ESTIMATING ACACIA MANGIUM PLANTATIONS STANDING TIMBER VOLUME USING AN UNMANNED AERIAL VEHICLE

A’AMIR HASHIM BIN ZAINI

A thesis submitted in fulfilment of the
requirements for the award of the degree of
Master of Science (Geomatic Engineering)

Faculty of Built Environment and Surveying
Universiti Teknologi Malaysia

JANUARY 2019

ACKNOWLEDGEMENT

First of all, Alhamdulillah to Allah SWT for giving me the time, strength, and opportunity to complete this master project. I would like to express my deepest thanks to my parents and family members for their supporting to complete this thesis.

In preparing this thesis, I sincerely want to thank you and express my appreciation to my supervisors, Dr Mohd Farid bin Mohd Ariff who had been giving me guidance, criticism and also a source of knowledge for me to complete this project.

A gratitude goes out to all the staff of Faculty of Build Environment and Surveying and Samling Reforestation (Bintulu) Sdn Bhd for all your great assistance, my friends, Helmi Kadir, Aubrey Nuing and Faery Sapikin for having me realize that it is good to have peoples around to be rely on.

Finally, I would like to express my whole-heartedly felt to my beloved and respected parents, Prof Dr Zaini bin Assim and Halimah bte Mohamed and also my siblings for their love and spiritual support in all aspects of my life. I could not have finished this work without assistance and guidance from all of you. I can just say thanks and may Allah give the best in return.

.

ABSTRACT

Forest plantations are anticipated to play the important roles to maintain the commercial supply of logs and reducing timber demand from the natural forest. Thus the estimation of timber volume is crucial for the management to assess their productivity potential. Generally, the estimation of timber volume is considered a difficult task as ground measurement is expensive. The extensive use of Unmanned Aerial Vehicles (UAV) in forest plantations and indirect measurements of basic tree attributes is suitable for monitoring and timber volume estimation. The UAV measurement has the advantage that it can acquire the high resolution digital imagery through photogrammetry and Structure from Motion (SfM) to estimate basic tree attributes such as tree heights, diameter at breast height (DBH) and crown diameters. The purpose of this study is to estimate the timber volume of Acacia mangium plantations using ortho-mosaic, digital surface model (DSM) and digital terrain model (DTM), which are derived from UAV data. The involved workflow used Canopy Height Models (CHM) for the tree height extraction, the smoothing of raster images to find the local maxima and Inverse Watershed Segmentation (IWS) for estimation of the crown diameters which indirectly used to estimate the DBH and the calculation of Acacia mangium timber volume. All this workflow is done with the help of geographical information system. Finally, the accuracies of the two methods are validated by testing their significance. Results showed higher agreement between field measured and estimated UAV data for tree heights than for DBH based on RMSE, which ranged from 1.97 m – 3.33 m for height and 3.67 cm – 4.49 cm for DBH. However, the Pearson's r for DBH derived from UAV measurement data shows weak correlation than that of the field measurement which ranged from 10% – 48%, while tree height shows the strong correlation between UAV measurement and field measurement which ranged from 75% – 99%. For the timber volume estimation, the RMSE ranged from 0.25 m^3 – 0.34 m^3 and Pearson's r ranged from 33% - 62%. In overall, the accuracy of the results is acceptable and showed that the methods were feasible for *Acacia mangium* timber volume estimation.

ABSTRAK

Perladangan hutan memainkan peranan penting untuk memenuhi permintaan kayu komersial dan mengurangkan pemusnahan hutan semulajadi. Oleh itu, anggaran isipadu pokok sangat penting terutama kepada pihak pengurusan ladang hutan untuk menentukan potensi hasil tanaman mereka. Secara amnya, tugasan untuk menentukan isipadu pokok adalah sukar dan memerlukan kos yang tinggi. Penggunaan *Unmanned Aerial Vehicle* (UAV) sangat sesuai digunakan untuk tujuan pemerhatian dan juga penentuan isipadu pokok. Pengukuran menggunakan UAV mempunyai kelebihan dimana ianya dapat menghasilkan gambar digital beresolusi tinggi melalui teknik fotogrametri dan *Structure from Motion* (SfM) dan seterusnya digunakan untuk mengukur parameter asas pokok seperti tinggi pokok, *diameter at breast height* (DBH) dan saiz kanopi pokok. Tujuan utama kajian ini dijalankan adalah untuk menentukan isipadu pokok *Acacia mangium* daripada ladang hutan dengan menggunakan fotograf udara, *digital surface model* (DSM) dan *digital terrain model* (DTM), dimana ianya diperolehi daripada data UAV. Dengan menggunakan teknik *local maxima* daripada *Canopy Height Model* (CHM), tinggi pokok dapat ditentukan, manakala dengan menggunakan teknik *Inverse Watershed Segmentation* (IWS) pula, kanopi pokok dapat ditentukan dimana secara tidak langsung ianya digunakan untuk menentukan DBH, dan seterusnya pengiraan isipadu pokok. Kesemua jalan kerja ini dilakukan dengan bantuan sistem informasi geografik. Akhir sekali, ketepatan hasil kajian disahkan dengan menguji hubungkait antara dua kaedah, iaitu pengukuran menggunakan UAV dan pengukuran di lapangan. Hasil kajian menunjukkan hubungkait yang tinggi diantara tinggi kayu dan DBH yang diukur menggunakan kedua-dua kaedah berdasarkan nilai *root mean square error* (RMSE) dimana nilainya diantara 1.97 m – 3.33 m untuk tinggi pokok dan 3.67 cm – 4.49 cm untuk DBH. Walaubagaimanapun, korelasi Pearson's untuk DBH yang diperolehi daripada pengukuran menggunakan UAV menunjukkan korelasi yang rendah berbanding pengukuran dilapangan menunjukkan nilai peratusan diantara 10% ke 48% manakala untuk tinggi pokok menunjukkan korelasi yang tinggi diantara dua kaedah dimana nilai peratusannya diantara 75% - 99%. Untuk penentuan isipadu kayu, RMSE menunjukkan nilai diantara 0.25 m^3 – 0.34 m^3 dan korelasi Pearson's menunjukkan peratusan diantara 33% - 62%. Secara keseluruhan, ketepatan hasil kajian boleh diterima dan menunjukkan bahawa kaedah ini boleh digunakan untuk menentukan anggaran isipadu kayu *Acacia Mangium*.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

2D	-	Two-Dimensional
3D	-	Three-Dimensional
ALS	-	Airborne Laser Scanner
BBA	-	Bundle Block Adjustments
CHM	-	Canopy Height Model
DBH	-	Diameter at Breast Height
DEM	-	Digital Elevation Model
DGPS	-	Differential Global Positioning System
DSM	-	Digital Surface Model
DTM	-	Digital Terrain Model
FMU	-	Forest Management Units
FPMU	-	Forest Plantation Management Units
GPS	-	Global Positioning System
GIS	-	Geographic Information System
IMU	-	Inertial Measurement Unit
IWS	-	Inverse Watershed Segmentation
LPF	-	License Planted Forest
NRMSE	-	Normalised Root Mean Square Error
RMSE	-	Root Mean Square Error
RTK	-	Real Time Kinematic
SfM	-	Structure-from-Motion
UAV	-	Unmanned Aerial Vehicle
UVS	-	Unmanned Vehicle Systems-International
VTOL	-	Vertical Take-off and Landing

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Background of Study

Forest plantations is not a new thing in Malaysia. Forestry Departments were the pioneer who directly involved in developing forest plantations. The Compensatory Forest Plantation is one of the program that developed by the Forestry Department in 1982. This program planted the fast-growing tropical hardwood species such as *Acacia mangium*, *Gmelina arborea* and *Paraserianthes falcataria* (Abdul Rasip *et al*., (1997). In Peninsular Malaysia, a total of 0.07 mil. ha of natural forests had been transformed into forest plantations since 1996.

Since 1973 and 1981, forest plantations were actively operational in East Malaysia. There were estimated around 10,000 ha of forest plantations planted in Sabah and Sarawak which consists of hardwood species such as *Acacia mangium*, *Gmelina arborea*, *Paraserianthes falcataria* and *Swietenia macrophylla*. The *Acacia mangium* species was the most species planted in East Malaysia particularly in Sarawak.

The State Government's commitment on sustainable forest management and establishment of enormous commercial forest plantation are among the proactive actions to make sure the timber industry is a sunrise industry. The implementation of sustainable forest management practices impacts the timber production from natural forests. Therefore, forest plantations play an important role to maintain the commercial logs supply.

Demand for supply of timber from forest plantations is expected to increase in the coming decades (Elias and Boucher, 2014). From 1990 to 2015, the global area of forest plantations increased from 167.55 to 277.9 mil. ha or approximately 4.06% to 6.95% of the global forest area (Payn *et al*., 2015). The spike in global and regional forest plantations shows the importance role of forest plantations in supplying timber to the downstream of forest industries.

In 2016, there are two Forest Plantation Management Units (FPMU) and eight Forest Management Units (FMU) certified area that covering 3.97 mil. ha in Malaysia, including Sabah and Sarawak (MTC, 2016). Figure 1.1 shows the distribution of FMU and FPMU in Malaysia. The FMU is a demarcated land area where it was predominantly covered by natural forests and has been managed in a long run basis to set out clear objectives in the forest management plan (ITTO, 2004).

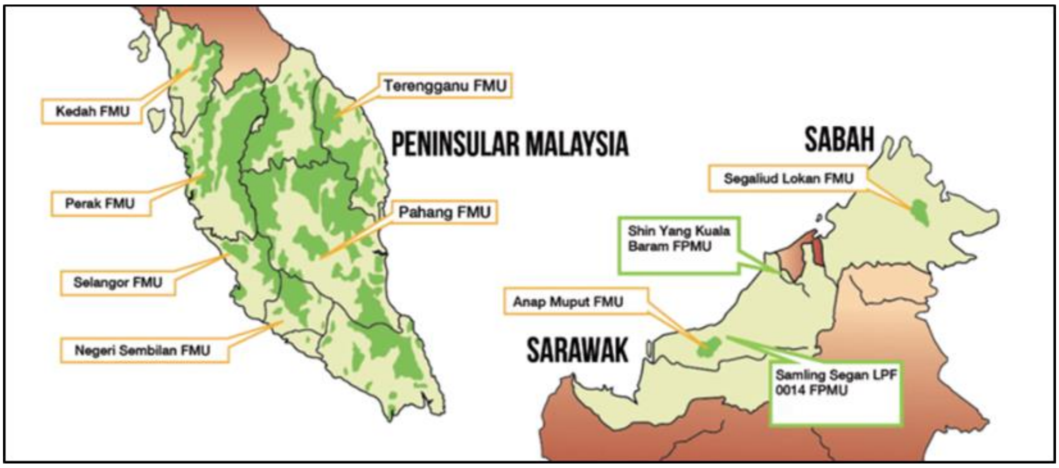

Figure 1.1: FMU and FPMU location in Malaysia (MTC, 2016)

Collecting accurate tree attributes information faster and more efficiently is one of the concerns and challenges of forest management. For planning and decision making in forest plantations, it is important to have the accurate quantification of basic tree attributes such as tree height, diameter at breast height (DBH) and crown diameter. With the help of basic tree attributes measurement, the timber stand volume of small extent areas can be calculated.

Inventory information on timber stand volume is required for harvesting rotations planning. With improvements of unmanned aerial vehicles (UAV), it is now possible to acquire high resolution imagery and three-dimensional (3D) data for basic tree attributes measurements.

Conventional methods for forest inventory measurements is slowly replaced by high spatial resolution data from satellite imagery. Within this few years, the use of UAV for collecting various spatial information is tremendously increased. Recent studies have reported the use of UAV in various analyses, including forestry applications (Goodbody *et al*., 2017). The UAV imagery acquisition and post-processing it with the structure from motion (SfM) method is one of the major new approaches to analyse forest structures (Mlambo *et al*., 2017). SfM is a photogrammetric method for building 3D models based on many two-dimensional (2D) images received a lot of attention in remote sensing fields with the use of airborne platforms. The advantage of UAV data is that high resolution ortho-mosaic images can be generated that clearly detect tree canopies (Panagiotidis *et al*., 2017). Moreover, this approach can be used to construct 3D models of an area through photogrammetry. This means that there are possibilities for extracting forest inventory from UAV data (Wallace *et al*., 2016).

Thus, the purpose of this study is to assess the use of UAV system for estimating timber stand volume, focusing on extraction of the tree height and DBH, using both an ortho-mosaic image and a 3D model constructed using the SfM method.

1.2 Problem Statement

Many interested parties such as commercial sector, merchantable timber and wood products require information of the forest biophysical parameter such as stand volume, growing stock volume and aboveground biomass. This interested parties need proper tree attributes measurement in order to determine the exact value in that tree. Not only used for downstream woodworking mills to produce furniture, these timber also manufacture the mouldings, doors and flooring. Researchers and foresters need this basic tree attributes in order to estimate timber volume from individual tree. Estimation of timber stand volume is important in observing for reasons of planning and documentation in forest plantations industry.

Generally, tree attributes measurement is done using conventional technique, in which the measurement is carried out using field instruments such as measuring tape, scale stick and inclinometer (Luoma *et al*., 2017). Conventional methods in plantations areas are time consuming. Basic measurements of tree attributes are tree height, DBH and crown diameter. Tree DBH is measured at 1.3 m above the ground (Avery and Burkhart, 2002). Height of tree and height to crown is measured using sine and tangential method from the distance observer or scaling method. This conventional technique is usually use as the most accurate measurement that should be use for validation of other remotely sensed measurements and estimation. The main issue with conventional method is that it required a lot of time to complete where many manpower needed for the measurements of numerous trees in small area.

To estimate timber stand volume, the spatial information of individual tree crown delineation for *Acacia mangium* plantations is needed. This will help to balance the harvesting cost for forest plantations management. The precise estimation for forest inventory is important in achieving sustainable forest management. Normally, the pre harvesting estimation of standing timber volume is very critical for successful operation especially in the forest plantations. This will decide the basis for harvesting maps and help to balance the harvesting cost and expected incomes from wood sales.

For spatially larger areas, modelling of volume requires the use of remote sensing information for practical purposes. Moreover, the value of inventory data of remote sensing can have increased with the detailed coverage at lower cost. The high resolution imagery can be obtain from UAV system and it has abilities to generate digital surface model (DSM). This is one of the advantage using the UAV system because of the cost that is cheaper than that airborne laser scanner (ALS) system.

This study utilizes the data generated from UAV for tree attributes measurement. The purpose of this study is to evaluate the accuracy of basic tree attributes measurement using 3D data obtain from UAV. The accuracy of the measurement during this study tested and validated with the conventional measurement technique on the field.

1.3 Research Objectives

The aim of this study is to assess the capability of UAV system for timber volume estimation of *Acacia mangium* forest plantations in Sarawak. This aim is supported by several specific objectives:

(a) To estimate basic tree attributes (tree height, DBH) and timber stand volume at plot-level based on UAV data.

(b) To evaluate the accuracy of basic tree attributes measurement and timber stand volume obtained from UAV with the conventional field measurement.

1.4 Scope of Study

This study was conducted in Segan Reforestation Project, own by Samling Reforestation (Bintulu) Sdn Bhd, located at latitude 2º 58' N to 3º 12'N and longitude 112º 58' E to 113º 12'E near the town of Bintulu, Sarawak in Malaysia. Segan Reforestation Project is one of the two FPMU in Malaysia. The first planting for this project was carried out in the year 1999/2000 and it was the earliest Industrial Tree Plantations (ITP) established in Sarawak. There are several species planted in Segan Reforestation Project such as *Acacia mangium*, *Falcataria moluccana* and *Eucalyptus pellita*.

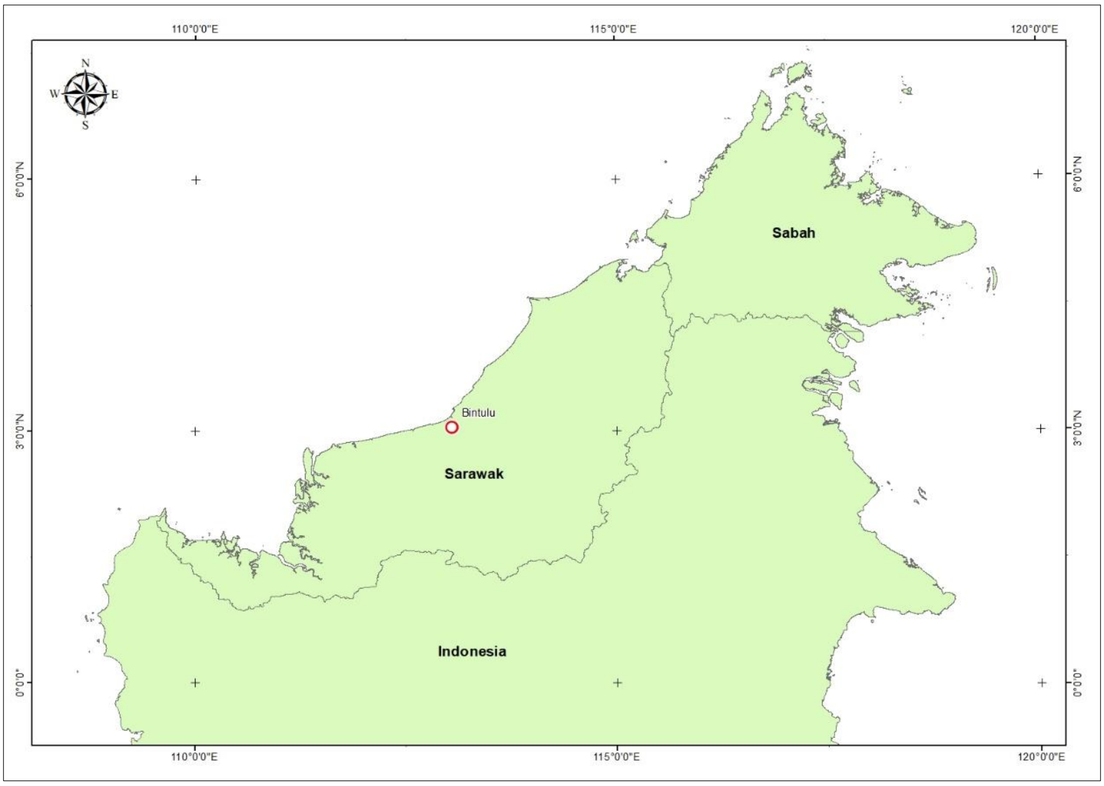

Figure 1.2: Location of study area

However, this study only focuses on the *Acacia Mangium* species, with 10 years old planting age. The *Acacia mangium* is a fast growing species where the harvesting for this species is done when the trees reach matured ages which is within 13 to 15 years.

Figure 1.3: Wild *Acacia mangium* tree

For this study, primary data collected from DJI Phantom 3 Professional, a multi-rotor UAV system. Previous studies have shown that UAV can be used to retrieve basic tree attributes such as tree height, DBH, tree delineation and crown projection area (Panagiotidis *et al*., 2017). However, this study only focused on measuring basic tree attributes for timber stand volume estimation which is tree height, DBH and crown size. The selection of this attributes is based on the previous studies on timber stand volume estimation (Abdollahnejad *et al*., 2018).

The timber stand volume is measured roughly using conventional field measurement that involve lots of manpower, inaccurate and not applicable for large plantations area. Same goes to the estimated timber stand volume using ALS in which the results are reliable but the data is very expensive to be use for large plantations area. Further study on this matter is required to access the timber stand volume estimation from 3D data that generated from UAV and see how accurate the timber volume estimation using this approach. In this study, the *Acacia mangium* species was selected to be estimated its volume in Sarawak.

For processing of UAV images, the Pix4Dmapper Pro software was used. Pix4Dmapper Pro developed by Swiss company, Pix4D, which is a computer vision-based software company. This software has a capability to create a geo-referenced 2D ortho-mosaic and 3D point cloud based on the images captured from the UAV. The processing using Pix4Dmapper Pro is automated. However, some options can be set for the SfM, the bundle block adjustments (BBA) and the camera self-calibration (Benassi *et al*., 2017).

For spatial analysis, the ArcGIS 10.2.1 software was used. This software is a Geographic Information System (GIS) basis products developed by Esri. The ArcGIS software is powerful tool to manipulate spatial data for geographical information.

For analysis part, all statistical analyses were conducted in Microsoft Office Excel. The linear regression analysis is used to assess the relationship between the measured and estimated parameter.

1.5 Methodology

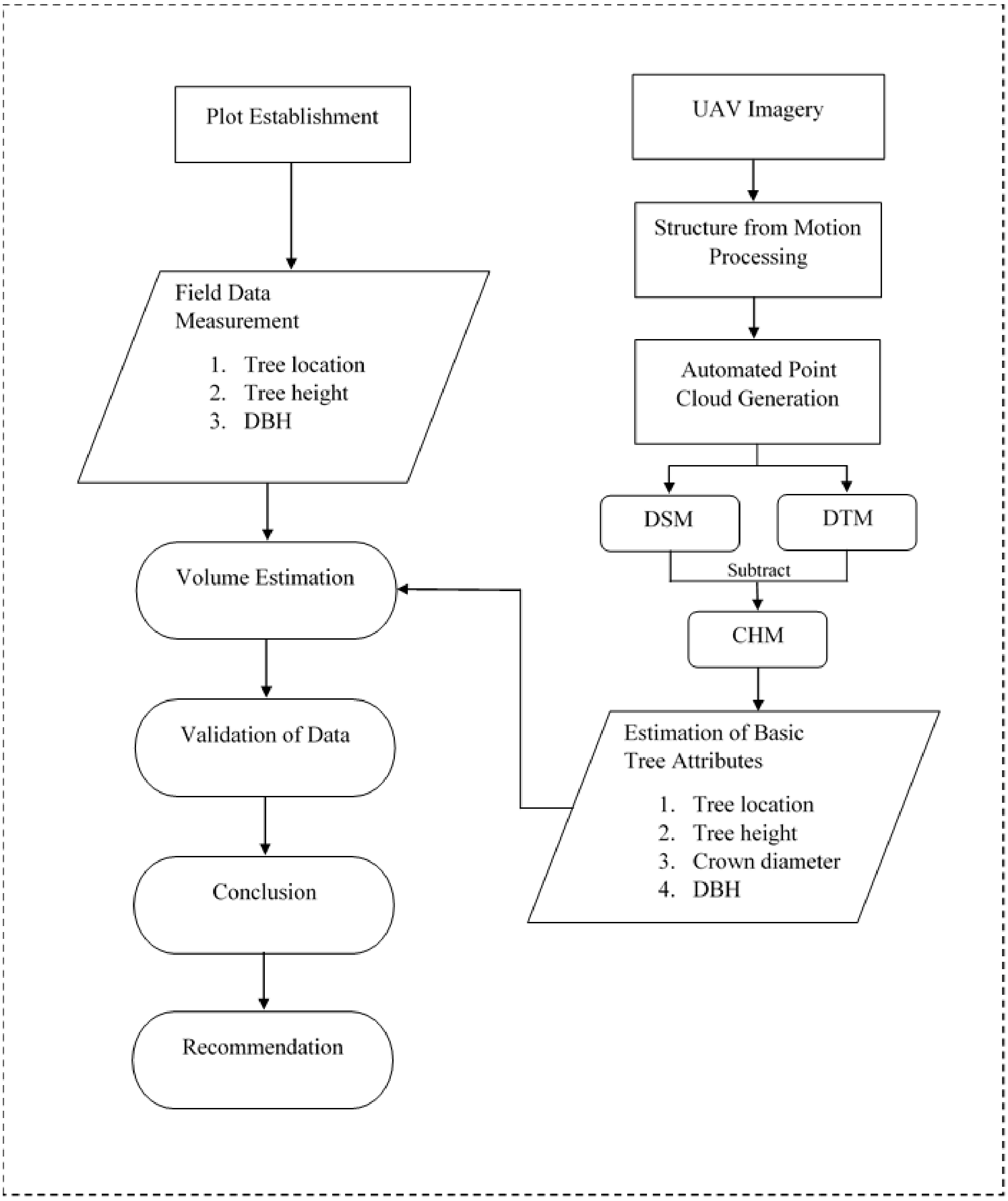

Figure 1.4: Flowchart of the methodology

1.6 Significant of Study

Timber stand volume estimation from basic tree attributes have drawn attention of research society mainly to support sustainable forest management and retrieving the necessary data for silviculture activities. This study utilized the UAV system in retrieving basic tree attributes for timber stand volume estimation. Conventional methods for tree attributes measurements are time consuming and expensive to conduct. Currently, the accurate measurement of timber stand volume from basic tree attributes is completed through felling and weighting processes. This process is not practical in forest plantations as it will cause loss to the operation since the trees need to be cut down in order to calculate the timber stand volume.

This study is an effort to estimate the timber stand volume over the large plantations area based on the tree attributes measurement. The tree attributes measurement such as tree height, DBH and crown diameter can be estimated from UAV system. The 3D data from UAV such as DSM provide effective and time consuming estimation of timber stand volume in which it has been investigated throughout this study. Precise timber stand volume estimation is very beneficial in achieving sustainable forest management.

This study will promote UAV system as an option for timber stand volume estimation to replace the conventional methods. Forest plantations companies such as Samling Reforestation (Bintulu) Sdn Bhd which actively involved with forest plantations can expose to this kind of technology and utilize it in their plantations. This study also proved that UAV system can be used in forest plantations for monitoring through temporal measurement for management decision making. Therefore, the output of this study which is timber stand volume estimated using UAV system can be seen as a future potential in replacing conventional methods.

1.7 Thesis Outline

This thesis consists of five chapters in which each chapter are separated systematically to clearly show the significance of this study towards timber stand volume estimation using UAV system.

Chapter 1 contains sub-chapters that initiate the idea in conducting this study with background of the study showing the importance of timber stand volume estimation for forest plantations. This chapter also stated the problem faced with conventional methods for tree attributes measurements and timber stand volume estimation. The objectives developed for this study also outlined in this chapter as a guideline throughout the study. Significance of the study discussed the contributions of this study to acknowledge the usage of UAV system in forest plantations particularly in timber stand volume estimation. Scope and limitation of this study also highlighted in this chapter to ensure that this study can be completed within the suggested timeframe.

Chapter 2 summarizes reviews from the related literatures in which this chapter discusses on the advancement of remote sensing technology particularly in timber stand volume estimation and basic tree attributes measurements from conventional methods to satellite based and UAV based approach. This chapter also underlined the problems faced from the conventional methods and also not enough studies focusing on usage of UAV system for standing timber volume estimation for forest plantations.

Chapter 3 is completely devoted to introduce datasets and methodologies used in this study. Methodologies highlighted are the sample plots configuration in the field, SfM methods to generate point clouds from UAV data, spatial analyses to extract tree attributes from UAV data and calculation of the standing timber volume. Methods of validation were also discussed in which estimated and measured tree measurements and volume is validated.

Chapter 4 focuses on presenting and discussing the results from processing outlined in Chapter 3. This chapter shows statistical analyses from the measurements data.

The results obtained shown in Chapter 4 are used in Chapter 5 to prove that objectives from this study were achieved. Chapter 5 also presented recommendation to improve the results as the continuation of this study is highly recommended based on the findings show in this study which timber stand volume estimation by using UAV system.

REFERENCES

Abdollahnejad, A., Panagiotidis, D., & Surový, P. (2018). Estimation and Extrapolation of Tree Parameters Using Spectral Correlation between UAV and Pléiades Data. Forests, 9(2), 85.

Abdul Rasip, A.G. Mohd. Noor, M., Ahmad Zuhaidi, Y. & Krishnapillay, B. (1997). Conference on Forestry and Forest Products Research: Proceedings of the Fourth Conference, October, 2-4, 1997. Kepong: Forest Research Institute Malaysia.

Adam, N. S., Jusoh, I., & Ishak, N. D. (2012, November). Growth characteristics of Acacia mangium plantation in Sarawak. In 3rd International Plantation Industry Conference and Exhibition (pp. 5-7).

Ahmad, A., Tahar, K. N., Udin, W. S., Hashim, K. A., Darwin, N., Hafis, M., ... & Azmi, S. M. (2013, November). Digital aerial imagery of unmanned aerial vehicle for various applications. In Control System, Computing and Engineering (ICCSCE), 2013 IEEE International Conference on (pp. 535-540). IEEE.

Anderson, K., & Gaston, K. J. (2013). Lightweight unmanned aerial vehicles will revolutionize spatial ecology. Frontiers in Ecology and the Environment, 11(3), 138-146.

Avery, T.E., Burkhart, H.E., (2002). Forest Measurements, 5th ed. McGraw-Hill Higher Education, New York, USA, p. 456.

Banu, T. P., Borlea, G. F., & Banu, C. (2016). The Use of Drones in Forestry. Journal of Environmental Science and Engineering B, 5(11).

Bardon, R. E. (2013). Estimating the Volume of a Standing Tree Using a Scale (Biltmore) Stick.

Benassi, F., Dall'Asta, E., Diotri, F., Forlani, G., Morra di Cella, U., Roncella, R., & Santise, M. (2017). Testing accuracy and repeatability of UAV blocks oriented with GNSS-supported aerial triangulation. Remote Sensing, 9(2), 172.

Chianucci, F., Disperati, L., Guzzi, D., Bianchini, D., Nardino, V., Lastri, C., & Corona, P. (2016). Estimation of canopy attributes in beech forests using true colour digital images from a small fixed-wing UAV. International Journal of Applied Earth Observation and Geoinformation, 47, 60-68.

Chris H., Owen B., Jordan W., Thomas B., Paul N., Maja K., Steve M. (2013). Spatial accuracy of UAV-derived orthoimagery and topography: comparing photogrammetric models processed with direct geo-referencing and ground control points. Department of Geography, University of Calgary, Calgary, Alberta, Canada.

Chongrak, W., Somphat, K., Ladawan, P., Sakhan, T. & Monton, J. (2005). Effect of Thinning on Growth and Yield of Acacia mangium-Dipterocarpus alatus Mixed Plantation. Trat Agroforestry Re-search Station (TAfRS), Kasetsart University Research and Devel-opment Institute (KURDI), Chattuchak, Bangkok, Thailand.

Colomia, L., & Molina, P. (2014). Unmanned aerial systems for photogrammetry and remote sensing: A review, Volume 92, June 2014, Pages 79-97 Centre Tecnològic de Telecomunicacions de Catalunya, Spain

Dandois, J. P., & Ellis, E. C. (2010). Remote sensing of vegetation structure using computer vision. Remote Sensing, 2(4), 1157-1176.

Díaz-Varela, R. A., Zarco-Tejada, P. J., Angileri, V., & Loudjani, P. (2014). Automatic identification of agricultural terraces through object-oriented analysis of very high resolution DSMs and multispectral imagery obtained from an unmanned aerial vehicle. Journal of environmental management, 134, 117-126.

Edson, C., & Wing, M. G. (2011). Airborne light detection and ranging (LiDAR) for individual tree stem location, height, and biomass measurements. Remote Sensing, 3(11), 2494-2528.

Elias, P., & Boucher, D. (2014). Planting for the future: How demand for wood products could be friendly to tropical forests. Union of Concerned Scientists.

FAO. (2002). Case study of tropical forest plantations in Malaysia by D.B.A Krishnapillay. Forest Plantations Working Paper 23. Forest Resources Development Service, Forest Resources Division. FAO, Rome.

Goodbody, T. R., Coops, N. C., Marshall, P. L., Tompalski, P., & Crawford, P. (2017). Unmanned aerial systems for precision forest inventory purposes: A review and case study. The Forestry Chronicle, 93(1), 71-81.

Harwood C. (2011). Strengthening the tropical Acacia plantation value chain: the role of research. Journal of Tropical Forest Science 23: 1–3.

Hashim, M. N., Hazim, M., & Syafinie, A. M. (2015). Strategic forest plantation establishment in Malaysia for future product development and utilization. In Proceeding of the Kuala Lumpur International Agriculture, Forestry and Plantation Conference (pp. 236-40).

Hopkinson, C., Chasmer, L., Young-Pow, C., & Treitz, P. (2004). Assessing forest metrics with a ground-based scanning lidar. Canadian Journal of Forest Research, 34(3), 573-583.

Hormigo, T., & Araújo, J. (2013, August). A micro-UAV system for forest management. In Conference Paper, ISPRS Archives (Vol. 1, p. W2).

Ionescu, I., Badea, D. and Dogaru, M., (2008). Digital Photogrammetric Products from Aerial Images, used for Identifying and Delimitting Flood Risk Areas. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences. Vol. XXXVII. Part B5. (pp. 361-364). Beijing, China.

Jakubowski, M. K., Li, W., Guo, Q., & Kelly, M. (2013). Delineating individual trees from LiDAR data: A comparison of vector-and raster-based segmentation approaches. Remote Sensing, 5(9), 4163-4186.

Jeyanny, V., Lee, S. S., & Rasidah, K. W. (2011). Effects of arbuscular mycorrhizal inoculation and fertilisation on the growth of Acacia mangium seedlings. Journal of Tropical Forest Science, 404-409.

Jusoff, K., & Taha, D. (2008). Sustainable forest management practices and environmental protection in Malaysia. WSEAS Transactions on Environment and Development, 4(3), 191-199.

Jusoh, I., Suteh, J. K., & Adam, N. S. (2017). Growth and Yield of Acacia mangium Based on Permanent Sampling Plots in a Plantation.

Kajiwara, R. and Shigematsu, T. (2008). Estimation of Diameter Breast Height and Shrub Layer Vegetation Cover Ratio of Cryptomeria japonica Plantation through Aerial Photographs, Journal of Environmental Information Science, Vol (No 22).

Karantzalos, K. G., & Argialas, D. P. (2004). Towards automatic olive tree extraction from satellite imagery. In Geo-Imagery Bridging Continents. XXth ISPRS Congress (pp. 12-23).

Ke, Y., & Quackenbush, L. J. (2007). Forest species classification and tree crown delineation using QuickBird imagery. In Proceedings of the ASPRS 2007 Annual Conference (pp. 7-11).

Leverett, B., Bertolette, D. (2014). American Forests Champion Trees Measuring Guidelines Handbook.

Lisein, J., Pierrot-Deseilligny, M., Bonnet, S., & Lejeune, P. (2013). A photogrammetric workflow for the creation of a forest canopy height model from small unmanned aerial system imagery. Forests, 4(4), 922-944.

Luoma, V., Saarinen, N., Wulder, M. A., White, J. C., Vastaranta, M., Holopainen, M., & Hyyppä, J. (2017). Assessing precision in conventional field measurements of individual tree attributes. Forests, 8(2), 38.

Mlambo, R., Woodhouse, I. H., Gerard, F., & Anderson, K. (2017). Structure from Motion (SfM) photogrammetry with drone data: a low cost method for monitoring greenhouse gas emissions from forests in developing countries. Forests, 8(3), 68.

Nature Conservation Practice Note. (2006). Measurement of Diameter at Breast Height (DBH), pp. 1-6.

Nurminen, K., Karjalainen, M., Yu, X., Hyyppä, J., & Honkavaara, E. (2013). Performance of dense digital surface models based on image matching in the estimation of plot-level forest variables. ISPRS Journal of Photogrammetry and Remote Sensing, 83, 104-115.

Oderwald, R. & Johnson, J. (2009). Measuring Standing Trees and Logs.

Ota, T., Ogawa, M., Shimizu, K., Kajisa, T., Mizoue, N., Yoshida, S., & Sokh, H. (2015). Aboveground biomass estimation using structure from motion approach with aerial photographs in a seasonal tropical forest. Forests, 6(11), 3882-3898.

Panagiotidis, D., Abdollahnejad, A., Surový, P., & Chiteculo, V. (2017). Determining tree height and crown diameter from high-resolution UAV imagery. International journal of remote sensing, 38(8-10), 2392-2410.

Panagiotidis, D., Surový, P., & Kuželka, K. (2016). Accuracy of Structure from Motion models in comparison with terrestrial laser scanner for the analysis of DBH and height influence on error behaviour. J. For. Sci, 62, 357-365.

Parrish, C. E. (2003). Analysis of airborne laser-scanning system configurations for detecting airport obstructions.

Payn, T., Carnus, J. M., Freer-Smith, P., Kimberley, M., Kollert, W., Liu, & Wingfield, M. J. (2015). Changes in planted forests and future global implications. Forest Ecology and Management, 352, 57-67.

Sari, N. A., Ahmad, A., Sari, M. A., Sahib, S., & Rasib, A. W. (2015). Development Of Rapid Low-Cost Lars Platform For Oil Palm Plantation. Jurnal Teknologi, 77(20), 99-105.

Skovsgaard, J. P. (2008). Analysing effects of thinning on stand volume growth in relation to site conditions: a case study for even-aged Sitka spruce (Picea sitchensis (Bong.) Carr.). Forestry, 82(1), 87-104.

Tang, L., & Shao, G. (2015). Drone remote sensing for forestry research and practices. Journal of Forestry Research, 26(4), 791-797.

Vazirabad, Y. F., & Karslioglu, M. O. (2010). Airborne laser scanning data for tree characteristics detection. In ISPRS Istanbul Workshop (pp. 11-13).

Verma, N. K., Lamb, D. W., Reid, N., & Wilson, B. (2016). Comparison of canopy volume measurements of scattered eucalypt farm trees derived from high spatial resolution imagery and LiDAR. Remote Sensing, 8(5), 388.

Wallace, L., Lucieer, A., Malenovský, Z., Turner, D., & Vopěnka, P. (2016). Assessment of forest structure using two UAV techniques: A comparison of airborne laser scanning and structure from motion (SfM) point clouds. Forests, 7(3), 62.

Whitehead, K., Hugenholtz, C. H., Myshak, S., Brown, O., LeClair, A., Tamminga, A., & Eaton, B. (2014). Remote sensing of the environment with small unmanned aircraft systems (UASs), part 2: Scientific and commercial applications. Journal of unmanned vehicle systems, 2(3), 86-102.

Zhang, X., Xiao, P., Feng, X., Wang, J., & Wang, Z. (2014). Hybrid region merging method for segmentation of high-resolution remote sensing images. ISPRS Journal of Photogrammetry and Remote Sensing, 98, 19-28.

Zhen, Z., Quackenbush, L., & Zhang, L. (2016). Trends in automatic individual tree crown detection and delineation—Evolution of LiDAR data. Remote Sensing, 8(4), 333.