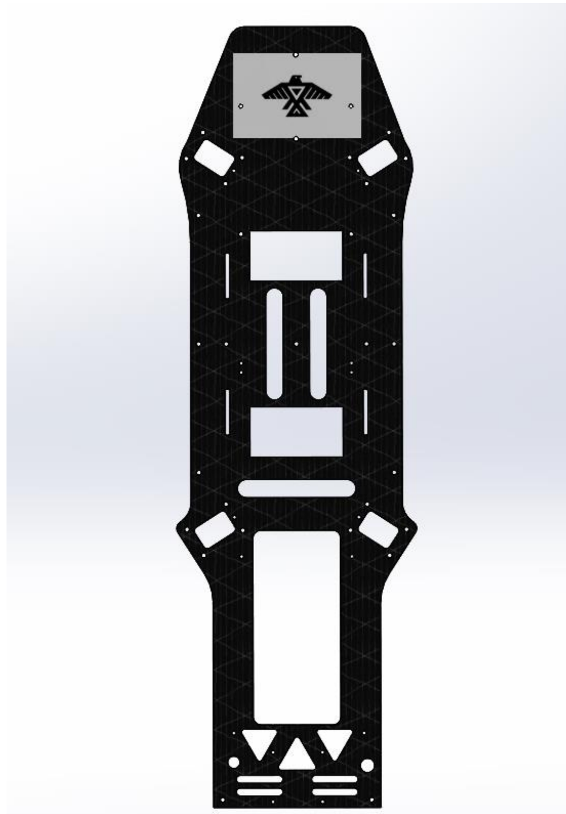

Figure 17. Condor Upper Frame Design

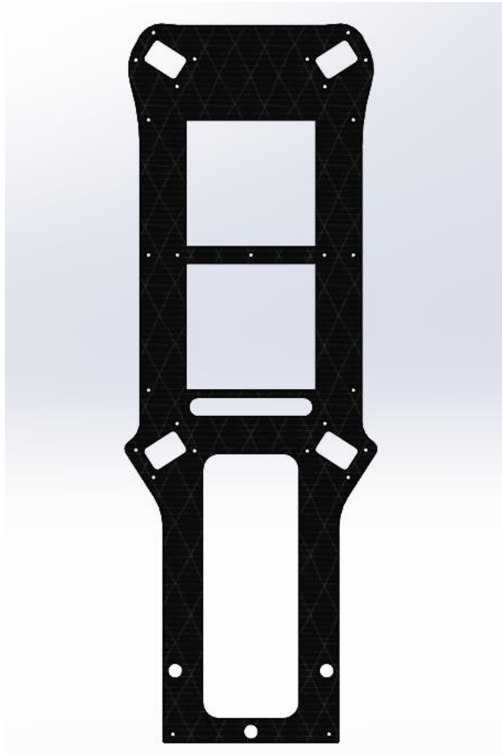

Figure 18. Condor Lower Frame Design with Battery Cutouts

The battery compartment design was of particular importance due to their relatively large weight. By designing the compartments in the center of the vehicle, it provided Condor with aerial stability. Also, by allowing the batteries to be hung from the upper frame via Velcro straps, as seen in Figure 19, this raised the center of gravity closer to the propeller line, which inherently improves in-flight stability. Both frames were then cut via a CNC machine from 1/16” thick carbon fiber, as seen in Figure 20.

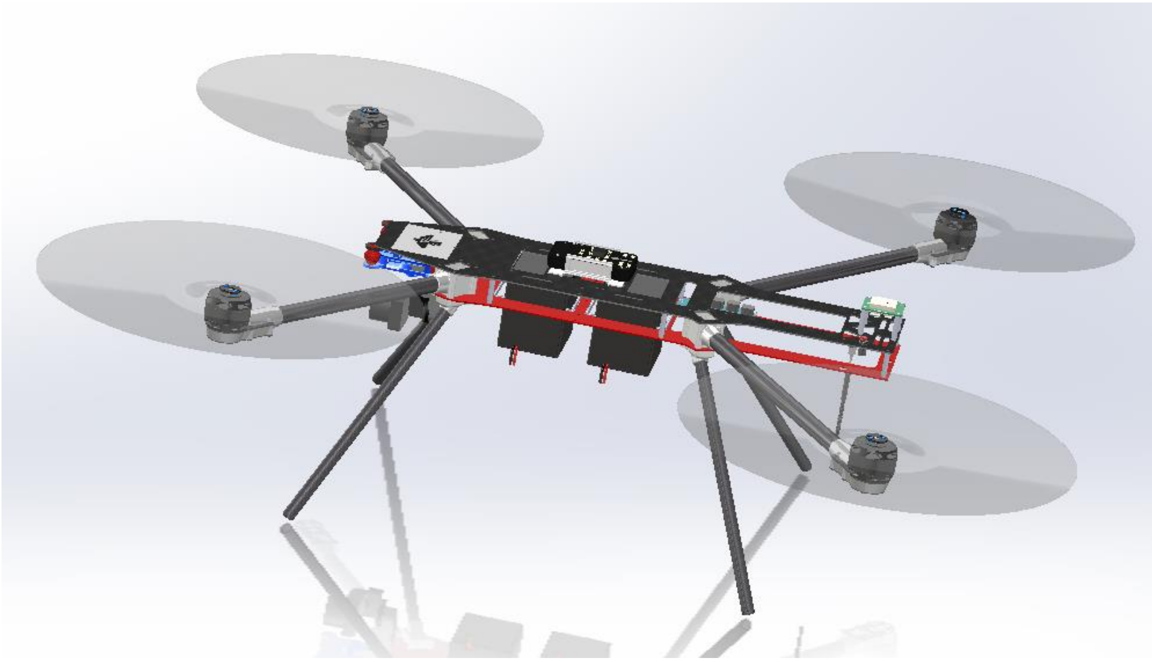

Figure 19. Condor Batteries Hung from the Upper Frame

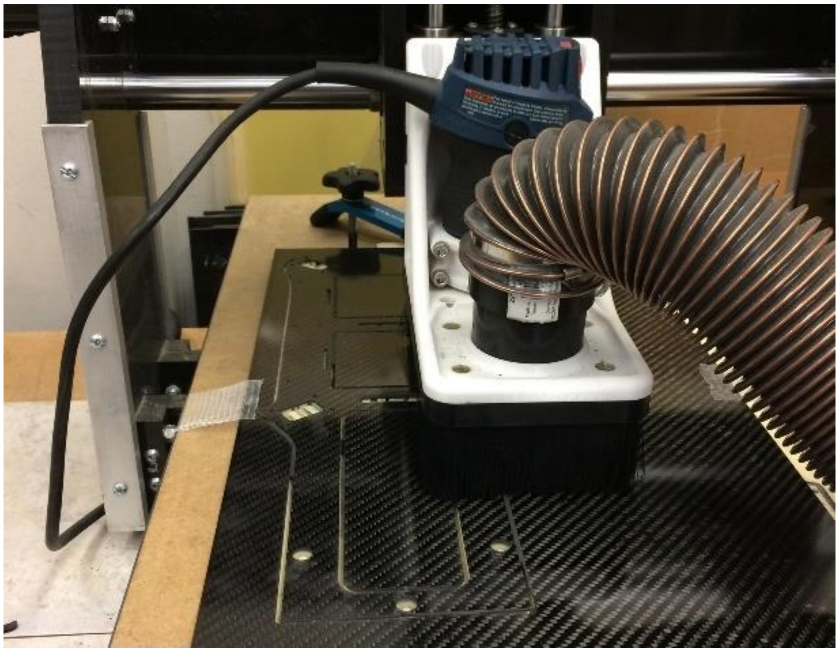

Figure 20. Condor Lower Frame Being Cut on CNC Router

Various other components of Condor needed to be created as well; the four dual-purpose frame supports/tubular arm holders, the two battery compartment snap-in supports, the four motor mounts, and the four landing gear supports were all created in Solidworks and 3D printed, as seen in Figure 21. Some of these components were created from scratch and others, such as the motor mounts and PIXHAWK mount, were generously provided by Dr. Kevin Jones from some of his previous research work.

Figure 21. Condor Parts Designed in Solidworks and 3D Printed

All told, almost every component of Condor, save for the wiring, screws, were assembled virtually in Solidworks prior to any physical construction of the quadcopter. This virtual assembly allowed Condor to be as weight conscious as possible, given the size of its PV array, and meant that different versions of Condor could easily be replicated in the future, should such a desire exist. The final Solidworks assembly of Condor as well is a blown up image of all its various components can be seen in Figures 22 and 23, respectively.

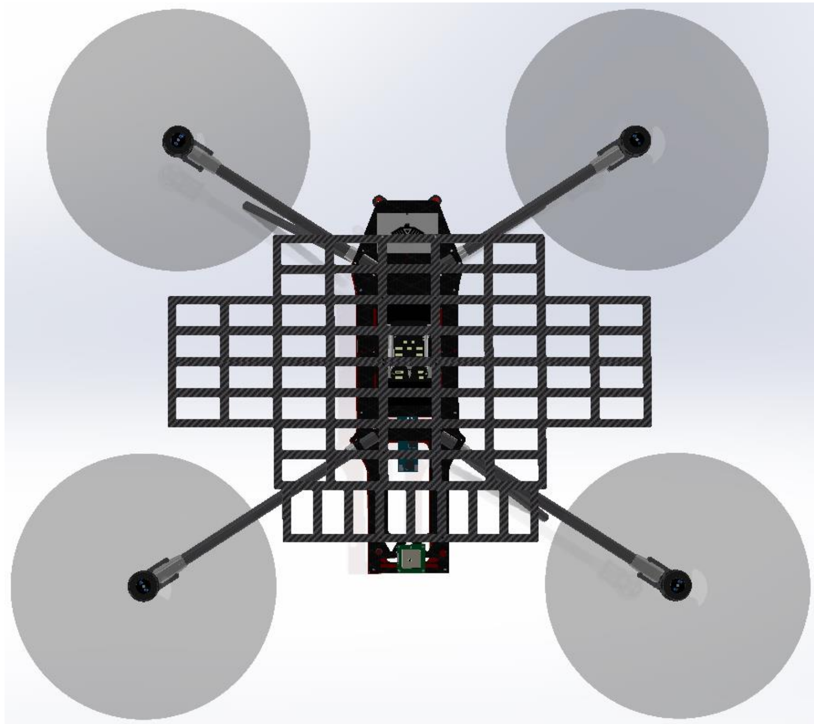

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Figure 22. Condor Fully Assembled in Solidworks

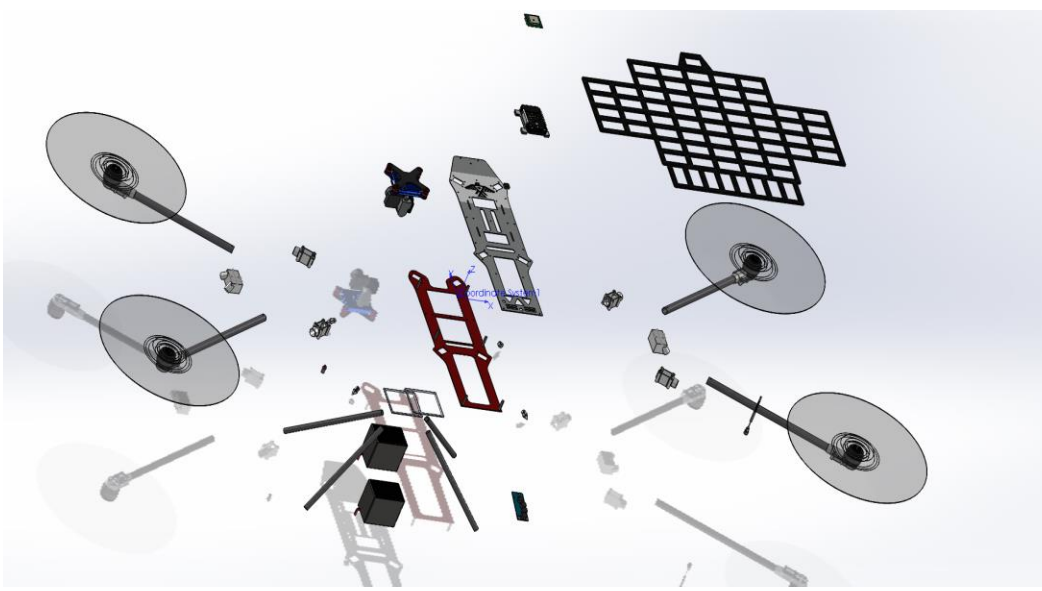

Figure 23. All Condor Components Used in the Virtual Model

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III. TESTING

In this chapter, the focus is on the actual qualitative and quantitative testing of Condor's PV array as well as ensuring the vehicle was capable of sustained flight and could meet the mission requirements of persistent surveillance with the onboard payload.

A. PV ARRAY TESTING

In order for Condor to be capable of meeting its mission requirement of persistent surveillance, the PV array and MPPT had to physically perform as theoretically advertised. In order to ensure both the ability of the PV array to capture solar energy and the ability of the MPPT to regulate the array output power and charge Condor's batteries, numerous tests were conducted outside in the Monterey sunlight. The PV array was positioned as normal to the incoming sunlight as possible in order to provide maximum solar insolation to the array. The output from the array was fed into the MPPT and the MPPT output was connected to a 4S3P battery, which was previously drained to 30% capacity. Two Fluke multi-meters, configured as a voltmeter and an ammeter, as well as an Astro Flight Inc. watt meter were all connected in line between the MPPT and battery to capture the voltage, current, and power being sent from the MPPT to the battery. This setup can be seen in Figure 24.

Figure 24. PV Array and MPPT Power Output Test Setup

In direct Monterey sunlight, the PV Array was successfully sending its electrical output to the MPPT and the MPPT was sending about 35W of power to charge Condor's batteries. It is also important to note that the MPPT was successfully regulating its volt and current output to match the current state of charge of the batteries. In order to ensure that the MPPT would act as a viable charge control and not overcharge the batteries, it was important to conduct another test near the 100% charge state of the batteries. Ideally, when the LiPo batteries approached close to full-charge, around 16.8 volts, the MPPT should begin drastically limiting the amount of current flowing into the batteries and instead slowly trickle charge the batteries to keep them at 100% charge, but not anything greater. A test scenario was set up in a similar manner. As can be seen from the ammeter and voltmeter readings in Figure 25, when the batteries reached their state of full-charge, 16.8V, the MPPT decreased the current flow to only 0.1A to trickle charge the batteries.

Figure 25. MPPT Trickle Charge Testing

With the PV array and MPPT optimally working to both charge the Condor's batteries to full capacity as well as prevent over-charging, it meant that the power generation system for Condor was functioning as expected. It then became possible to assemble the entire UAV and prepare it for actual flight testing.

B. FLIGHT TESTING

Because the intention of Condor was only to provide a proof-of-concept, the flight testing portion of the thesis was aimed only at ensuring that Condor was capable of stable and sustained flight with its functioning PV array attached. The first portion of the flight testing involved assembling Condor without the PV array attached and calibrating the PIXHAWK flight controller gain values to ensure 3-axis (roll, yaw, pitch) stability. Condor was assembled and numerous flights were conducted indoors, outside of any wind or weather-related destabilizing forces, as seen in Figures 26 and 27.

Figure 26. Condor Indoor Flight Setup

Figure 27. Condor Demonstrating Stable Flight Indoors

With Condor demonstrating the ability to maintain stable flight indoors without its PV array, the array was then attached and the same indoor flight tests were conducted as seen in Figures 28 and 29.

Figure 28. Condor Fully Assembled Indoor Flight Setup

Figure 29. Condor Fully Assembled Stable Flight Indoors Mission Planner GUI in View

Condor was again successful at maintaining stable flight indoors in its fully assembled configuration. The final step was to conduct an outdoor flight test and ensure that Condor was able to maintain stable flight and mitigate any perturbations from the wind.

The outdoor flight test was conducted on the NPS baseball field. An image from Condor's outdoor flight test can be seen in Figure 30.

Figure 30. Condor Outdoor Flight Testing in its Fully Assembled Configuration

Like all previous flight tests before, Condor was able to maintain stable flight and the onboard flight controller was able to easily mitigate any perturbations due to the minimal amount of wind that day. For all intents and purposes, this test flight demonstrated a fully mission-capable platform that met all operational requirements.

C. DETECTABILITY

One important aspect of any UAV that is used in any surveillance role is the question of whether or not the platform can be detected by the enemy. Sometimes it is advantageous to a unit to deploy a loud or large surveillance platform, which is easily detectable. In this sense, the platform acts as a deterrent rather than a surreptitious collection platform. Oftentimes, especially in a surveillance capacity, it is preferred to have a platform which can conduct collection and remain completely undetected by the enemy. This is where the perch-capable nature of Condor really shines.

Because of its small size, Condor can be easily flown into an area under the cover of darkness and land in a location which provides a certain degree of stand-off from the target location. Unless the enemy is actively scouring the environment for the platform, it can easily remain unnoticed. A virtual representation of this can be seen in Figure 31. In this image, generated in Solidworks, the fully assembled Condor platform was placed on top of a building off in the distance. The platform is still exposed to the sun, allowing its batteries to maintain charge, but is also in the direct line of sight of the viewpoint location.

Figure 31. Virtual Representation of Condor's Perch Capabilities in an Urban Environment

While the prototype developed in this thesis only utilized a simple GoPro camera as its imaging payload, it can easily be understood how the employment of a more powerful camera, possibly with optical zoom capabilities, would provide even further standoff and greatly enhance Condor’s ability to operate undetected by the enemy.

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IV. CONCLUSION AND FUTURE WORK

This thesis proved successful in designing, constructing, and testing of a persistent surveillance capable unmanned aerial vehicle that was proven to be capable of persistent ISR and met all operational requirements. The true innovation captured in this thesis lies in the utilization of the photovoltaic array for all power generation needs as well as the unique employment of an operational duty cycle where the platform is allowed to continue surveillance duties in a perched configuration while recharging its batteries. At an estimated cost of around $2000 for parts, and a weight of around 2 kg, Condor is both cheap and lightweight. On the battlefield, Condor can be operated organically by a small unit and be available at virtually all times to help meet the operational needs of that unit, without having to compete with other deployed units for control of surveillance assets. Given the hypothetical operational constraints of the Afghanistan scenario, Condor has proven that it can successfully meet the mission requirements and fill a niche gap in current organic UAV capabilities on the battlefield.

Should the operational environment change, Condor’s configuration can also adapt and be redesigned or modified to meet the unique constraints of the new environment. This is where employment of cheap COTS parts as well as the utilization of 3D printed components really becomes crucial. Pre-deployment site surveys of deployment environments can easily be conducted prior to the embarkation of the unit and a specific version of Condor can be constructed to operate optimally given the weather and solar insolation characteristics of that specific environment.

A. ENDURANCE

Further endeavors can be undertaken to better capture and understand Condor’s endurance capabilities. Extensive testing can be done to build specific datasets that outline exactly how long it takes for Condor to recharge its batteries. Due to the immense distance between Monterey, where the platform was constructed, and Afghanistan, where Condor was designed to be operated, actual testing in the expected operational environment was simply not possible. Also, further testing could be conducted to find the most efficient form factor for Condor; one which provides the greatest inflight endurance and agility while maximizing the array's ability to capture as much solar energy as possible. For instance, a mechanically foldable array would provide the platform with the ability to stow the array for better flight performance and unfurl the array upon landing to capture the maximum amount of solar insolation.

During this thesis, quantitative testing was conducted to determine the best motor and propeller combination, from those already available in the laboratory, to maximize efficiency. However, it was deemed that the discussion of these factors was simply too tangential to the scope of this thesis.

B. POWER GENERATION

Future versions of Condor could greatly benefit from further research into the power generation aspects of the platform, including the solar array as well as the MPPT. The solar array would be modified with more efficient solar cells or a steerable array could be implemented on the platform to track the sun and maximize its power generation capabilities. Solar cells exhibiting efficiencies around 38% are currently commercially available and the incorporation of these cells into Condor would both greatly enhance the speed of the recharge cycle or would allow the PV array size to be dramatically decreased. In addition to these endeavors, studies could also be conducted to determine if the MPPT utilized on Condor could be modified or redesigned to improve upon its current limitation of 90% efficiency.

C. WEAPONIZATION

An interesting capability of some UAV's is their ability to actively engage the enemy with ordinance. While that endeavor was beyond the scope of this thesis, further work could be conducted to modify Condor and give it the capability to not only surveil the enemy, but also deploy some type of kinetic strike to neutralize a threat. Along those same lines, additional sensors could be implemented to give Condor anti-tampering capabilities, so that if the platform should happen to be left in the field or captured by the enemy, it would not be able to be repurposed and used against friendly forces.

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