UNDERGRADUATE PROJECT: DEVELOPMENT OF SOLAR-POWERED UNMANNED AERIAL SYSTEM (UAS)

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DEVELOPMENT OF SOLAR-POWERED UNMANNED AERIAL SYSTEM

LEONG JOE YEE

A thesis submitted in fulfilment of the
requirements for the award of the degree of
Bachelor of Mechanical Engineering (Aeronautics)

School of Mechanical Engineering
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LIST OF ABBREVIATIONS

UAS	-	Unmanned Aerial System
UAV	-	Unmanned Aerial Vehicle
EU	-	European Union
PV	-	Photovoltaic
Li-Po	-	Lithium Polymer
NASA	-	National Aeronautics and Space Administration
HALE		High Altitude Long Endurance
VTOL	-	Vertical Take-Off Landing
UTM	-	Universiti Teknologi Malaysia
ESC	-	Electronic Speed Controller
GPS	-	Global Positioning System
MPPT	-	Maximum Power Point Tracker
DC	-	Direct current
STC	-	Standard Test Condition
MH45	-	Martin Hepperle MH 45
RPM	-	Revolutions per minute

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CHAPTER 1

INTRODUCTION

1.1 Project Aim

To develop a Solar-Powered Unmanned Aerial System for research purposes.

1.2 Background study

Defination and Components of UAS

According to Regulation (EU) 2019/945, Unmanned Aerial System (UAS) is defined as the unmanned aerial vehicle (UAV) and the equipment to control the aircraft remotely. The equipment can be any instrument, mechanism, apparatus, software or accessory that is necessary for the safe operation of a UAV. In general, an UAS has three components:

i. An autonomous or human-operated control system
ii. An UAV
iii. A command and control system to link the two.

Defination and Application of UAV

One of the critical components in the UAS is the UAV. An unmanned aerial vehicle (UAV) is a flying robot, in other words can be defined as vehicles that operating on air autonomously or controlled telemetrically with no pilot on board. (Boukoberinea, Zhoub, & Benbouzid, 2019) UAVs have received great interest and a lot of research on UAV has been conducted since the past decades. They are widely used in several applications in both military and civil domains, such as minesweeping, monitoring, delivery, wireless coverage, and agriculture uses.

Concept of Solar-powered fixed wing UAVs

In recent years, one of the active research area is the use of photovoltaic (PV) power system as alternative energy source for fixed wing UAV. Solar-powered fixed wing UAVs promised significantly increased flight endurance over purely electrically or even gas-powered UAV. (Philipp, et al., 2017) (Morton, D'Sa, & Papanikolopoulos, 2015) The solar power is obtained from the PV cells is then available to propel the motor, power the electronics components, and recharge the batteries. (Morton, D'Sa, & Papanikolopoulos, 2015)

1.3 Project Background

Project focus

A solar-powered hand-launched, fixed wing UAV is designed in this project. Optimization of the solar energy obtained is the prior study in this project, therefore the arrangement of PV cells and choosing the correct specifications of electronics components played important role. A lightweight and good aerodynamics characteristics design of the UAV can helped to reduced drag and produced higher efficiency, thus the study of weight and aerodynamics characteristics of this solar-powered UAV is part of this project as well. The application of this solar-powered UAV includes surveillances, agriculture and forestry, search and rescue, as well as military related operations.

1.4 Problem Identification

The problem statements of the project are:

harness of solar energy & factors reduce the efficiency of PV cells

a) Challenge on the harness of solar energy due to the low power output efficiency of the PV cells, which are approximately of 20%. There are few main factors that can reduce the efficiency of PV cells, which are the sun's angle of incidence, operating temperature and sun's intensity.

Challenge on maintain constant power supply

b) Challenge to maintain a constant power supply to the load and battery. Also, integrated PV power system results in extra weight, also possibly increasing drag due to the installation of PV cells on wing. Thus, the the PV power system must design such that power generated is sufficient to maintain a steady flight of UAV.

1.5 Project Objectives

The objectives of the project are:

Develop methodology for PV system design

i. To develop a set of methodology for a PV power system design on UAV. Propose a PV panels arrangement, do the set up on UAV. The power generated from PV panels is dependent on the arrangement of the PV panels. The selection of PV panels and respective components are based on their weight and specifications.

Perform analysis and performance data collection on solar-powered UAV

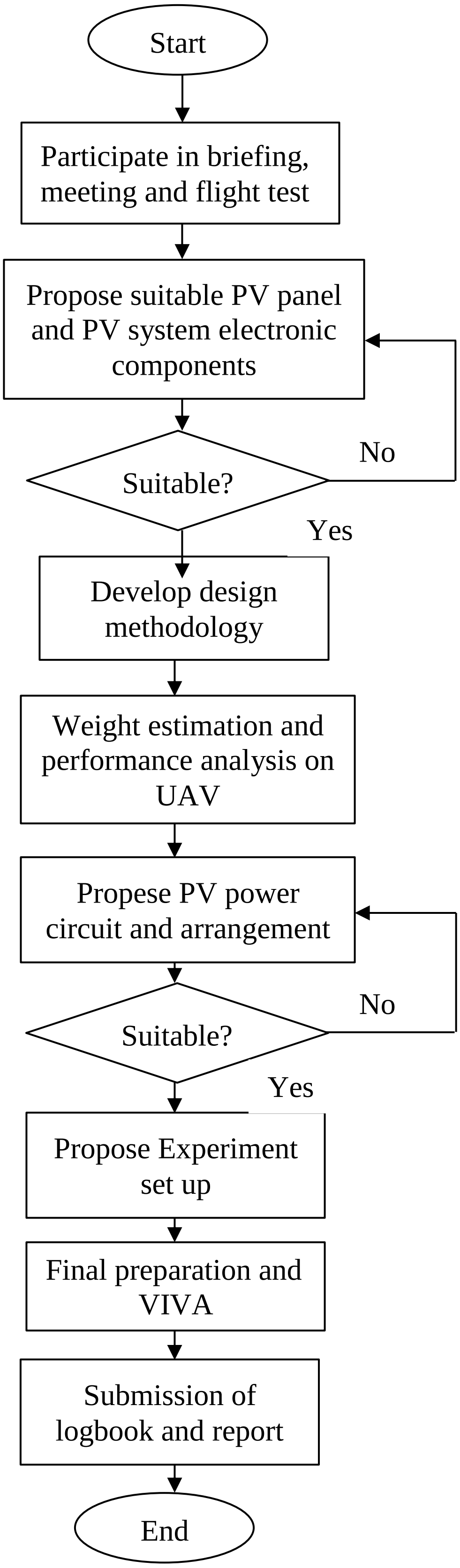
ii. To perform parametric analysis and performance data collection on solar-powered UAV. Also, perform analysis to determine the best angle of incidence, operating temperature and sunray intensity for optimization power generation from PV power system. The power generated should be able to maintain a steady flight of UAV.

1.6 Project Scope

Scope of project

There are few scopes in this project. The UAV is a hand launched, low altitude solar-powered UAV. The design of the UAV should be a light weight, plank flying wing aircraft. The monocrystalline silicon cells are arranged in series on the wing, as the main and only power source. The power generated from PV cells will only support the weight of UAV up to 1.2kg only. The weight includes the airframe, payload, PV cells, electronic parts and rechargeable Li-Po battery.

1.7 Project Planning



CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

In this chapter, first it begins with the history overview of solar-powered aircraft, followed by the types and categories of UAV, the principle of photovoltaic power system and its respective electronic component.

2.2 History of solar-powered aircraft

Revolution of Photovoltaic (PV) technology, launch of Nimbus

Solar-powered airplane is no longer a newly introduced technology, but can be traced back in the 1970s. A comprehensive historical overview of solar-powered airplane is referred on Abbe & Smith (2016). By 1839, experiments by Edmund Becquerel had discovered that exposure of electrolytic cells to lightning can led to electricity generation, which also can called as the Photovoltaic Effect. In 1945, Daryl Chapin, Calvin Fuller, and Gerald Pearson have announced their discovery and development of Photovoltaic (PV) technology in the United States. The silicon PV cell proposed was capable to convert solar energy to domestic electrical energy. This technology has been firstly applied on the satellites systems, where the Nimbus satellite was launched by the National Aeronautics and Space Administration (NASA) and powered by a 470W solar array in 1964.

Details of Sunrise I & subsequent solar a/c design

On November 4, 1974, the first solar powered aircraft, named Sunrise I, was built and flown. The aircraft is designed by Astro Flight Inc, which equipped with 4096 PV cells of 11% efficiency. It weighed about 12kg and it flew about 20min at an altitude of 100m before crashing in a sandstorm. The successful of Sunrise I has led to the development of Sunrise II and Solaris, which both capable to perform at a higher efficiency than Sunrise I.

Details of Gosammer Penguin, Solar Challenger & subsequent solar a/c design

In 1980, solar powered aircraft technology enter another milestone when the Gossamer Penguin by Dr. Paul Mac-ready is developed and flown. It was the first manned solar aircraft to demonstrate flight. Then, Dr Paul continued his invention in the following year by building the Solar Challenger. The aircraft flew with over 16,000 solar cells mounted on its wings which produced 2500W of power with no energy storage devices. Further efforts subsequently led to the improvement design such as Solair I by Gunter Rochelt, the Sunseeker by Eric Raymond, Icare 2 by Prof. Rudolf Voit-Nitschmann, Solair II in 1998 by Prof. Gunter Rochelt and O Sole Mio by Dr. Antonio Bubbico.

Figure 2.1: The Gosammer Penguin

Notoble designs of modern solar-powered UAV

Some of the modern solar-powered UAV that attracted the attention of researchers and publics includes the Pathfinder in 1995, Pathfinder Plus in 1998, Centurion, Helios in 2001 by NASA Environmental Research Aircraft Sensor Technology (ERAST) program as well as Solong in 2005 by Alan Cocconi. These aircrafts capable to perform long endurance perpetual flight at altitude about 96,000 ft above sea level.

Details of Solar Impulse

In 2003, Betrand Piccard and Andre Borschberg started their development of manned Solar Impulse, which targeted to circumnavigate around the globe using only solar power. (Hartney, 2011) After few years of hard work, finally in July 8, 2010, the

Solar Impulse has achieved flight duration of 26 hours at a maximum of 28,600 ft above sea level. These are some of the notable achievement in the design of high altitude, long endurance (HALE) solar-powered aircrafts, which proved that solar-powered aircrafts has now equipped with advanced technology, which capable to do perpetual flight across seasons and latitudes, at the same time carry significant amount of payloads.

2.3 Classifications of UAV

Introduction and classification of UAV

While a variety of definitions of the term Unmanned Aerial Vehicle (UAV) have been suggested, this paper will use the definition suggested by (Singhal, Bansod, & Mathew, 2018), who defined it as a remotely operated aircraft, that has no pilot onboard and able to be operated autonomously or through remote pilot control. Due to technological advancements, modern UAV have different features and configurations which vary widely based on their mission and purposes requirements. Various types of classifications can be found in the literature focusing on different parameters. However, in this section, we focus on the classifications of UAVs according to the configurations of UAV, mass, range, flight altitude and endurance of UAV and lastly application of UAV.

2.3.1 Based on configurations of UAV

Introduction to 4 types of UAV

The main types of UAV includes the fixed wing systems, multirotor systems, single rotor helicopter systems and Hybrid system. Each of these systems has own characteristics, as well as advantages and drawbacks.

Pros and cons of fixed wing system

Fixed wing systems utilize fixed, static wings in combination with forward airspeed to generate lift force. The velocity and steeper angle of air flowing over the fixed wings controls the lift produced. (Singhal, Bansod, & Mathew, 2018) The good thing is most fixed wing UAV have an average flying time of a couple of hours, which make it ideal for mapping and surveillance. Besides, it is cheaper in manufacturing and has higher fuel efficiency. The downsides of fixed wing UAV is its inability to hover at a spot, which make it not suitable for general aerial photography work. Then, require skills and a big area to fly fixed wing UAV, also a lot of practices to control it from launching, cruising and then bring it back to a soft landing.

Pros and cons of multirotor system

Multirotor system equipped with two or more small rotors, to generate thrust for both lifting and propelling. (Singhal, Bansod, & Mathew, 2018) For instance, tricopter, quadcopter, hexacopter and octocopter are normally referred to three, four, six and eight rotor rotorcraft respectively. The strengths of multirotor UAV are easy vertical take-off and landing (VTOL), able to to maintain the speed and perform static hovering at a place. The great control over position and framing makes it perfect for small scale aerial photography work, surveillance purpose and monitoring. However, the concern with multirotors is that large portion of energy go to fight gravity and maintain stable in the air. Therefore, multirotor UAV has limited flying time, limited endurance and speed, thus not suitable for large scale aerial mapping, long endurance monitoring and long distance inspection such as pipelines, roads and power lines. (Chapman, 2019)

Pros and cons of single rotor system

For single rotor system, the structure of is relatively more direct and simple, with just one rotor to generate thrust, and a tail rotor to control its heading. (Carholt, Andrikopoulos, & Nikolakopoulos, 2016) identify the advantages of single rotor UAV when compared to multirotor system is less complex in structure, where there is no gearbox, less motors, thus less points of failure and a more economical solution. Also, a ducted propeller leads to a higher efficiency. However, A number of research articles such as (Tahir, Böling, Haghbayan, T.Toivonen, & Plosila, 2019) has countered the statement saying that, single rotor UAVs have more mechanical complexity and operational risks such as vibration and large rotating blades. Therefore, they are costly. Also, (Chapman, 2019) provided another statement to support why single rotor is more efficient. It is because aerodynamically that the larger the rotor blade is and the slower it spins, the higher the efficiency. This is why a quad-copter is more efficient than an octo-copter, and special long-endurance quads have a large prop diameter.

Pros and cons of Hybrid system

Hybrid systems are the combination of automation and manual gliding. Hybrid systems designed with the characteristics of both fixed wing and multirotor systems. For example, hybrid quadcopter uses multiple rotors to take-off and land vertically but also has wings achieve longer endurance and flying time. (Vergouw, Nagel, Bondt, & Custers, 2016) However, the technology of Hybrid UAV system is still under development, which expected to be more advances with the arrival of modern equipment such as autopilots, gyros and accelerometers.

2.3.2 Based on mass, range flight altitude and endurance of UAV

categories of UAV

Room & Ahmad (2014) is used as reference here to evaluate and group the UAVs based on range, mass, flight altitude and endurance. Table 1 shows the categories of every group of UAV with its respective description. There are 5 categories of UAV, which are micro, mini, close range, medium range and high altitude long endurance (HALE). Each categories has given an example of aircraft, which shown in the table below.

Table 2.1: Categories of UAV

Category Name	Mass (kg)	Range (km)	Flight altitude (km)	Endurance (hours)	UAV
Micro	<5	<10	<250	1	Israeli IAI Malat Mosquito
Mini	<25/30/ 150	<10	150/250/300	<2	RQ-11 Raven by US Aero Vironment
Close range	25-150	10-30	3000	2-4	the Optimus
Medium range	50-250	30-70	3000	3-6	Israel Aeronautics Defense Dominator
HALE	>250		>3000	>6	Phantom Eye

2.3.3 Based on UAV applications

2.3.3.1 Survey and Monitoring

Application of UAV in survey & monitoring

Versatile and low-cost UAVs have been utilized in aerial surveys, for monitoring purposes, in numerous fields such as traffic controls, geophysics and agriculture. For example, surveillance of a facility or environment might require updates of every movement detected after office hours. (Tahir, Böling, Haghbayan, T.Toivonen, & Plosila, 2019) Also, appropriate image processing operators or software are used to extract valuable data about the state of the agricultures and health information such as moisture and soil properties. Then, UAVs help in continuously collect data in real-time about roads and traffic conditions and transfer information to the monitoring center. (Boukoberinea, Zhoub, & Benbouzid, 2019)

2.3.3.2 Environmental Mapping

Application of UAV in environmental mapping

Recently, governments and researchers from all around the globe, are in continuous interest on the environmental issues regarding the climate changes and their impacts. Periodic measures are conducted on top of volcanoes, mountains, rivers, seas, and even in the atmosphere and continuous data needed to be taken for analysis. In this case, UAVs are then used a lot to collect samples due to their dynamic characteristics. Also, civil protection institutions are using UAVs to accurately monitor water resources before, during, and after flood occurs, which then help in preparing a flood damage control plan. (Boukoberinea, Zhoub, & Benbouzid, 2019)

2.3.3.3 Military Surveillance

Application of UAV in military surveliance

UAVs have traditionally been restricted only in military surveillance missions, which then extend to civil sector afterwards. (Tahir, Böling, Haghbayan, T.Toivonen, & Plosila, 2019) The applications of UAVs in military sector are included radio and data relay, artillery guidance, transport of equipment and supplies, borders surveillance, communication disruptors and electronic warfare, maritime operations (anti-ship missile defense, naval fire support, over the horizon targeting), reconnaissance flights and minesweeping raking. (Boukoberinea, Zhoub, & Benbouzid, 2019)

2.4 Plank Flying Wings UAV with Winglet

Defination and history of plank flying wing

The term plank is generally understood to be mean as an unswept wing, while flying wings is defined as tailless fixed-wing aircraft that has no definite fuselage. The idea of a true flying-wing aircraft originated in Europe. Experiments by Otto Lilienthal. (Schwader, 1997) After study on different types the UAV, I decide that the configuration used is a plank flying wing UAV. Miligan (2000) has pointed out the major advantages and drawback of a plank flying wing. (Milligan, 2000)

Advantage of plank flying wing

The chief reason of why the flying wing is chosen is because of its lower drag coefficient. Since a pure plank flying wing possesses no fuselage and no horizontal tail surface, it may be possible to achieve very low zero-lift drag coefficient. Due to the lack of tail surfaces, the glider will have a lower weight, and hence the wing loading will be reduced. Because the wing loading is reduced, the bending moments on the wing will be less, and hence less structure will be needed to maintain wing strength and integrity. Besides, weight is one of the main concern when building a solar-powered aircraft as solar panels will be attached on the wing surfaces afterwards, which contribute to additional overall weight of aircraft.

Drawback of plank flying wing

The drawback of a plank flying wing is that a typical cambered wing is aerodynamically unstable and hard to achieve longitudinal stability. Therefore, the stability can be improved by two ways. Firstly, a weighted boom can be added to the front of the glider so that the center of gravity is ahead of the aerodynamic center. This would satisfy the first condition of a stable airfoil section. The second way is by adjusting the airfoil to a reflexed airfoil where the trailing edge has been turned upward reflex airfoil gives a stable center-of-pressure travel over the whole useful range of incidences.

Concept, type and advantages of winglet

Winglet is defined as a wing tip extension that helps in reducing the wingtip vortex. The vortices are formed by the difference between the pressure on the upper and lower surface of an airplane's wing, causing sideways airflow motion by the wingtip. These vortices effect is unwanted because it created downwash of the flow stream at the wing tip, which lead to induced drag. Therefore, winglets are designed to reduce the vortex , cut off the sideways airflow, thus reduce induced drag. There are various winglets available in UAV industries, for examples the blended sharklets and Spiroid winglets. In this project, the Sharklets wingtip fence design is chosen as they are suited for low speed flying aircraft, and are easy to manufacture. (Dagur, Singh, Grover, & Sethi, 2018)

Figure 2.2: Plank Flying Wing

2.5 Electronic Components in Solar Powered UAV

Main components in RC airplanes

The electronics components in the solar powered UAV are included the battery, brushless motor with propeller, electronic speed controller (ESC), servo, receiver and flight controller, power module, GPS tracking device and telemetry.

2.5.1 Electronic Speed Controller (ESC)

Usage of ESC

An electronic speed controller or ESC is an electronic circuit which use to control an electric motor's speed, its direction and also function as a dynamic brake. (Corrigan, 2019) It converts DC battery power to a 3-phase AC in order to drive the brushless motors.

2.5.2 Brushless motor with propeller

Usage & structure of brushless motor

The main function of a brushless motor is to spin the propeller, which then the propeller will generate thrust which make the UAV move forwards. Generally, brushless motor contains a bunch of electromagnets (coils) which connected together in specific pairs. The motor controller, normally ESC activating and deactivating specific sections of electromagnets in the motor at every specific period to cause the rotor of the motor to spin due to the electromagnetic force. These electromagnets are connected into three main sections which is why all brushless motors have 3 wires coming out of them. (Sam, 2014) There are two main components in a brushless motors, which is the rotor that rotated and consists of magnets that mounted in a radial position, also the stator part that does not rotate, and consists of coils.

Usage of propeller

A propeller consists of radiating blades that are set at a pitch. When the motor rotates, the rotational motion of the blades is converted into thrust due to pressure difference between the two surfaces.

2.5.3 Battery

Usage and type of battery

The battery function as energy storage device in a soalr-power airplane. In general, some requirements for UAV batteries include high energy/weight ratio, high discharge rates, resilience to shock and vibration, and fuel gauging to indicate remaining mission time. (VanZwol, 2017) The common battery used on UAVs are the Lithium-ion (Li-ion) battery and Lithium Polymer (Li-Po) cell. In this project, the type of battery selected is the Li-Po battery, as this battery can be customized into different sizes according to the power required by the airplane. A light-weight solar-powered UAV do not required a high power, thus Li-Po battery with 2s (7.4 volt) is sufficient.

2.5.4 Servo

Usage of servo

Servos or actuators are one of the critical components for the operation of UAV because they provide the ability to move control surfaces. This movement is on the servo will only move as much as the transmitter stick on your radio is moved.

2.5.5 Receiver

Usage of receiver

In UAS, the radio control (RC) system is consists of two important elements, the transmitter from ground control station and the receiver that attached on the UAV. In simple, receiver collects input data from transmitter in near real time. Then, the information will pass to the UAV's flight controller which makes the electronic system react accordingly. (Drone Transmitter and Receiver – Radio Control System Guide, 2015)

2.5.6 Power Module

Usage of power module

An analog power module is installed in the UAV to converts the battery voltage to a stable power supply of approximate 5V to the flight controller. Besides, it also supports in measuring the battery voltage and current consumption, so that we won't overuse our battery, which can deteriorate the performance of rechargable battery. (Common Power Module, 2019)

2.5.7 Flight controller

Components and Usage of Flight controller

The flight control system is always described as the heart of UAS. Elements on the ground is the Ground Control Station (GCS), while elements on board the aircraft is the flight controller which include the autopilot, a datalink for communicating with the GCS, and peripherals such as accelerometer, gyrometer, magnetometer and barometer. (Flight Control Systems for Unmanned Aerial Vehicles, Drones and Remotely Piloted Aircraft Systems, 2019) The flight controller collects all data received from GCS and calculates the suitable commands to ESC so that the UAV will react accordingly.

2.6 Telemetry and GPS module

Usage of telemetry

Both Telemetry and GPS module are working close with the flight controller. A radio telemetry is crucial as it allows users to establish a telemetry connection between the UAV and the ground control system. The telemetry has the ability to collect data at specify altitude and flight condition and transmit automatically to the ground control system for monitoring purposes. The ideal radio telemetry should be lightweight, economical, and the open source radio platform that can extend to several kilometers.

Usage of GPS module

The GPS module are commonly installed on most UAV, while mainly is for navigation purposes. The GPS module transmit information such as location and altitude information to the GCS, thus allows the user to track the UAV location precisely, and steer the UAV. (Using UAV GPS, 2019)

2.7 Photovoltaic Power System

Defination and component of photovoltaic power system

According to Patel (1999), the photovoltaic effect is defined as the electrical potential produced between two p-type and n-type materials when their common junction is illuminated with radiation of light ray photons. The photovoltaic cell that presence in the solar panel, thus converts light energy into electrical energy. In an UAV, the photovoltaic power system has simple configuration which consists of few main components. Firstly, the PV cells to convert sun ray into electrical energy. Then, the battery act as the energy storage device. Also, the MPPT, also known as charge controller to regulate the voltage by preventing excessive discharge and overcharge of battery.

2.7.1 PV Panels

working principle of solar panel

The working principle of PV panel is very straightforward. When solar spectrum strikes the silicon atoms at the junction, the electron leaves the cell, creates electrons and holes as charge carriers, which caused a potential difference as well, where current then start to flow to cancel out the potential. The electron will move to p-type layer, while the holes to n-type junction. When a circuit is made, the free electrons from p-type, pass through certain load and finally recombine with holes at n-type layer and, in this way, the current is generated. Then, the solar panels are arranged in series on the top surface of wing. In this project, the airplane is probably a hand-launched short endurance UAV, which means the energy obtained from solar panels are stored the battery during the gliding period. In other words, flying the UAV by using solar energy alone and storing the energy in the battery help to extend the endurance of the airplane.

Efficiency of solar Panel

Also, to measure the PV panels' efficiency, the equation below can be used:

$$\eta_{max} = \frac{P_{max}}{E \times A_c} \times 100\%$$

Where P_{max} is the maximum power output, E is the Incidence Radiation Flux while A_c is the area of collector.

2.7.2 Maximum Power Point Trackers (MPPT)

Usage of MPPT in PV power system

In order to obtain required voltage to safely charge the Li-PO battery and load, Maximum Power Point Trackers (MPPT) are installed. The MPPT is a high frequency DC to DC current converter, main function is to maximize the amount of power obtained from the solar panels. This power is prioritize to run the propulsion system and the onboard electronics, then secondly to charge the battery. In the daytime, depending on the sun irradiance and the inclination of the rays, the solar panels convert light energy into electrical energy and energy is collected. At night, as no power can be collected from the solar panels, the battery supplies power to various elements to run the electronics devices. (Noth & Siegwart, 2006) The overall concept is schematically represented on the Figure 1.

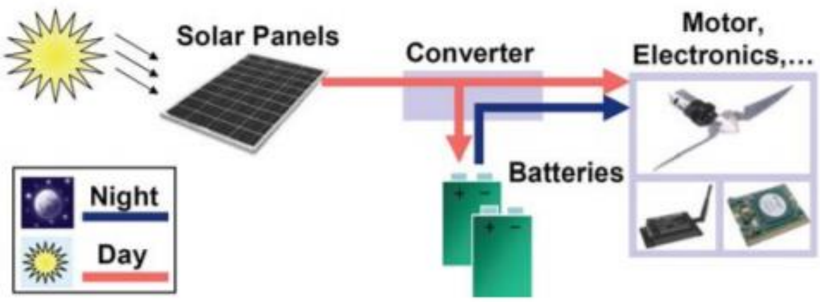


Figure 2.3: Schematic diagram of power conversion

MPPT algorithms are necessary in a solar-powered UAV's PV system because the maximum power point of a PV cells varies with few external factors, thus the use of a charge controller with MPPT technology is essential in order to obtain the maximum power from the PV cell. For example, at STC of 25°C, PV cells produces power P_{MPP} of around 17 V, it can drop to 15 V on a hot day and it can also rise to 18 V on a cold day, thus MPPT keep track of the output of PV cells, compares it to battery voltage, then decide the best power that PV module can produce to charge the battery and converts it to the best voltage to get maximum current into battery. (Basics of MPPT Solar Charge Controller, 2013)

CHAPTER 3

METHODOLOGY

3.1 Introduction

Difference on design methodology of solar-powered UAV and conventional UAV

The design methodology of UAV is simplified as there's no onboard pilot and fuel system. Also, in this project the airframe design proposed is a plank flying wing, thus, the tail design also can be eliminated. However, the design procedure of a solar unmanned aerial vehicle varies considerably from that of a conventional design. As the technologies of solar-powered UAV has gained interest in more and more researchers in recent year, thus a few sizing methods and design procedures of solar-powered UAV have developed. According to (Panagiotou, Tsavlidis and Yakinthos, 2016), some of the differences between the design of a solar and a conventional airplanes are included:

1. Weight sizing of solar-powered UAV. The ideal concept is to have a lightweight material to build the airframe structure, thus less power required to operate the UAV and less PV cells needed.

2. Wing sizing of solar-powered UAV. Conventional UAV wing area parameter (S) is crucial in determine the performance of airplane. For solar powered aircraft, the total PV cells area or consequently the power required for the flight is one of the main consideration in decide the wing area.

3. Performance characteristics of solar-powered UAV is difference from the conventional UAV. As the wing area is considerably larger to make space for more PV cells, thus the cruising, loiter and stall speeds are expected to be lower. The thrust and power required are expected to be lower as well.

Introduction on design methodology of solar-powered UAV

Therefore this chapter will start with two analysis, which is the analysis on the weight sizing as well as the analysis of performance of this airplane. On the second part of this chapter, the methodology on the system setup and experiments conducted is discussed. The design and set up procedures of PV power system on the solar-powered airplane is proposed. Then, experiment methodology to study on the factor affecting the characteristics of PV cells and thus the performance of airplane is discussed.

3.2 Weight sizing

Weight estimation introduction

Weight estimation in the preliminary sizing is essential for the performance prediction, centre of gravity determination, design of the undercarriage and providing weight limits to various departments. (Jenkinson & III, 2003) Using this value, the engine and wing sizes can be determined as well. There are few categories in the weight estimations to be considered, which is:

1. Airframe structural parts
2. Electronic components and wiring system
3. PV power system

3.2.1 Airframe Structural Weight Estimation

Weight estimation of airframe structural

As the design is a plank flying wing UAV, thus there is only two parts available, which is the fuselage as the compartment to store the electronics components and wing to generate lift and act as the control system to maneuver the flight movement. In order to reduce the overall weight, the material used must be a lightweight material, which is the foam. For the planning phase, the weight of the project can be determined by using the formula as below:

$$mass, m = \text{material density}, \rho \times \text{volume}, V$$

$$weight, W = \rho \times V \times \text{gravitational acceleration}, g$$

One of the lightweight material is Styrofoam, where the density is $50kg/m^2$. Then, by obtaining the volume of airplane on AutoCAD drawing, the mass and the weight of the airplane can be obtained. The total structural weight is described as

$$W_{struc} = W_{wing} + W_{fuselage}$$

Weight estimation of electronic components

The electronics parts in the fuselage compartment are the brushless motor, propeller, ESC, receiver, battery, servo, MPPT and wiring system. The weight of the parts can be obtained from the components specification datasheets or by measuring using a weigh scale in the UAV Lab. Same goes to the PV cells, where according to the specifications sheet, it weighed 10g each. By multiply the weight with the number of PV cells used, we can obtain the total weight of cells mounted on the wing.

$$W_{PV cells} = W_{single\ cells} \times number\ of\ cells\ mounted$$

$$W_{elec} = W_{PV cells} + W_{MPPT} + W_{motor} + W_{propeller} + W_{ESC} + W_{receiver} + W_{battery} + W_{servo} + W_{wiring\ systems}$$

Total weight estimation

It is important to identify all components and structures weight in order to know the gross take-off weight of the airplanes, which the equations are stated as below. This parameter in important in determine the aerodynamics characteristics, and hence the overall performance.

$$W_{GTO} = W_{struc} + W_{elec}$$

As mentioned in the scope of this project, optimum performance is when the weight of the UAV is kept below 1.2kg. Thus, the UAV is designed with the weight distribution of the airframe, payload and electronics component as below in table 3.1.

Table 3.1: Weight distribution

Components	Weight (gram)
2S 7.4V Li-Po cell	81g
30A Skywalker ESC	37g
Sunpower C60 PV cell	9g x 16= 144g
Brushless motor	102g
Propeller	15g
Pixhawk Flight controller	58g
Receiver	16.8g
MPPT	185g
Telematry and GPS module	50g
Wiring System	60g
Airframe Structure	400g
Total	1155g

3.3 Aerodynamic Analysis of Solar Powered UAV

Introduction on aerodynamic analysis

The design objective of the wing is to optimize smooth flight for solar-powered UAVs, which at the same time respond to flight and sensory requirements. Some of the important considerations are payload capacity, maneuver controllability, and hand launched takeoff. (Boukoberine, Zhou and Benbouzid, 2019) We take a level flight condition in the planning and analysis of flight, where it is a condition the aircraft is operating at steady state with minimal power consumption.

3.3.1 Wing Sizing

Important parameters in wing sizing

During wing sizing, some of the important parameters are weights, wing area (S), wing span (b), aspect ratio (AR), height, total length, root, and tip chord length of wing. Similarly, in aerodynamic analysis, lift and drag coefficient estimation are based on various wing and airfoil characteristics.(Rajendran and Smith, 2018) It is also important to understand the behavior of plank flying wing.

Airfoil selection

The choosen aerofoil is MH45, which is a popular aerofoil for tailless model aircraft due to its low moment coefficient, comparatively high maximum lift coefficient, also suitable to be used at Reynolds numbers of 100 000 and above. (Hepperle, 2018) The MH45 aerofoil shape is shown as in Figure 3.3.

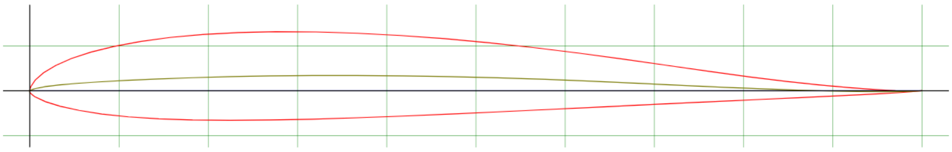


Figure 3.1: The MH45 Aerofoil (airfoiltools.com)

Reasons on plank wing selection

Also, plank wing is chosen because it is easy to fabricate, suitable for small, low-speed airplanes. This wing provide the efficient lift at low speeds. Also, a rectangular plank wing could simplify the arrangements of PV cells.

Parameters on lift coefficient

Then, the lift coefficient can be predicted by using the lift equation, as shown below. In level flight, the aircraft lift is equal to the take-off weight. Because the air density, airspeed, and wing area are known, the lift coefficient, C_L, may be estimated.

$$C_L = \frac{2L}{\rho V^2 S} = \frac{2W}{\rho V^2 S}$$

Parameters on drag coefficient

Next, the drag coefficient C_D can also be estimated. The aircraft zero-lift-drag coefficient, C_{Do} is expected to be at 0.015 for low altitude UAV. The fuselage drag component for a lightweight UAV is not accounted since the value is very small. (Rajendran and Smith, 2018)

$$C_{D,W} = C_{Do,W} + \frac{{C_L}^2}{\pi ARe}$$

Lift and Drag Equation

Then, with the lift and drag coefficient calculated as above, the lift and drag can be now predicted using equation as below,

$$L = \frac{1}{2}\rho V^2 S C_L$$

$$D = \frac{1}{2}\rho V^2 S C_D$$

3.4 Performance Analysis

3.4.1 Power Generated

Equations on power generated from PV cells

In a solar-powered UAV, PV cells are the primary source of energy to turn the motor. They convert photovoltaic energy into electric energy. (Dwivedi, Kamath, & Kumar, 2018) The power generated by PV cells are calculated using equation from (Manuel H., 2013) :

$$P_{PV} = \eta_{PV} \times \eta_{MPPT} \times S_{PV} \times G$$

where η_{PV} is the efficiency of PV cells used, η_{MPPT} is the efficiency of MPPT, S_{PV} is the total area of the PV cells installed, G is the available irradiance and P_{PV} is the power generated from PV cells.

Irradiance analysis in Kuala Lumpur

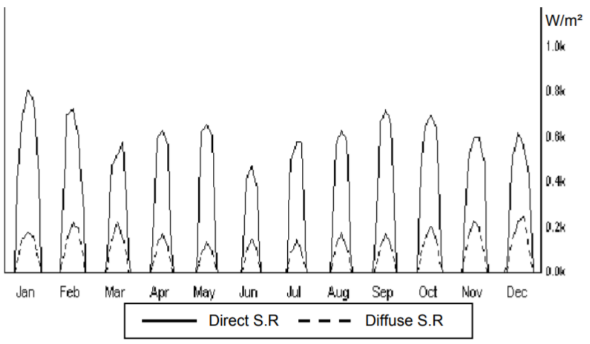
We get the average irradiance, G in Kuala Lumpur from ECOTECT 5.2v-weather, where

$$\frac{7191.8}{11.9} = 604.353W/m^2$$

$$P_{PV} = 0.225 \times 0.96 \times (0.125 \times 0.125 \times 16cells) \times 604.353$$
$$P_{PV} = 32.635W$$

Table 2 Monthly average daily global solar radiation and solar hours for Kuala Lumpur, Malaysia. (Source: ECOTECT 5.2v - weather)

Month	Solar radiation (Wh/m^2)	Solar hours
Jan.	10146	13.0
Feb.	8821	13.0
Mac	6690	12.0
Apr.	6287	11.0
May	6072	10.5
Jun.	4353	10.0
Jul.	5499	10.8
Aug.	6231	11.0
Sep.	7233	11.5
Oct.	8240	12.3
Nov.	8487	13.9
Dec.	8242	13.7
Avg.	7191.8	11.9



Graph 1 Monthly diurnal averages for solar radiation in Kuala Lumpur, Malaysia. (Source: ECOTECT 5.2v - weather file)

Figure 3.2: Average Solar Radiation in Kuala Lumpur (ECOTECT 5.2v-weather)

3.4.2 Power Required

Equations and calculation on power required

We calculated and predicted the power required for a steady, unaccelerated climb as it required more power than steady cruise and landing. Figure 3.3 give general picture of steady climb, which assist the power required calculation. (Jr., 2016) Anderson, 2016 is used as reference for steady climb analysis.

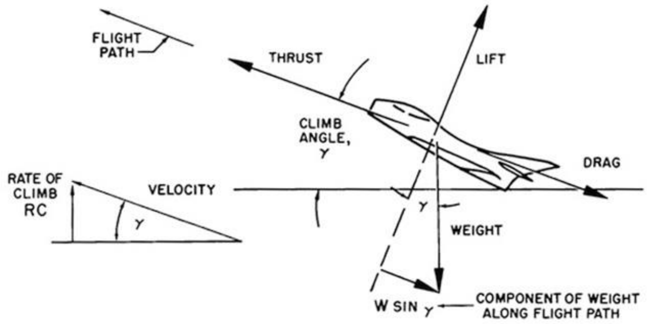


Figure 3.3: Steady climb of UAV

Thrust T is assumed to be aligned with flight path and UAV is flying at sea level. Summing up forces parallel to the flight path, we obtained

$$T = D + W\sin\gamma$$

And perpendicular to flight path, we get

$$L = W\cos\gamma$$

$$C_L = \frac{2W}{\rho V^2 S}$$

$$C_L = \frac{2(1.2)\,(9.81)\cos 5°}{(1.225)(10)^2 0.299} = 0.64$$

$$C_D = C_{Do} + \frac{{C_L}^2}{\pi ARe}$$

$$C_D = 0.015 + \frac{0.64^2}{\pi(4.423)0.7} = 0.057$$

$$D = \frac{1}{2}(1.225)(10)^2(0.299)(0.057) = 1.044N$$

By multiply velocity V on the equation,

$$TV = DV + WV\sin\gamma$$

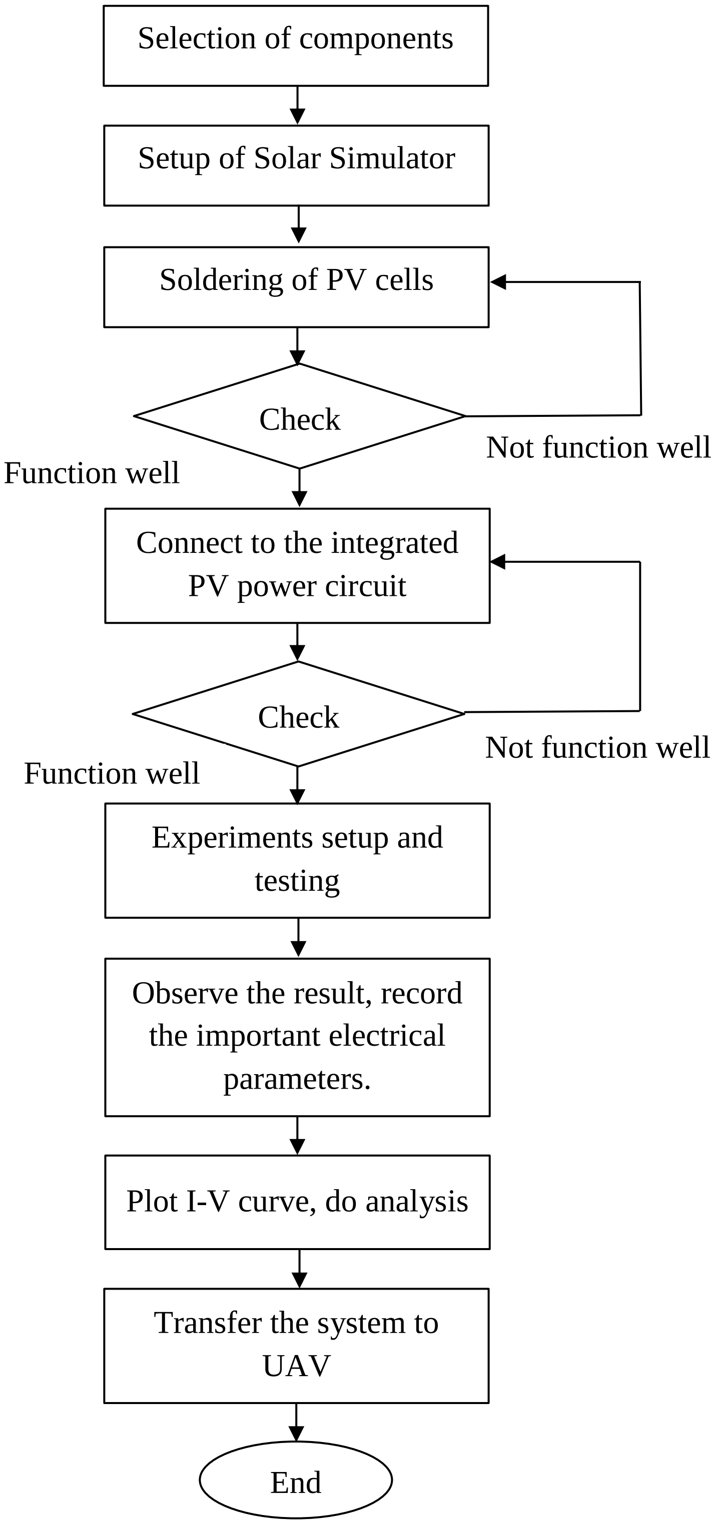
$$TV = (1.044)(10) + (1.2)(9.81)(10)\sin 5° = 20.7N$$

$$P_{required} = 20.7N$$

Thus, this proof that the power obtained for PV cells are enough to operate a steady climb of UAV.

3.5 System Setup and Testing

The flow below shows the methodology for the setup of integrated PV power system and experiments testing. Detail explanation will be showed in next following sections.



3.5.1 Selection of Components

Selection of PV Cells

Criteria in selection of PV cells

As PV panels are one of the most critical components in a solar-powered aircraft, thus the selection of PV panels is the main concern in this projects. The PV panels are selected based on few criteria, which included the type of solar panels, the flexibility of PV cells, weight and size of PV panels, and the cost.

Advantage of monocrystalline cell

The type of PV panel chosen is monocrystalline cells. The major reason for the selection is because monocrystalline silicon cells has highest efficiency compared to polycrystalline and thin film PV cells. A normal monocrystalline cells has efficiency on average at 13% to 19%, while nowadays a number of improvements have brought the monocrystalline cell efficiency increased to about 25%. Then, the price of high efficiency monocrystalline silicon cell is surprisingly low, which almost the same as polycrystalline and thin film panels. The other reason is flexibility of PV cells, which the PV panels selected needed to be flexible and rollable so that they can be mounted accordingly on the airfoil.

Monocrystalline vs Polycrystalline vs Thin Film PV Panels

To understand the factors that contribute to the efficiency of PV panels, Bayod-Rújula (2019) has outlined the nature and manufacturing processes of different types of PV cells needed to be analysed and compared. (Bayod-Rújula, 2019)

Structure & manufacture of monocrystalline, improvement on cell

Monocrystalline silicon cells has the entire volume of the cell covered with just a single crystal of silicon. The silicon has only a single continuous crystal lattice structure with almost no defects or impurities, therefore it has higher efficiency and perform better in high heat and low light environment. Then, the latest PV cells efficiency up to 25% due to several improvements. Firstly, the light capture through trapping structures that minimize reflection in directions which not benefiting the collection area. Then, the doping degree is altered near electrodes (n+ and p+ areas), and a thin oxide layer further helps to prevent electrons from reaching the surface rather than the electrode. Further, top electrodes may be buried, in order not to produce shadowing effects for the incoming light.

Structure & manufacture of polycrystalline

On the other hand, polycrystalline cells are produced through numerous grains of monocrystalline silicon. To manufacture the polycrystalline cells, fragment of silicon is melted together and casted into ingots, which are subsequently cut into thin-layered wafers and assembled into complete cells. Thus, it is less efficient as there are defects appeared on the cells' surfaces. Figure 2.4 showed the visible difference when observed from the surfaces of PV cells, where uniformed grain sizes and grain boundaries can be observed on polycrystalline cells, while there's only one grain on monocrystalline cells.

Structure & manufacture of thin film cells

For the case of thin film cells, the main difference between thin films and the previous two cells is, instead of the crystalline structure, thin film are made up of amorphous silicon cells, which composed by a thin homogenous layer of silicon atoms. In general, the manufacture of thin film cells are basically depositing a thin layer of conductive PV substances on a backing plate, which normally glass or plastic. Therefore, it is lightweight, least expensive and suitable for large scale utility project. However, it is not recommend to be mounted on a solar-powered aircraft due to its low efficiency and low power to weight ratio.

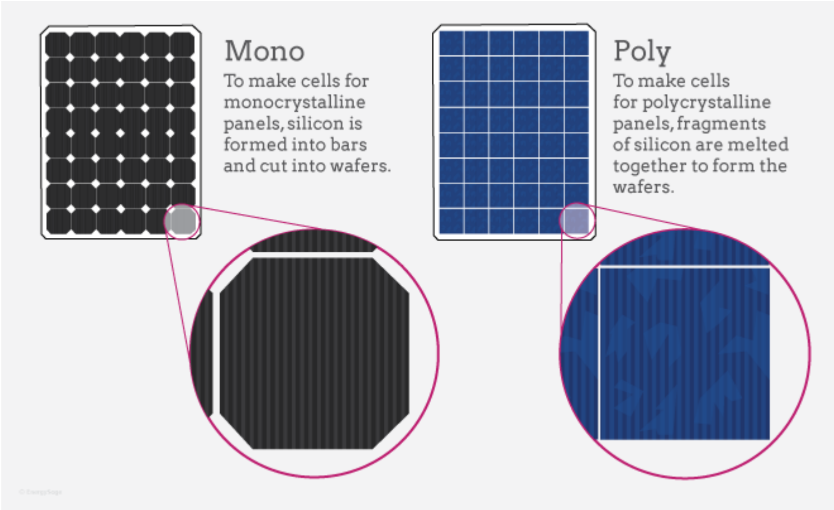


Figure 3.4: Difference between Monocrsytalline and Polycrystalline

Selection of MPPT

Criteria in selection of MPPT

Meanwhile, the selection of MPPT is relatively more direct. The criteria based on the selection are the input and output current, weight and dimension of MPPT and the cost of MPPT. The ideal MPPT should be lightweight, economic and in a handy size. Also, the selection of MPPT are depend on the solar module array current as well as system voltage. Below are the calculations and description for the selection of suitable MPPT based on this project, by referring to Diehl(2015) :

Calculation in selection of MPPT

There's 16 PV Panels mounted on the wing. On average, every Sunpower Monocrytalline cell with efficiency of 22.4% can produce a power of 3.3 Watts. Then a 2s Li-Po battery is used, which hold a 7.4 Volts.

$$16 \times 3.3W = 52.8Watts$$

In other words, you could have a 52.8 watt of solar module array with the battery bank of 7.4 volts DC. It is necessary to take note that the MPPT are rated by the output current that they can handle, not the input current from the PV panels. Therefore, to determine the output current that the MPPT will have to handle, the basic formula for power is applied:

$$P = IV$$
$$52.8W = I \times 7.4V$$
$$I = 7.135 + 25\% \ = 8.92A$$

The 25% is taken into account as special conditions might where the PV panels produce more power than it is normally rated (probably due to sunlight's reflection). Based on the calculation, it is concluded that a 10 Amp MPPT Charge Controller is recommended.

Function of MPPT

The primary feature of MPPT enable us to install a PV panels with a much higher voltage than your battery bank's voltage. Also, the MPPT control and regulate the voltage go on respective electronic components as the amount of sun ray intensity received is greatly affected by the time the airplane is tested, which as shown as Figure2.5. (Diehl, 2015)

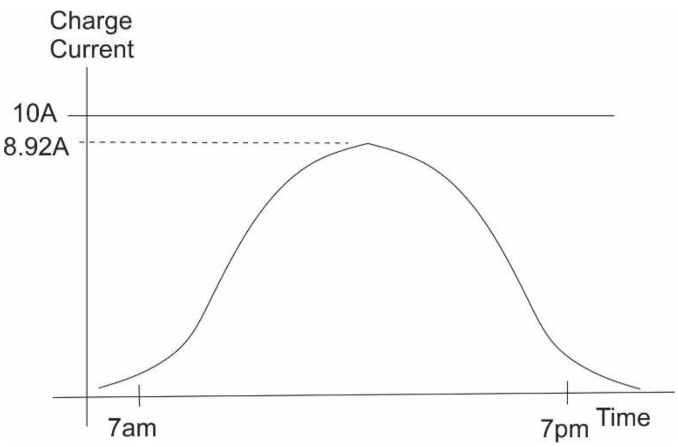


Figure 3.5: Input Charge Current At Different Hour

<u>Selection of Electronics Components</u>

<u>Battery</u>

Figure 3.6: 2S 7.4V Li-Po cell (hobbyking.com)

Table 3.2: Battery Parameter

Configuration	7.4v / 2Cell
Capacity	1300mAh
Constant Discharge	20C
Pack Weight	81g
Pack Size	73 x 35 x 17mm

<u>ESC</u>

Figure 3.7: Skywalker ESC (hobbyking.com)

Table 3.3: ESC Parameter

Continuous Current	30A
Burst Current	40A (10 Sec.)
BEC Mode	Linear Mode, 5V@2A
Weight	37g
Pack Size	68.0 x 25.0 x 8.0mm

<u>PV Cell</u>

Figure 3.8: Sunpower C60 PV cell (eshop.terms.eu)

Table 3.4: PV cell Parameter

Pmpp	3.42W
Vmpp	0.582 V
Impp	5.90A
Voc	0.687V
Isc	6.28A
Efficiency	22.5%
Size	125.0 x 125.0 x 0.165mm

<u>Brushless Motor</u>

Figure 3.9: Turnigy Brushless Motor (rchopez.com)

Table 3.5: Motor Parameter

Type	Turnigy D3536/9 910KV Brushless Outrunner Motor
Battery	2 to 4 Cell /7.4 to 14.8V
Propeller Size	7.4V/12 x 5
RPM	910 kv
Maximum Current	25.5A
Maximum Power	370W
Weight	102g

Flight Controller

Figure 3.10: Pixhawk Controller (synosystems.de)

Table 3.6: Flight controller parameters

Type	PX4 2.4.6 pixhawk AutoPilot
Extension	- 433 MHz Telemetry Module - GPS Module uBlox NEO 7 - LED/USB EXT. module - APM OSD mini - Digital airspeed sensor - Analog Airspeed Sensor - PX4FlowKit - APM Power module - APM PPM Encoder
Weight	58g
Size	80 x 45 x 15 mm

Receiver

Figure 3.11: X8R Receiver (hobbyking.com)

Table 3.7: Receiver Parameter

Type	FrSky X8R 8 Channel ACCST Telemetry Receiver
Operating Current	100mA/ 5V
Range	>1.5km
Weight	16.8g
Size	46.5 x 27 x 14mm

<u>MPPT</u>

Figure 3.13: Genasun MPPT (cdn.shopify.com)

Figure 3.12: MPPT Parameters

Type	FrSky X8R 8 Channel ACCST Telemetry Receiver
Rated battery (ouput) Current	10.5A
Max input current	19A
input voltage	0 - 34V
Weight	185g
Size	14 x 6.5 x 3.1cm

3.5.2 Setup of Solar Simulator

Literature review and requirement of solar simulator

The connecting of PV cells require soldering of PV cells in series, therefore a Solar simulator is planned and built. The simulator is used to perform soldering of PV cells, also as the main facility to execute all the experiments. The indoor setup and testing are facilitated in a controlled environment with constant solar irradiance intensity supply and ambient temperature, which expected to shorten experiments time and obtain results in higher accuracy. American Society of Heating, Refrigerating & Air Conditioning Engineers (ASHRAE, 2003) suggested that this solar simulator should fulfil the requirements as below:

(a) Light source used should be the same as real solar spectrum and complied with the air mass standard of 1.5 solar spectrum.

(b) Light spectrum produced should not be affected by input voltage variation to control the irradiance intensity of the light.

(c) The light spectrum distribution on the solar collector testing area should be uniformed and irradiance mapping shall be executed to calculate irradiance intensity uniformity.

Design specification of solar simulator proposed

The small scale solar simulator is setup at P20 AeroLab. The design of the simulator is as Figure 3.15 and Figure 3.16. The main structure was made of wood with dimension of 1.5m × 0.85m × 0.9m, while the test area is made of transparent glass surface that can be flipped open. The center space of the simulator is design to hold all 8 pieces of 500W halogen lamps that were arranged in 2 rows as depicted in Figure 3.16. Specifications of the selected halogen light is displayed in table 3.8. Distance between centers of each light bulb was approximately 0.35m. The distance between the lamp and the test area was approximately 0.2m. The irradiance produced measures by a pyranaometer. The arrangement of PV cells are sketched on the test area surface. All lamps were arranged perpendicular (90 °) towards the solar collector test area to gain maximum irradiance intensity. Each lamp was connected in parallel circuit, which then connect to the main DC power supply. Also, 2 units of fans were placed between the lamps and test area to reduce the Infra-Red effect from the lamps.

Figure 3.14: 500W Halogen Lamp (alibaba.com)

Table 3.8: Halogen Lamp Parameters

Type	Halogen Light Bulb
Voltage	230V
Power	500W
Average Life	300 hours
Luminous flux	11000 lumens
Diameter	23mm

Test area

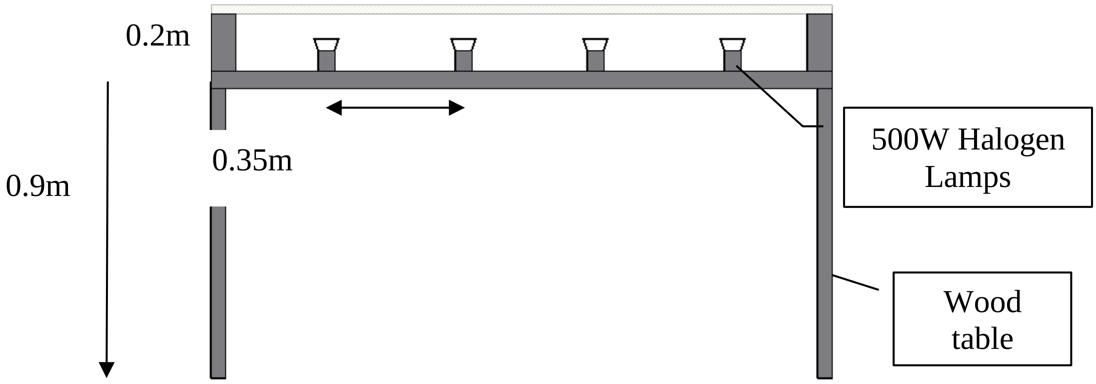


Figure 3.15: Front view of solar simulator

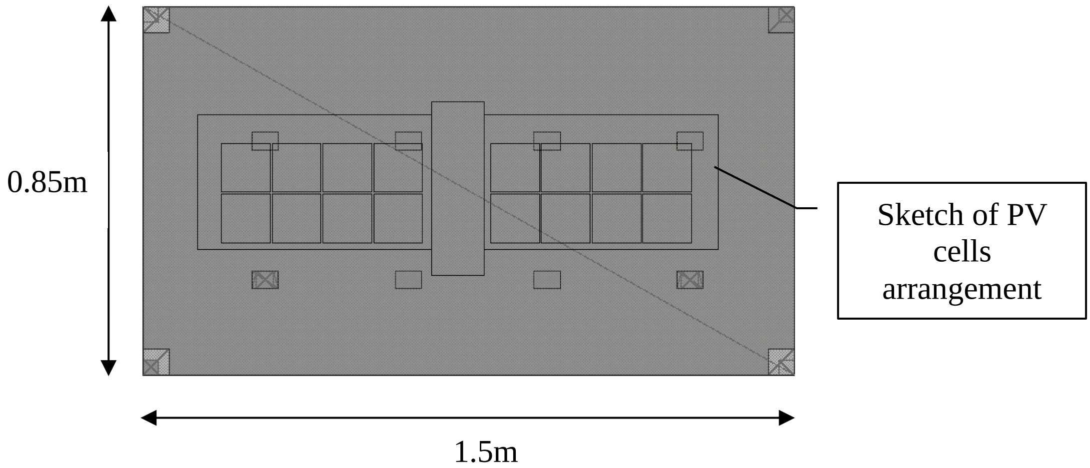


Figure 3.16: Top view of Solar Simulator

3.5.3 Setup of Integrated PV Power System

Objective : To connect the electronic components according to the circuit and run the testings to check the functionality.

Apparatus : 2S 7.4V LiPo cell, 30A Skywalker ESC, 16 Sunpower C60 PV cells, 910KV Brushless Outrunner Motor, Genasun 10.5A MPPT, tabbing wire, Interconnect tab, papers, transparent film, hot glue adhesive

Equipment : PPE equipment (rubber gloves), solar simulator(soldering table), soldering iron, multimeter

<u>PV Cells Arrangement</u>

Arrangement of PV cells

Figure 3.11 showed how PV cells are arranged in series circuit. Size of each PV cell are 0.125m × 0.125m, where 16 cells are arranged in 2 rows, where left and right wing has 8 cells respectively. There will be no cell mounted on the fuselage. Thus, a wing span of 1.15m and chord of 0.26m will be sufficient. Also, interconnect tab is placed between the PV cells is required for the soldering purpose. The cells are 1 to 2cm away from the elevon to avoid disrupting the performance of control surface.

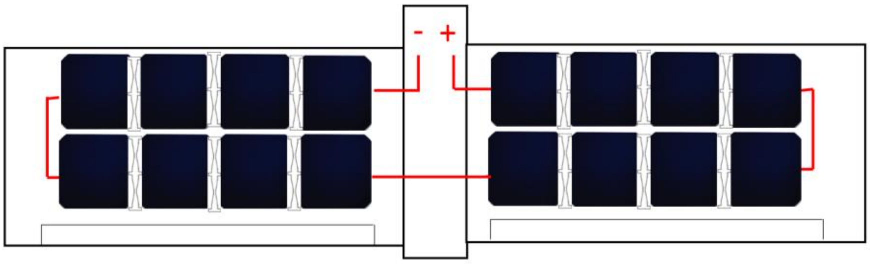


Figure 3.17: PV Cell arrangement

<u>Intergrated PV power system circuit</u>

Intergrated PV power system circuit

The integrated circuit consists of a MPPT and a set of PV cells as the preliminary source of power. Figure 3.22 shows the integrated circuit, where MPPT is connected in between the PV cells and battery. When airplane fly at different angle, the PV cells will experience different levels of solar irradiance, which causes the solar arrays to operate at a different location on their V-I curve. However, it is required to provide a constant regulated voltage source to the battery and ESC. Unbalanced cells can lead to components overcharging and reduced life, thus MPPT is installed as battery and ESC protection.

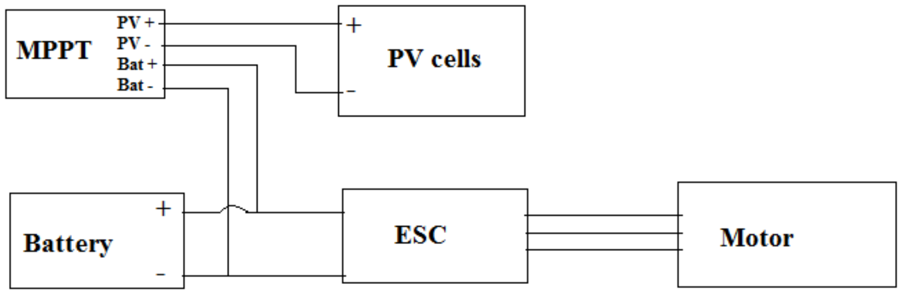


Figure 3.18: Intergrated Circuit

Procedures on PV power system set up

The procedures to do the setup of PV power system is explained as below, which included the arrangement of PV cells, connecting the integrated PV power circuit as well as the transport of system to the UAV.

<u>PV cells</u>

1. PV cells are arranged as showed in figure 3.17. Interconnect tabs are located between PV cells.
2. Solder the edge of PV cells to the interconnect tab using soldering iron.
3. After every complete connection of PV cells, switch on the halogen lamps, check the functionality of the cells using multimeter.
4. Solder the connecting wires on the circuit as shown in Figure 3.17.
5. Again, turn on the halogen lamps, check the functionality of the complete PV cells circuit using multimeter.
6. Record the power, voltage and current produce by the cells, compare with the datasheet specifications.

<u>PV Power System</u>

1. Install and connect the right components properly as shown in Figure 3.19.
2. Turn on the halogen lamps, check the functionality of the complete PV power system using multimeter.
3. Perform testing to check if all components are running.
4. Record the power generated by the system. The system is now ready for experiments.

Transfer to UAV

1. After experiments are complete, final step is to transfer the whole PV power system to UAV.
5. Mount the PV cells to the wing. Secure the location of cells with adhesive.
6. The cells are covered with a layer of transparent film.
7. Connect the PV power system with the avionics part in the fuselage compartment of UAV. Check the functionality.

3.5.4 Experiment Setup and Testing

Title : Factors affecting the characteristics of PV cell

Objective : To calculate the efficiency of PV cells, after considering all the factor that influence the capturing of solar irradiance.

Apparatus : Complete PV power system, transparent film, masking tape

Equipment : PPE equipment (rubber gloves), solar simulator, air conditioner

Theory:

Open circuit voltage and short circuit current

The two important parameters which often used when studying the performance of solar cell is the open circuit voltage V_{oc}, and short circuit current, I_{sc}. The equivalent circuit at Figure 3.4 assisted the explanation of both parameters. Generally, the short circuit current can be measured by shorting the output terminals, and measure the terminal current under full illuminations. In other words, the short-circuit current, I_{sc}, is the current passed through the PV cell when the voltage across the PV cell is zero. The short circuit current in this condition also can be defined as I_L. (Patel, Wnd and Solar Power Systems, 1999)

The open-circuit voltage, V_{oc}, is the maximum photovoltage produced from a PV cell, which normally occurs at zero current. The equation for V_{oc} is as below, by setting the net current equal to zero in the PV cell equation.

$$V_{oc} = \frac{AKT}{Q} Log_n\left(\frac{I_L}{I_D} + 1\right)$$

Where $\frac{KT}{Q}$ is the absolute temperature in voltage (STC 300K=0.026V), while A is curve fitting constant.

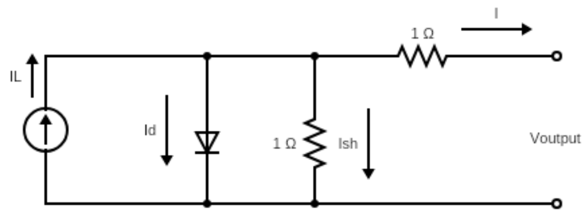


Figure 3.19: Equivelent Circuit of PV cells

<u>I-V curve and P-V curve</u>

The characteristics of PV cell are generally represented through the I-V curve. As Figure 3.5 shown, the red curve trend represent the I-V curve. On the left region of I-V curve, the cell work in a constant current souce, generating voltage to work match with the load resistance. On the right region, the current reduced rapidly even with small increase in voltage. In the middle between two region, there's a knee point, denoted as V_{MP} andI_{MP}. (Patel, Wnd and Solar Power Systems, 1999)

The blue curve trend represent the P-V curve, where the power output is the product of voltage and current produced. (IV Curve, 2019) No power is generated when at zero current and zero voltage. The power curve has a maximum power point, P_{MPP} at voltage corresponding to the knee point.

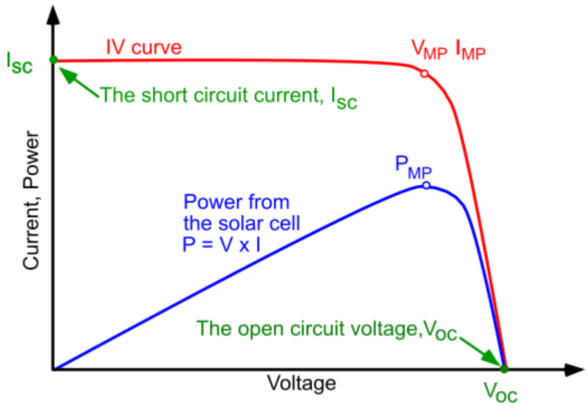


Figure 3.20: I-V Curve and P-V Curve of PV cell (pveducation.org)

<u>Factors Affecting the Characteristics of PV Cell</u>

The major factor that affect the characteristics of solar cell are included:

- The sun intensity

The magnitude of photocurrent is maximize under full bright sun. The I-V curve trend shift downwards at a cloudy day. As the sun intensity decreases, the short circuit current decreases significantly, however the reduction in open-circuit voltage are small. (Patel, Wnd and Solar Power Systems, 1999) Same concept apply on when a layer of thin transparent film that installed on top of the PV cells, which are also expected to decrease the efficiency of PV cells.

- The solar angle of incidence

The solar angle of incidence is depend on the axes of flight as well as the azimuth angle. The axes of flight are the lateral, longitudinal and vertical axes. The motion of airplane along the axes are pitching, rolling and yawing respectively. The electrical output and power density is expected to reduce as the angle of incidence increase.

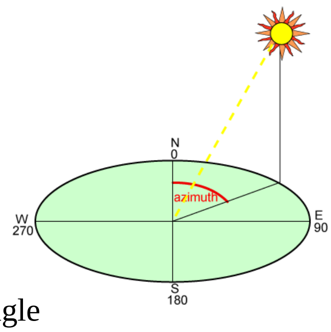


Figure 3.21: Azimuth Angle

The azimuth angle, α, and defined as a horizontal angle measured clockwise from a north base line. The reference plane for an azimuth is typically true north, measured as a 0° azimuth. Figure 3.6 show the azimuth angle. (Sousa, 2015)

- The operating temperature

  Theoretically, as the temperature rise, the short circuit current of PV cell increase, while the open-circuit voltage decrease. Also, maximum power available at lower temperature. Therefore, a bright, cooler environment is can increase the efficiency of PV cells. (Patel, Wnd and Solar Power Systems, 1999)

Detailed procedures to conduct all 3 experiments are explained below:

<u>Experiment 1: The sun intensity</u>

Experimental procedures to see the effect of sun intensity

In this experiment, film covering study was conducted in order to understand the influence of the transparent film used to cover wings on the PV cell efficiency. Solar simulator is used to simulate the condition, replacing the sunray. The operating temperature and light irradiance is remain constant throughout the experiment. The procedures include:

1. Set up the complete PV power system on the solar simulator.
2. Turn on the halogen lamps, record the PV cell electrical parameters with a layer of transparent film covering on the cell.
3. The waiting time is set to 15 minutes, until stable reading can be obtained using multimeter.
4. Record the operating voltage and current of the system.
5. The experiments is repeated by removing the transparent film.
6. Switch off the power. Plot the results in I-V curve to perform analysis.

	Irradiance	Voltage	Current	Power	Efficiency
Without transparent film					
With transparent film					

Experiment 2: Solar angle of incidence

Experimental concepts to determine azimuth angle

In this experiment, we investigate on the how the change of pitch and roll angle will effect the efficiency of PV system. Figure 3.22 and Figure 3.23 showed the setup of the solar simulator for this experiment. The solar simulator is designed such that the test area (glass surface) can be tilted along longitudinal (Figure 3.22) and lateral axis (Figure 3.23) to facilitate the experiment. Variation of the pitch angle within range of 0° to 45° and roll angle within range of 0° to 15° simulates the change of direction of UAV during manuever.

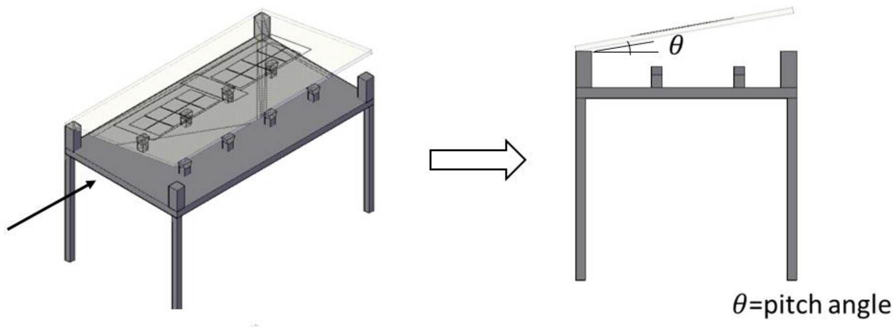


Figure 3.22: Test area tilted at required pitch angle

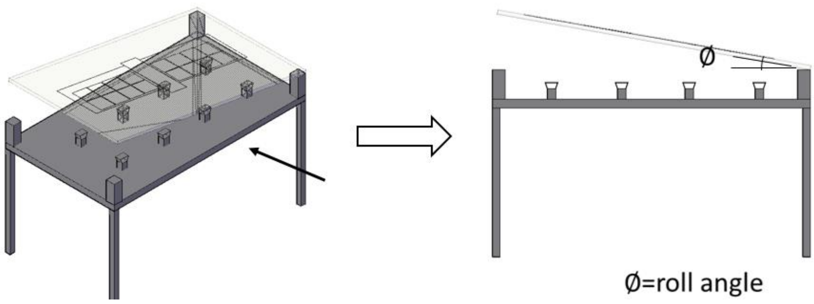


Figure 3.23: Test area tilted at required roll angle

Experimental procedures to see the effect of pitch and roll angle

The experiment is performed in following steps as below:

1. Set up the complete PV power system on the solar simulator. Secure the position of PV cells with masking tape.
2. The aircraft was set for 0º pitch angle and 0º roll angle.
7. Turn on the halogen lamps, the waiting time is set to 15 minutes, until stable reading can be obtained using multimeter.

3. Record the operating voltage and current of the PV power system.
4. The experiments is repeated at different set of pitch and roll angle as set at table below.
5. Switch off the power. Plot the results in I-V curve to perform analysis.

Pitch Angle	Roll angle	Irradiance	Voltage	Current	Power	Efficiency
0°	0°					
	5°					
	10°					
	15°					
10°	0°					
	5°					
	10°					
	15°					
20°	0°					
	5°					
	10°					
	15°					
30°	0°					
	5°					
	10°					
	15°					
40°	0°					
	5°					
	10°					
	15°					
45°	0°					
	5°					
	10°					
	15°					

The operating temperature

Experimental concepts to determine the operating temperature

The power output of that PV cells is higher at lower operating temperatures, considering the same irradiance conditions. The surrounding temperature is controlled using air-conditioner. The execution of the experiments is as below:

Experimental procedures to see the effect of operating temperature

1. Set up the complete PV power system on the solar simulator.
2. Turn on the halogen lamps, record the PV cell electrical parameters at ambient temperature.
3. The waiting time is set to 15 minutes, until stable reading can be obtained using multimeter.
4. Record the operating voltage and current of the system.
5. Repeat the experiments by adjusting the surrounding temperature. Record the operating voltage and current of the system.
6. Switch off the power. Plot the results in I-V curve to perform analysis.

Temperature (°C)	Irradiance	Voltage	Current	Power	Efficiency
28 (ambient)					
25					
20					
15					

CHAPTER 4

CONCLUSION

4.1 Reflection

As the Undergraduate Project I has now come to an end, I'm so grateful that I was given opportunity to take part in this project and be part of Dr Nazri Nasir's research team. I believe one of the purpose of the undergraduate project is to apply our knowledge and skills we learnt from past academic years to a project. Throughout the semester, I've gain a lot of exposure and new knowledge, which include the working principles of UAV propulsion system and avionics, the trend of latest solar technologies, the use of Mission Planner and Pixhawk on UAV and lastly the synchronisation of every electronics part to produce one successful flight mission. Also, I've improved some soft skills which is equally important, which is project planning and management, presentation and communication skill as well as execution of project according to time frame. I looking forward to the experiment execution part in UGP 2.

4.2 Comments from VIVA

There are 2 suggestions of improvement from panels, which include the energy analysis and management, and the aerodynamics study of proposed airplane. For the power generated analysis, they suggest to find out more on the power produced throughout the day from sunrise till sunset, then obtain the maximum and minimum power produced. For the power required, more study on the motor is required, some of the parameters to take note are the RPM and efficiency of motor. Then, obtain the relationship between power required and power generated, also the performance of system within a certain range of velocity. Also, although the focus of this project is on the PV power system, the aerodynamics of the proposed UAV design need to be analysed. For example, the drag polar of the UAV.

CHAPTER 5

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Appendix A Gantt Chart UGP1

TASK/WEEK	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
First Meeting with Supervisor			■																	
Discuss and decide objective & scope of project			■																	
Participate in briefing, talk and flight test			■	■	■	■	■	■	■	■										
Literature Review			■	■	■															
Report Writing					■	■	■	■	■	■	■	■	■	■	■	■	■			
Presentation to Supervisor			■	■	■	■	■	■	■	■	■	■	■	■	■	■				
Propose solar panel electronic components					■	■														
Develop design methodology							■	■	■	■										
Performance characteristics analysis of UAV									■	■	■	■								
Design solar panel arrangement on UAV									■	■	■	■								
Propose experiment set up												■	■	■						
Finalise methodology														■	■	■				
Final Preparation for Seminar Presentation																	■	■		
Seminar Presentation (VIVA)																			■	
Report Submission to Supervisor																			■	
Repairing Report																				■
Report and Logbook Submission to Faculty																				■