Jurnal Teknologi

Full paper

Individual Tree Measurement in Tropical Environment using Terrestrial Laser Scanning

Muhammad Zulkarnain Abdul Rahman[a]*, Zulkepli Majid[b], Md Afif Abu Bakar[a], Abd Wahid Rasib[a], Wan Hazli Wan Kadir[a]

[a]*TropicalMAP Research Group*

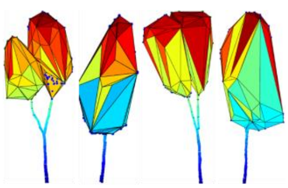
[b]*Photogrammetry & Laser Scanning Research Group, Department of Geoinformation, Faculty of Geoinformation and Real Estate, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia*

*Corresponding author: mdzulkarnain@utm.my

Article history

Received :6 February 2014
Received in revised form :
21 December 2014
Accepted :26 February 2015

Graphical abstract



Abstract

Detailed forest inventory and mensuration of individual trees have drawn attention of research society mainly to support sustainable forest management. This study aims at estimating individual tree attributes from high density point cloud obtained by terrestrial laser scanner (TLS). The point clouds were obtained over single reference tree and group of trees in forest area. The reference tree is treated as benchmark since detailed measurements of branch diameter were made on selected branches with different sizes and locations. Diameter at breast height (DBH) was measured for trees in forest. Furthermore tree height, height to crown base, crown volume and tree branch volume were also estimated for each tree. Branch diameter is estimated directly from the point clouds based on semi-automatic approach of model fitting i.e. sphere, ellipse and cylinder. Tree branch volume is estimated based on the volume of the fitted models. Tree height and height to crown base are computed using histogram analysis of the point clouds elevation. Tree crown volume is estimated by fitting a convex-hull on the tree crown. The results show that the Root Mean Squared Error (RMSE) of the estimated tree branch diameter does not have a specific trend with branch sizes and number of points used for fitting process. This explains complicated distribution of point clouds over the branches. Overall cylinder model produces good results with most branch sizes and number of point clouds for fitting. The cylinder fitting approach shows significantly better estimation results compared to sphere and ellipse fitting models.

Keywords: Individual tree measurement; forest; terrestrial laser scanning

Abstrak

Inventori hutan dan pengukuran pokok secara individu yang terperinci telah mendapat perhatian dari penyelidik terutamanya bagi menyokong pengurusan hutan yang mampan. Kajian ini bertujuan untuk menganggar sifat-sifat pokok secara individu daripada *point cloud* yang diperolehi dari pengimbas laser daratan (TLS). *Point clouds* ini diperolehi dari pokok rujukan tunggal dan kumpulan pokok di kawasan hutan. Pokok rujukan dianggap sebagai penanda aras kerana pengukuran terperinci diameter dahan pokok telah dibuat di dahan terpilih dengan saiz dan lokasi yang berbeza. Diameter pada paras dada (DBH) telah diukur untuk pokok-pokok di hutan. Di samping itu ketinggian pokok, ketinggian asas rimbun pokok, isipadu rimbun pokok, dan isipadu dahan pokok juga dianggarkan bagi setiap pokok. Diameter dahan pokok dianggarkan terus dari awan titik berdasarkan pendekatan separa automatik iaitu penyesuaian model sfera, elip dan silinder. Isipadu dahan pokok dianggarkan berdasarkan isipadu model yang disesuaikan pada point clouds. Ketinggian pokok dan ketinggian asas rimbun pokok kepada dikira dengan menggunakan analisis histogram daripada ketinggian point clouds. Isipadu rimbun pokok dianggarkan dengan menyesuaikan model *convex-hull* pada rimbun pokok. Hasil kajian menunjukkan bahawa Ralat Punca Min Kuasa Dua (RMSE) anggaran bagi diameter dahan itu tidak mempunyai corak yang spesifik dengan saiz dahan dan bilangan titik yang digunakan dalam proses penyesuaian model. Ini menunjukkan bahawa point clouds mempunyai taburan yang rumit di atas dahan pokok. Secara keseluruhan, model silinder menghasilkan keputusan yang terbaik dengan hampir semua saiz dahan pokok dan jumlah point clouds. Model silinder mempunyai keputusan anggaran diameter dahan pokok jauh lebih baik berbanding dengan model sfera dan elip.

Kata kunci: Pengukuran pokok secara individu; hutan; pengimbas laser daratan

1.0 INTRODUCTION

Malaysia is a country situated in the equatorial region which habitats are mostly consisted of tropical rainforest that are rich in biodiversity. Undoubtedly Malaysia has been one of the most popular spots for forest study in tropical climate. Tropical rainforest is known as the most productive forest in the world and rainforest in Southeast Asia including Malaysia are believed to be the oldest and comprise of highest variation in term of biological aspect.[1] Other than forest, Malaysia is blessed with fertile soil, adequate rainfall throughout the year and suitable climate for high production of food in agricultural sector that become the main factor of making Malaysia as one of the countries that able to export and commercialize food in the international level. Individual tree measurement normally done manually based on conventional method using instruments such as measuring tape, caliper and inclinometer. The measurement need to be done by any means necessary such as climbing or chopping part of the tree in order to gather as much as possible measurement.[2] Problem faced by the conventional techniques is that it is a time consuming task where the measurement of many trees require a lot of manpower and it covers only a small area where the sampling is exposed to bias due to variation of tree structure and species in complex tropical rainforest environment in Malaysia. Another limitation of this technique is that it is hard to get the information of higher level within the tree canopy that is inaccessible or out of reach for the measurements

Advancements in remote sensing technology have introduced laser technology which fills the gap of satellite imagery capability to penetrate the vegetation canopy. This allows substantial and accurate measurements of underneath forest or tree structure and terrain. Efforts on study of laser scanning in producing forest stand profiles have started since the 1980s where laser pulse had been utilized to measure various forest canopy attributes including tree height accurately.[3] Apart from airborne laser scanning, terrestrial laser scanning can be utilized for more accurate and detailed tree attributes estimations.

Previous studies have been focusing on plot based scanning [4-9] that search within the scanning radius and create a small plot of the area to extract tree parameters in that area and this method have shown good results in finding the trunk and diameter at breast height measurement. Another approach of tree measurement using terrestrial laser scanning is by scanning single tree with multiple scanning position [10-14] to cover the whole tree structure and model the tree through three-dimensional tree reconstruction from point cloud.

Several methods have been proposed that aimed to model and measure individual tree structure based on point clouds obtained by terrestrial laser scanner. This includes an effort that developed an algorithm that capable to automatically reconstruct structure of single trees by fitting cylinders and tracking neighboring cylinders until the whole tree is completely modelled.[11] In another study, tree structure was reconstructed based on rasterization of point clouds into 3D voxel domain. The 3-dimensional mathematical morphology was used to reconstruct the entire tree structure and a special algorithm had been developed to segment tree parts into different part of branches and how they are connected to each other.[10] Recently there was an effort to develop a new precise method for 3D tree model reconstruction using stepwise approach and applied this method on four trees scanned using a phase-based terrestrial laser scanner Leica HDS6100.[12] This method used cover sets which is are small, connected surface patches which each patch containing small sample of point clouds group together. Small cover sets allow the reconstruction of tree with much more detail of the tree surface. Reasonable accuracy of small branches measurement which is less than 1cm error were retrieved using this stepwise approach while accurate results of few percent error achieved on measurement of volume and large branches. In another study a graph based skeletonization approach called SkelTre has been introduced to improve the previous version of tree skeletonization by CAMPINO.[13-14] This method had been compared with the CAMPINO on trees that contain noise, undersampling, occlusion effects and varying point density and the result shows some significant improvement in the results. The tree skeleton was used as a baseline to for various individual tree attributes estimation.

The aim of this study is to access the capability of terrestrial laser scanning for individual tree measurement in tropical environment by utilizing the high density point cloud generated from terrestrial laser scanner. Three different fitting methods (cylinder, sphere and ellipse) are tested in this study to retrieve the trunk and branch diameter that allows estimation of tree volume. In addition, the same point-clouds will be also utilized to estimate other related important tree characteristics. The aim can be articulated into specific objectives as follows:

i) To derive high density point cloud of trees with different size and characteristic using terrestrial laser scanning.
ii) To construct trunk and branch structure from the scanned trees point cloud and estimate several tree attribute (diameter of branch, tree height, height of crown base).
iii) To validate the estimated tree attributes from terrestrial laser scanning based on field measurement.

2.0 MATERIALS AND METHOD

The methodology is divided into four main phases which are data collection, pre-processing, estimation of individual tree attributes, and evaluation of results (Figure 1). The first stage is focusing on collecting field data and LiDAR data at two different plots i.e. isolated trees and trees in forest. The pre-processing stage will register the point clouds to a common coordinate system and separate the point clouds into individual trees and different parts of tree. The estimation of individual tree attributes is accomplished in the third stage. Finally the estimated tree attributes are compared with the real values measured in the field.

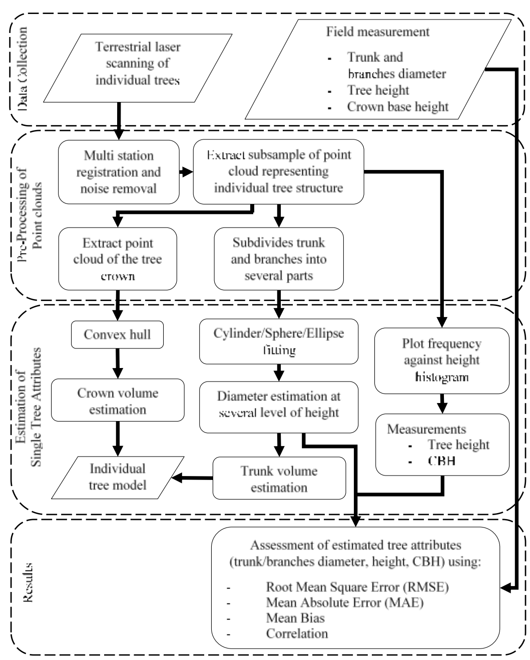


Figure 1 Flow chart of the methodology

2.1 Description of Data and Study Area

The study is located at several areas in Universiti Teknologi Malaysia, Johor (Figure 2). The campus is surrounded by various tree species that is naturally growth and treated as ornamental trees. This main campus with an area of 1222 hectares is filled with a variety of flora and fauna. This is in line with the aim of the university that is to promote ecotourism in the campus. The study area is divided into 2 sub-area i.e. isolated ornamental trees and trees that are naturally grow in a forest. The latter contains reasonably dense understorey vegetation with different sizes of trees.

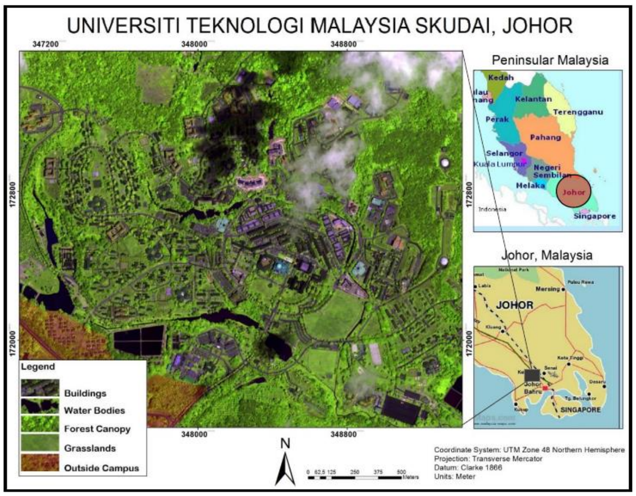


Figure 2 Universiti Teknologi Malaysia, Johor, Malaysia

In the phase of data collection two different data were collected that are high density point clouds and field data of individual tree attributes i.e. tree diameter at breast height (DBH), tree height, branch diameter, height to crown base and tree location. The latter is used to validate tree attributes estimation results based on the point clouds. Proper planning is required before conducting the field measurement especially for terrestrial laser scanning to ensure high quality of point cloud data. Data collection planning includes the setting-up of terrestrial laser scanner that considers: i) distance between the laser scanner and tree, ii) number of scanning position required to scan the whole tree structure, iii) number of tie points needed in order to reduce registration error in the upper part of tree, and iv) resolution for the scanning. The point clouds were collected using Leica Scanstation C10 laser scanner that operates with the green wavelength at 532 nm. This scanner is capable to scan at most 300 m distance object with the nominal accuracy of 4.5 mm. In this study, the scanning resolution is set to high density of data acquisition with 0.05 m vertical and horizontal point spacing. The point clouds were obtained at two different sites i.e. individual isolated trees and group of trees in forest area. The former site is used a benchmark for a detailed tree attribute measurements. Two individual trees were scanned and 70 branch diameters were measured that account different size of the branches. In the second site, the DBH measurements were carried out over 15 individual trees. Data collection for site 1 (isolated trees) was conducted in February 2014 and for site 2 (trees in forest) in May 2014.

2.2 Pre-processing of Data

The second phase devoted to the pre-processing of the point clouds. This involves preparing the raw data for further processing such as aligning all scanning positions together and removing unnecessary point cloud that may affect the tree attribute estimate stage. For the purpose of point clouds registration, tie points are used as a reference to merged point clouds obtained from all scanning positions into one projected coordinate system. This is known as registration. The registration starts by registering one scanning session and select this session as a reference for other scanning sessions. The minimum number of tie points required to register two scanning position together is three and all these tie points is set up on a tripod with height approximately 1.5 m above ground. The registration process is done using Leica Cyclone software.

After the registration, the unnecessary or noise point clouds of those originate from neighbouring trees, understory trees and ground surface are removed to avoid confusion and complexity in data processing. The point clouds are then separated into individual trees for further processing to estimate tree attributes. Further cleaning process of leaf and small branches are required to separate the trunk and branches prior to diameter estimation at different height intervals. The noise removal procedure has been done manually by a careful inspection of every single trees marked in the field as well as in the point clouds.

2.3 Estimation of Tree Attributes

Estimation of individual tree attributes is divided into: 1) tree height, 2) height to crown base, 3) crown volume, 4) DBH and 5) diameter of branch. Tree height and height to crown base were estimated using histogram analysis of the point clouds elevation. The crown volume was estimated based on the Convex-hull analysis method of the point clouds belong to tree crown. Estimations of trunk and branches diameter were based on different fitting models on point clouds. Prior to tree attribute estimation process, the point clouds of a single tree should be sub-divided into different parts i.e. different parts of branches and tree crown. The fitting process is done using three types of fitting models i) cylinder, ii) sphere and iii) ellipse in Matlab software (Figure 3).

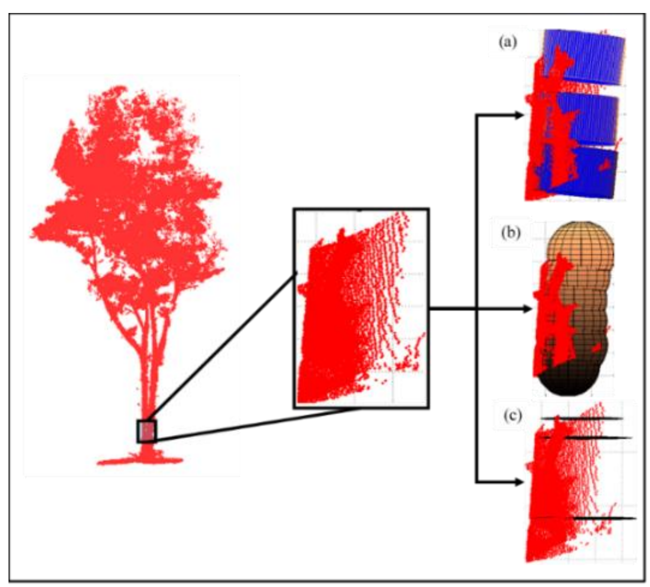


Figure 3 Point clouds fitting using (a) cylinder (b) sphere and (c) ellipse

Prior to point clouds collection campaign each trunk of trees in forest and branch for isolated trees are numbered and marked systematically with board. This signage can be seen clearly in the point clouds and photos that are taken simultaneously. Based on this mark, individual trees are extracted and irrelevant points originated from understorey vegetation are removed manually. For trees in forest area, tree DBH is estimated at the tree trunk 1.5m from ground level. The point clouds of tree trunk are fitted by sphere, cylinder and ellipse models at different height or horizontal intervals. Detailed fitting process is done for isolated trees, which accounts different locations and sizes of tree branch. In total 70 branches have been measured in the field at different parts of the trees. The fitting process requires two input parameters namely distance interval and axis where (X, Y or Z) the point clouds should be partitioned.

Methods for tree height and crown base height estimation were adopted from method introduced by previous study.[15] The method employed Gaussian model fitting on the histogram of elevation value for height and crown base height estimation. Figure 4 shows the example of histogram constructed based on point clouds obtained for a single tree. The histogram was fitted with multiple Gaussian functions, in which the crown base height is marked by two Gaussian curves of the tree crown and ground surface. The start boundary is determined by subtracting three-standard deviation from the mean value of the lowest Gaussian function from tree crown. The end point is determined by adding three -standard deviation with the mean value of Gaussian function of ground surface. Finally the crown base height is calculated by subtracting the value of end boundary from the start boundary. Tree height is calculated based on the highest Gaussian function of the tree crown. The height is determined by adding three-standard deviation with the mean value of the Gaussian function.

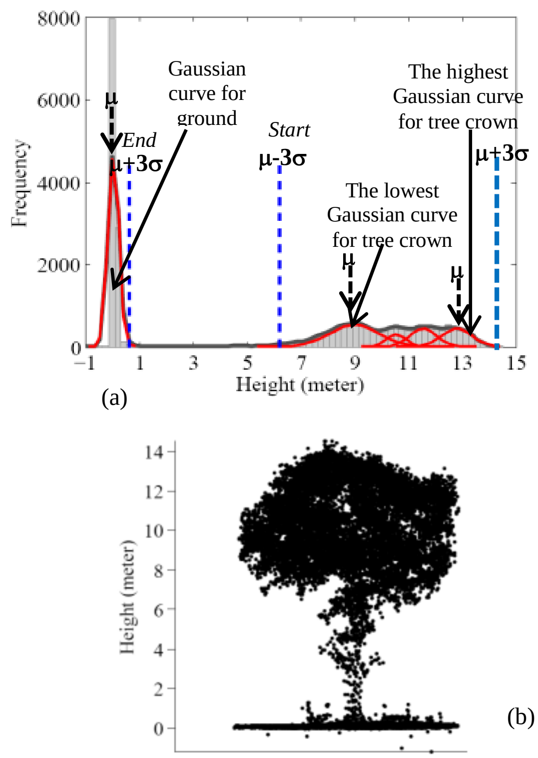


Figure 4 Histogram for elevation value of point clouds fitted with multiple Gaussian models (a) and the corresponding point clouds of a single tree (b)

Previous studies have shown that estimation of tree crown volume is very important for the management of plantations.[16] The tree volume has been defined as the apparent geometric volume that includes all the branches, leaves and the gaps between them. The crown volume is estimated using convex hull algorithm, which construct the three-dimensional boundary of a closed convex surface based on Delaunay Triangulations of the outer points.[16] The points belong to tree crown were separated from the other parts of a tree. The convex hull algorithm was applied on these points and the tree crown volume was estimated from the volume of the closed surface. In our study tree crown volume is estimated using closed surface created by the convex-hull algorithm. Tree branch volume is estimated based on the total volume of the fitted cylinders over major branches of individual trees.

2.4 Evaluation of the Estimated Tree Branch Diameter, Tree Height and Crown Base Height

The estimated tree branch diameters, tree height and crown base height are evaluated based on the root mean square error (RMSE), mean absolute error (MAE) mean bias and correlation between estimated and measured branch diameter (Equation 1 to Equation 3). The evaluation of the estimated tree branch diameter accounts fitting models, different size of branches and number of points on the branch.

$$RMSE = \sqrt{\sum_{i=1}^{n} \frac{(Estimate_i - Measure_i)^2}{n}} \quad (1)$$

$$MAE = \sum_{i=1}^{n} \frac{|Estimate_i - Measure_i|}{n} \quad (2)$$

$$Mean\ bias = \sum_{i=1}^{n} \frac{(Estimate_i - Measure_i)}{n} \quad (3)$$

where *Estimate* is the estimated tree attributes from point clouds, *Measure* is the tree attributes measured in the field and n is the number of samples used in the analysis.

3.0 RESULTS AND DISCUSSION

The overall results for branch diameter estimation of ornamental trees and DBH for trees in forest area show that cylinder fitting method has the lowest RMSE value with 2.8 cm, followed by sphere and ellipse with 3.2 cm and 5.9 cm respectively. Cylinder fitting tends to slightly underestimate the diameter value with average bias of 0.6 cm. Both sphere and ellipse fitting overestimated the diameter value with the average overestimation of 1.1 cm and 1.2 cm respectively (Figure 5 and Table 1).

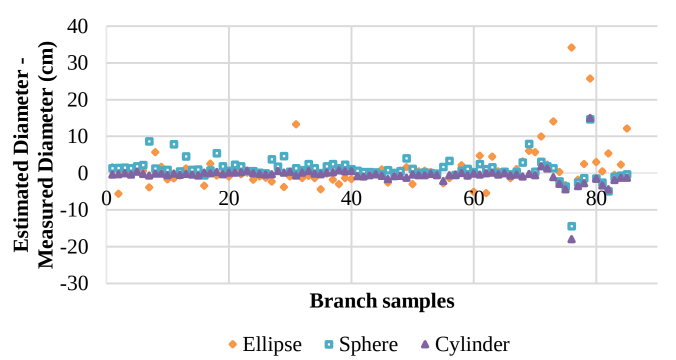


Figure 5 Differences between measured and estimated branch diameter using ellipse, sphere and cylinder fittings

Table 1 Root mean squared error (RMSE), mean absolute error (MAE), and mean bias and correlation between field-measured diameter and estimated diameter

Fitting model	RMSE (cm)	MAE (cm)	Mean Bias (cm)	Correlation
Cylinder	2.8	1.1	-0.6	0.982
Sphere	3.3	1.9	1.1	0.975
Ellipse	5.9	3.0	1.2	0.960

The analysis on the impact of branch sizes begins with the classification of the point clouds of tree branches into eight classes (Table 2).

Table 2 Classes for branch diameter

Class	Branch diameter (cm)
1	< 2.5
2	2.5 - 3.6
3	3.6 – 5.7
4	5.7 - 7.4
5	7.4 – 10.0
6	10.0 - 15.3
7	15.3 - 30.1
8	> 30.1

Figure 5 shows the RMSE values of branch diameter estimation for tree branches with different sizes and fitting methods. The branches for ornamental isolated trees are classified between class 1 and class 8. The results show that the diameter of branch can be estimated at the best of 0.3 cm RMSE with cylinder fitting method over the smallest branch size class. In general cylinder fitting method is the best method for branch diameter estimation and outperformed sphere and ellipse fitting models in almost tree branch sizes. Furthermore tree branch diameter estimation using cylinder fitting showed consistent estimation results over different branch size classes.

The maximum RMSE for cylinder fitting method is 6 cm for trees located in the forest area. Tree trunk and branches of ornamental trees can be estimated with higher accuracy as compared to the DBHs of trees in forest area which mostly classified with class 7 and 8.

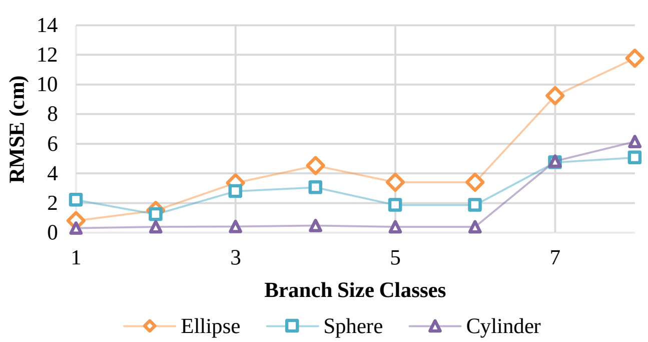


Figure 5 Relationship between RMSE of diameter estimation and branch size classes for three different fitting models

The smallest and the largest RMSE values for diameter estimation of sphere fitting are 1.2 cm and 5 cm respectively. While the smallest and the largest RMSE values for ellipse fitting are 0.8 cm and 11 cm. There is no clear relationship between the size of the branch and the estimation accuracy. Estimation of DBH of trees in forest area is challenging due to several factors i.e. occlusion during laser scanning, complicated tree trunk shape and understorey vegetation. These complicate the distribution of point clouds and significantly decreased the density of point clouds of individual trees.

The main reason of higher RMSE value for branch and DBH diameter estimation using sphere and ellipse fitting from class 1 to 6 is the sphere and ellipse fitting cannot comprehend with missing point cloud as a result from occlusion problem. The point clouds gaps created by missing points complicate the fitting process of sphere and ellipse, especially with small distance interval, and mostly give overestimated branch diameter value. However with proper distance interval adjustment the same condition has less effect on the cylinder fitting process (Figure 6).

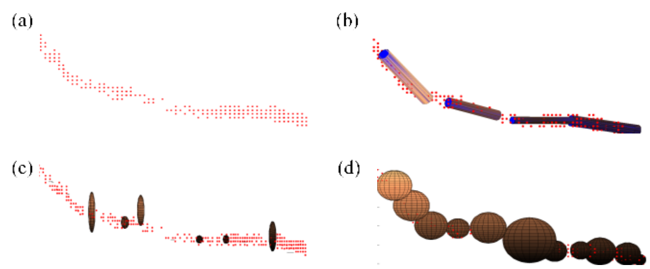


Figure 6 Fitting on set of point cloud with gaps (a) by cylinder (b), ellipse (c) and sphere (d)

It was noted that size of branch does not have a direct relationship with the number of points intersected on its surface. Further investigation is devoted between the number of points and accuracy in branch diameter and DBH estimations. The point clouds are divided into eight classes of number of points (Table 3).

Table 3 Classes for branch diameter

Class	Number of points
1	< 13
2	13 - 32
3	32 - 63
4	63 - 91
5	91 - 177
6	177 - 672
7	672 - 1336
8	> 1336

Figure 7 shows the relationship between RMSE of the estimated branch diameter and DBH for ornamental trees and trees in forest area. The results suggest that there is no clear relationship between number of points on the branch and trunk with their estimation accuracies. Therefore we can conclude that the error of diameter estimation is dominated by the distribution of point clouds rather than its density, size of branch and tree trunk.

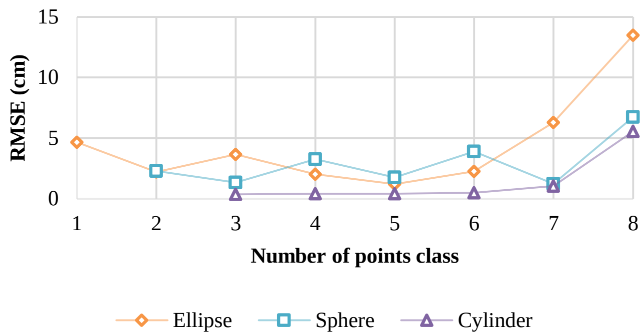


Figure 7 Relationship between RMSE and number of points classes for three different fitting models

It is noted that cylinder fitting can only works with larger set of point clouds compared to sphere and ellipse models. However, for all number of points classes cylinder fitting gives almost consistent estimation accuracy better than sphere and ellipse models. All fitting models failed to give good estimation value for branch and trunk classified under Class 7 and 8 which are from trees in forest area.

Measurement of tree height and crown base height are only collected for trees in forest area. Table 4 shows the validation results of tree height and crown base height estimation based on individual tree measurement from the point clouds. TLS overestimated both tree parameters and the RMSE values are far from the accuracy as obtained for diameter estimation.

Table 4 Root mean squared error (RMSE), mean absolute error (MAE), and mean bias and correlation between field-measured parameter and estimated parameter

	RMSE (m)	MAE (m)	Mean Bias (m)	Correlation
Tree Height	0.916	0.696	0.598	0.970
CBH	1.064	0.864	0.350	0.967

Volume of crown, trunk and branch were estimated for trees in the forest area. The relative volume of tree crown is calculated by applying convex hull wrapping over point clouds belong to tree crown (Figure 9). For trunk and branches their volumes are estimated based on the fitted cylinder models at different height intervals (Figure 8). The total volume of a tree is basically the sum of crown, trunk and branch volumes (Figure 9). Table 5 shows the total volume of trees found in the forest area.

Table 5 Total tree volume for trees in forest area

Tree Coordinate		Estimated Crown	Estimated Trunk
Lat	Long	Volume (m³)	Volume (m³)
1º34'22.71"	103º37'16.9"	535.448	0.925
1º34'22.40"	103º37'16.8"	214.392	0.439
1º34'23.07"	103º37'16.2"	361.937	0.887
1º34'23.33"	103º37'16.5"	477.817	0.871
1º34'23.15"	103º37'16.8"	267.193	0.599
1º34'22.16"	103º37'16.6"	667.345	4.634
1º34'22.99"	103º37'16.6"	214.256	0.929
1º34'22.91"	103º37'16.3"	664.825	1.000
1º34'23.03"	103º37'16.0"	432.031	1.279
1º34'23.05"	103º37'15.9"	364.417	1.112
1º34'22.91"	103º37'16.1"	279.290	1.308
1º34'22.80"	103º37'16.1"	162.569	1.050
1º34'22.54"	103º37'16.2"	137.860	0.691
1º34'22.18"	103º37'16.2"	474.524	1.657
1º34'22.20"	103º37'16.2"	579.904	0.472

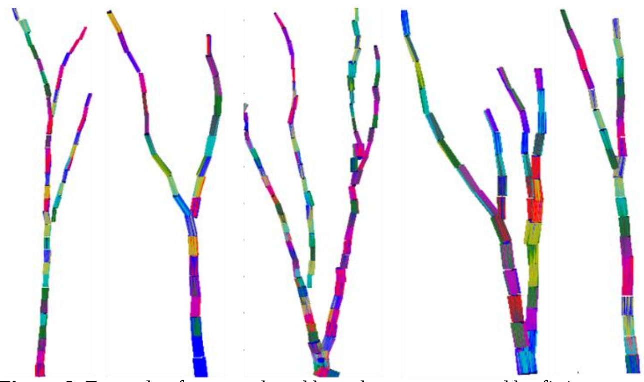


Figure 8 Example of tree trunk and branches reconstructed by fitting cylinder models around the point clouds

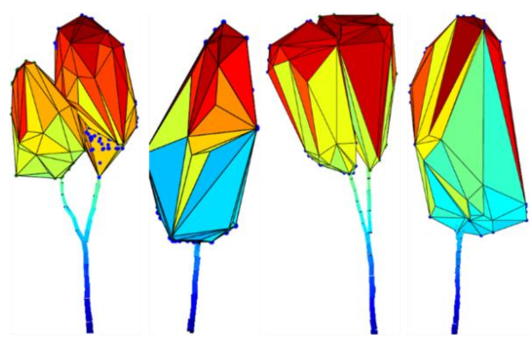


Figure 9 Reconstructed individual trees that combine convex hull and cylinder models

4.0 CONCLUSION

We have demonstrated that dense point clouds collected using terrestrial laser scanner can be used for detailed individual tree measurements i.e. branch diameter and volume, tree height, height to crown base and crown volume. Different parts of tree were measured by employing different approach of measurements i.e. geometric reconstruction and statistical analysis on point clouds height values. The technology can be reliably used to complement individual tree measurement at plot level which later can be up-scaled to other small-scale remotely sensed data i.e. satellite and aerial remote sensing data. Accurate individual tree measurement is very important for detailed total above ground biomass estimation, which has direct relationship with forest carbon stock. Furthermore the introduced framework can be used to enhance the establishment of detailed allometric equation for forest properties measurement in tropical rainforest.

References

[1] WWF-Malaysia. 2013, 21 November. The Malaysian Rainforest. Available: http://www.wwf.org.my/about_wwf/what_we_do/forests_main/the_malaysian_rainforest/.

[2] KoutaR, *et al*. 2013, 2 November. Exactly measuring tree height. Available: http://www.monumentaltrees.com/en/content/measuringheight/.

[3] R. Nelson, *et al*. 1984. Determining Forest Canopy Characteristics Using Airborne Laser Data. *Remote Sensing of Environment*. 15: 201–212.

[4] C. Hopkinson, *et al*. 2004. Assessing Forest Metrics with a Ground-based Scanning Lidar. *Canadian Journal of Forest Research*. 34: 573–583.

[5] J. Lovell, *et al*. 2011. Measuring Tree Stem Diameters Using Intensity Profiles from Ground-Based Scanning Lidar from a Fixed Viewpoint. *ISPRS Journal of Photogrammetry and Remote Sensing*. 66: 46–55.

[6] X. Yang, *et al*. 2013. Three-dimensional Forest Reconstruction and Structural Parameter Retrievals Using a Terrestrial Full-waveform Lidar Instrument (Echidna®). *Remote Sensing of Environment*. 135: 36–51.

[7] T. Yao, *et al*. 2011. Measuring Forest Structure and Biomass in New England Forest Stands Using Echidna Ground-based Lidar. *Remote Sensing of Environment*. 115: 2965–2974.

[8] M. Thies, *et al*. 2004. Three-dimensional Reconstruction of Stems for Assessment of Taper, Sweep and Lean Based on Laser Scanning of Standing Trees. *Scandinavian Journal of Forest Research*. 19: 571–581.

[9] P. Watt and D. Donoghue. 2005. Measuring Forest Structure with Terrestrial Laser Scanning. *International Journal of Remote Sensing*. 26: 1437–1446.

[10] B. Gorte and N. Pfeifer. 2004. Structuring Laser-scanned Trees Using 3D Mathematical Morphology. *International Archives of Photogrammetry and Remote Sensing*. 35: 929–933.

[11] N. Pfeifer, *et al*. 2004. Automatic Reconstruction of Single Trees from Terrestrial Laser Scanner Data. In Proceedings of 20th ISPRS Congress. 114–119.

[12] P. Raumonen, *et al*. 2013. Fast Automatic Precision Tree Models from Terrestrial Laser Scanner Data. *Remote Sensing*. 5: 491–520.

[13] A. Bucksch and R. Lindenbergh. 2008. CAMPINO-A Skeletonization Method for Point Cloud Processing. *Isprs Journal of Photogrammetry and Remote Sensing*. 63: 115–127.

[14] A. Bucksch, *et al*. 2010. SkelTre Robust Skeleton Extraction from Imperfect Point Clouds. *Visual Computer*. 26: 1283–1300.

[15] M. Z. A. Rahman, *et al*. 2012. A Generic Approach in Estimating Vegetation Density for Hydrodynamic Roughness Parameterization Using High Density Airborne Laser Scanning Data. *Journal of Hydroinformatics*.

[16] A. Fernández-Sarría, *et al*. 2013. Different Methodologies for Calculating Crown Volumes of Platanus Hispanica Trees Using Terrestrial Laser Scanner and a Comparison with Classical Dendrometric Measurements. Computers and Electronics in Agriculture.90: 176–185.