UNIVERSITI PUTRA MALAYSIA

UAV-BASED PM2.5 MONITORING SYSTEM FOR SMALL SCALE URBAN AREAS

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UAV-BASED $PM_{2.5}$ MONITORING SYSTEM FOR SMALL SCALE URBAN AREAS

By

HUDA JAMAL JUMAAH

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfillment of the Requirements for the Degree of Master of Science

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DEDICATION

This thesis is dedicated to:

My precious father (may Allah have mercy on him), my mother, my uncle, my brothers, my sisters, my colleagues and my friends.

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Master of Science

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July 2018

Chairman : Professor Dato' Shattri Mansor, PhD
Faculty : Engineering

In urban areas, air particle pollution is of precise interest because of its impact on health. Air quality data collection near the ground surface is difficult, particularly in small complex regions, and the usage of satellites image may not suffice and do not achieve the required accuracy. A variety of Unmanned Aerial Vehicles (UAVs) based on remote sensing technology enables data collection in these particular regions and overcoming obstacles and the difficulties obtaining required data. Remote sensing can be considered the best significant tool to assist in data monitoring for estimating and predicting air quality parameters.

The recent monitoring stations are fixed stations and are not designed to denote exposure on a small scale adequate. Most of the studies rely on satellite observations from Aerosol Optical Depth (AOD) and have used lower resolution AOD to estimate $PM_{2.5}$ levels. In general, this used resolution of AOD products is often insufficient to define exposure estimations in urban areas. In this manner evaluation at different altitudes can offer extra information to assess air quality. The research aims to introduce a $PM_{2.5}$ prediction algorithm based on $PM_{2.5}$ measurements from a developed a system capable of measuring $PM_{2.5}$ concentrations in small-scale areas and validate the model at specified low altitudes. Observations based on UAV-based $PM_{2.5}$ monitoring sensors were applied around 1.6 km² area for collecting data at low altitude. Meteorological parameters including temperature and humidity were collected. This study uses an empirical method via applying amassed records of $PM_{2.5}$ concentrations and meteorological par ameters to create a geographically weighted regression (GWR) model to estimate $PM_{2.5}$ concentrations in a small-scale area. For the predicted model, an accuracy value is computed from the probability value given by the regression analysis model of each parameter. To validate our method, we have utilized two types of data, training, and testing. To evaluate and validate the suggested

GWR model, we applied the model using testing measured points. Results showed a relatively good fit of the model to the observed data. Where the maximum accuracy obtained was set as 65% in July and 73% in August. Also, the obtained results showed that there is a good statistical correlation between the measured in situ data and testing data, the maximum accuracy was set as 93% in July and 94% in August. The developed tool can be considered as an independent method for sample collection demonstrated that the characteristics obtained by analysis are able to monitor and predict the concentrations of $PM_{2.5}$ in small-scale areas with high accuracy. This suggested approach is useful to cover the area within a short amount of time, with low cost and limitless flexibility.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Master Sains

SISTEM PEMANTAUAN PM2.5 BERASASKAN PESAWAT UDARA TANPA PEMANDU (UAV) BAGI KAWASAN BANDAR BERSKALA KECIL

Oleh

HUDA JAMAL JUMAAH

Julai 2018

Pengerusi : Profesor Dato' Shattri Mansor, PhD
Fakulti : Kejuruteraan

Di kawasan bandar, pencemaran partikel udara merupakan perkara yang diperhatikan dengan teliti kerana impaknya kepada kesihatan. Pengumpulan data kualiti udara berhampiran permukaan bumi adalah sukar, terutamanya di rantau kecil yang kompleks, serta penggunaan imej satelit tidak mencukupi dan tidak mencapai tahap ketepatan yang diperlukan. Di kawasan bandar, pencemaran partikel udara merupakan perkara yang diperhatikan dengan teliti kerana impaknya kepada kesihatan. Pengumpulan data kualiti udara berhampiran permukaan bumi adalah sukar, terutamanya di rantau kecil yang kompleks, serta penggunaan imej satelit tidak mencukupi dan tidak mencapai tahap ketepatan yang diperlukan.

Stesen pemantauan pada masa kini adalah stesen tetap dan tidak direka untuk menunjukkan pendedahan pada skala yang kecil. Kebanyakan kajian bergantung kepada pemerhatian satelit dari Jarak Optik Aerosol (AOD) dan menggunakan resolusi rendah AOD untuk menganggarkan tahap $PM_{2.5}$. Secara amnya, resolusi produk AOD ini adakalanya tidak mencukupi untuk menentukan anggaran pendedahan di kawasan bandar. Dengan cara ini, penilaian di ketinggian yang berbeza boleh memberi maklumat tambahan untuk menilai kualiti udara. Penyelidikan ini bertujuan untuk memperkenalkan algoritma ramalan $PM_{2.5}$ berdasarkan pengukuran $PM_{2.5}$ dari sistem yang dibangunkan yang mampu mengukur kepekatan $PM_{2.5}$ di kawasan berskala kecil dan mengesahkan model pada ketinggian rendah tertentu. Pencerapan $PM_{2.5}$ menggunakan sensor UAV dilakukan dalam kawasan seluas 1.6 km^2 bagi mengumpul data pada altitud rendah. Parameter meteorologi termasuk suhu dan kelembapan turut direkodkan. Kajian ini menggunakan kaedah empirikal dengan mengguna pakai rekod $PM_{2.5}$ terkumpul dan parameter meteorologi bagi membangunkan model regresi berwajaran geografi (GWR). Model ini digunakan untuk menganggarkan kepekatan $PM_{2.5}$ pada paras permukaan bumi di kawasan

berskala kecil. Bagi model ramalan, satu nilai ketepatan dikira daripada nilai kemungkinan yang diberikan oleh model analisa regresi bagi setiap parameter. Bagi mengesahkan kaedah ini, kami menggunakan dua jenis data iaitu latihan dan ujian. Untuk menilai dan mengesahkan model GWR yang dicadangkan, model tersebut diaplikasikan menggunakan mata-mata ujian yang diukur. Keputusan menunjukkan model yang agak baik bagi data yang diperhatikan, di mana ketepatan maksimum yang diperolehi ditetapkan sebanyak 65% pada bulan Julai dan 73% pada bulan Ogos. Selain itu, hasil yang diperoleh menunjukkan terdapat hubungan statistik yang baik antara data sedia ada dan data ujian yang diukur, ketepatan maksimum ditetapkan kepada 93% pada bulan Julai dan 94% pada bulan Ogos. Kaedah yang dibangunkan ini juga boleh dianggap sebagai kaedah tak bersandar kerana daripada pengumpulan sampel yang dilakukan menunjukkan bahawa ciri-ciri yang diperolehi daripada analisis berupaya untuk memantau dan meramalkan kepekatan $PM_{2.5}$ dalam kawasan berskala kecil dengan ketepatan yang tinggi. Pendekatan yang dicadangkan ini berguna untuk meliputi sesuatu kawasan dalam tempoh masa yang singkat, kos yang rendah dan kebolehubahan yang tidak terhad.

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This thesis was submitted to the Senate of the Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Master of Science. The members of the Supervisory Committee were as follows:

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Declaration by graduate student

I hereby confirm that:

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Declaration by Members of Supervisory Committee

This is to confirm that:

- the research conducted and the writing of this thesis was under our supervision;
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Name of Member of Supervisory Committee: Associate Professor Dr. Biswajeet Pradhan

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LIST OF ABBREVIATIONS

PM	Particulate Matter
USEPA	United States Environmental Protection Agency
EPA	Environmental Protection Agency
AQI	Air Quality Index
RMAAQG	Malaysia Ambient Air Quality Guidelines
API	Air Pollutant Index
WHO	World Health Organization
NOAA	National Oceanic Atmosphere Administration
UAVs	Unmanned Aerial Vehicles
AQPs	Air Quality Parameters
GIS	Geographic Information Systems
GWR	Geographically Weighted Regression
MODIS	Moderate Resolution Imaging Spectroradiometer
AOT	Aerosol Optical Thickness
MISR	Multi_angle Imaging Spectral-Radiometer
UAS	Unmanned Aircraft Systems
RPA	Remotely-Piloted Aircraft
UA	Unmanned Aircraft
GCS	Ground Control System
CS	Control System
FOB	Forward-Operating Base
HALE	High Altitude-long Endurance
LASE	Low Altitude-Short Endurance
NASA	National Aeronautics and Space Administration

ESRI	Environmental System Research Institute
R^2	Coefficient correlation
OLR	Ordinary or Least-Square Linear Regression
DR	Deming's-Linear Regression
PBR	Passing Bablok Linear Regression
AOD	Aerosol Optical Depth
GAM	Generalized Additive Model
SARA	SARA Simplified Aerosol Retrieval Algorithm
H	Humidity
WS	Wind speed
T	Temperature
LED	Light Emitting Diode Lamp
LPO	Low Pulse Occupancy

CHAPTER 1

INTRODUCTION

1.1 Background

Air quality data in urban areas such as fine particulate matter $PM_{2.5}$ is of high importance to control contamination of air and to preserve human life. Urban air quality changes by areas non-linearly and relies upon various factors, for example, meteorology, transportation, urban structure, and land use [1]. PM is typically described by its aerodynamic size, different Particles diameters have clear effects on the health [2]. Figure 1.1 illustrates three size fractions of PM sizes: $PM_{2.5}$, PM_{10}, and PMc (modified from the United States Environmental Protection Agency USEPA, 2013) [3].

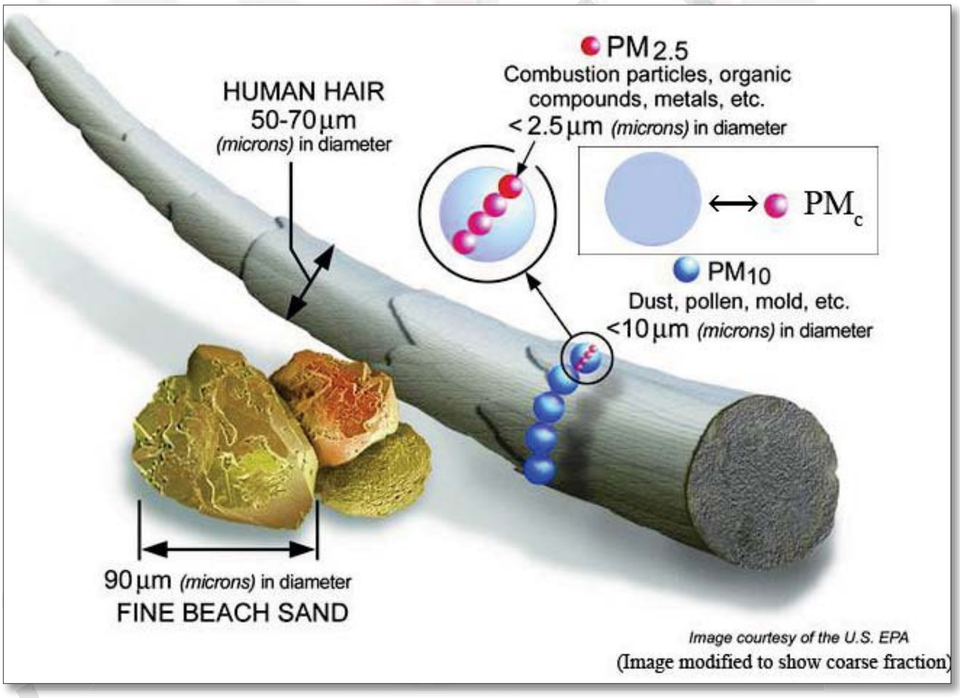

Figure 1.1 : Three size fractions of PM [3]

Hence ground-level (PM2.5) is the main part of urban air contamination where as planned by the Environmental Protection Agency EPA to come across federal standards. Where the EPA along these lines revised the first standards in 1979 and the alterations implemented in 1987, once the prime scale of particles was altered from Total Suspended Particles TSP to PM_{10}, completely depicting particles sufficiently tiny to penetrate into the respiratory tract and so it be more prone and impact on health. The new prime scale for PM_{10} not exceeded 150 $\mu g/m^3$ more than once per year and with mean annual of 50 µg/m^3. Next alteration started in 1994 that reviewed fine particle matter pm 2.5. This decision was according to studies that related to these small particles with severe health effects.

Standards of annual mean for $PM_{2.5}$ were set at 15 µg/m^3, and for 24-hour average were set at 65 µg/m^3. The values for PM_{10} were kept up at the same level as standard set in 1987. In 2006 $PM_{2.5}$ standards reduced the 24-hour values from 65 µg/m^3 to 35 µg/m^3 then, in 2012 the annual mean level was reduced to 12 µg/m^3 by EPA [4].

An Air Quality Index of health provided by EPA which facilitate understanding quickly unhealthy air pollution levels. Figure 1.2 represents the EPA AQI color coding [5].

Air Quality Index Levels of Health Concern	Numerical Value	Meaning
Good	0 to 50	Air quality is considered satisfactory, and air pollution poses little or no risk
Moderate	51 to 100	Air quality is acceptable; however, for some pollutants there may be a moderate health concern for a very small number of people who are unusually sensitive to air pollution.
Unhealthy for Sensitive Groups	101 to 150	Members of sensitive groups may experience health effects. The general public is not likely to be affected.
Unhealthy	151 to 200	Everyone may begin to experience health effects; members of sensitive groups may experience more serious health effects.
Very Unhealthy	201 to 300	Health warnings of emergency conditions. The entire population is more likely to be affected.
Hazardous	301 to 500	Health alert: everyone may experience more serious health effects

Figure 1.2 : EPA AQI color coding [5]

Most Asian countries have experienced fast economic growth over the latest decade. Expanded urbanization, industrial development and more vehicular utilization in these urban areas, combined with trans-limit haze contamination and dust spreading in the atmosphere in Asia, has added to the expansion of concentrations of particulate matter in the air. So it's not strange that studies on particulate air contamination, on spatial distribution and categorization and of pollution sources by particles, has achievement momentum in the most recent decade crosswise over Asia [6, 7]. Usually, air quality observations so mapping is directed by costly monitoring stations at fixed locations [2, 5]. Which frequently fairly sparse and irregularly set apart. The air contamination or air quality data obtained from a single monitoring station frequently, only denotes to data related to the major surrounding region. So Interpreting the statistics from these monitoring stations can rarely display a complete explanation of the regional air quality [2]. However, air pollution has come to be one of the chief problems currently, air pollution monitoring is required in order to scan the air quality. In Malaysia, they have specific guidelines intended for monitoring air quality which depends on the Recommended Malaysia Ambient Air Quality Guidelines (RMAAQG). The RMAAQG consider as a basis for calculating the Air Pollutant Index (API). These guidelines are derivative from existing approaches and human health records, and signify a safe level, below which no opposing health effects have been detected. The RMAAQG is commonly similar to the consistent air quality standards prescribed by the World Health Organization (WHO) and other states [8]. Satellites also used to predict air contamination concentrations along wide areas. However, they are inconvenient for applications on a small scale ranges, like cities, for the reason of limit spatial resolution [9]. Monitoring by the National-Oceanic Atmosphere-Administration (NOAA) satellite for the period of burning season during February and March 2002 which had displayed that Perak, Selangor, and Pahang have shown high burning activities in comparison to other places, the uncontrolled and Incomplete burning of vegetation can be a prospective polluter to the environment [7]. Most of the results from different studies offer an indication of air quality in Malaysia, if not completely, suffer from one weakness. Though the sampling was not directed continuously. A continuous sampling is needed to get a more dependable and true data about the air pollution in the atmosphere [8]. The meteorological effects on $PM_{2.5}$ particle matter concentrations were used to study the estimation of $PM_{2.5}$ concentration [10]. Uses of the Unmanned-Airborne Vehicles UAVs are an evolving tool to obtain different information. This information acquired with UAVs of a high resolution. UAVs are practical in all manners of environments of various sizes on a moment monitoring [11]. Providing Unmanned Aerial Vehicles (UAVs) with different contamination sensors, permitting them to become independent stations for air monitoring [12]. Air pollution monitoring over mobile sensors, which are low-power, low-cost, for sampling air contaminants in addition to the environmental temperature of the surface, humidity, and the air pressure using communication via Bluetooth with a smartphone [5]. Use of multiple linear regression to model the relationship between the dependent variable, the response variable air pollution with one or further independent variables an explanatory variables. So, the predicted values are used to describe air pollutant concentrations at sites without air pollution monitoring or sampler, and the predictor variables clarify the spatial variety of pollutant concentration properly well [9].

A regression analysis is presented in this study to predict $PM_{2.5}$ concentrations in small-scale area in UPM from data acquired by UAV based sensors.

1.2 Problem statement

i. However air contamination has come to be one of the main problems currently, $PM_{2.5}$ monitoring is required in order to scan air quality due to its tiny diameter which has clear effects on the health. Using small Unmanned Aerial Vehicles based sensors provides information at specified altitudes and overcoming obstacles and the difficulties obtaining required data, where can limit these data by sensor selection.

ii. The recent monitoring stations are fixed stations and are not designed to denote exposure on a small scale adequate. So the consequence may not sufficiently refer to small-scale conditions and consider a poor indicator for $PM_{2.5}$ concentrations away from the sampling position. In addition to the absence of $PM_{2.5}$ monitoring sites in some cities require an alternative method for information availability for $PM_{2.5}$ estimation.
iii. In small-scale areas where there are tall buildings, $PM_{2.5}$ monitoring at ground levels (1-3) meters is not sufficient. Therefore evaluation at different elevations can offer additional info to assess air quality

1.3 Research objective

The objective can be divided into the following sub-objectives:

i. To develop a UAV-based $PM_{2.5}$ Monitoring System.
ii. To develop a $PM_{2.5}$ estimation algorithm based on $PM_{2.5}$ measurements from the UAV-based sensor.
iii. To validate the model at low altitudes.

1.4 Research Scope

A UAV based sensors monitoring system will be developed in this study for purpose of data collection to generate a model for predicting $PM_{2.5}$ concentration. Three AQPs to predict $PM_{2.5}$ were selected, including; humidity, temperature, and wind speed. Three type of predictive models would be generated using statistical techniques, for instance, logistic regression a geographically weighted regression for modeling spatial relationships. The proposed model was validated by using trained and tested data which showed the probability and accuracy in the prediction. Each final output of each model was compared and validated using further data which were not used within the analysis.

1.5 Research contribution

This study applied a statistical approach to evaluate and validate the predicted model at different altitudes. The hypothesis of the study can be proved by verified results through generated models based on obtainability of data in the study area. The methodologies of integration of GIS and remote sensing involving UAV provide a fast, powerful tool and low-cost technique for analyzing and monitoring AQPs in small-scale areas compared to the further and current practices of predictable methods which most of them on large scale regardless of the type of regression used.

1.6 Thesis outline

CHAPTER 1: INTRODUCTION; This chapter described briefly the background of the study, which included air contamination in metropolitan areas and some types of information related to the subject with various studies in Malaysia, in addition to a brief explanation of the problem statement of the study, goal, objectives, and scope of the study.

CHAPTER 2: LITERATURE REVIEW; This chapter describes, environmental monitoring of $PM_{2.5}$, and environmental remote sensing. Next, an overview of the UAV based monitoring system, the method of data collecting in this study. Then, discussion describing the methodology used for modeling and predicting by regression analysis using ArcMap and applications of GIS for retrieving $PM_{2.5}$. Finally, a summary of related works using GWR and other regressing techniques.

CHAPTER 3: METHODOLOGY; This chapter describes in detail about the study area characteristics. Then followed by the design development and data collection, software analysis, and model validation.

CHAPTER 4: RESULTS AND DISCUSSION; This chapter concentrates on the outputs of the study including evaluation results of UAV-based $PM_{2.5}$ Monitoring System developing in different test areas and results of generation and validation of multivariate predictive algorithm which supported by graphs, tables, equations, and charts. Next, this chapter also discussed the regression analysis of GIS modeling technique of air quality in the study area.

CHAPTER 5: CONCLUSIONS AND FUTURE WORKS; This chapter provides the overall conclusion of this study and future works.

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