PATH PLANNING OPTIMIZATION FOR SOLAR-POWERED PERPETUAL FLIGHT ACROSS THE WORLD

by

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ENDORSEMENT

I, Lim Guang Ming hereby declare that all corrections and comments made by the supervisor and examiner have been taken consideration and rectified accordingly.

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Date:

DECLARATION

This thesis is the result of my own investigation, except where otherwise stated and has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any other degree.

(Signature of Student)

Date:

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Path Planning Optimization for Solar-Powered Perpetual Flight across the World

ABSTRACT

Unmanned Aerial Vehicle (UAV) has been widely used for mapping purposes recently in the agricultural, military and geographic information fields which covered small area. Researches on the solar power management strategy and enhancement of mission profiles have been done by the researchers around the world to prolong the endurance (mission duration) of the UAV. The technologies and strategies studied show the possibility for an UAV to perform solar-powered perpetual flight for mapping purpose across the world. In this research, the factors affecting the solar-powered flight such as elevation, density and solar irradiance available are studied. A validated algorithm with overall error percentage less than 10 % is developed to simulate the solar-powered flight. Next, the detailed path planning is planned which allow an UAV to perform mapping mission at constant altitude, 600 m above the Earth's surface with minimized geometric error without fail. The successful flight pattern done by (Tan) which has covered latitude of ±66 º at various longitude is used in this research with the attempt to reach the global coverage. Different combination of launching location and date time are simulated and studied based on the solar irradiance available from different regions. The results of the study are determined and displayed in terms of the perpetuality for the perpetual flight across the world. The findings of the simulation show that the solar-powered flight has the highest perpetuality (24.7%) or highest endurance (24364 hours) by launching at longitude 115 W of North America region in January and February. Study on launching multiple UAVs should be carried out to further investigate the interest of completing a global coverage mission in a shorter duration.

Pengoptimuman Perancangan Laluan Pernerbangan bagi Penerbangan Berterusan Bertenaga Solar di Seluruh Dunia

ABSTRAK

Baru-baru ini, Pesawat Undara Tanpa Pemandu (UAV) telah digunakan secara meluas untuk tujuan pemetaan bagi bidang pertanian, ketenteraan dan geografi informasi yang meliputi kawasan kecil. Banyak penyelidikan megenai strategi pengurusan tenaga suria dan peningkatan profil misi penerbangan telah dijalankan oleh para penyelidik di seluruh dunia untuk memanjangkan daya tahan (durasi misi) UAV. Teknologi dan strategi yang dikaji telah menunjukkan kemungkinan sebuah UAV melaksanakan penerbangan berterusan dengan hanya bergantung pada tenaga solar untuk tujuan pemetaan di seluruh dunia. Dalam kajian ini, faktor-faktor yang mempengaruhi penerbangan bertenaga suria seperti ketinggian penerbangan, ketumpatan udara dan sinar matahari yang boleh didapati juga telah dipelajari. Algoritma yang disahkan dengan jumlah keseluruhan ralat peratusan kurang daripada 10 % telah diciptakan untuk mensimulasikan penerbangan bertenaga suria. Seterusnya, perancangan laluan penerbangan yang terperinci telah dirancangkan supaya membolehkan UAV melaksanakan misi pemetaan pada ketinggian penerbangan 600 m dari permukaan bumi dengan ralat geometri yang diminimalkan tanpa gagal. Perancangan laluan penerbangan (Tan) yang berjaya meliputi latitud ±66 º pada pelbagai longitud telah digunakan dalam penyelidikan ini dengan percubaan untuk mencapai liputan global. Kombinasi lokasi dan tarikh waktu pelancaran yang berbeza telah disimulasikan dan dikaji berdasarkan sinar matahari yang boleh didapati dari pelbagai kawasan di seluruh dunia. Hasil kajian juga telah disiasatkan dan ditunjukkan dari segi keterusan untuk penerbangan tanpa berhenti di seluruh dunia. Keputusan yang

didapati dari simulasi ini menunjukkan penerbangan bertenaga suria mempunyai perpetualiti tertinggi (24.7 %) atau daya tahan tertinggi (24364 jam) jika dilancarkan di longitud 115 W rantau Amerika Utara pada bulan Januari dan Februari. Kajian mengenai pelancaran pesawat-pesawat UAV harus dijalankan untuk menyiasat lebih lanjut mengenai melaksanakan misi perlindungan global dalam tempoh yang lebih singkat.

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LIST OF ABBREVIATIONS

UAV	: Unmanned Aerial Vehicle
SOC	: State of Charge
DEM	: Digital Elevation Model
2D	: Two Dimensional
GMT	: Greenwich Mean Time
LiDAR	: Light Detection and Ranging
LALE	: Low-Altitude Long-Endurance
NOAA	: National Centers for Environmental Information

LIST OF SYMBOLS

a_1	: Lapse Rate [$= -6.5 \times 10^{-3} K/m$]
T	: Temperature [°C or K]
h	: Altitude [km]
P	: Pressure [Pa]
g	: Gravitational Acceleration [9.81 m/s^2]
R	: Gas Constant [287 J K^{-1} kg^{-1}]
ρ	: Air Density [kg/m^3]
Ir	: Solar Irradiance [W/m^2]
EIr	: Extra-terrestrial Solar Ir1rdiance [W/m^2]
AM	: Air Mass Coefficient
$k_{Solar\ Margin}$	: Diffused Factor
r	: Distance between Sun and Earth [km]
DN	: Day Number
EOT	: Equation of Time
AST	: Apparent Solar Time
$SOLALT$	: Solar Altitude [°]
DEC	: Solar Declination [°]
FOV	: Field of View [°]
$V_{Power_{min}}$	: Minimum Power Velocity [m/s]
V_{Stall}	: Stall Speed [m/s]
W_{UAV}	: Weight of UAV [N]
b	: Wingspan [m]

S	: Wing Area [m^2]
C_L	: Lift Coefficient
C_D	: Drag Coefficient
C_{Dow}	: Parasitic Drag Coefficient
T_R	: Thrust Required [N]
P_R	: Power Required [W]
$P_{LevelFlight_i}$	: Power Required for Level Flight [W]
$P_{SolarGain_i}$	: Solar Power Gained [W]
P_{flow_i}	: Net Power Flow [W]
A_{Solar}	: Solar Panel Area [m^2]
$Panel_{eff}$	: Solar Panel Efficiency [%]
$MPPT$	: Maximum Power Point Tracking Efficiency [%]
$Battery_{Cap}$	: Battery Capacity [Wh]
V_{op}	: Operating Voltage [V]
Perpetuality	: Percentage of Blocks Covered [%]

CHAPTER 1

INTRODUCTION

In the early 1900s, the Unmanned Aerial Vehicle (UAV) technology has been introduced. At the pioneer stage of UAV technology, UAVs in terms of rotary and fixed wing either being controlled remotely or autonomously are mainly for military purposes such as surveillance and attack. As the UAV technology is continuing to advance, the UAVs have been widely used to perform a variety of environmental, commercial, and scientific services. For instance, monitor the agricultural conditions, spot the beginning and monitor the evolution of natural disasters and perform high-resolution surveillance (Colella and Wenneker, 1996).

Recently, UAVs are being manufactured to perform missions globally. A new UAV that operates as a satellite known as a pseudolite has been developed for the future UAV-based positioning system (Tsujii et al., January 2007). UAVs are relatively cheap, easily launched and readily updated compared to satellite (G. et al., 2005). In addition, UAVs are also being used to obtain the Earth spatial information with minimized geometric error and has the ability to capture topography under the treetop cover and overhanging banks (Miloš Rusnák, 2017, Zongjian, 2008). However, these global missions require a long-endurance UAV to perform perpetual flight which gives huge global coverage to collect and distribute data (Oettershagen et al., 2016).

Perpetual flight is defined as the continuous flight performed by an aircraft throughout the days and nights without the need of landing. In this research, a small solar-powered UAV is used to study the possibility to perform perpetual flight solely based on solar irradiance and flight path optimization to provide sustainable power supply. It is proven that the combination of solar energy and rechargeable batteries can provide the UAV to achieve long endurance (Oettershagen et al., 2016). Also, with the aid of solar power management strategy and enhanced mission profile, the endurance of the UAV with reduced weight is increased effectively (Rajendran et al., 2016, Hosseini et al., 2013).

The intensity of solar irradiance is the major factor that affects the power production of Photovoltaic cells (Rajendran P, 2014). The coordinate of a given area on Earth also have effect on solar irradiance. It is found that the area within latitude +30° to -30° at various longitudinal position (Central region of the Earth) has sufficient solar irradiance and daylight duration which strengthen the potential of perpetual solar-powered flight. However, the regions with latitude more than ±35° including the northern and southern hemispheres are incapable of continuous flight all year round due to less solar irradiance available for longer period (Rajendran P, 2014, Rajendran and Smith, 2015a).

Various researches had been done on UAV path planning which had proved to enhance the endurance and flight performance without overlapped coverage. However, these researches are mainly focused on small area but not worldwide. In this paper, the possibility of perpetual solar powered flight over the land area which range from latitude of +82° to -146° covering the world excluding Antarctic region are studied with the prepared solar irradiance and elevation database.

In order to increase the accuracy of the simulation, factors affecting the solar power available are necessary to be taken into considerations. For example, the flight altitude, flight location and flight path (Rajendran and Smith, 2015a). The UAV is also required to fly at constant altitude relative to the Earth's surface as to ensure consistent high resolution mapping image and stable signal range with the aid of enhanced mission profile.

The simulation is done using MATLAB and the essential parameters are collected in order to determine the best launching time throughout the year at various locations. The status of battery is the key to determine the endurance of the solar powered flight as it should not be lower than State of Charge (SOC) 25% at any time. As the SOC is dropped lower than 25%, it indicates the UAV mission has to be stopped for maintenance.

1.1 Problem Statement

This research is a continuous work with referring to the work done by (P. Rajendran, M. H. Masral and H. A. Kutty, 2017) and (C. H. Tan, 2017) which have only studied the solar irradiance up to the main cities and latitude of ±66° around the world. Also, an UAV design which is sufficient to perform perpetual flight is stated.

Hence, it is essential to extend the work to study the possibility of the perpetual flight across the world to be done fully depending on the solar irradiance available and the best launching time to launch the solar-powered UAV at various locations around the world to give the highest endurance or perpetuality.

1.2 Research Objectives

The research work in this thesis is performed based on the following objectives:

1) To study the solar irradiance available in different regions at different time for sustainable solar-powered perpetual flight purpose.

2) To develop a validated solar-powered flight algorithm with error percentage less than 10%.
3) To study the best launching time to launch a solar-powered UAV at various locations across the world to enhance the endurance and perpetuality.

1.3 Thesis Layout

This thesis consists of 5 main chapters: Introduction, Literature Review, Methodology, Results and Discussion, and Conclusion. The Chapter 1 describes the overview of solar-powered UAV, problem statement and objectives of this research work. Chapter 2 shows the information extracted from the researches and studies done on the solar-powered UAV and long endurance solar-powered flight.

Chapter 3 is divided into 5 main sections: Data Preparation, Data Modelling, Validation, Designed Flight Path and Main Algorithm. The methods on preparing global elevation and solar irradiance data are further elaborated in Data Preparation section. For Data Modelling section, the mathematical equations and approaches taken from using the power consumption and solar irradiance data to generate the battery SOC are described. Then, the algorithms are validated with the research work done by (Oettershagen et al., 2016). Next, the flight path used is described in the Designed Flight Path section. In the last section of the chapter, the main algorithm is elaborated on the way to execute the simulation and evaluate the performance of solar-powered flight.

In Chapter 4, the results obtained through computing, validation and simulation are further discussed. Valid reasons and justifications are also stated based on the findings. Lastly, the findings of the thesis are concluded and future work recommendations are suggested in Chapter 5.

CHAPTER 2

LITERATURE REVIEW

The solar-powered UAV is one of the ambitious technologies being researched around the world as it is believed to have prolonged and enhanced endurance. Several approaches have been done to achieve solar powered flight duration more than 24 hours (Park et al., 2015, Romeo et al., 2007, Shiau et al., 2010, Oettershagen et al., 2016). The achievements show that the perpetual flight depending on solar power is possible. A solar-powered UAV uses renewable energy source, solar power to supply adequate energy to perform flight without carbon or nitrogen emissions. In addition, the high endurance enables an UAV to perform huge coverage missions or even perpetual flight with minimum maintenance or without maintenance at all. Hence, it is necessary to look further into the factors that affecting the endurance of a solar-powered UAV.

The literature review section is further discussed in the following 3 sections which are Solar Power Management, Enhanced Mission Profile and Path Planning.

2.1 Solar Power Management

Solar irradiance is essential for a solar cell to generate energy. The daylight duration is more important compared to the solar irradiance intensity (Gao et al., 2013, Rajendran P, 2014). However, it is necessary to have both long daylight duration and high solar irradiance intensity for solar module system to give the most power output (Rajendran P, 2014). The study on the real time solar irradiance and proper power management are essential to provide sustainable power supply for the perpetual flight.

Factors affecting the solar power available such as the flight altitude, flight location, flight path and more must be taken into account (Rajendran and Smith, 2015a). According to the studies, the SOC of battery should be best within 25% to 90% as to maintain the health of battery (Rajendran et al., 2016, Smith and Rajendran, 2014, Rajendran and Smith, 2013, Rajendran and Smith, 2015b). Therefore, the SOC throughout the solar-powered flight should not drop below 25%.

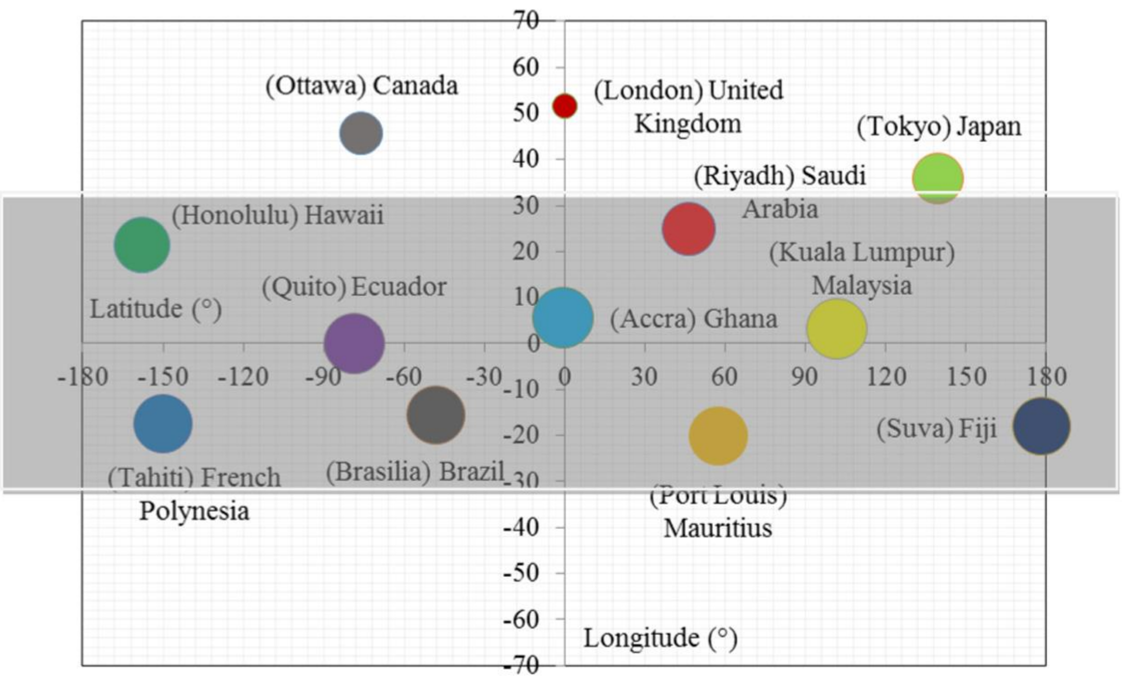

Figure 2.1: Optimal region in the world for the operation of solar-powered UAVs (P. Rajendran, H. Smith, 2015)

Figure 2.1 shows the study on the solar power available in the main cities across the world done by P. Rajendran (2015). The study has shown that the cities or locations within the latitude of ±30° at various longitude are suitable for solar-powered UAV flight all year round (Rajendran and Smith, 2015a). However, the perpetual solar-powered flight global mission is required to cover the world more than the latitude of ±30°. Hence, the enhanced mission profile and path planning are crucial to compensate the solar irradiance issues at the locations which latitude are more than ±30°.

Besides, the study on the Earth's season is important. The Earth revolves around the Sun throughout a year. The Earth is inclined at an angle of 23.5° and it has 4 seasons caused by the different locations of Earth respect to the Sun. The situation is often illustrated as Figure 2.2.

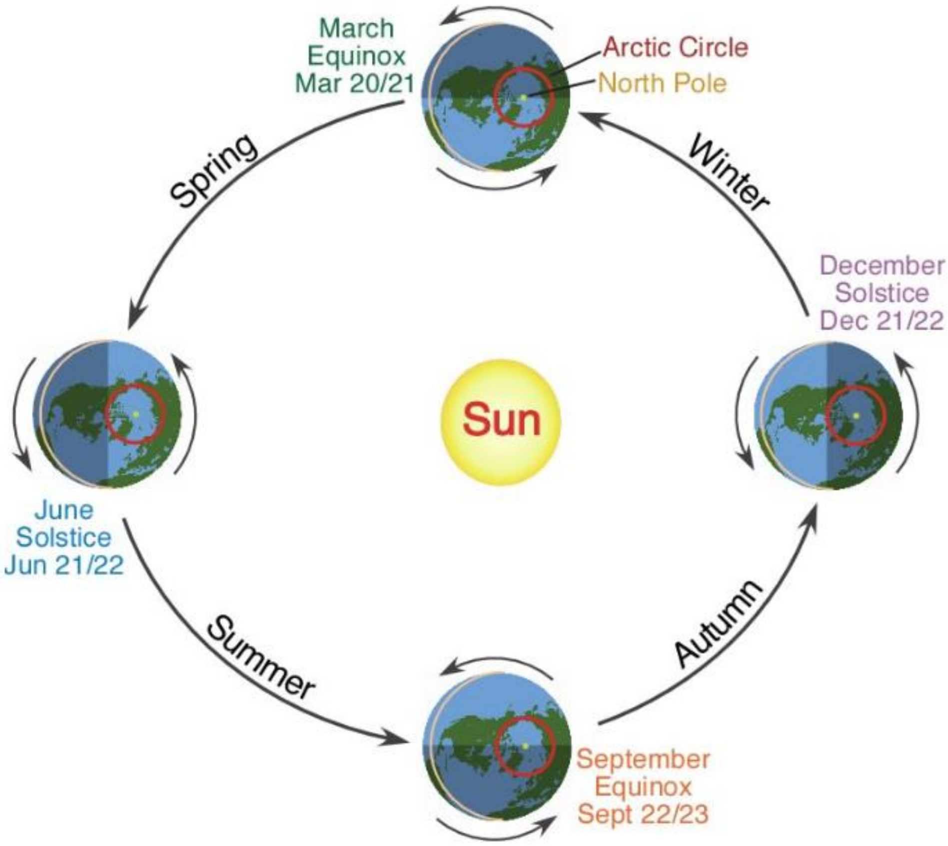

Figure 2.2: Earth's position in the 4 seasons

Retrieved from: goo.gl/qwTd8J

According to the phenomenon, the total daylight duration and solar irradiance across the world varies according to the date and time. When a region either Northern or Southern hemisphere experiences spring, the daytime duration is longer and the nighttime duration is shorter or winter, the daytime duration is shorter and the nighttime duration is longer. This situation is vice versa in both the hemispheres, or in another words, the Northern hemisphere is experiencing summer when the Southern hemisphere is experiencing winter.

Generally, the Northern hemisphere experiences longer daytime and the Southern hemisphere experiences shorter daytime around the month of June. Hence, considering for a solar-power UAV perspective, it is more favourable to perform solar flight in Northern hemisphere region around June. On the contrary, the Northern hemisphere experiences shorter daytime and the Southern hemisphere experiences longer daytime around the month of December. Hence, it is more favourable to perform solar flight in the Southern hemisphere region around December. However, the Earth experiences precession which can causes the summer and winter solstice to be occurred on earlier date than the mentioned date in Figure 2.2. The time of summer and winter solstice might get changed from year to year due to precession and hence, it is necessary to study the solar irradiance in the interested year of solar-powered flight mission.

2.2 Enhanced Mission Profile

The study shows that enhancing on the mission profile of solar-powered UAV can improve the power management (Rajendran et al., 2016). In another words, the power usage is decreased with better mission profile. The enhanced mission profile is further explained in 3 sections which are climbing, cruising and unpowered gliding. The UAV uses excess energy to increase its altitude in the ascending phase. Hence, the climbing and banking angle of an UAV must be studied to determine its best climbing and banking angle to reach a desired altitude at acceptable speed while consuming the least power. A positive net energy can be harvested if performed climbing which consumed less power during daytime. For a cruise flight, the UAV is able to discharge the battery with minimum power required to sustain a level flight. For unpowered gliding, an UAV should descend at the minimum sink rate by flying at maximum $\frac{C_L^{\frac{3}{2}}}{C_D}$. The 72-hour perpetual flight simulation have been done successfully without SOC being dropped lower than 40% by implementing the enhanced mission profile as mentioned above. (Rajendran et al., 2016).

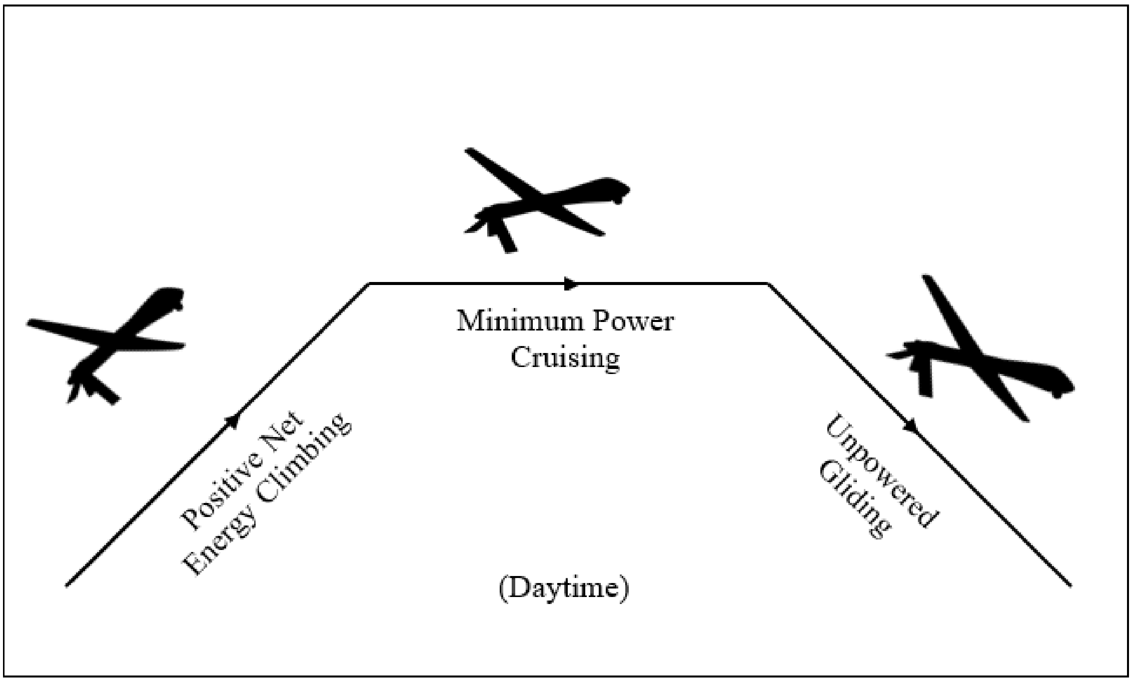

Figure 2.3: Enhanced mission profile in daytime

The cruising speed is a crucial parameter as it determines the mission duration and power consumption. The UAV performed cruising speed of 45 km/h throughout its perpetual flight mission successfully without reaching any SOC dropped below 25% (Tan, 2017). However, there is no exact fixed optimum cruising speed. The cruising speed is highly depended on the density and it must be varied according to the elevation. As the cruising speed varies due to elevation, the UAV is believed to perform solar-powered flight better by having lesser power consumption with shorter mission completion duration.

Besides, by implementing proper mission profile, the battery weight can also be reduced up to 75%. Theoretically, the reduced overall weight of UAV allows the level flight to be carried easily. However, the trend shows that using larger battery capacity will have lowest point of SOC reached (Tan, 2017). Therefore, it is necessary to have large battery capacity for a solar powered perpetual flight. Hence, there is a need to utilize the enhanced mission profile and select a suitable battery capacity to prevent having unacceptable extra weight from the batteries.

In a nutshell, the combination of solar power management and enhanced mission profile is able to increase the endurance of the UAV effectively with the reduced weight (Rajendran et al., 2016, Hosseini et al., 2013).

2.3 Path Planning

Various researches have been done on the UAV path planning to enhance the endurance and mission performance (Singh and Sujit, 2016, González et al., 2017, Zhang et al., 2011). However, most of the researches simulate or launch the solar powered flight in small region only. The detailed path planning is able to reduce the flight duration and distance effectively as well as to avoid obstacles with the reference to the Earth's topography or environment scenario (Singh and Sujit, 2016, González et al., 2017, Zhang et al., 2011). In Tan's work, 2 flight paths have been proposed. The flight path B is a successful perpetual solar-powered flight path which covered the land regions excluding the Arctic and Antarctic regions (Tan, 2017). The flight path B is a zig-zag flying pattern which covers the world section by section. The flight path B is illustrated as the Figure 2.4.

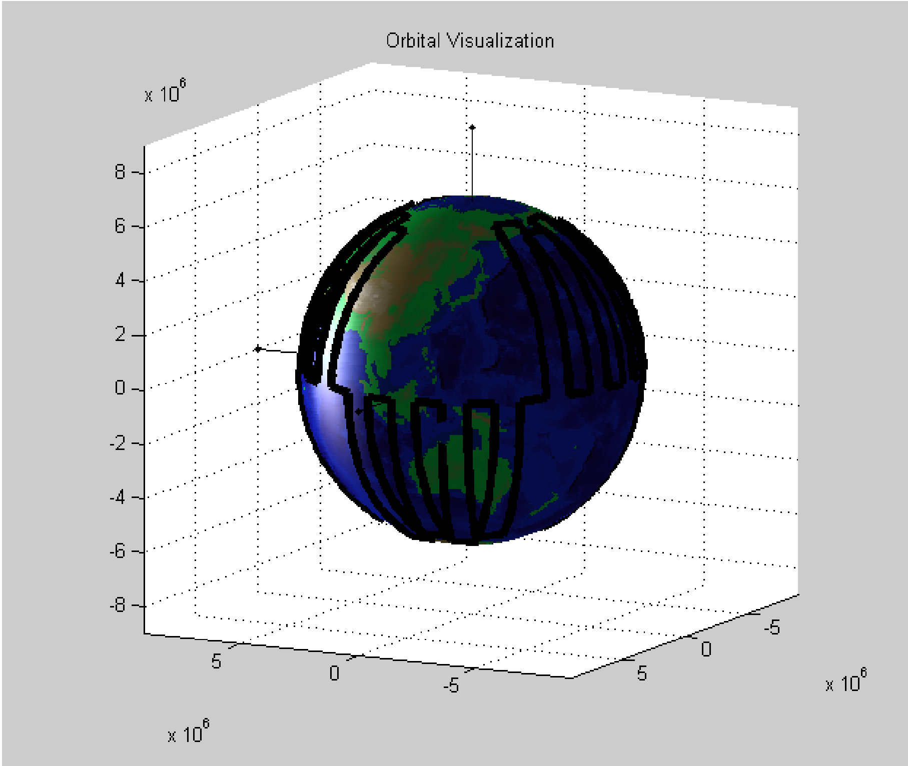

Figure 2.4: Flight path B with zig-zag flying pattern

The Figure 2.5 shows the initial method used by Tan is by dividing the world into 4 sections. However, it is found out that the best solar-powered flight path is to divide the world into 7 sections. The world map is divided evenly into 7 sections with each section having the Northern and Southern hemisphere. The UAV will visit from section to section (refer to the coloured sections). This method is able to avoid the UAV to perform mission in the period of insufficient solar irradiance in certain regions such as Northern and Southern hemispheres for a long time (Tan, 2017).

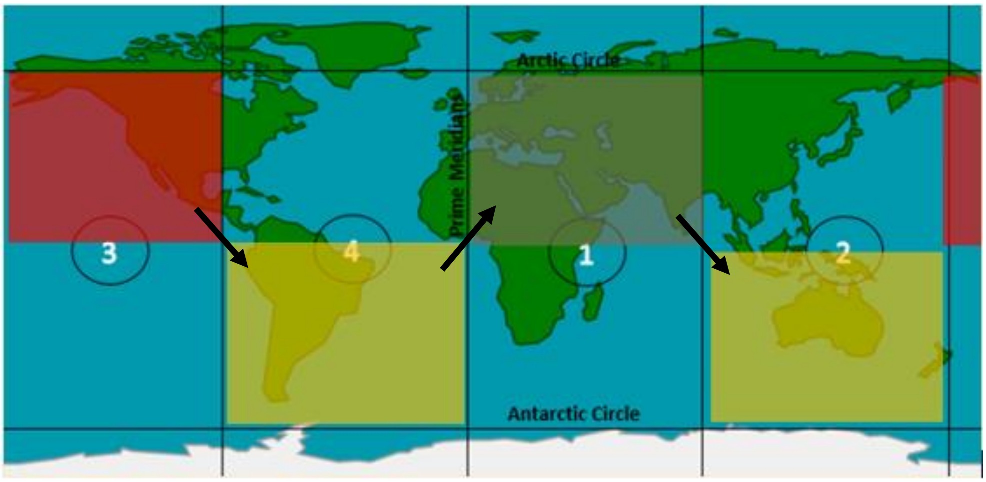

Figure 2.5: World map with 4 sections

This zig-zag flying pattern mentioned above has given the solar-powered UAV an ability to cover the major land regions with an average SOC of 92.13 %. Also, the minimum point of SOC reached is only 63.27 %. The result is encouraging that the solar-powered UAV is able to cover huge coverage and maintain the SOC of battery at the healthy range at the same time.

CHAPTER 3

METHODOLOGY

This chapter presents the methods of data preparation and mathematical models used and developed to carry out the validation and numerical simulation. A validation is done by comparing the results obtained from the algorithms developed with the experimental and simulation results from the journal. The validated algorithms is then used to simulate the world solar powered-flight.

The overall project flow can be illustrated as the flow chart below:

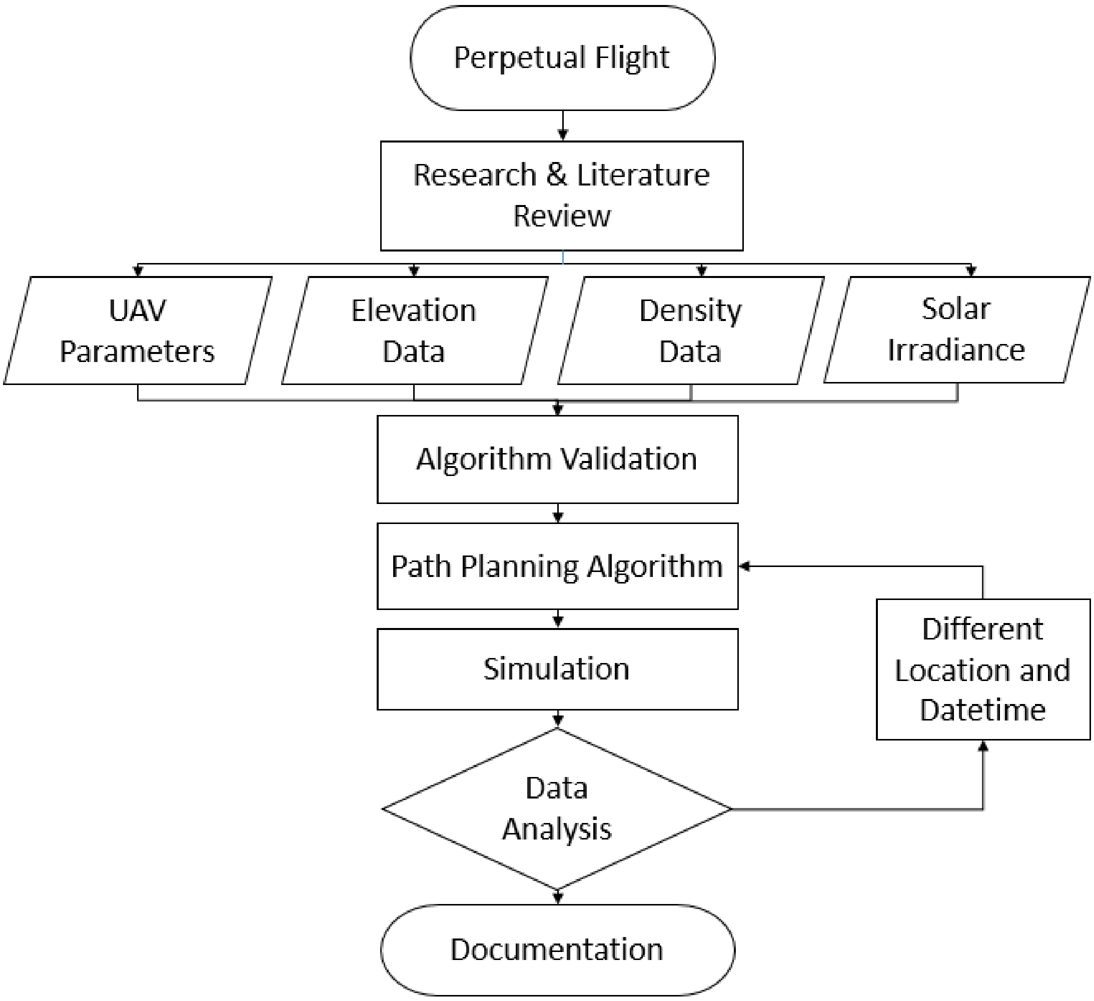

Figure 3.1: Overview of project flow chart

3.1 Data Preparation

The database for world average elevation, world density and world solar irradiance available are generated before the validation and main simulation. The database are generated with the aids of MATLAB and Excel software. In this section, the methods in preparing the database are described in detail:

3.1.1 Digital Elevation Model (DEM)

The world Digital Elevation Model is the essential data for this research work. As mentioned in Chapter 2, elevation is the key factor that affect the cruise flight altitude as well as the solar irradiance. Hence, it is necessary to obtain the accurate DEM from a trusted source. The world DEM files with longitude of ±360° and latitude of ±180° which are downloaded in the '.hgt' format are obtained from the website (http://www.viewfinderpanoramas.org/dem3.html). A total of 70GB files are downloaded in order to obtain the full global DEM. The DEM are then extracted from the '.hgt' format files using MATLAB. The coding scripts – readhgt.m and Elevation_Extraction.m that are used to extract the elevation data are available in Mathworks website. Then, the extracted elevation data is plotted in Microsoft Excel in a 180x360 2D array using xlsfile.m.

Each DEM includes the data of topography and elevation covering 1° of latitude and 1° of longitude (1° block). In this research, the average elevation data of each 1° block is used for generating the necessary data: Density and Solar Irradiance. Also, the average elevation is used to determine the flight altitude.

3.1.2 Density Data

Density is a crucial parameter to determine the flight speed which affects the mission power consumption. Meanwhile, density is a function of the elevation. Therefore, it is important to prepare an accurate global elevation database. The reason to prepare a global density database is to speed up the iteration process in a huge data generating coding.

The density are calculated based on the elevation data available using the formula obtained in “Introduction to Flight” (John D. Anderson, 2016). Theoretically, the temperature decreases when the elevation increases at the altitude less than 80km. As the highest peak in this world is Mt. Everest which is 8.85 km above the sea level, the UAV mission will only involve the altitude below 10 km.

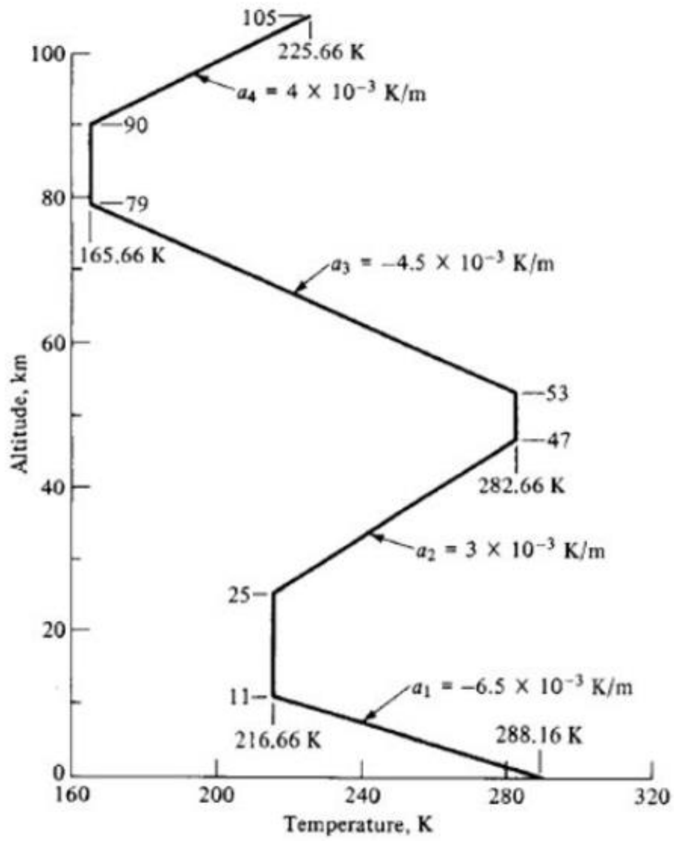

Figure 3.2: Temperature distribution in the standard atmosphere

Referring to the Figure 3.2, the temperature below 10 km is considered falling at the gradient region, $a_1 = -6.5 \times 10^{-3} K/m$ and not treated as isothermal. Hence, the temperature of any altitude below 10 km is the sum of the sea level temperature and the product of lapse rate (a_1) and the difference between altitude and sea level altitude. Or, the equation is illustrated as equation (1):

$$T_{Elevation} = T_{SeaLevel} + a * (h_{Elevation} - h_{SeaLevel}) \tag{1}$$

Considering the hydrostatic equation, the lapse rate is further integrated and yields equation (2).

$$P_{Elevation} = P_{SeaLevel} * \left(\frac{T_{Elevation}}{T_{SeaLevel}}\right)^{-\left(\frac{g}{a*R}\right)} \tag{2}$$

The density is finally calculated using the equation of state which the pressure and temperature at specific elevation are known.

$$\rho = \frac{P_{Elevation}}{R * T_{Elevation}} \tag{3}$$

3.1.3 Solar Irradiance Data

After the global elevation database is prepared, the launching year of solar-powered flight is then determined – year 2015 (Algorithm Validation with Journal) and year 2019 (Simulation). MATLAB is used to generate the solar irradiance available. The solar irradiance and daylight duration are generated referring to the Solar Radiation and Daylight Models (Rajendran and Smith, 2016, Muneer and and Kambezidis, 1997).

The actual solar irradiance reached on Earth's surface is the product of the extra-terrestrial solar irradiance (before being disturbed by the Earth's atmosphere) and the disturbing factor due to air and Earth's atmosphere.

$$Ir = EIr * k_{Solar\ Margin} * AM \tag{4}$$

The model begins by determining if the given date falls on a leap year using equations (5 and 6).

$$LeapYear\ =\ True \quad if(4 \times floor(0.25Year) > Year) \tag{5}$$

$$\begin{aligned} &LeapConst\ =\ 62; \quad if(LeapYear = True) \\ &LeapConst = 63; \quad if(LeapYear) = False) \end{aligned} \tag{6}$$

Then, the LeapConst is used to determine the general number of days elapsed in the given year, *DayNo* based on the month using equation (7).

$$\begin{aligned} &Day\ No = Day + floor\big(0.5LeapConst(Month - 1)\big); \qquad if\ Month = 1 \\ &DayNo\ =\ Day + floor(30.6(Month + 1) - LeapConst; \quad if\ Month > 2 \end{aligned} \tag{7}$$

The day number is further corrected based on the location and distance between the Sun and the Earth, *r* (equation (8)) and the altitude of the location (AltGeo) to determine a more precise day number, DN using equation (9).

$$r = 1.496 \times 10^8 \left(1 + 0.017 \sin\left(\frac{DayNo - 93}{365} \times \frac{360\pi}{180}\right)\right) \quad (8)$$

$$DN = sin^{-1}\left(\frac{\left(\frac{r + AltGeo}{1000 \times 1.496 \times 10^8} - 1\right)}{0.017}\right)\left(\frac{180}{\pi}\right)\left(\frac{365}{360}\right) + 93 \quad (9)$$

Next, the solar time functions are necessary to be determined. The solar time function parameters are the local time (equation (10)), equation of time, EOT (equation (11)) and the apparent solar time, AST (equation (12)). The local time of a day is calculated in the unit of hour.

$$LocalTime = Hour + \left(\frac{Minutes}{60}\right) + \left(\frac{Seconds}{3600}\right) \quad (10)$$

The EOT and AST are the times used in all solar geometry calculations. These parameters apply the corrections due to the difference between the longitude of the given locality and the longitude, LONG of the standard time meridian.

$$EOT = 0.1236 \sin\left(\frac{360(DN-1)}{365.242\left(\frac{\pi}{180}\right)}\right) - 0.0043 \cos\left(\frac{360(DN-1)}{365.242\left(\frac{\pi}{180}\right)}\right) + 0.1538\, sin\left(\frac{(2)360(DN-1)}{365.242\left(\frac{\pi}{180}\right)}\right) + 0.0608\, cos\left(\frac{(2)360(DN-1)}{365.242\left(\frac{\pi}{180}\right)}\right) \quad (11)$$

$$AST = LocalTime + \frac{LONG - 15\, GMT}{15} + EOT \quad (12)$$

In this research, the Greenwich Mean Time, GMT is treated to be distributed evenly across the longitudes. In another words, there will be difference of 1 hour in time zone for each 15° changes of longitudes across the world. Figure 3.3 shows the relationships between longitudes and time zone.

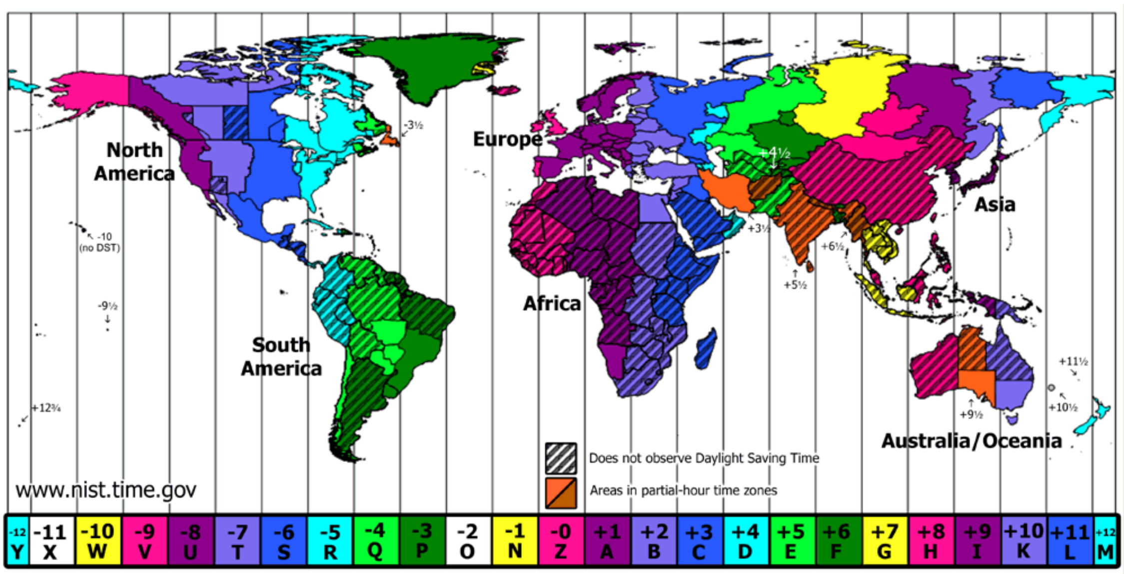

Figure 3.3: Normal GMT world map

Apart from the solar time function parameters, the solar altitude, SOLALT and solar declination, DEC are necessary to be determined. The solar declination, DEC is the angle between Earth-Sun vector and the equatorial plane. DEC is considered to be positive when the Earth-Sun angle vector lies northwards of the equatorial plane as shown in Figure (3.4).

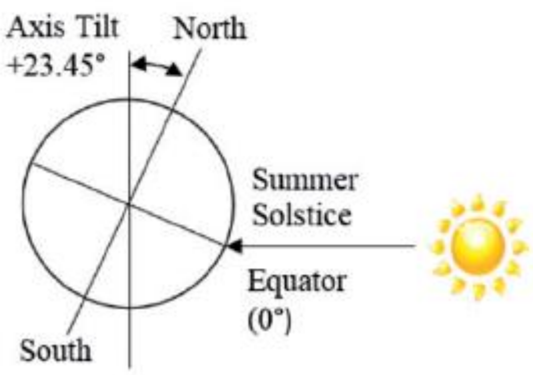

Figure 3.4: Earth-Sun vector

$$DEC = \frac{180}{\pi} sin^{-1}(0.3979 \sin((0.017203(DN + 284)) + 0.007133 \sin\left((0.017203(DN + 284)\right) + 0.03268 \cos(0.017203(DN + 284)) - 0.000318 sin2(0.017203(DN + 284)) + 0.000145 cos2(0.017203(DN + 284))\right) \quad (13)$$

Solar altitude, SOLALT is the angle of the Sun relative to the Earth's horizon. The solar altitude varies based on the time of the day, the time of the year and the latitude on Earth. The value of the SOLALT will also affect the intensity of the extra-terrestrial solar irradiance. Referring to the Figure 3.5, the SOLALT is highly affected by the DEC. With the known DEC value, the SOLALT at varies latitude at different time can be found using equation (14):

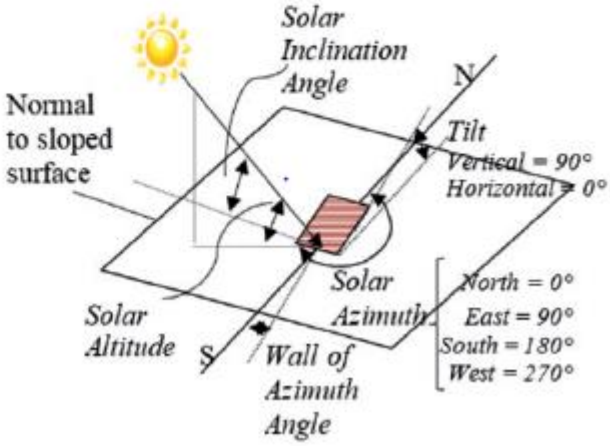

Figure 3.5: Solar geometry of a sloped surface

$$SOLALT = \frac{180}{\pi} sin^{-1}(\sin\left(LAT\frac{\pi}{180}\right)\left(\sin\left(DEC\frac{\pi}{180}\right)\right) - \cos\left(LAT\frac{\pi}{180}\right)\cos\left(DEC\frac{\pi}{180}\right) \times \cos\left(15AST\frac{\pi}{180}\right) \quad (14)$$

The Extra-terrestrial Solar Irradiance, EIr is defined as the maximum intensity of the solar power at the top of the Earth's atmosphere which is not disturbed by any disturbance from the Earth's atmosphere. The EIr can be calculated based on equation (15).

$$EIr = 4.8708 \times \frac{\left(1 + 0.033\cos\left(0.017203DN\frac{\pi}{180}\right)\right)\sin\left(SOLALT\frac{\pi}{180}\right)}{3600} \quad (15)$$

As the solar radiation passes through the Earth atmosphere, some of the solar radiation are scattered out by clouds, water vapour, air molecules and aerosols. Therefore, the air mass coefficient, AM of 1.5 and diffused factor, $k_{Solar\ Margin}$ of 0.7 (A et al., 2008) are used to estimate the actual solar irradiance, Ir reaching the ground. In a nutshell, the Ir can determined by substituting the known values into equation (4).

As this research is aimed to find the suitable launching time, the solar irradiance available of each month in year 2019 will be generated and further discussed. The study is necessary as to avoid the solar-powered UAV to perform mission in the period which Arctic and Antarctic have lesser daytime duration and solar irradiance.

3.1.4 Overview of Solar Irradiance Algorithm Coding

The overview of the Solar Irradiance Algorithm coding to generate the solar irradiance available throughout the year of 2019 is summarized in the Table 3.1. Besides, the Solar Irradiance Algorithm coding is also illustrated as flowchart in section Appendix C. The algorithm is able to be adjusted accordingly to find out the solar irradiance available in the interested location (latitude and longitude) or at interested time (year, month, day, minute and second).

Table 3.1: Overview of solar irradiance algorithm coding

```
Input: Year, World Elevation Data and Distance between Sun and Earth

Determine the Leap Year based on equation (5) and (6).

for Longitude = -179:180

    Define Timezone by using Timezone function in MATLAB

    for Latitude = -89:90

        Define the current AltGeo based on the elevation data base.

        for Month = 1:12

            if Month==2
                AA=28;
            elseif Month == 4 || Month == 6 || Month == 9 || Month == 11;
                AA=30;
            else
                AA=31;
            end

            for Day = 1:1:AA;

                for Hour = 0:23

                    Minutes = 0;
                    Seconds = 0;
                    Determine DayNo.
                    Compute the r and DN.
                    Compute the Local Time, Equation of time, and the Apparent Solar
                    Time.
                    Compute the Solar Declination Angle.
                    Compute the Solar Altitude.
```

```
                Compute the Extra-terrestrial Irradiation.
                Compute Solar Irradiance Available.

            end

         end

      end

   Store Solar Irradiance data with reference to the Longitude and Latitude

   end

end

Output: Solar Irradiance Available
```

The output, Solar Irradiance Available data are stored in a 3D array with reference the Date Time, Longitude and Latitude. This is a necessary format as the solar irradiance available is highly affected by the world elevation data used earlier. The solar irradiance database is then being used for validation and main algorithm purposes.

3.2 Mathematical Models

3.2.1 Mission Altitude

The mission altitude is determined before calculating the cruise speed. This is highly affected by the mission requirements and the specification of telemetry signal strength or the specifications of the high resolution camera. In this research, the interest is to obtain the terrain topographic mapping. The high resolution camera with Light Detection and Ranging, LiDAR sensor is assumed to be used in this simulation. LiDAR sensor provides impressive 3D topographic mapping with resolution down to 1-3 inches per pixels. Every LiDAR sensor has its operating range. Thus, the flight altitude of the UAV can be determined using the ground sample distance method if equipped with high resolution camera or depending on the operating range of the LiDAR sensor used.

Generally, the mapping UAV (Airbus Zephyr) flies at high altitude such as 18 km height to obtain higher coverage area. However, considering the UAV design used in this simulation is small and interested to obtain more detailed topographic model, the UAV is assumed to fly at 0.6 km above from the Earth's surface using a high-end LiDAR sensor with the ability to obtain precise and high resolution of topographic model. The reason to perform mission at 0.6 km altitude is to prevent the performance of LiDAR sensor to be affected by the cloud. The clouds normally appear at the height between 2 km to 6 km above the Earth's surface. By performing mapping at 0.6 km above the Earth's surface, the mapping mission elevation on most of the land regions will still remain less than 2 km. Hence, at most of the time, the mapping mission will not be disturbed by the clouds.

Undeniably, the altitude of the mission is highly dependent on the type of mission to be carried out and the specification of the payload. Some powerful advanced payloads allow the UAV to fly at the altitude above the clouds and still providing desired results.