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

July 2018
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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

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

By

HUDA JAMAL JUMAAH

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 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 km$^2$ 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 parameters 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 PM2.5. 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 PM2.5 berdasarkan pengukuran PM2.5 dari sistem yang dibangunkan yang mampu mengukur kepekatan PM2.5 di kawasan berskala kecil dan mengesahkan model pada ketinggian rendah tertentu. Pencerapan PM2.5 menggunakan sensor UAV dilakukan dalam kawasan seluas 1.6 km² bagi mengumpul data pada altitud rendah. Parameter meteorologi termasuk suhu dan kelembapan turut direkodkan. Kajian ini menggunakan kaedah empirikal dengan menggunakan pakai rekod PM2.5 terkumpul dan parameter meteorologi bagi membangunkan model regresi berwajaran geografi (GWR). Model ini digunakan untuk menganggarkan kepekatan PM2.5 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 dari 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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In the name of Allah the Almighty, the most Gracious and most Merciful. Endless thankful for the completion of this thesis.

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Special thanks go to the member of the supervisory committee Assoc. Prof. Dr. Biswajeet Pradhan for his excellent guidance and inspiration throughout my study period.

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At last, my deepest gratitude for my uncle, my mother, my brothers, my sisters, my friends, and my colleagues who keep being my best accompany, and who were ready to assist in carrying out this work, until the last word I put in this thesis. I owe you this.
I certify that a Thesis Examination Committee has met on 10 July 2018 to conduct the final examination of Huda Jamal Jumaah on her thesis entitled "UAV-Based PM$_{2.5}$ Monitoring System for Small Scale Urban Areas" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Master of Science.

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Name of Chairman of Supervisory Committee: Professor Dato’ Dr. Shatri Bin Mansor

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Name of Member of Supervisory Committee: Associate Professor Dr. Biswajeet Pradhan
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<td>PM</td>
<td>Particulate Matter</td>
</tr>
<tr>
<td>USEPA</td>
<td>United States Environmental Protection Agency</td>
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<tr>
<td>EPA</td>
<td>Environmental Protection Agency</td>
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<tr>
<td>AQI</td>
<td>Air Quality Index</td>
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<td>RMMAAQG</td>
<td>Malaysia Ambient Air Quality Guidelines</td>
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<td>API</td>
<td>Air Pollutant Index</td>
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<td>WHO</td>
<td>World Health Organization</td>
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<td>NOAA</td>
<td>National Oceanic Atmosphere Administration</td>
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<td>UAVs</td>
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<td>AQPs</td>
<td>Air Quality Parameters</td>
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<td>GIS</td>
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<td>GWR</td>
<td>Geographically Weighted Regression</td>
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<td>MODIS</td>
<td>Moderate Resolution Imaging Spectroradiometer</td>
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<td>AOT</td>
<td>Aerosol Optical Thickness</td>
</tr>
<tr>
<td>MISR</td>
<td>Multi_angle Imaging Spectral-Radiometer</td>
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<td>UAS</td>
<td>Unmanned Aircraft Systems</td>
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<td>RPA</td>
<td>Remotely-Piloted Aircraft</td>
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<td>UA</td>
<td>Unmanned Aircraft</td>
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<td>GCS</td>
<td>Ground Control System</td>
</tr>
<tr>
<td>CS</td>
<td>Control System</td>
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<tr>
<td>FOB</td>
<td>Forward-Operating Base</td>
</tr>
<tr>
<td>HALE</td>
<td>High Altitude-long Endurance</td>
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<td>LASE</td>
<td>Low Altitude-Short Endurance</td>
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<td>NASA</td>
<td>National Aeronautics and Space Administration</td>
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<td>Abbreviation</td>
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<td>ESRI</td>
<td>Environmental System Research Institute</td>
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<td>R²</td>
<td>Coefficient correlation</td>
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<td>OLR</td>
<td>Ordinary or Least-Square Linear Regression</td>
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<td>DR</td>
<td>Deming’s-Linear Regression</td>
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<td>PBR</td>
<td>Passing Bablok Linear Regression</td>
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<td>AOD</td>
<td>Aerosol Optical Depth</td>
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<td>SARA</td>
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<td>H</td>
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<td>WS</td>
<td>Wind speed</td>
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<td>T</td>
<td>Temperature</td>
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<td>LED</td>
<td>Light Emitting Diode Lamp</td>
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<td>LPO</td>
<td>Low Pulse Occupancy</td>
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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 µg/m$^3$ more than once per year and
with mean annual of 50 μg/m³. 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/m³, and for 24-hour average were set at 65 μg/m³. 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/m³ to 35 μg/m³ then, in 2012 the annual mean level was reduced to 12 μg/m³ 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].

<table>
<thead>
<tr>
<th>Air Quality Index Levels of Health Concern</th>
<th>Numerical Value</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>Good</td>
<td>0 to 50</td>
<td>Air quality is considered satisfactory, and air pollution poses little or no risk</td>
</tr>
<tr>
<td>Moderate</td>
<td>51 to 100</td>
<td>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</td>
</tr>
<tr>
<td>Unhealthy for Sensitive Groups</td>
<td>101 to 150</td>
<td>Members of sensitive groups may experience health effects. The general public is not likely to be affected</td>
</tr>
<tr>
<td>Unhealthy</td>
<td>151 to 200</td>
<td>Everyone may begin to experience health effects; members of sensitive groups may experience more serious health effects</td>
</tr>
<tr>
<td>Very Unhealthy</td>
<td>201 to 300</td>
<td>Health warnings of emergency conditions. The entire population is more likely to be affected</td>
</tr>
<tr>
<td>Hazardous</td>
<td>301 to 500</td>
<td>Health alert: everyone may experience more serious health effects</td>
</tr>
</tbody>
</table>

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.
REFERENCES


[99] Ruslan, N. (2015). Air Pollution Index (API) real time monitoring system (Doctoral dissertation, Universiti Tun Hussein Onn Malaysia)