MODELLING OF SOLAR IRRADIANCE FOR SIZING GLOBAL AND PERPETUAL SOLAR-POWERED UNMANNED AERIAL VEHICLE (UAV)

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by

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TABLES OF CONTENTS

CHAPTER FIVE: CONCLUSION

APPENDICES

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

n	Hours of bright sunshine
N	Hours of possible sunshine
l_o	Solar constant
H_{max}	Maximum radiation
φ	Latitude
γ	Longitude
α	Altitude
n_{di}	Number of day
DN	Number of day (precise)
n_d	Day of each month
δ	Declination angle
ω_s	Sunrise hour
ω	Hour angle
s/s_o	Relative number of sunshine hours
R_j	Transmission function for hourly variation
R_i	Transmission function for daily variation
H_{ext}	Extraterrestrial solar irradiance
H	Global solar irradiance
H_{bh}	Beam radiation on horizontal plate
H_d	Diffuse solar irradiance
δ_o	Total optical depth
ε	Eccentricity correction
Z	Zenith angle

θ_{zt}	Zenith angle at certain time
m	Air mass
M	Month
GMT	Green meridian time
EOT	Equation of time
AST	Apparent solar time
SOLALT	Solar altitude
SOLAZM	Solar azimuth
SOLINC	Solar incidence angle
TILT	Tilt angle
WAZM	Wall azimuth angle
SOLHRA	Solar hour angle
P_Solar	Solar module system power (W)
Ir_Max	Solar irradiance (W/m^2)
eff_Solar	Efficiency of solar module
eff_MPPT	Efficiency of maximum power point tracker (MPPT)
A_Solar	Solar module area (m^2)
P_Required	UAV power required (W)
C_L	Lift coefficient
C_D	Drag coefficient
W_TOmax	Maximum take-off weight (N)
P	Air density (kg/m^3)
S	Wing area (m^2)
V	Air speed (m/s^2)
C_Do_W	Zero-lift-drag coefficient

E	Oswald efficiency
AR	Wing aspect ratio
B	Wing span (m)
W_Struct	Structure weight (N)
W_Batt	Battery weight (N)
W_Solar	Solar power system weight (N)
W_Electric	Propulsion system weight (N)
W_Ctrl	Control system weight (N)
W_Pay	Payload weight (N)
$\overline{H_{obs}}$	Averaged observed solar irradiance
H_{obs}	Observed solar irradiance
$\mathrm{H}_{\mathrm{est}}$	Estimated solar irradiance

LIST OF ABBREVIATIONS

PM	Proposed model
RMSE	Root mean square error
R^2	Coefficient of determination
MBE	Mean bias error
MSE	Mean squared error
MTOW	Maximum take-off weight
SI	Solar irradiance
UAV	Unmanned aerial vehicle
AUAV	Average Unmanned aerial vehicle
GUAV	Global Unmanned aerial vehicle
RE	Renewable energy
PV	Photovoltaic
NASA	National Aeronautics of space administration
GSI	Global solar irradiance
GTI	Global tilted irradiance
DHI	Diffuse horizontal irradiance
GHI	Global horizontal irradiance
DNI	Direct normal irradiance
FOV	Field of view
GOES	Geostationary operational environmental satellite
API	Air pollution index
ANN	Artificial neural network
PM	Particulate matter

PEMFC	Polymer electrolyte membrane
DFMC	Direct methanol fuel cells
RAT	Ram air turbine
SoDa	Solar radiation data
MMD	Malaysia meteorology department
TSP	Total suspended particulate
MOSTI	Ministry of science, technology and innovation
ANN	Artificial Neural Network
BP	Back Propagation

PEMODELAN BAGI SINARAN SURIA UNTUK PENSAIZAN GLOBAL DAN PENERBANGAN BERTERUSAN BAGI PESAWAT SOLAR TANPA PEMANDU

ABSTRAK

Sejak kebelakangan ini terdapat pelbagai aplikasi kenderaan kecil udara tanpa pemandu untuk kedua-dua penerbangan tentera dan awam.Peluang untuk meningkatkan keupayaan UAV berkuasa solar untuk beroperasi seperti satelit sebagai pseudolite. Walau bagaimanapun, berat dan sekatan kuasa sentiasa menjadi punca utama yang menghadkan UAV untuk beroperasi sebagai menyerupai satelit.Tujuan kajian ini adalah untuk merapatkan jurang ilmu di dalam bidang penerbangan berterusan di seluruh rantau di seluruh dunia untuk operasi selama setahun. Melalui kajian ini, tumpuan telah diberikan 1) untuk mengkaji model solar tempatan dan global serta 2) bagaimana data solar mungkin membolehkan kemungkinan membangunkan reka bentuk UAV bagi operasi global.Dalam kajian ini, untuk pemodelan solar tempatan, 14 model telah diusul dan dikaji dengan parameter yang berkaitan menggunakan teknik regresi. Untuk permodelan sinaran global, pendekatan secara teoritikal digunakan untuk menkaji kesemua dua belas bandar. Prestasi setiap model solar yang dicadangkan dalam menganggarkan sinaran suria untuk Malaysia dianalisa berdasarkan Ralat Relatif Min Square (*RMSE)*, Pekali Penentu(R^2) dan Min Ralat Pincangan (*MBE).*Analisis secara simulasi telah dilaksanakan bagi memahami kemampuan untuk penerbangan kekal bagi peasawat tanpa pemandu. Di sini, terdapat 2 jenis kajian 1) AUAV; simulasi data solar tahunan purata untuk reka bentuk UAV solar yang sesuai untuk operasi di setiap bandar-bandar, dan 2) GUAV; satu UAV yang dioptimumkan reka bentuknya yang mampu untuk beroperasi di semua bandar. Model yang ke 12 telah di cadangkan sebagai model bagi Malaysia, dengan penemuan *RMSE* 0.856%, *MBE* 0.282% dan R^2 0.988. Specifikasi untuk pesawat tanpa pemandu global yang telah disimulasi sepanjang tahun adalah, 0.5057 kg bagi Berat Berlepas Maksima, Panjang Kepak 2.03 m dan Nisbah KawasanSayap sekitar 40%. Berdasarkan sinaran suria global bagi tahun 2013, kami berjaya mengenal pasti faktor resapan bagi Malaysia adalah 60.8% dengan mengunakan teknik interpolasi.

Kata kunci; radiasi solar global; data jabatan meterologi; awan; suhu; kelajuan angina; kelajuan tiupan; hujan; lembapan; tekanan; kaedah regresi; kapal terbang tanpa pemandul; beban; konfigurasi saiz

MODELLING OF SOLAR IRRADIANCE FOR SIZING GLOBAL AND PERPETUAL SOLAR-POWERED UNMANNED AERIAL VEHICLE (UAV)

ABSTRACT

There are various applications of small unmanned aerial vehicle for both military and civil aviation in recent years. The opportunity to enhance of solar-powered UAV capabilities to operate as pseudolite satellite enables all countries around the world an endless possibility of their own technology. However, weight and power restriction are always the main cause which limits UAV to operate as pseudolite satellite. The aim of this work is to bridge the knowledge gap in the area of perpetual flight across regions around the world for a yearlong operation. Through this study, focus has been given 1) to study both local and global solar modelling and 2) how these solar data may enable the possibilities of developing a UAV design capable of global operation. In this study, for local solar modelling, 14 variant proposed models are studied with its relevant parameters using the regression technique. Then, as for global solar modelling, the theoretical approach has been used to study twelve cities spreading all over the world. The performance of each proposed solar model in estimating the solar irradiance (SI) for Malaysia is analysed based on its Root Mean Square Error (*RMSE)*, Coefficient of Determination (R^2) and Mean Bias Error (*MBE)*. Finally, the analyses carried out to understand the feasibility of a perpetual solar-powered UAV operated around the world have been simulated. Here, the two modes of study include 1) AUAV; the yearly average solar data simulation to design solar-powered UAV suitable for operation at each city, and 2) GUAV; a single optimized solar-powered UAV design that is capable for operation in all cities investigated in this work.

Proposed Model (PM) 12 had been recommended as solar estimation model for Malaysia, the result showed that the *RMSE* for the model is 0.856%, *MBE*0.282% and R^2 is 0.988. An optimum design specification for Global UAV (GUAV) successfully to simulate perpetual flight for whole year with specification of Maximum Take-Off Weight (MTOW) 0.5057 kg, Wingspan (S) 2.03 m and Solar Wing Area Ratio (SWAR) 40%. Based on Global SI data year 2013, we able to estimate the best diffuse factor value for Malaysia, which is 60.8% by using interpolation method.

Keywords-component; global solar irradiance; meteorology station data; clouds cover; temperature; wind speed; gust speed; rain precipitate; relative humidity, pressure, regression method; UAV; pseudolite; weight; sizing configuration.

CHAPTER ONE

INTRODUCTION

1.1 Overview

For this chapter, 1.2 and 1.3 will discuss the available renewable energy, type of solar irradiance and the equipment that are used to measured solar radiation. The objective, problem statements and the research scope are presented in 1.5 till 1.7. Thesis outline will explain more about chapter overview for each of it.

1.2 Research Background

Energy is important to drive this world's functionality. For instance, energy is divided to two categories, namely renewable and unrenewable energy. Renewable energy (RE) is clean and sustainable energy which has good potential to reduce the greenhouse effect and it is also a good substitute to the depleting fossil fuels (Mirzaei,Tangang et al., 2014). Study on renewable energy is crucial since fossil fuels are still the primary energy supply which is almost 88%. Based on data in 2008, the present oil supply will only last for 42 years. Hence, in less than half a century, our crude oil supply may be depleted (Urguhart, 2011).

In addition, the development and study on RE application have been diversified in the past few years, earning its high appreciation (Solangi,Lwin et al., 2011). Some of the different types of RE resources which may be utilized to produce clean energy are solar, hydro, wind, wave, thermal and biomass. The two most common technologies of solar are the photovoltaic (PV) cells and solar thermal energy. PV cells convert solar radiation to electricity, whereas solar thermal energy implements the concept of heating and cooling through absorption and emission of solar radiation.

Ironically, the study on solar power system has been around for more than 100 years, till the discovery of the PV cell. PV evolution increases drastically since; from 1 to 2 % efficiency around 1876, up to 10 % efficiency in late 1970. Since then, the world record for solar cell efficient has achieved almost 44.7 % in efficiency (Daily, 2013) developed by Fraunhofer Institute for Solar Energy Systems. Besides, technology has advanced much with a variety of rigid, semi-rigid and flexible PV development and available commercially-off-the-shelf.

Subsequently, many countries in the world have already implemented and developed their solar power plants as an alternative power generator (Urguhart, 2011). The total amount of power produced at present solar power plant in Malaysia is about 20,493MW. Moreover, the power consumption is estimated to increase up to 23,099MW in 2020, whereas thermal power plants and hydro power plants in Malaysia produced 7,103MW and 1,911MW respectively for year 2013. Therefore, generating energy source through solar is a good option as it provides unlimited renewable energy. In addition, it does not pollute the surrounding or produce any hazardous waste(Hazim Masral,Parvathy Rajendran* et al., 2015).

There is an extensive use of solar energy especially in industries such as military, telecommunication, agricultural, water desalination, aviation and building industry. Common applications of solar power systems includes pumps, engines, fans, refrigerators and water heaters. Lately, both the military and aviation industries have raised their initiatives in solar energy development in order to reduce its dependence on fossil fuels(Mekhilef,Saidur et al., 2011).

It is believed the military will play a key role in leading and bringing solar to the mass market. Therefore, this study intends to study the feasibility of conventional solar-powered Unmanned Aerial Vehicle (UAV) global solar-powered flight operations. Currently, the existing solar-powered UAV are Solar Eagle, Zephyr, Helios, Sky-Sailor and Solong (Smith&Rajendran, 2014). As to date, a lot of efforts has been done to establish long endurance UAV over the past few decades.

Thus, this study aims to understand 1) the meteorology parameter and its relation in solar irradiance intensity and 2) to study feasibility of a small solar-powered UAV for global operation. Besides, the knowledge on available solar irradiance is essential in various application, especially to design highly efficient solar module system, which solely depends on the amount of solar radiated to earth surface. Moreover, the study for global operation may elucidate the practicality of solar-powered flight in aviation industry.

1.3 Solar Irradiance

Generally, solar radiations are divided into two types, 1) solar radiation outside the earth atmosphere or known as extra-terrestrial solar irradiance and 2) solar radiation at the earth surface. The solar radiation on earth surface part consists of three main elements, which are global, direct and diffuse solar irradiance. The global is the combination of direct and diffuse solar irradiance. The direct solar irradiance is the amount of radiation that goes through atmosphere falling in a unit area perpendicular to the beam at Earth's surface.

However, the diffuse solar irradiance is the solar irradiance that is scattered and reflected through the cloud, air particles and other atmospheric components that are available in the sky that may prevent direct solar radiation (Zhao,Zeng et al., 2013, Kaushika,Tomar et al., 2014, Mohammadi&Khorasanizadeh, 2015) refer Figure 1.1.

Information about solar data availability is vital in the assessment and modelling of active solar energy systems, regardless if it is for aircraft or home application. The main two parameters involved in this study are the solar irradiance intensity and solar irradiance availability duration or commonly referred to daylight duration. Conventionally, solar irradiance data collection can be obtained in three techniques; 1) direct collection through in-situ ground measurements, 2) indirect methods through satellite estimation and 3) modelling techniques.

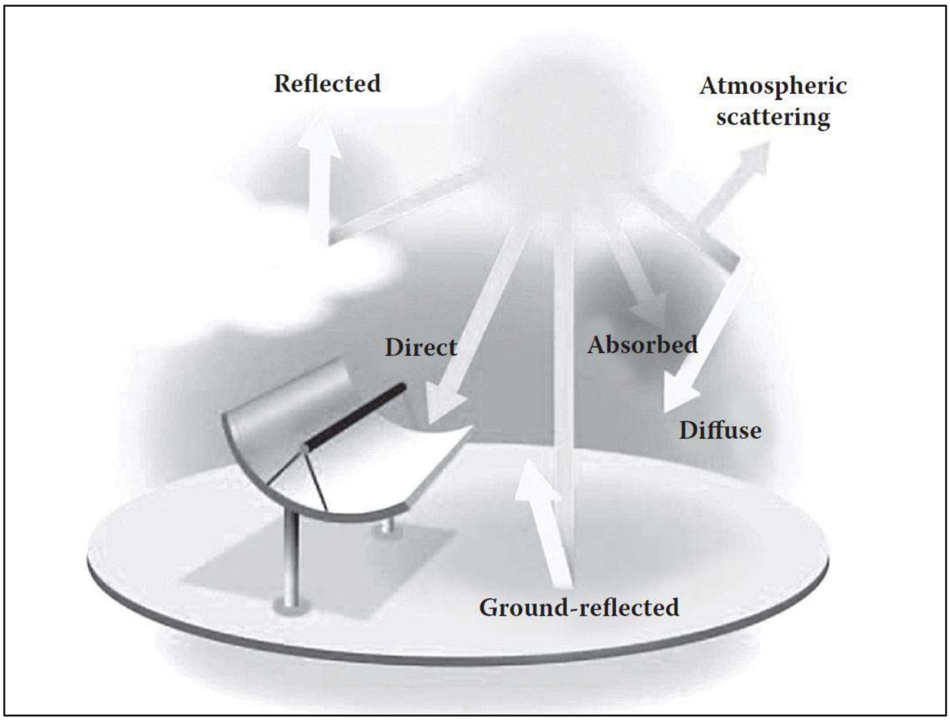

Figure 1.1 Solar Irradiation components

1.3.1 Direct Solar - Ground Measurements

In-situ measurement is more complex as compared to indirect method, as it requires measurement sensor and equipment that is highly cost as well as their maintenance. Meanwhile, to ensure reading from an instrument is consistent with other measurements, every equipment requires yearly calibration to establish the reliability of the instrument. The equipment that is normally used for measuring and monitoring solar radiation is pyranometers.

Other than that, several other equipment and sensors such as hygrometer, anemometer, barometer, thermometer and rain gauge to measure typical weather parameter. Unfortunately, this instrument is not widely used in this country, only certain meteorology stations are available with pyranometer and other stations not.

Due to this constraint, only a few data locations are available for the solar irradiance study. In addition, most of the available data worldwide consisting of extra-terrestrial solar irradiance are either limited or without diffuse irradiance component.

Generally, Pyranometers as shown in

Figure 1.2are used to measure total hemispherical radiation or horizontal solar irradiance for horizontal surface. The incoming solar irradiance from a 2π solid angle can be measured on a planar surface, 180° from horizon to zenith to horizon and 360° around the horizon. It consists of an outer glass dome and inner glass dome covers made of glass for shield the electrical equipment such as sensor from thermal convection. The dome also functions to protect equipment from weather (rain, dust and wind). A cartridge or desiccator contains silica gel inside the dome for soaking up water vapor and maintaining the dome dry. Moreover, pyranometer also measures the tilted irradiance for tilted surface. The diffuse solar irradiance (DHI) can also be measured using the pyranometer, while the direct beam component will be eliminated by small shading disk. The pyranometer needs to continuously be shaded, so the disk will be mounted on an automated solar tracker. Hence, the disk acts as a shadow ring and may prevent the direct component (DNI) from reaching the sensor as shown in Figure 1.2.

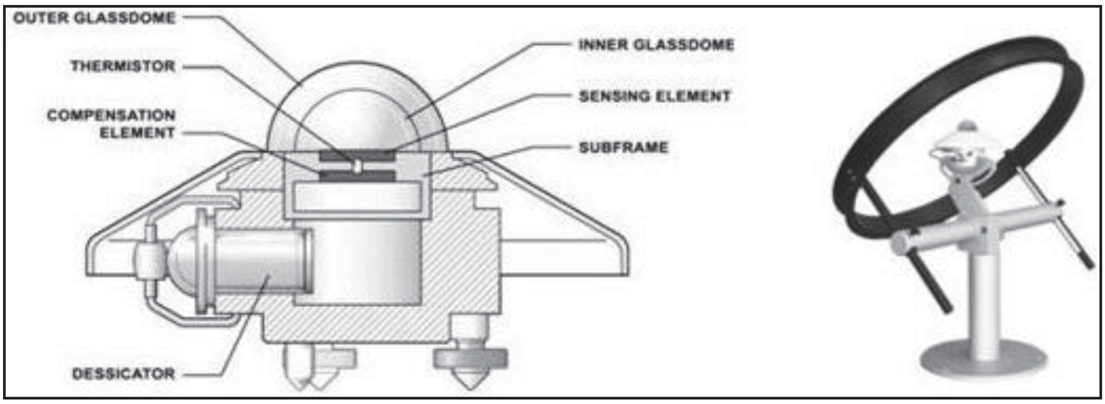

Figure 1.2: Schematic of a pyranometer with shading disk.(Instruments, 2009)

1.3.2 Indirect Solar -Estimation using Satellite Observation

The assessment of the solar energy resources over large areas and the elaboration of solar radiation maps are nowadays conducted using satellite derived information. Among the existing methodologies, those based on parametric models are common to estimate the clear-sky solar radiation. However, the fittingness of that option depends both on the accuracy of the solar radiation algorithm and the satellite derived information and their relationship (López&Batlles, 2014). However, it is very expensive and difficult to maintain as it can only be sustained through communication between satellite and ground stations. Even though, there are free data available of the interest location from National Aeronautics and Space Administration (NASA), the data are out dated for most locations (NASA, 2013).

In the last decades, various models have been produced for estimating solar irradiance using geostationary satellite image (Blanc,Gschwind et al., 2011, Marquez,Pedro et al., 2013, Rusen,Hammer et al., 2013). Geostationary satellites are useful for various applications and mission, and one of it is for meteorological purposes. The images that are captured by the meteorological satellite over a large area and with high quality also allow recognition and estimation of the clouds' change. These data may be further analysed to generate forecast of solar radiation at the ground level.

There are several weather satellites still in operation, such as the Geostationary Operational Environment Satellite system GOES-12, GOES-13, and GOES 15 which are owned by United States. The Elektro-L 1 is a new-generation weather satellite by Russia (Zak, 2013) and the MTSAT-2 located over the mid Pacific is owned by Japanese (JMA, 2014). The European have the Meteosat series from 6 till 9, which covers Indian and Atlantic Ocean. Besides, China currently has three Fengyun series