

ESTIMATING SINGLE TREE STEM AND BRANCH BIOMASS USING TERRESTRIAL LASER SCANNING

Nurliyana Izzati Ishak, Md Afif Abu Bakar, Muhammad Zulkarnain Abdul Rahman*, Abd Wahid Rasib, Kasturi Devi Kanniah, Alvin Lau Meng Shin, Khamarrul Azahari Razak

TropicalMAP Research Group, Department of Geoinformation, Faculty of Geoinformation and Real Estate, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia

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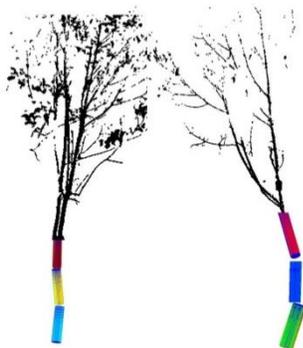
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*Corresponding author
mdzulkarnain@utm.com

Graphical abstract



Abstract

This paper presents a novel non-destructive approach for individual tree stem and branch biomass estimation using terrestrial laser scanning data. The study area is located at the Royal Belum Reserved Forest area, Gerik, Perak. Each forest plot was designed with a circular shape and contains several scanning locations to ensure good visibility of each tree. Unique tree signage was located on trees with diameter at breast height (DBH) of 10cm and above. Extractions of individual trees were done manually and the matching process with the field collected tree properties were relied on the tree signage and tree location as collected by total station. Individual tree stems were reconstructed based on cylinder models from which the total stem volume was calculated. Biomass of individual tree stems was calculated by multiplying stem volume with specific wood density. Biomass of individual was estimated using similar concept of tree stem with the volume estimated from alpha-hull shape. The root mean squared errors (RMSE) of estimated biomass are 50.22kg and 27.20kg for stem and branch respectively.

Keywords: Terrestrial laser scanner; stem and branch biomass

Abstrak

Kertas kerja ini membentangkan pendekatan novel bagi anggaran biomass dahan dan batang pokok secara individu tanpa melibatkan penebangan menggunakan data imbasan laser. Kawasan kajian terletak di Hutan Simpan Royal Belum, Gerik, Perak. Setiap plot hutan telah direka dengan bentuk bulat dan mengandungi beberapa lokasi imbasan untuk memastikan penglihatan yang baik bagi setiap pokok. Papan tanda yang unik di letak pada setiap pokok dengan garis pusat pada paras dada (DBH) daripada 10cm dan ke atas. Pengekstrakan pokok individu telah dilakukan secara manual dan proses yang hampir sama dengan bidang dikumpulkan sifat-sifat pokok telah bergantung kepada papan tanda timbul pokok dan pokok lokasi yang dipungut oleh total station. Pokok individu batang telah dibina semula berdasarkan model silinder yang jumlah keseluruhan batang dikira. Biomass pokok individu batang dikira dengan mendarabkan jumlah batang dengan ketumpatan kayu tertentu. Biomass individu dianggarkan menggunakan konsep yang sama batang pokok dengan jumlah yang dianggarkan daripada bentuk *alpha-hull*. Nilai punca min kuasa dua ralat (RMSE) anggaran biomass adalah 50.22kg dan 27.20kg untuk batang dan dahan pokok.

Kata kunci: Pengimbas laser daratan; biomass batang dan dahan pokok

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1.0 INTRODUCTION

Forest structure information obtained from LiDAR has been widely used in various applications e.g. forest science and management for inventory analysis, biomass estimation, and wildlife habitat analysis[1]. Terrestrial Laser Scanner (TLS) provides three dimensional (3D) representation of objects' surface that resulting in a very large number of measured points on an object [2]. Three dimensional (3D) scene reconstruction has also attracted interest in the computer vision field, where the trees are reconstructed from the photograph for visualization purposes [3]. Nowadays, there are increasing interests in utilizing terrestrial laser scanner as a method of capturing data for biomass tree estimation [4-6]. The total above-ground volume, the branch size distribution, and other size and shape parameters of trees are the current scientific and economic interest [7-10]. For example, forests carbon cycle estimations of require information on branch size distribution of trees for accurate determination of branch decay times. One way to approximate these parameters is to use dense terrestrial laser scanner produced point clouds [11-13].

For obtaining the tree attributes, previous researchers employed various methods that can be grouped into conventional method and methods that are based on remote sensing technology. Conventional methods of tree attributes measurements for biomass estimation and allometric equation development were based on destructive approach. Tree need to be cut and its individual parts were measured including their weight [14-17].

Remotely sensing based tree attributes measurement are generally dominated by terrestrial laser scanner. Previous studies have introduced various methods in estimating the biomass for each tree parts. For example, the tree structure and leaf area were estimated using precise voxel based tree model. The 3D point clouds information from the TLS was reproduced in terms of voxel attributes in the 3D voxel arrays. The K-Dimensional tree (KD-Tree) algorithms were applied to the voxelisation of the point cloud data and the 3D visualization of trees [18]. Other than that, there are also studies that used small footprint waveform LiDAR data to get branch-level tree reconstruction for leaf-off and leaf-on tree condition. In this research, the DIRSIG simulation environment algorithm was chosen to validate the result. The result show show the potential of 3D object reconstruction by using corresponding simulated waveform lidar data, in contrast to airborne discrete return lidar data. This approach is suitable for the airborne laser scanner system for more accurate estimation of forest biomass, forest inventory, land degradation and many more for the large scale application [19]. In another study airborne laser scanning has been used to estimate single-tree crown biomass of Norway Spruce. The reference or ground data were obtained from conventional approach and estimates of terrestrial laser scanning. The result shows that good predictions of single-tree crown biomass of Norway spruce can be obtained from ALS data and TLS

can be used to obtain the ground reference values. [20]. There was also a study focuses on potted juvenile *Fagus sylvatica* L. trees. Their purpose is to test the practicability and accuracy of the portable 3D-laser scanner. According to the results, it is proven that the laser scan data have good correlations with the total above-ground biomass[14]. It was also an attempt to determine stem and crown biomass which which considered individual tree stem, bark, branch and needles to estimate above ground biomass of a tree. The results proved that TLS could give high accuracy of biomass estimate compared to available allometric equation[4].

This study aims at estimating biomass of tree stem and crown of individual trees using tree measurement obtained from terrestrial laser scanning data. The aim is supported by the following specific objectives:

- i. To extract individual trees from point clouds obtained using terrestrial laser scanner
- ii. To estimate individual tree stem and branch biomass based on geometric reconstruction of a single tree using points clouds.
- iii. To compare the estimated stem biomass and branch with the value obtained by conventional approach (allometric equation)

2.0 MATERIALS AND METHOD

The methodology is divided into four (4) parts namely data collection, data pre-processing, estimation of individual tree attribute and biomass and evaluation of results (Figure 1). The first stage is focusing on terrestrial laser scanner data collection and field measurement. Second phase involves registration of point clouds generated from different scan stations, noise removal, and extraction of individual trees. Noise removal process is required to clean point clouds of individual trees from understory vegetation and neighbouring trees.

The second stage will also include extraction of individual tree from the neighbouring trees and subdivides the single tree to stem, branch and crown. The third phase is devoted for individual tree attributes estimation. In this stage, the stem point clouds will undergo the process of cylinder fitting for DBH and stem volume estimation. The point clouds of branches will be wrapped with alpha hull and crown will be processed using convex hull. The fourth stage is the assessment of results using root mean square error (RMSE), correlation, mean bias and mean absolute error (MAE).

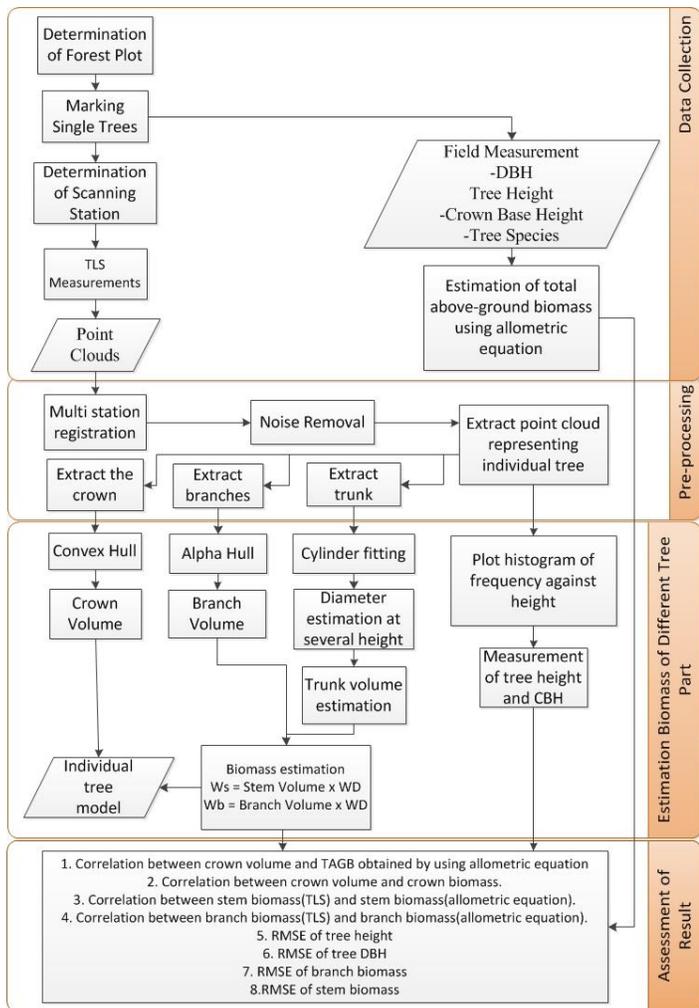


Figure 1 Research flow chart

2.1 Description of Study Area

The study area is in Belum Forest Reserve, Perak, Malaysia. Belum-Temenggor is believed to have been in existence for over 130 million years making it one of the world's oldest rainforests, older than both the Amazon and the Congo[21]. In the heart of the forest lies the manmade lake of Tasik Temenggor, covering 15,200 Hectares which is dotted with hundreds of islands. The research area of Belum is entirely contained within the forest complex. In the forest you can also find 3,000 species of flowering plants, including 3 species of Rafflesia, the world's largest flower. Due to its uniqueness, it had been gazette as the State Park [22].

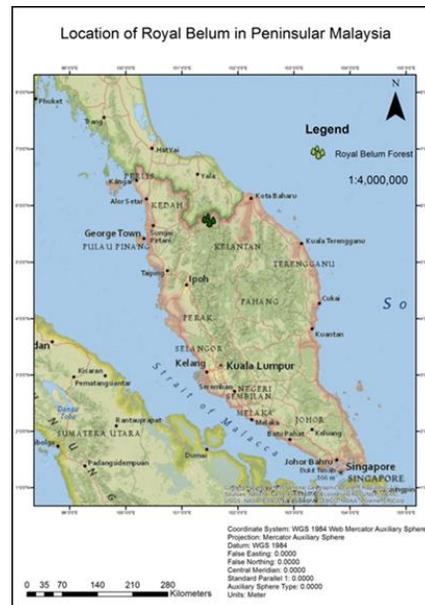


Figure 2 Location of Royal Belum Reserve Forest in Peninsular Malaysia

Among the tree species accommodated by this forest are;

- i. Resak (*Vatica umbonata*)
- ii. Keruing (*Dipterocarpus costatus*)
- iii. Mempening (*Lithocarpus kingianus*)
- iv. Kelat (*Eugenia filiformis*)
- v. Merbau (*Intsia palembanica*)
- vi. Sepetir (*Sindora echinocalyx*)
- vii. Medang (*Alseodaphne insignis*)
- viii. Temponek (*Artocarpus rigidus*)
- ix. Pelung (*Pentaspadon motleyi*)
- x. Kempas (*Koompassia malaccensis*)
- xi. Penarahan (*Gymnacranthera bancana*)
- xii. Perah (*Elateriospermum tapos*)
- xiii. Keledang (*Artocarpus gomezianus*)
- xiv. Mempising (*Goniothalamus giganteus*)

2.2 Data Collection

The field data collection is divided into individual tree measurement using conventional approach and terrestrial laser scanning. Both measurements were carried out in 36 forest plots. The forest plots were design with circular shape of 14.6 m radius to ease laser scanning process (see Figure 3). Before the scanning process each tree was marked with unique number and tree properties e.g. location of trees, diameter at breast height (DBH), tree species, tree height (whenever possible) and crown base height were recorded in a special form. The locations of trees were measured using total station (TS) with local coordinate reference observed by static GPS in the open area.

Detailed measurement of individual trees was assisted by terrestrial laser scanner. We have scanned all 36 plots which contain different density of dominant

and understory vegetation. Each plot was scanned with 4 scanning position which includes one position in the center and three positions at the edge of plot. Each scanning position was registered to the local coordinate system based on the total station measurements. Generation of point clouds of trees in forest area using TLS requires multiple scanning processes with careful selection of scanning positions. This is very important to ensure that the scanning process will be able to produce detailed and dense point clouds for individual trees. Each point clouds produced by separate scanning process will be combined and registered using common tie points located in the selected points in each forest plot. The highly reflective tie points were located randomly in the field and mostly should be seen by all scanning positions. The point clouds will be transferred to the local ground coordinate system by using the real coordinate measurement produced by TS and GPS. In this study, we use Riegl VZ-400 (Table 1).

Table 1 Riegl VZ-400 characteristics

Laser Scanning System (Riegl VZ-400)	
Laser Class	1
Range	600 m
Field of View	100 ° x 360 °
Minimum Range	1.5 m
Laser Wavelength	Near Infrared
Measurements per second	122 000 measurements / sec
Weight	9.6 kg

SCANNING CONFIGURATION FOR ROYAL BELUM RESERVE FOREST

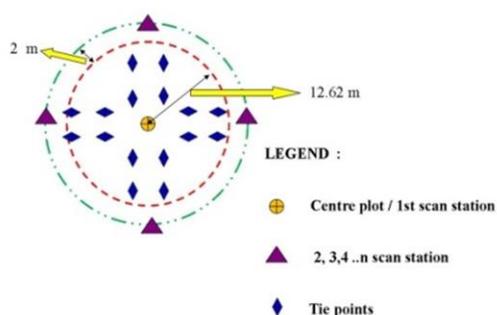


Figure 3 Laser scanning configuration for forest plot in royal belum forest reserve

2.3 Pre-Processing of Point Clouds

The data pre-processing phase aims at extracting point clouds of individual trees found in each forest plot. Extraction of individual trees is assisted by tree locations and tree signage collected during field campaign. The whole process involves registration of individual point clouds, geo-reference the point clouds, extracting

point clouds of individual trees and separating point clouds into different tree parts. For the point clouds registration, tie points were used as a common point between centre plot and other scan stations to act as a reference station to align all the scanning positions. The registered point cloud is geo-referenced to projected coordinate system. Registration process is done using Riegl RiscanPro software.

Next step is noise removal for individual trees delineation. Noise removal process involves clearing and deleting the unwanted point cloud data from the targeted individual tree to avoid confusion and complexity in data processing. The noises that need to be removed are, for example, bushes, understory tree, neighbouring trees and ground surface. Point clouds of individual trees is further separated into different parts of tree i.e. branches, leaves and trunk. This allows separate estimation of biomass being made for a single tree.

2.4 Estimation Biomass of Different Tree Parts

The third phase of this research is devoted for biomass estimation of different parts of individual tree. Biomass estimation is divided into tree stem, branches and tree crown. The biomass estimation of tree stem starts with cylindrical models fitting over point clouds. The fitting procedure is done using Matlab. The total volume of cylinders being used for the fitting process is assumed to be equivalent to the total volume of tree trunk. For the cylinder fitting process user is required to specify fitting height intervals, direction of fitting, and portion of points to be fitted. Each tree species has specific wood density (Table 2), in which the total biomass can be estimated by multiplying this value with the total trunk volume (Equation 1). Wood density is determined by multiple growth and physiological factors compounded into "one fairly easily measured wood characteristic" [23].

$$W_s = V_s \times W_D \quad (1)$$

where, W_s is the weight of stem, V_s is the total volume of stem and W_D is the wood density. Estimation of branch biomass is similar to tree stem. In the phase of branch volume estimation, the first step to extract the branch from the individual tree crown. The noise for example leaves and unwanted point cloud should be cleaned. The point clouds belong to tree branch is separated from leaves based on the assumption that leaves pose smaller intensity value compared to branches. The point cloud of branches is fitted with Alpha shape surface in Matlab. In the Matlab software, the tree branch will be inserted by referring to the value of x,y and z that being exported from the RiscanPro software in Ascii format. Volume of tree branches is estimated based on the volume of Alpha shape. Biomass of tree branches is estimated by multiplying its volume with the corresponding wood density.

Table 2 Wood density for different tree species

Species	Wood density (g/cm ³)
Resak (<i>Vatica umbonata</i>)	0.79
Keruing (<i>Dipterocarpus costatus</i>)	0.76
Mempening (<i>Lithocarpus kingianus</i>)	0.8
Kelat (<i>Eugenia filiformis</i>)	0.71
Merbau (<i>Intsia palembanica</i>)	0.63
Sepetir (<i>Sindora echinocalyx</i>)	0.61
Medang (<i>Alseodaphne insignis</i>)	0.71
Temponek (<i>Artocarpus rigidus</i>)	0.55
Pelung (<i>Pentaspadon motleyi</i>)	0.5
Kempas (<i>Koompassia malaccensis</i>)	0.76
Penarahan (<i>Gymnacranthera bancana</i>)	0.54
Perah (<i>Elateriospermum tapos</i>)	0.65
Keledang (<i>Artocarpus gomezianus</i>)	0.54
Mempisang (<i>Goniothalamus giganteus</i>)	0.38
Balik angin (<i>mallothus biaceae</i>)	0.56
Akasia (<i>acacia auriculiformis</i>)	0.68

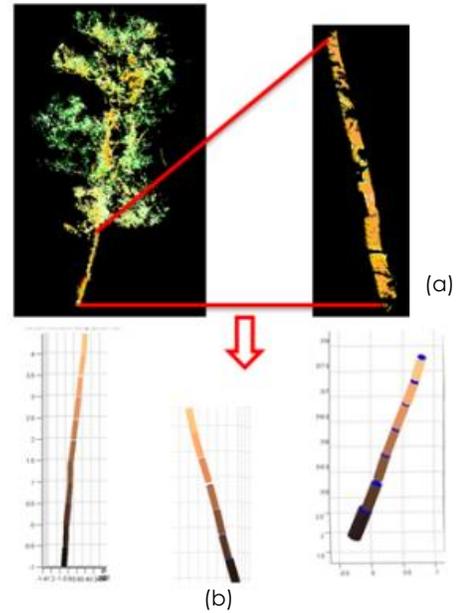


Figure 4 Cylinder fitting process (b) on individual tree stems point clouds (a)

Biomass of tree crown (combination of leaves and tree branches) will be estimated using regression model that relates crown volume estimated from TLS with crown volume calculated using allometric equation [27]. Individual tree crown volume is calculated based on the volume of crown model. Tree crown model is constructed by fitting the convex-hull surface [24] on the point clouds belong to tree crown.

The estimated individual tree biomass using TLS will be compared with the value obtained by using allometric equation [27]. The total above ground biomass can be divided into different parts of tree i.e. tree stem (Equation 2), leaves (Equation 3) and branches (Equation 4)

$$W_s = 0.0313 \times (DBH^2 \times H)^{0.9733} \tag{2}$$

$$\frac{1}{W_L} = \frac{1}{0.124 W_s^{0.794}} + \frac{1}{125} \tag{3}$$

$$W_B = 0.136 \times (W_s)^{1.070} \tag{4}$$

where W_s is the weight of stems, W_b is the dry weight of branches, W_L is the dry weight of leaves, DBH is the diameter at breast height, and H is the tree height. Individual tree height is determined by analysing the shape of histogram generated using normalized height value of point clouds (Figure 5). DBH value is obtained from the conventional tree census.

In this study we also estimate additional tree properties i.e. tree height and crown base height, which can be derived from the histogram graph of frequency against height (meter) [25]. Density of point cloud will affect the shape of histogram which reflects tree structure. The shape of the histogram allows distinction of tree ground, trunk, and crown. CBH and the tree height is measured started from the ground level to the crown base height and tree height estimated point as shown in Figure 5.

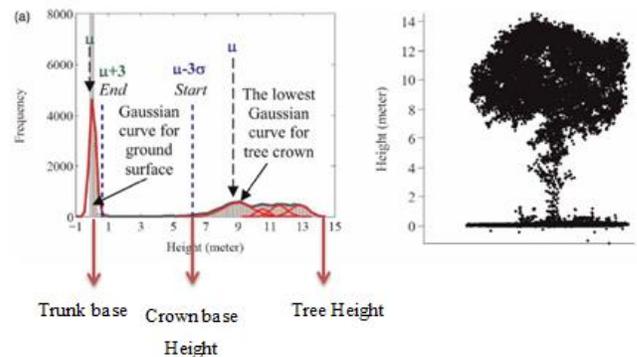


Figure 5 Histogram determining trunk base, crown height and tree height [12].

2.5 Evaluation Of Result

Evaluation of results is divided into two parts i.e. estimated biomass and estimated tree properties using point clouds generated from TLS. The TLS-based biomass estimates will be compared with the biomass value estimated using allometric equation. On the

other hand the estimated tree properties i.e. tree height, DBH and CBH will be evaluated using field collected data.

Root mean square error (RMSE), mean absolute error (MAE), mean bias and correlation are used in this research to analyze the results of the comparison.

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (D_i - D_m)^2}{n}} \tag{5}$$

$$MAE = \frac{\sum_{i=1}^n |D_i - D_m|}{n} \tag{6}$$

$$BIAS = \frac{\sum_{i=1}^n (D_i - D_m)}{n} \tag{7}$$

where,

- D_i = Estimated value
- D_m = Measured value

In this study we understand that the estimated biomass value should be compared to the conventional method of tree biomass calculation i.e. using cut and weight. This conventional method is however prohibited in our study area and most of the time the biomass of a tree is usually estimated using available allometric equation.

3.0 RESULTS AND DISCUSSIONS

3.1 Data Pre-Processing

In this data pre-processing stage we only processed 3 plots out of 36 plots. Table 3 shows the properties of scan station 3, 5 and 6.

Table 3 Scan station properties of plot 3,5 and 6

Number	Plot	Standard Deviation of registration	Number of Tie points
1	3	0.0128	16
2	5	0.0174	16
3	6	0.0199	16

Biomass of tree branch is estimated separately from leaves. Tree branches have been separated from leaves based on the assumption that branches reflects more infrared EMR compared to leaves which are known as infrared absorption features mainly for photosynthesis. Figure 6 shows the example of histogram of intensity value obtained from the point clouds. The threshold imposed on the histogram was manually defined based on two different populations as shown on the right and left side of the histogram. Figure 7 shows an example of point clouds that have been separated into different parts of tree.

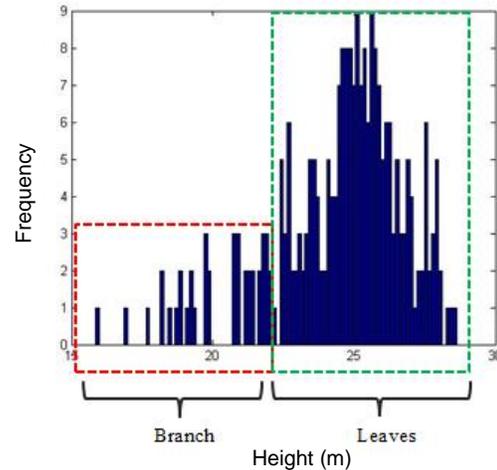


Figure 6 Histogram of intensity value and threshold used to separate branch and leaves

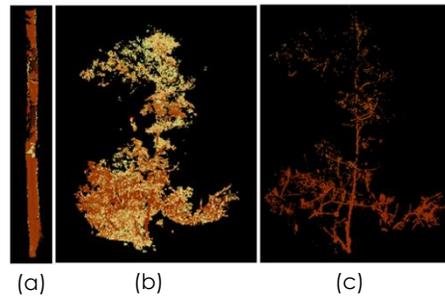


Figure 7 Tree components: tree stem (a) tree crown (b) and tree branches (c)

3.2 Estimation of Single Tree Attribute

Tree height measurement in the study site was obtained by applying tangent method to the clinometer angle measurement. This method however only can be applied on selected trees with relatively large gaps which allow clear view of tree tops. Tree height and CBH as measured from the point clouds relied on the vertical distribution of point clouds as depicted by the histogram generated from elevation values (Figure 8). Tree DBH obtained from point clouds was estimated based on the cylinder fitting at the height of 1.5 m from ground level.

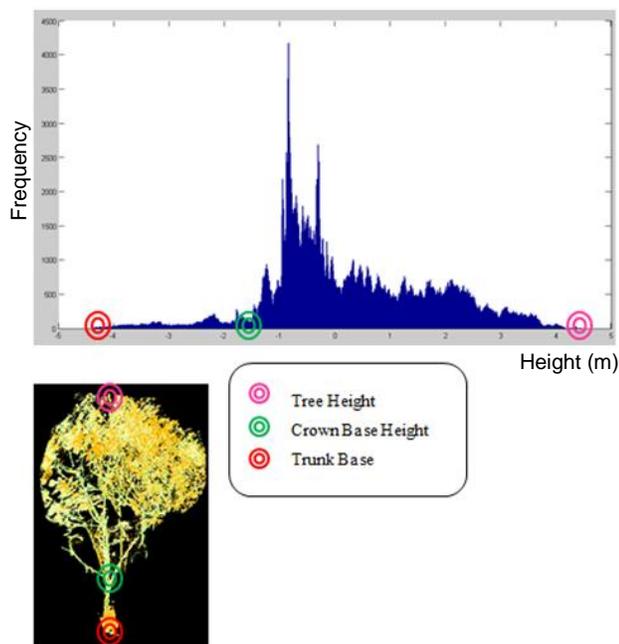


Figure 8 Estimation of tree height, crown base using histogram generated from elevation values

The results of 38 tree samples show that the RMSE for tree height measured using point clouds of TLS is 3.38 m (Table 4). TLS method tends to underestimate the real tree height by 1.79 m. TLS shows very promising results for DBH estimation with the total RMSE of 3.2 cm. This method also gives almost unbiased DBH estimation results. Underestimation of tree height is predictable as the scanning process took place at the forest floor which limits laser reflection from the upper part of tree crown. On the other hand the field tree height was also hindered by dense forest canopy cover which limits the visibility of observer. Both measurements show good correlation values (Figure 9 and Figure 10). Both estimates have small differences between RMSE and MAE value which implicates very few samples with extreme residual between estimated and measured values.

Table 4 Root mean square error (RMSE), Mean absolute error (MAE) and correlation of field measured height with estimated height and field measured DBH with estimated DBH

	RMSE (m)	MAE (m)	Correlation	Mean Bias (m)
Tree Height	3.38	2.62	0.67	1.79
DBH	0.032	0.027	0.773	-0.006

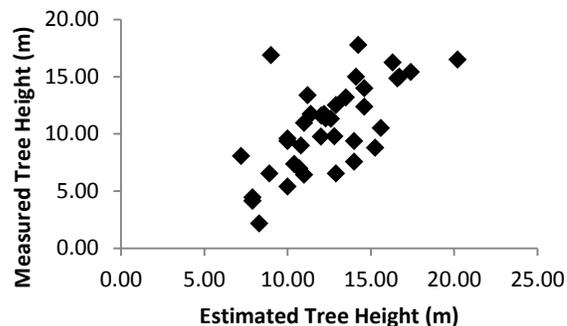


Figure 9 Relationship between estimated tree height and measured tree height

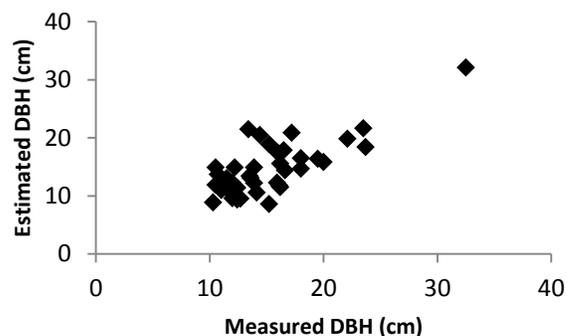


Figure 10 Relationship between measured tree DBH and estimated tree DBH

3.3 Estimation of Individual Tree Biomass

In this study, estimation of stem biomass using reconstructed tree structure resulted 50.22 kg RMSE for the total 38 tree samples (Table 5). This value however has large deviation with the MAE (31.03 kg) which implicates large number of samples with extreme residual values. In this case the value of MAE is the best value to represent the accuracy of biomass estimate. According to the mean bias, the method tends to overestimate the biomass of tree stem by 9.01 kg. The estimated biomass was heavily relied on the quality of cylinder fitting on the point clouds. The laser scanning process has been done over a group of trees, However with only 4 locations of scanning perfect coverage of tree trunk for individual trees is impossible. Uneven distribution of point clouds on the trunk would complicate the cylinder fitting process and it may produce error in volume calculation (Figure 12). Figure 11 illustrates the relationship between weight of stem estimated using TLS and weight of stem obtained using allometric equation.

Biomass estimation of tree branch using TLS has better estimation accuracy with 27.20 kg RMSE. The value of MAE is slightly deviates from the RMSE which implicates very few samples with extreme residual between estimated and measured biomass. This method tends to underestimate biomass estimation for tree branch. Errors in branch biomass estimation may attributed by several factors including poor density of

point clouds over tree crown, manual separation between leaves and branch and reconstruction of tree branches using alpha-hull in Matlab. Figure 14 shows the relationship between measured weight of branch and estimated weight of branch.

Table 5 Root mean square error (RMSE), Mean absolute error (MAE) and correlation of allometric-based biomass and biomass estimated using TLS

	RMSE (kg)	MAE (kg)	Correlation	Mean Bias (kg)
Stem biomass	50.22	31.03	0.821	-9.01
Branch biomass	27.20	16.18	0.130	5.18

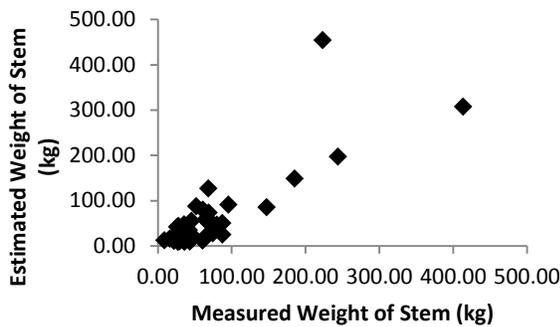


Figure 11 Relationship between measured weight of stem and estimated weight of stem

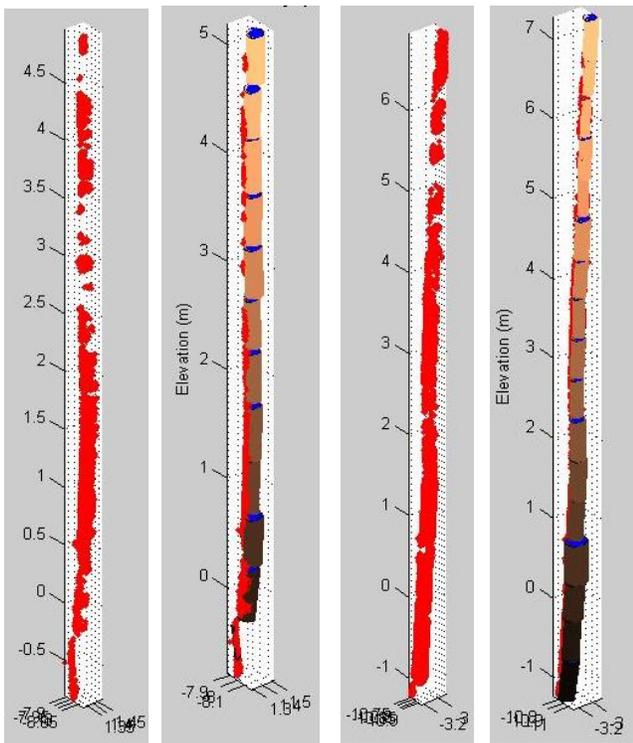


Figure 12 Uneven distribution of point clouds around tree stem and difficulties in cylinder fitting

Figure 13 shows an example of reconstructed tree branches using alpha hull in Matlab. There is huge number of gaps between branches, hanging small branches and some of the major branches are combined in a strange form.



Figure 13 Reconstructed tree branches using Alpha-hull surface

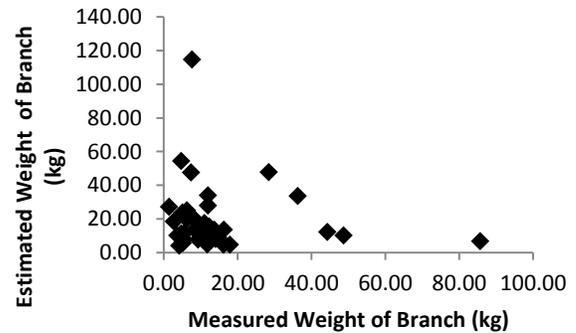


Figure 14 Relationship between measured weight of branch and estimated weight of branch

Though point clouds belong leaves have been separated from branches direct leaves biomass estimation from the point clouds is impossible. Therefore in this case the point clouds should be combined with branches and tree crown biomass is estimated based on regression model between tree crown volume and calculated crown biomass using allometric equation. The point cloud of tree crown is used as the input for convex hull wrapping process. This process will wrap the crown as an object, joining from point to point and edge to edge using Delaunay triangulation (Figure 15).

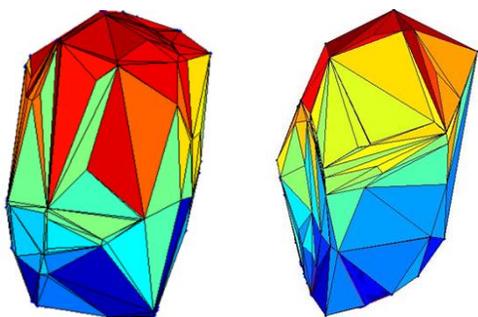


Figure 15 Convex hull of tree crown

Figure 16 shows low correlation ($R = 0.23$) between the total above ground biomass and volume of tree crown. The results might be affected by several reasons, i.e. density of point clouds generated for tree crown, the convex-hill wrapping process that still have large gaps between branch and leaves.

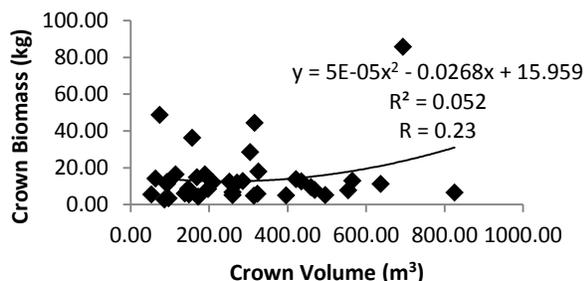


Figure 16 Correlation and regression model between crown volume and calculated tree crown biomass

4.0 CONCLUSION

We have demonstrated a novel non-destructive method for individual tree biomass estimation using terrestrial laser scanner. The biomass estimation has been done for different tree parts i.e. tree stem, branch and crown (combination of branch and leaves). The high density point clouds permits direct estimation of individual tree DBH and but not so much for tree height. The nature of the terrestrial-based LiDAR measurement and tree obstructions has become one the major obstacles. This has a significance influence on the capability of TLS in estimating individual tree biomass. Conventional tree census is usually based on plot observation which involved group of trees. In this case, the first challenge for TLS is to ensure good coverage of point clouds over different tree parts. The second challenge lies on individual tree extraction where significant number of point should be properly removed especially for forest area with considerably dense understory vegetation.

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