GLOBAL PATH PLANNING FOR SOLAR-POWERED UAV

by

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ENDORSEMENT

I, Abdul Aniq Aqil bin Abd Wahab 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: 6 July 2021

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Date: 6/7/2021

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: 27/6/2021

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GLOBAL PATH PLANNING FOR SOLAR-POWERED UAV

ABSTRACT

The unmanned aerial vehicle (UAV) is widely use nowadays due to its functionality and capable of undergoes many types of mission. The solar-powered unmanned aerial vehicle (SUAV) is preferable over conventional UAV as it provide high-level of sustainability and endurance. This solar-powered UAV need comprehensive mission planning to make sure that it has enough power to sustain a perpetual flight. In this research, a simulation using MATLAB to test various optimal flight path pattern for UAV is configurated and analyzed, then a best flight pattern to sustain a continuous mission will be selected. The study of daylight duration and solar irradiance on earth is included in this research to plan a best flight path in term of endurance. The simulated solar-powered UAV is maintained at 100 m above ground level and fly at minimum cruise velocity throughout the mission. The simulation is carried out by creating a hexagonal discrete global grid over the 0.03% of earth map and testing as many as possible path in each hexagon cell. The path is pre-determined, and the hexagon cell is generated by declaring the points on side of hexagon shape based on latitude-longitude coordinates system of earth. The path is further analyzed to find best path for UAV in term of least distance travelled and longest flight time or perpetual flight with most SOC state. Overall, the horizontal systematic path pattern emerges as the best systematic path pattern as for the horizontal path pattern the percentage of usage is the highest which at 88% compared to diagonal path pattern which only at 12%.

PERANCANGAN LALUAN GLOBAL UNTUK UAV SOLAR

ABSTRAK

Kenderaan udara tanpa pemandu (UAV) digunakan secara meluas pada masa kini kerana fungsinya dan mampu menjalani banyak jenis misi. Kenderaan udara tanpa pemandu bertenaga solar (SUAV) lebih disukai daripada UAV konvensional kerana ia memberikan tahap kesinambungan dan daya tahan yang tinggi. UAV bertenaga solar ini memerlukan perancangan misi yang komprehensif untuk memastikan ia mempunyai kekuatan yang cukup untuk melakukan penerbangan secara berterusan. Dalam penyelidikan ini, simulasi menggunakan MATLAB untuk menguji pelbagai pola jalur penerbangan yang optimum dimana UAV telah dikonfigurasi dan dianalisis, maka corak penerbangan terbaik untuk misi penerbangan secara berterusan akan dipilih. Kajian mengenai jangka waktu siang dan cahaya matahari di bumi termasuk dalam penyelidikan ini untuk merancang laluan penerbangan terbaik dari segi daya tahan. UAV berkuasa solar yang disimulasikan dikekalkan terbang pada ketinggian 100 m di atas permukaan tanah dan terbang dengan kecepatan pelayaran minimum sepanjang misi. Simulasi dilakukan dengan membuat grid global diskrit heksagon di atas 0.03% peta bumi dan menguji seberapa banyak laluan penerbangan di setiap sel heksagon. Laluan ditentukan terlebih dahulu, dan heksagon dihasilkan dengan menyatakan titik-titik di setiap sisi heksagon berdasarkan sistem koordinat garis lintang-bujur bumi. Laluan dianalisis denagn lebih lanjut untuk mencari jalan terbaik untuk UAV dari segi jarak perjalanan yang paling sedikit dan waktu penerbangan terpanjang atau penerbangan kekal dengan keadaan SOC yang baik. Secara keseluruhan, corak jalur sistematik mendatar muncul sebagai pola jalan sistematik terbaik kerana bagi corak jalur mendatar peratusan

penggunaan adalah yang tertinggi iaitu pada 88% berbanding dengan corak jalur pepenjuru yang hanya pada 12%.

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LIST OF ABBREVATIONS

UAV : Unmanned Aerial Vehicle

SUAV : Solar-powered Unmanned Aerial Vehicle

DGGS : Discrete Global Grid System

SAA : Stimulate Anneal Arithmetic

SOC : State-of-Charge

RRTs : Rapidly-exploring Random Trees

PRMs : Probabilistic RoadMaps (PRMs)

VGs : Visibility Graphs

ACA : Ant Colony Algorithm (ACA)

PSO : Particle Swarm Optimization

CSPSO : Chaotic and Sharing-Learning Particle Swarm Optimization

IFDS : Interfered Fluid Dynamical System

RIFDS : Restrained IFDS

WOA : Whale Optimization Algorithm

IWOA : Improved Whale Optimization Algorithm

BR : Bot-Right

BL : Bot-Left

TR : Top-Right

TL : Top-Left

DBR : Diagonal-Bot-Right

DBL : Diagonal-Bot-Left

DTR : Diagonal-Top-Right

DTL : Diagonal-Top-Left

LIST OF SYMBOLS

T	: Atmospheric temperature
a	: Altitude
ρ	: Air density
g_0	: Gravitational acceleration
R	: Gas constant
DN	: Precise day number
EOT	: Equation of time
AST	: Apparent solar time
GMT	: Greenwich mean time
DEC	: Solar declination angle
$SOLALT$	: Solar altitude
LAT	: Latitude
EIr	: Extra-terrestrial solar irradiance
$k_{solar\ margin}$	: Diffused factor
AM	: Air mass coefficient
$V_{min\ power}$	: Velocity at minimum power consumption
W	: Weight
S	: Area of wing

C_{D0} : Coefficient of drag at zero lift

AR : Aspect ratio

e : Oswald 's efficiency

Ir : Solar irradiance

r : Solar panel efficiency

MPPT : Maximum power point tracker efficiency

P_{gained} : Power gained

$P_{required}$: Power required

P_{net} : Net power flow

CHAPTER 1

INTRODUCTION

1.1 Research background

In this era of modernization, unmanned aerial vehicle (UAV) are promptly developing into different forms with different functionality. The UAV has assisted mankind in many ways such as search and rescue missions, agriculture, military, weather forecasting, land surveying and even video making. This project focused on the idea to launch perpetual solar UAV (SUAV) around the world. This UAV have to be capable of utilizing sunlight energy to fly during the day and amass the excess energy in battery for night operation (Tan & Rajendran, 2019). For the UAV to maintain it perpetual flight, a good energy optimization of solar cell (M. Wu et al., 2019) and power management system (Chen et al., 2015) plays a major role.

Aircraft path planning is crucial for UAV navigation. The path planning is a task to find an optimal path of the UAV to conduct its mission from starting point to the target point based on its performance indicators (Lu et al., 2018), for example the shortest flying time or flying distance. The path planning is divided into two types which are local path planning and global path planning (Biswas et al., 2021). Firstly, the local path planning is planning which use the path that is generated by collecting data from sensors during the movement of robot or the UAV (Biswas et al., 2021). Besides, the global path planning is a path planning which require the start along with target location in a constructed map or global map where the environment is static to evaluate an initial path (Lu et al., 2018). The path planning that used in this research is a global path planning.

For the path planning to be successful, there are four essential criteria that must be considered which are the optimization, completeness, accuracy or precision and lastly the execution time (Biswas et al., 2021). The optimization make sure that the chosen solution is the best path in term of its performance indicators such as distance, cost and time consumption. For the completeness criteria, the path planning algorithm must be capable of providing all possible solutions for the path. Next, the accuracy or precision is to lead all states from origin to get to the goal states. Lastly, the objective of the execution time is to ensure the best-case setting for controlling the problem given.

For the path planning, the UAV must be pre-selected, thus the analysis on the solar-powered UAV that have been used globally is crucial for this research. The UAV can greatly increase their flight range with the use of high efficiency solar cells installed directly on its wings which also help in reducing the weight to minimum and maintain the proper aerodynamics of the UAV. Table 1.1 is a list of solar-powered UAV that has been built globally.

Table 1.1:Solar-powered UAV built globally.

Year	Model	Country	Power Source	Endurance (Hours)
2010	Zephyr 2010 (Colomina & Molina, 2014)	USA	Battery, solar power	336
2013	Silent Falcon UAV (R. et al., 2017)	USA	Battery, solar power	500
2015	Eav-3 (Rajendran et al., 2017)	Korea	Battery, solar power	9
2015	Atlantik Solar 2 (Rajendran et al., 2017)	Switzerland	Battery, solar power	81

2015	Solar Impusle 2 (Rajendran et al., 2017)	Switzerland	Battery, solar power	120
2015	Airstrato (Rajendran et al., 2017)	USA	Battery, solar power	20
2018	Zephyr 8 (Rajendran et al., 2017)	UK	Battery, solar power	624
2020	Mini Phantom (Zhao et al., 2020)	China	Battery, solar power	29.7
2020	Suwawe (Tetreault et al., 2020)	Canada	Battery, solar power	N/A

Based on the table 1.1, the Zephyr 8 gives the highest endurance among all the SUAV listed. In 2010, the Zephyr 2010 gives high endurance at 336 hours but the new variant which is Zephyr 8 greatly improve the endurance at 624 hours.

1.2 Problem statement

The UAV for this project is completely autonomous where it have been systemed to operate and make decision by itself with a very minimal human guidance. This autonomous UAV use a flight path that have been planned by global path planning to operate and fly perpetually around the world. Path planning give assistance for UAV 's user to plan the flight path based on their perspective missions. The study of daylight duration and solar irradiance on earth is essential for the project to plan a best flight path in term of endurance for UAV. The UAV is required to change it direction according to solar irradiance to gain solar energy as much as possible (J. Wu et al., 2018) to maintain the flight time. The simulation of systematic path pattern algorithm is used for this project where the path is pre-determined with different numbers of pattern or direction. Then, the paths are further analyzed to find the best path for UAV in term of distance travelled and longest flight time or perpetual flight.

Table 1.2: List of research on flight path pattern for UAV and its finding.

No	Research done	Pattern	Distance covered	Duration	Remarks
1	(Tan & Rajendran, 2019)	zig-zag pattern	Whole earth	3.6688 years	At altitude 1km
2	(Tan & Rajendran, 2019)	Spiral pattern	Whole earth	Half year	At altitude 1km, during spring and summer
3	(Cabreira et al., 2019)	Back and forth	N/A	N/A	Able to minimize the turning manoeuvres
4	(Theile et al., 2020)	Using grid by grid, 32x32 cells and 50x50cells.	N/A	N/A	N/A
5	(Cabreira et al., 2019)	Parallel, creeping line, square, sector search, barrier patrol.	N/A	N/A	N/A

The path planning method for this research is vital as the UAV 's mission is to achieve non-stop flight to cover the whole world. For the global path planning, many researchers have used an intelligent algorithm to work out the problem. The most popular algorithm used are genetic algorithm and stimulate anneal arithmetic (SAA) algorithm (Lu et al., 2018). The global path planning method can produce the path under the fully known environment as the position and shape of the obstacle is pre-determined (Biswas et al., 2021). The global path planning consist of two part which is establishment of environmental model (as for this research is the hexagonal global discrete grid over the world map) and the path planning strategy. The environmental model creation involved the formation of a precise spatial location description of the several objects involved in research environment (Biswas et al., 2021), for example, in this research is ground elevation and air density. As for the path planning strategy, it need to be adjusted in real time based on the research requirement.

For this research, the path pattern for the UAV is pre-determined where the grid is created over the earth map and each grid cell is tested with as many as possible path with different patterns and directions. There are variety research have been done with different type of flight path or pattern as detailed in table 1.2. The common type of flight path used is zig-zag pattern in rectangular or square grid area. Besides the zig-zag pattern there are other type of flight pattern that be use in research such as spiral, back-and-forth/Zamboni and diagonal (Tan & Rajendran, 2019).

For global path planning for UAV project, the discrete global grid system (DGGS) is used to generate grids over the surface of earth to ease the storing and application of data such as earth elevation and density data using geographic coordinates system. The discrete global grid system can be defined by five design parameters which are the base regular polyhedron, the fixed orientation of the base regular polyhedron relative to earth, the spatial partitioning method, transformation of planar partition to corresponding earth model and method of assigning points to grid cells (Sahr et al., 2003).

There are some limitations faced during this research as this research require the environmental model based on real earth environment. The earth does not have a flat surface as the earth ‘s shape is basically sphere, thus it is hard to create an equal grid size to cover the whole earth for geospatial analysis. There are some factors that are not taken into account in this research such as earth movement, solar irradiance fluctuation as well as weather effect on solar UAV because all of these factors cannot be predicted precisely. Moreover, the altitude elevation factor and the complex earth surface results in more simulation time, thus the coverage area for this research is reduced.

1.3 Research objectives

There are two goals to be achieved in this research:

a) To study distance travelled by UAV and cumulative solar irradiance around the world.

b) To obtain the best path planning method among systematic path pattern.

1.4 Thesis outline

This thesis consists of five major chapters which include an introduction, literature review, methodology, results and discussions, conclusions and recommendations.

Chapter 1 introduces the main idea of the project and some information concerning the research background, problem statement, research objectives and thesis outline.

Chapter 2 describes the literature review which serves as a review and critical analysis. The study of daylight duration and solar irradiance on earth is briefly explained and this study gives an insight on factors effecting the exposure of sunlight on different location of the earth. The algorithm and techniques used in global path planning will be also explained in this chapter.

Chapter 3 clarified the method and technique used for global path planning. This chapter explained on how the data is collected, parameter considered, path planning method and formula to calculate the solar irradiance, power consumption and battery start of charge (SOC).

For Chapter 4, the result obtained from the simulation is discussed. The result consists of analysis on 8 types of paths in terms of distance travelled, time taken and the reading of cumulative irradiance. The result obtained is represented in graph for further analysis.

Chapter 5 concludes all the findings and recommendation for future works.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview

The demand for Unmanned Aerial Vehicles (UAVs) using solar power as its power source has increases rapidly. For the UAV to use solar power efficiently for its flight, the path planning method can be used to make sure the flight path that it taken provide enough sunlight to power the UAV. The path planning for the UAV is also one of the ways for the researchers to plan the flight path based on the mission that will be carried out by the UAV.

2.2 Daylight Duration and Solar Irradiance

Irradiance is the amount of light energy hitting a surface of square meter area for per unit time (Daut et al., 2012). Thus, for solar irradiance it is the output of light energy obtained from the sun that irradiates a wide region on earth at a particular time (Rajendran et al., 2017). The study of solar irradiance is important for this research as the solar-powered UAV is used and it helps in planning to provide the best flight path in terms of endurance.

The research that have been conducted by (Rajendran & Smith, 2016) proved that the daylight duration is different based on its location. The daylight duration tends to be longer at the place which situated at higher latitude of earth. The longitudinal coordinates and elevation from the surface of earth gives a slight effect on the estimation of daylight duration.

Therefore, during summer the northern hemisphere daylight duration is longer compared to southern hemisphere and vice versa. Based on this study, the location chosen for this research is somewhere around Africa continent which situated at the center between both hemispheres.

For solar irradiance, it is determined by solar azimuth and solar altitude angles. From the solar data simulation that have been done in research by (Rajendran & Smith, 2016), the highest global irradiance reading occurred at the longest day length in the year which is day 196 at 12 noon time which the global solar irradiance reading is approximately at 900 W/m^2.

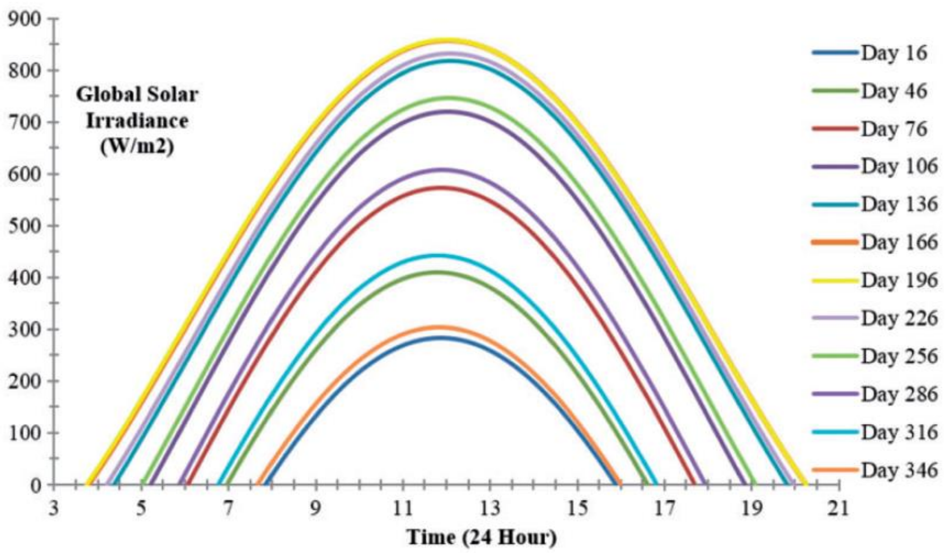

Figure 2.1: Global solar irradiance at various day number of the year versus time (Rajendran & Smith, 2016)

A research done by (Mohammad et al., 2020) involves the study of global and direct normal solar irradiance in Seri Iskandar and comparison with other cities of Malaysia. From this research, it is found that the average daily and maximum global irradiance are higher during dry season and lower during high rain season. The maximum direct normal solar irradiation recorded on day 250 in month of September 2018 that is around 915 W/m^2.

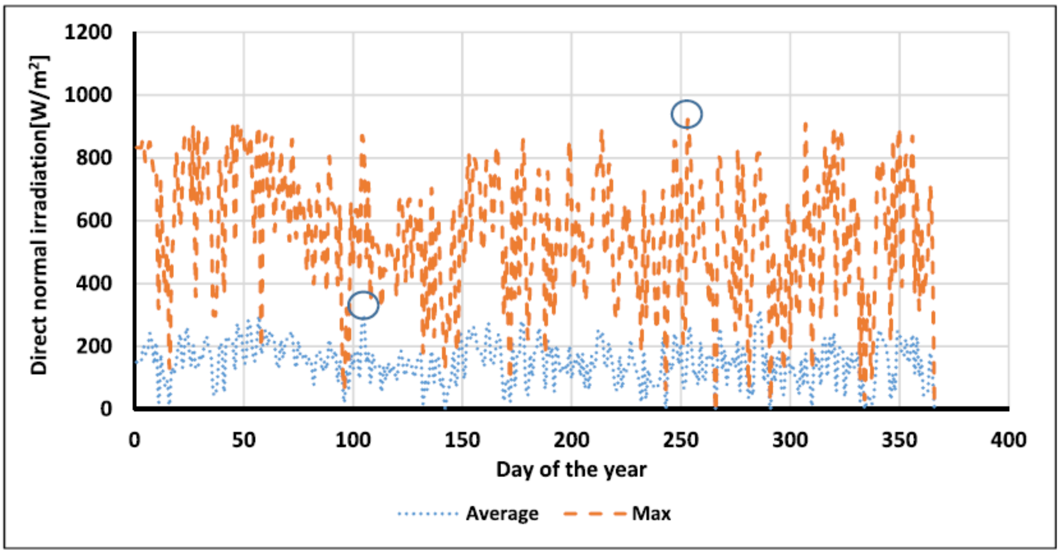

Figure 2.2: Daily averages and daily recorded peaks of direct normal irradiations throughout the year 2018 (Mohammad et al., 2020).

From both research that have been done by (Rajendran & Smith, 2016) and (Mohammad et al., 2020), it can be interpreted that the highest global irradiance is around 900 W/m^2 .

Another research is done by (Ramírez et al., 2021) to study the solar irradiance hourly mean at Hawaii, Us and Oregon, US. This research finding as in Figure 2.3 shows that the solar irradiance reading is at its peak around 12 to 13 hours the day which at 800 W/m^2.

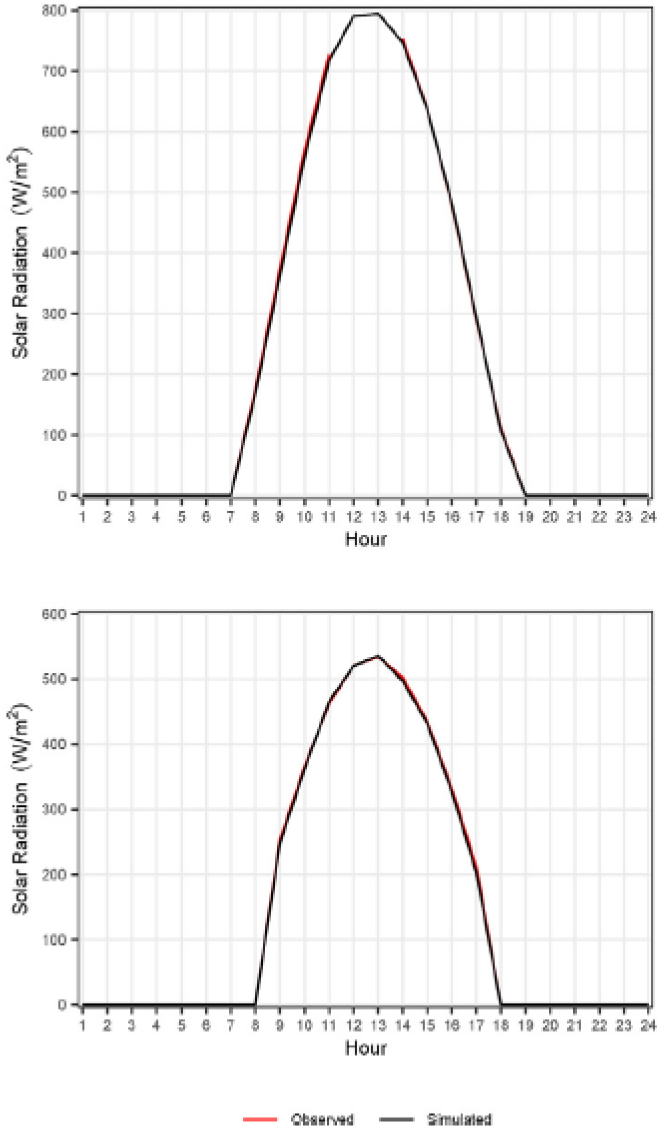

Figure 2.3: Solar radiation or solar irradiance reading at Hawaii and Oregon (Ramírez et al., 2021).

Based on the research done by (Ramírez et al., 2021) and (Rajendran & Smith, 2016), it can be seen that in between the hour 12 and hour 13, the solar irradiance reading will be at it maximum value and this duration of time is preferable to launch UAV that need abundance of solar energy to carried out its mission.

2.3 Path Planning Method

There are four main types of path planning that are model-based, conventional, learning-based and cell-based (Qadir et al., 2021). A model-based path planning contains the algorithm that are based on mathematical and visual modelling. Next, the conventional type of path planning relies only on a mathematical model for path analysis. Learning-based involve the processes to imitate the learning behaviour of human beings. Lastly, the cell-based method uses graphs in conjunction with mathematical models for path planning. This research involved the model-based, conventional and cell-based method for path planning.

For this research, an analysis on path planning that have been used previously by the researches is conducted to select the most suitable algorithm. The algorithm needs to be done carefully for the path planning to obtain the reliable result for the research to be successful. The good algorithm also will reduce the possibilities of error and will help the simulation to run smoothly. Table 1.3 shows the list of method used in global path planning.

Table 2.1: List of method or algorithm used in global path planning.

Research	**Methods/Algorithm**
(Lu et al., 2018)	A-star search
	Dynamic A-star search
	Rapidly-exploring Random Trees (RRTs)
(Tsardoulias et al., 2016)	Probabilistic RoadMaps (PRMs)
	Visibility Graphs (VGs)
	Rapidly exploring Random Trees (RRTs)
	Space Skeletonization

(Wang et al., 2021) (Konatowski & Pawłowski, 2018)	Ant Colony Algorithm (ACA)
(X. Wu et al., 2018)	Particle Swarm Optimization (PSO)
(Zhong et al., 2017)	FTC-A* algorithm
(Guo et al., 2020)	Chaotic and Sharing-Learning Particle Swarm optimization (CSPSO) algorithm
(J. Wu et al., 2018)	Interfered Fluid Dynamical System (IFDS)
	Restrained IFDS (RIFDS)
	Whale Optimization Algorithm (WOA)
	Improved Whale Optimization Algorithm (IWOA)
(ZHOU et al., 2021)	Plant Growth Algorithm

Based on the research done by (Lu et al., 2018), A-star search method is rapidly developed in recent years in which this algorithm effectively lowers the computation complication by adding together constraints to space searching during path planning. Later, from the A-star search, the dynamic A-star search have been developed that is also known as D-star algorithm which capable in updating the map from unknown environment as well as replanning the path when it detects a new obstacle on its path. Lastly, the rapidly-exploring random trees (RRTs) efficient in keeping the motion path planning from failure even there is no prior information on the environment given.

From the research done by (Tsardoulias et al., 2016), there are four method used in which all of these method is tested in two-dimensional Occupancy Grid Maps. The four methods are probabilistic roadmaps (PRMs), the visibility graphs (VGs), rapidly-exploring random tress (RRTs) and lasty the space skeletonization. Based on the result done by (Tsardoulias et al., 2016), the probabilistic roadmaps (PRMs) appeared to be the best choice among the four method. This PRMs method offer a great success rate with small execution time and the paths produced by this algorithm were in short length and less excessive turns. The space skeletonization method gives a great result as produce 100% success rate and manage to construct efficient paths but it is not preferred as it cannot be used in obstacle free environment. As for the RRTs, it only gives out the medium quality result especially in obstacle dense spaces. Lastly, for the VGs method, the result obtained from this algorithm produce a poor-quality path and gives low success rate as the experiment environmental were not sparse.

In research done by (Wang et al., 2021), the ant colony algorithm is used for global path planning in which this algorithm is inspired by natural phenomenon of ants searching for food. This ACA function is to perform optimization by simulating the division and cooperation of ants. The ants are referred as the subject to be tested. The ACA ‘s advantage is it can prevent high threat areas or the area with concentrated obstacles (Konatowski & Pawłowski, 2018). Besides, the ACA can focus in keeping the minimum value of the path length.

Particle swarm optimization is algorithm tested in research done by (X. Wu et al., 2018). This PSO algorithm works as direction-based perturbations and have a simple approach with the premature convergence and stagnation prone. The drawbacks of PSO is the loss of efficiency and sub-optimal solution occurs repeatedly in solving the path planning problem.

FTC-A* algorithm is also called as ‘fin-to-coarse’ A* algorithm in which this algorithm is an innovative on-line global incomplete path planning (Zhong et al., 2017).

In this algorithm, the route is temporarily saved and can be retrieved by the target generator to generate the next closest goal for goal executor to execute until it reaches the goal. This algorithm gives the ability to develop a detailed plan for movement decisions along the roads.

A chaotic and sharing-learning particle swarm optimization (CSPSO) algorithm is an improved version of PSO algorithm (Guo et al., 2020). The CSPSO gives the outstanding performance in convergence, diversity and distribution because the algorithm have a good computing performance.

Improved Whale Optimization Algorithm (IWOA) ‘s advantage is it can avoid the optimum local issue and have ability of better local search for an optimum solution (J. Wu et al., 2018).

The path planning method or pattern for this research is pre-determined pattern and it will be explained further in this section.

2.3.1 Pre-determined Path Pattern Method

Pre-determined path pattern method is method that use a simple geometric pattern as its path. The flight path patterns that are commonly used for UAV path planning are back-and-forth and spiral (Cabreira et al., 2019). For this pattern, the motions are in form of straight line crossed in both direction and with the closed-angle manoeuvre at the end of each round. From research done by (Cabreira et al., 2019), some of the flight path pattern are introduced which are parallel, creeping line, square, sector search and barrier patrol.

Back-and-forth pattern is also called as a zig-zag pattern. The advantages for spiral pattern is it can be easy to be implement and for the zig-zag pattern can keep the UAV battery state-of-charge (SOC) at more than 20% (Tan & Rajendran, 2019). The zig-zag pattern able to minimize the turning manoeuvres of the UAV and desirable for the mission to search large area (Cabreira et al., 2019).

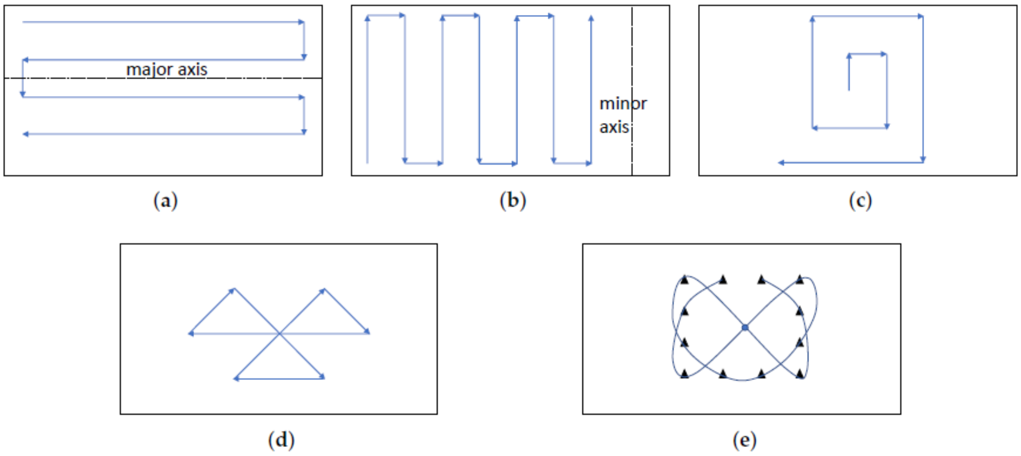

Figure 2.4: Simple flight patterns in rectangular areas with no decomposition: (a) Parallel; (b) Creeping Line; (**c**) Square; (**d**) Sector Search; (**e**) Barrier Patrol. (Cabreira et al., 2019)

In research done by (Theile et al., 2020), the cells is used as the flight path pattern where the cells in in form of 32x32 cells and 50x50 cells in square shape with two starting and landing zone in the top left and bottom right corners. This flight path pattern is used in the research, but the square cell is change to hexagonal cell and the cells occupied a larger area on surface of earth.

2.4 Discrete Global Grid System (DGGS)

The world nowadays relies on data and algorithm to solve most of the problem. Discrete Global Grid System (DGGS) is getting traction as a data model for digital earth framework which devised as geospatial big data (Robertson et al., 2020).

There are four type of global discrete grid shapes that are commonly used for partitioning which are triangles, squares, diamonds and hexagons (Robertson et al., 2020). The most compact type of global discrete grid shape are the hexagon as it give smallest average error as well as highest angular resolution.

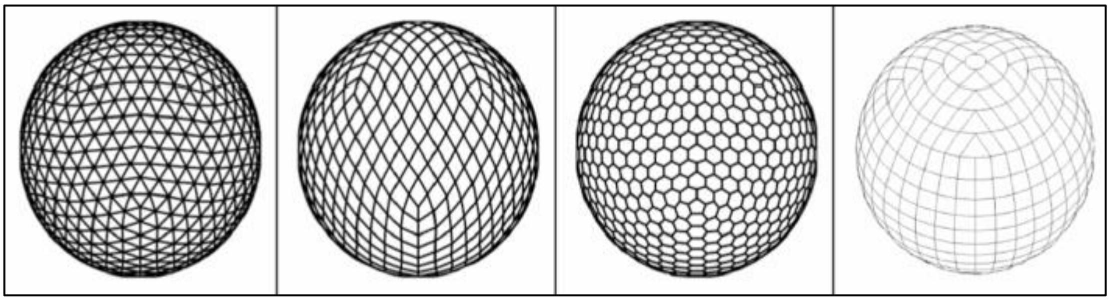

Figure 2.5: The shapes of global discrete grid available which from left are triangles, diamonds, hexagons and squares (Robertson et al., 2020).

Hexagonal global discrete grid has many advantages due to its lower distortion characteristics. This type of global discrete grid is suitable for many applications because of the equal-area cells (Sahr et al., 2003). Due to this, this type of global discrete grid used for this research.

The use of global discrete grid helps in integrating geospatial data. Therefore, this DGGS are commonly used for aircraft and satellite path planning, urban planning and to collect atmospheric properties (Ulmer et al., 2020) . For this research, it is used to plan the flight path for UAV and to collect the solar irradiance reading as well as earth elevation data at certain location on earth.

2.5 Research gap

As reviewed, there are many research on path planning for UAV. Although this is the case, the previous research only focused on certain small area and using only one flight path pattern throughout the research. Thus, for this research, a total of 8 different path pattern is analysed to understand further and compare the performance of these pattern in a similar location.

The hexagonal global discrete cell is chosen among the four types of DGGS due to its properties which suits the requirement for creating the flight path for the solar UAV in this research.

CHAPTER 3

METHODOLOGY

3.1 Overview

There are 4 phases to carry out this research that is survey, data collection, simulation and result analysis. The survey phase is phase to choose the efficient method for UAV path planning. When the method is chosen, the data will be collected for the simulation. After that, simulation is carried out by creating hexagon cell at locations on world map using MATLAB to obtain the parameters for further analysis. Lastly, the result is analysed to be documented.

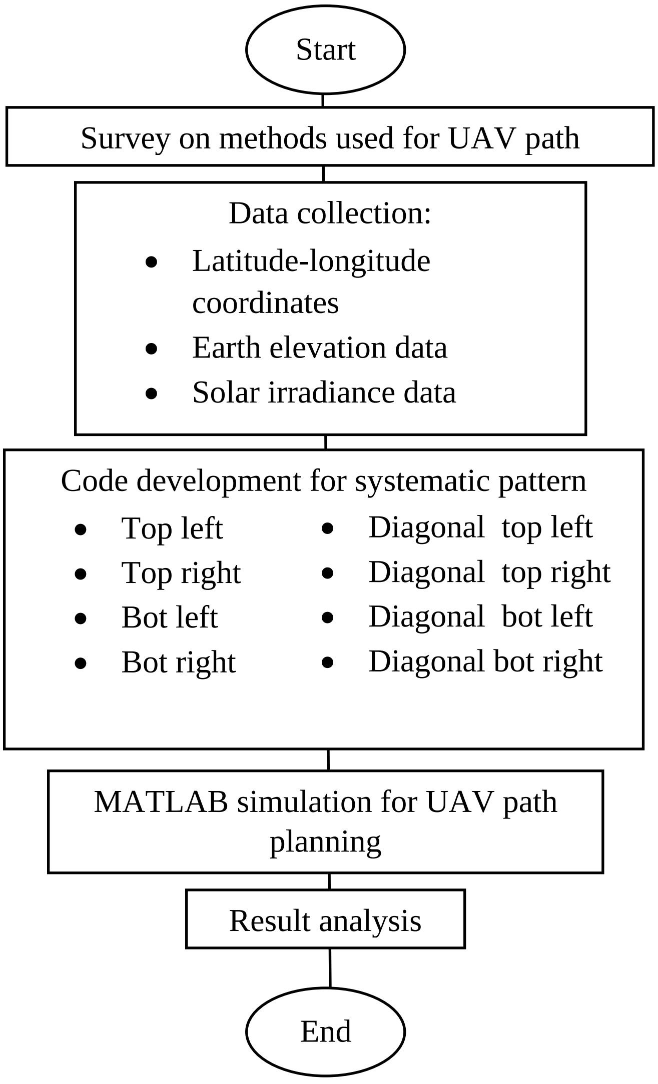

Figure 3.1: Research flow chart

3.2 Data Collection

To carry out the simulation, some data need to be collected for the UAV path planning. The data needed are latitude-longitude coordinates of hexagonal global grid cells, actual elevation data, air density data and solar irradiance data.

3.2.1 Latitude-Longitude Coordinates Data

For this research, the hexagonal global discrete grid system was used to create the area or path for the UAV to collect geospatial data on each cell. The UAV moved from one cell to another cell and the purpose of these cells are to calculate or analyse which cell or location gives the best performance for the UAV in term of solar power and SOC.

The latitude-longitude coordinates data for this hexagonal cell were gathered from a reliable website (Adams, 2017) in form of '.gen' files. There are many projections for hexagonal grid cell as shown in table in Figure 3.2, but the Discrete Global Grid System (DGGS) configuration used in this research was the Icosahedral Snyder Equal Area Aperture 3 Hexagonal Grid (ISEA3H) level 9. This projection consists of 196,832 cells covering the whole earth in which each cell area is approximately the same at 2,591.4 km^2 (Adams, 2017).

Each cell contains 24 coordinate points and 6 of them acts as edge point for a hexagon cell. Each cell coordinates data was converted from '.gen' file into '.mat' file in MATLAB to ease the simulation process. Based on the 24 coordinates , there are 8 possible paths generated which shown in appendix A that consists of horizontal and diagonal movement.

Projection	Level	# cells	Cell area (km^2)	Densification
ISEA3H	1	32	17,002,187.39	12
ISEA3H	2	92	5,667,395.80	12
ISEA3H	3	272	1,889,131.93	12
ISEA3H	4	812	629,710.64	12
ISEA3H	5	2,432	209,903.55	10
ISEA3H	6	7,292	69,967.85	10
ISEA3H	7	21,872	23,322.62	8
ISEA3H	8	65,612	7,774.21	8
ISEA3H	9	196,832	2,591.40	7
ISEA3H	10	590,492	863.80	6
ISEA3H	11	1,771,472	287.93	4
ISEA3H	12	5,314,412	95.98	3
ISEA4H	1	42	12,751,640.54	12
ISEA4H	2	162	3,187,910.14	12
ISEA4H	3	642	796,977.53	12
ISEA4H	4	2,562	199,244.38	12
ISEA4H	5	10,242	49,811.10	10
ISEA4H	6	40,962	12,452.77	10
ISEA4H	7	163,842	3,113.19	8
ISEA4H	8	655,362	778.30	8
ISEA4H	9	2,621,442	194.57	4
ISEA4H	10	10,485,762	48.64	3
ISEA4T	1	80	6,375,820.27	12
ISEA4T	2	320	1,593,955.07	12
ISEA4T	3	1,280	398,488.77	12
ISEA4T	4	5,120	99,622.19	12
ISEA4T	5	20,480	24,905.55	10
ISEA4T	6	81,920	6,226.39	10
ISEA4T	7	327,680	1,556.60	8
ISEA4T	8	1,310,720	389.15	8
ISEA4T	9	5,242,880	97.29	4
ISEA4T	10	20,971,520	24.32	3

Figure 3.2: Table of Discrete global grid statistics for the grids (Adams, 2017).

3.2.2 Actual Earth Elevation Data

Earth elevation data is used to plan the UAV movement in 3D where it considers the obstacle data. This data was stored for each latitude and longitude of the whole earth. The data collected are in unit of meters with reference to sea level. This data was gathered from Spaceborne Global Digital Elevation Models (GDEMs) which is reliable (Hawker et al., 2019) and extracted according to the coordinates and stored in MATLAB as a '.mat' file which used for analysis of simulation.

The elevation data that have been converted consist of numerical data with size of 181 rows by 360 columns that represent a total of 181 latitudes and 360 longitudes coordinates. These elevation data represent the average earth elevation reading of that region and the collected data are in the unit of meters. For earth elevation data collected, the data accuracy is at 1° latitude and 1° longitude. Therefore, the air density and solar irradiance data were generated based on same accuracy of coordinate.

3.2.3 Air Density Data

Air density data is vital for this research as the density of air change based on the UAV ‘s flight altitude with reference to sea level. During the research, when the UAV faced the obstacle, it will move upward to avoid the obstacle so the altitude of the UAV will be change as well as the air density. According to (Guinn & Barry, 2016), an aircraft performance will be higher at the region with high humidity environment compared to aircraft at region with low humidity. The region with high humidity is at low altitude while region with low humidity is at high altitude, hence the low altitude atmosphere is preferable. The UAV flight altitude for this research was maintained at 100 m altitude throughout the mission.

3.2.4 Solar Irradiance Data

Solar irradiance data for this research were collected for everyday at each latitude-longitude coordinate throughout a year. The data is collected hourly for 24 hours a day. Thus, the solar irradiance data was collected for 365 days with 24 hours each and this data accumulate a total of 8,760 data of solar irradiance per coordinate. For all coordinate of earth, the amount of solar data collected were about 570,801,600 data. The solar irradiance data collected for the result was the solar irradiance reading when the UAV pass through the region based on the local time it is flying.

There are some parameters that interdependent to each other which need to calculate to evaluate the solar irradiance. Initially, the year is identified as a leap year using Eq. 1 (Rajendran & Smith, 2016) and Eq. 4 (Rajendran & Smith, 2016) is used to calculate the elapsed day in the year involved.

$$LeapYear = True\ if\ (4xfloor(0.25year) > year \tag{1}$$

$$LeapConst = \begin{cases} 62, LeapYear = True \\ 63, LeapYear = False \end{cases} \tag{2}$$

The Eq. 3 is used to calculate the approximate number of elapsed days in a specific year involved. The LeapConst value calculated previously is used in this formula.

$$Day\ No = \begin{cases} Day + floor(0.5LeapConst(month - 1), & month = 1 \\ Day + floor(30.6(mont + 1) - LeapConst), & month > 2 \end{cases} \tag{3}$$

The distance between sun and earth are varies due to location of the sun, r, which is calculated using Eq. 4 (Rajendran & Smith, 2016). The Day No calculated previously is used in the formula. The calculate location of sun, r, and altitude of the location, AltGeo is later used to evaluate the precise day number, DN as shown in Eq. 5 (Rajendran & Smith, 2016).

$$r = 1.496 \times 10^8 \left(1 + 0.017 \sin\left(\frac{DayNo - 93}{365} \times \frac{360\pi}{180}\right)\right) \tag{4}$$

$$DN = \sin^{-1}\left(\frac{\frac{r + AltGeo}{1000 \times 1.496 \times 10^8}}{0.017}\left(\frac{180}{\pi}\right)\left(\frac{365}{360}\right) + 93\right) \tag{5}$$

From the precise day number, DN, the equation of time, EOT can be evaluated as shown in Eq. 6 (Rajendran & Smith, 2016).

$$EOT = 0.2136 \sin\left(\frac{360(DN-1)}{3.65.242\frac{\pi}{100}}\right) - 0.0043 \cos\left(\frac{360(DN-1)}{365.242\frac{\pi}{100}}\right) + 0.1538 \sin\left(\frac{(2)360(DN-1}{365.242\frac{\pi}{100}}\right) + 0.0608 \cos\left(\frac{(2)360(DN-1}{365.242\frac{\pi}{100}}\right) \tag{6}$$

Local time is calculated using 24-hour system through Eq. 7 (Rajendran & Smith, 2016). Then, the apparent solar time, AST is calculated through Eq. 8 (Rajendran & Smith, 2016) using the values of local time and EOT calculated previously.

$$LocalTime = Hour + \left(\frac{Minutes}{60}\right) + \left(\frac{Seconds}{3600}\right) \tag{7}$$

$$AST = LocalTime + \frac{LONG - 15GMT}{15} + EOT \tag{8}$$

Solar declination angle, DEC, is the angle between the solar ray and the equatorial line. The DEC need to be calculated using Eq. 10 (Rajendran & Smith, 2016) as it influences the value of solar altitude, SOLALT as presented in Eq. 11 (Rajendran & Smith, 2016).

$$\begin{aligned} DEC = \frac{180}{\pi} \sin^{-1}\big(0.3979 \sin\big(0.017203(DN+284)\big)\big) + \\ 0.007133 \sin\big(0.017203(DN+284)\big) + \\ 0.03268 \cos 0.017203(DN+284) - \\ 0.000318 \sin 2\big(0.017203(DN+284)\big) + \\ 0.000145 \sin\big(0.017203(DN+284)\big) + \end{aligned} \tag{9}$$