Retrieving structural parameters of individual tree through terrestrial laser scanning data

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Abstract: Terrestrial Laser Scanning (TLS) has shown great potential in obtaining the structural parameters of individual trees in past decades. In this work, three-dimensional point cloud data generated from TLS were obtained for a homogeneous forest plot with 20 Pinus bungeana (Pinus bungeana Zucc) trees. Through the analysis of the vertical profile of the point cloud data of an individual tree, a voxel-based method was developed to estimate crown base height. Further, the tree crowns were delineated by calculating the convex hull of each horizontal sliced point cloud data at different heights. In addition, crown volume, crown width, tree height, and Diameter at Breast Height (DBH) were estimated at the same time. The TLS-based estimation captured 97% variation of the manually measured clear bole height ($n=20$, Root Mean Square Error (RMSE) $=0.21$ m, $p=0.01$). The R^2 and RMSE of DBH provided the coefficient of R^2 was 0.79 and 1.07 cm ($n=20$), respectively. Crown length, DBH, and crown width were selected to predict crown volume by the stepwise linear regression method, and statistical analysis showed that the linear regression m odel explained 96.7% of the crown volume variance with an RMSE of 2.64 m^3 ($n=20$, $p=0.01$). The method developed in this i nvestigation accurately estimated crown base height and crown geometry and can thus facilitate the application of TLS in precision forestry.

Key words: terrestrial laser scanning, voxel, convex hull, crown base height, crown outline, crown volume

CLC number: S757 **Document code:** A

Citation format: **Liu L X, Pang Y, Li Z Y, Xu G C, Li D and Zheng G. 2014. Retrieving structural parameters of individual tree through terrestrial laser scanning data. Journal of R emote Sensing, 1 8(2): 365 – 377 [DOI: 10. 11834/jrs. 20143091]**

1 INTRODUCTION

Forest inventory is the basis for forest management. For sustainable forest management, a great amount of information is required for planning future forest management and documenting activities of the past (Koch, et al., 2006). Parameters such as tree height, crown base height, crown area, and Diameter at Breast Height (DBH), are usually needed in traditional forest inventory. Traditional forest inventory based on manual measurements is very labor-intensive and time consuming. With the emergence of new technologies, remote sensing has been used to investigate forest resources at a larger scale with frequent revisiting abilities as a supplemented approach. Passive optical systems, such as photography and the Landsat Thematic Mapper, have been satisfactory for many ecological applications, such as mapping land cover onto broad classes and estimating aboveground biomass and leaf area index (Lefsky, et al., 2002). However, passive s ensors are limited in obtaining the three-dimensional structural parameters of forests (Kwak, et al., 2007). Light detection and ranging is an active remote sensing technology. Airborne Laser Scanning (ALS) and Terrestrial Laser Scanning (TLS) have had a wide range of applications in forests and have become important means of forest inventory (Nesset, 1997; Tesfamichael, et al., 2009; García, et al., 2010; Kelbe, et al., 2012; Seidel, et al., 2012). TLS has provided vast and high-quality three-dimensional points of forests. TLS has emerged as a tool for detailed data collections in forestry applications, and methods have been p roposed to derive various parameters, such as tree position, DBH, stem density, tree height, crown shape, and stem volume, with TLS data.

Different researchers have explored methods for extracting forest structural parameters (including of single trees) and the a lgorithm of forest structural parameter extraction based on TLS (Bienert, et al., 2006, 2007; Strahler, et al., 2008; Moorthy, et al., 2011). Aschoff, et al. (2004) produced a digital terrain model from a triangulated irregular network. Based on this model, the point cloud was sliced at different heights above ground and p rojected in two-dimensional layers. Hough transformation was then used to detect the trees.

Received: 2013-04-17; **Accepted:** 2013-08-29; **Version of record first published:** 2013-09-06

Foundation: National High Technology Research and Development Program of China (863 Program) (No. 2012AA12A306); National Basic Research Program (973 Program) (No. 2013CB733404)

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Li, et al. (2012) used modified Hough transformation and the vertical continuity testing of the point cloud to extract a single tree's location, DBH, and height of complex forest. Hopkinson, et al. (2004) measured parameters, such as stem location, tree height, DBH, stem density, and timber volume, with TLS data. These retrieved parameters were compared with field manually collected validation data. Mean tree height was slightly underestimated systematically because of canopy shadow effects and suboptimal scan sampling distribution. Pfeifer, et al. (2004) reconstructed a single tree trunk, individual branches, and the whole crown. Jung, et al. (2011) estimated the crown variables of individual trees through airborne and terrestrial laser scanners, and the accuracy was better than that with ALS only.

The voxel-based method is simple and effective. By setting up a voxel of appropriate size, we can both reduce the density of the TLS point cloud and keep the real dimensions of the trees. Many researches have used the voxel-based method. Hauglin, et al. (2013) estimated the single-tree branch biomass of Norway spruce with TLS based on a voxel-based method. The accuracy of prediction from TLS-based models was higher than that from the conventional allometric model. At the same time, crown size information has also been derived from point cloud data generated by TLS. The point cloud was sliced at different heights above ground by the voxel-based method and was then projected onto a two-dimensional layer. The two-dimensional raster image is used for detecting trees (Li, et al., 2012). García, et al. (2011) evaluated the potential of TLS to characterize forest canopy fuel characteristics at plot level. Several canopy properties, namely, canopy height, canopy cover, canopy base height, and fuel strata gap, were estimated, and canopy base height was estimated from vegetation vertical profiles derived from an occupied/non-occupied voxel approach. Zheng & Moskal (2012a, 2012b, 2012c) used a new voxel-based method called point cloud slicing to extract the effective leaf area and leaf orientation.

This study aims to:

(1) Extract clear bole height and crown length from tree vertical profiles derived from TLS data by the voxel-based approach.

(2) Delineate the outline of crowns from the two-dimensional raster image by the convex hull approach.

(3) Estimate the crown volume of an individual tree through the point cloud data generated from TLS.

2 MATERIALS

2.1 Study area

A forest plot with 20 Pinus bungeana (Pinus bungeana Zucc) trees located in the Chinese Academy of Forestry (CAF) (40°00′18.16″N, 116°14′32.51″E) was used to obtain point cloud data by TLS. P. bungeana originates from northern China, and its bark is very beautiful. The P. bungeana forest in CAF was planted in 1928. The area is 0.57 ha, and the spacing is 1.67 m × 1.67 m. Soil improvement and thinning studies have been conducted in this field. This plot is the oldest P. bungeana plantation in China and has the value of scientific research, historic preservation, and conservation.

2.2 Field data and acquisition of TLS data

We measured the DBH, clear bole height, and tree height of 20 select trees. TLS data were collected in June 2011 with a Riegl VZ-400, which was operated at a wavelength of 1550 nm and can quickly and accurately acquire three-dimensional images up to a range of about 600 m. The laser beam was 10 mm in diameter as it left the device and had a beam divergence of 0.3 mrad, which equates to a beam 13 mm wide at a 10 m range. The scanner was mounted on a tripod, and a full 360×100° scan (the scanner's maximum field-of-view) was performed from each scanner position at an angular resolution of 0.1°. We implemented two scans so that each tree was visible.

2.3 Pre-processing of raw data

Flying points came from the edge of the target, and their laser pulse shape had a higher bias value. The bias of the laser pulse shape implied that the measuring results have high uncertainty. Therefore, the data were filtered to remove "flying points" with a bias threshold of 25. Because of the ambiguity problem of the range measurement, many incorrect points were included in the raw data. The incorrect points were reflected points outside the ambiguity interval that were calculated in the first interval. Such points usually have low intensity because of the long distance to the actual reflected points. A defined intensity threshold of 1000 was used as an initial filter. The last step was the registration of two TLS scans. First, the coordinate of the reflector plate from the total station was imported into RISCAN software. Second, both scans were registered to the WGS-84 coordinate. Finally, the second scan was manually adjusted to the first scan. Fine registration was performed through polydata, as described by Li, et al. (2012).

All the extractions of the forest parameters were based on the normalized point cloud to eliminate the influence of terrain on tree height. The height of the tree point was the value relative to the height of the ground. We generate a DEM by extracting the local lowest height value. The normalized point cloud was that the height of the point cloud minus the DEM.

3 METHOD

The flow chart of this study is shown is Fig. 1.

3.1 Stem position and DBH

The stem position was the base to extract other single-tree parameters. The DBH, tree height, and canopy structure parameters were extracted after the tree position was identified. Hough transformation was used in the detection of the trees, and circle fitting was used to calculate their DBH.

A horizontal layer of the trunk was cut from the scanned point cloud at 1.3 m above the ground, the layer was 10 cm thick. To use standard pattern recognition methods, the layer was mapped onto a regular raster with a grid size of 0.5 cm × 0.5 cm. The pixel value of the raster was the number of points in the 0.5 cm × 0.5 cm × 10 cm cell. If the number of points in a pixel was less than 3, then the pixel value was set to zero. To detect circles in this raster image, Hough transformation, which required a predefined diameter, was used. Because the diameter was unknown before the algorithm was used and DBH was d istributed between 5 cm and 25 cm, we began with a diameter of 5 cm and increased the diameter with an increment of 0.5 cm. For each tree position, several circles were detected. We extracted the points within the 97%—103% range of the circles and calculated the number of these points N, the diameter of the circles R, and the standard deviation of these points to the circles S. We chose the circle with minimum $2R/N$ as the correct circle. When several minimum results were obtained, we chose the one with a minimum of S.

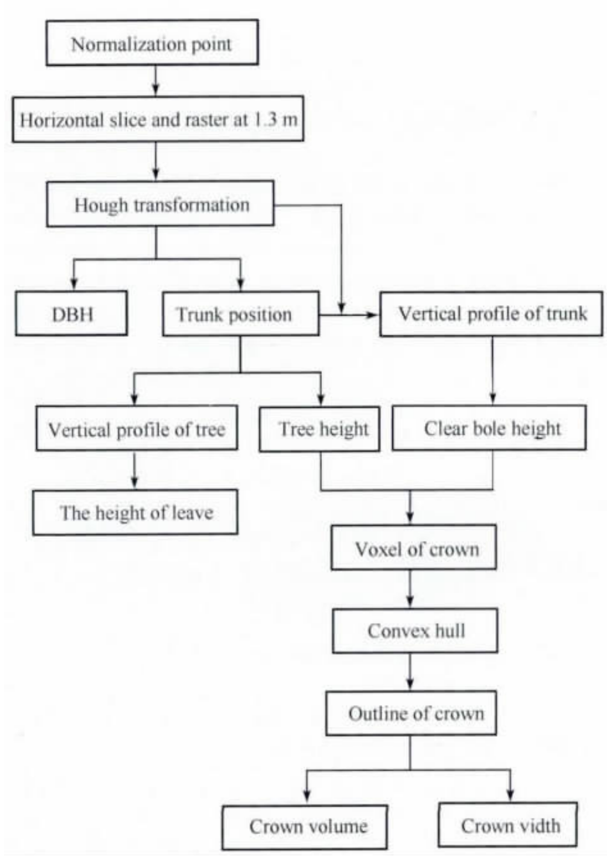

Fig. 1 Flow chart of this study

3.2 Clear bole height

The position of the clear bole height is the separation location between the crown and trunk, and the height of the first branch is the clear bole height. The clear bole height equals the height of the main trunk. If the tree is bifurcated below 1.3 m, then it is deemed to two tree trunks. Therefore, if the tree is b ifurcated above 1.3 m, then it is deemed to branch. The point cloud from the trunk was sliced into several horizontal layers. We then used the method introduced in Section 3.1 to extract the diameter and position of the whole trunk.

The scan points from a tree of a height between 1.3 m and 7.0 m were segmented into a series of slices with a 10 cm thickness. For each layer, we used the method described in Section 3.1 to extract the DBH and position of the circle and the mean radius of the circle R. The approach used in this study to estimate clear bole height used a grid of occupied/non-occupied cells. The TLS return points of one layer were arranged in an x-y grid as d escribed in Section 3.1, and cells occupied by at least three points were assigned a value of 1. The number of voxels in the range of $2R$ with a value in one layer was marked N. We then calculated the N of all the layers and analyzed the vertical profile of the point cloud data for the tree trunk.

The scan points from the trunk were focused so that its N was stable. On the position of the first branch, the girth of the trunk was large (Fig. 2(c)). As a result, the value N was much greater than the value N from the trunk (Fig. 2(a)). The vertical profile of the stem also shows the variation of N b ecause of the smaller branch. The spring below the first branch has small girth, so that it never disturbs the detection of the first branch. Fig. 2 shows the vertical profile of N, and the clear bole height is in p osition with the first dramatic change of the profile.

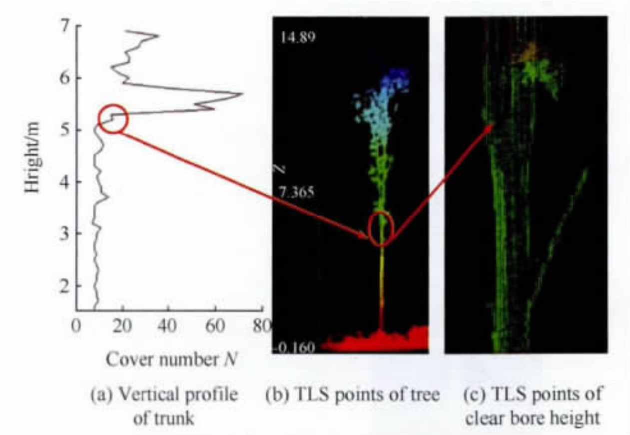

Fig. 2 Detecting clear bore height from vertical profile of trunk

3.3 Vertical distribution of leaves

The TLS return points of the single tree were divided into the voxel space with dimensions of 10 cm × 10 cm × 10 cm. A voxel with more than two points was assigned a value of 1. The number of voxels in one layer with a value was marked N. We then calculated the N of all the layers and analyzed the vertical profile of the point cloud data for the whole tree.

The tree height is the highest Z-value of the TLS return points from a single tree. In this paper, two crown lengths were defined. One is defined as the difference between the top height and the clear bolt height. The other is called the leaf-filled crown length. Few leaves are found on the bottom branches of the P. bungeana tree's crown. The value of N was changed quickly in the vertical profile of the tree, and the position was above the clear bole height (Fig. 3(a)). Thus, many leaves appeared in this position. The length between the tree top and this position was the crown length filled with leaves. The vertical profile of the tree can display the vertical distribution of leaves, so that we s egmented the single tree into three parts by the vertical profiles of the tree and trunk (Fig. 3(b)).

3.4 Outline of crown, crown width, and crown volume

In this paper, a convex hull was used to extract the outline of the crown. A set of points were defined as convex if it contained the line segments connecting each pair of its points. The convex hull of a given set $\boldsymbol{Q}$ may be defined as the (unique) minimal convex set containing $\boldsymbol{Q}$ (Wang, et al., 2011).

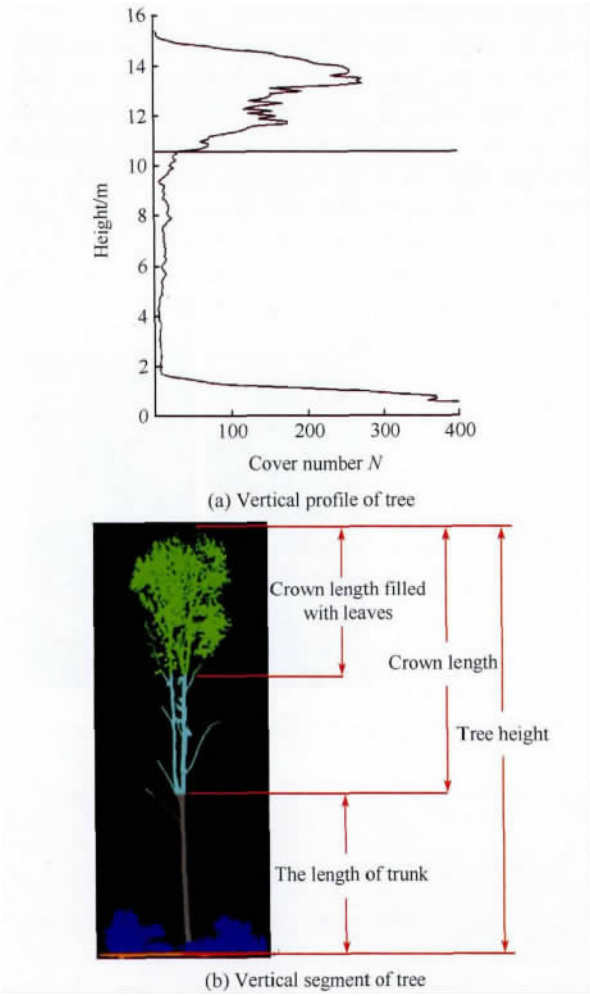

Fig. 3 Vertical profile of tree and vertical segment of tree

Quickhull is a method of computing the convex hull of a finite set of points in a plane. This method uses a divide-and-conquer approach similar to that of quicksort, from which it derives its name (Wikipedia, 2012). The algorithm can be broken down into the following steps:

Step 1 The points that have the minimum and maximum x coordinates and are bound to be a part of the convex are identified.

Step 2 The line formed by the two points is used to divide the set into two subsets of points, which will be processed recursively.

Step 3 The point on one side of the line with the maximum distance from the line is determined. The two points found before along with this one form a triangle.

Step 4 The points lying inside the triangle cannot be a part of the convex hull and can therefore be ignored in the next steps.

Step 5 The previous two steps are repeated on the two lines formed by the triangle (not the initial line).

Step 6 The steps are repeated until no more points are left, the recursion has come to an end, and the points selected constitute the convex hull.

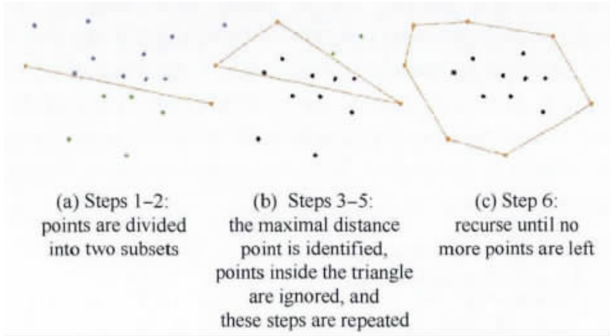

Fig. 4 Sketch map of quickhull algorithm (Wikipedia, 2012)

The TLS return points of the crown were divided into the voxel space with dimensions of 10 cm × 10 cm × 0.5 m. The voxel was occupied if the number of laser points in it was more than 2. The position of the occupied voxel of every layer was regarded as the set of points used to extract the outline by the quickhull algorithm. The read pane was the outline of crown (Fig. 5).

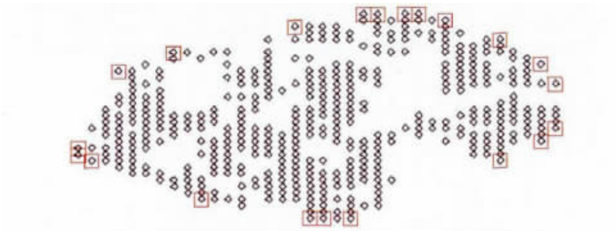

Fig. 5 Outline of one layer of crown

Afterward, we can calculate the area of this crown layer according to the following expression:

$$S = \frac{1}{2}\sum_{k=1}^{m}\left(x_k y_{k+1} - x_{k-1} y_k\right) \tag{1}$$

where m is the number of vertices and x_k, y_k are the coordinates of the vertex. All vertices from all layers were mapped onto the ground. The crown area was the area calculated from the vertices extracted by the convex hull algorithm of the point set of all layers.

The traditional method for measuring crown volume assumed that the crown had regular geometry. However, the crown in the real world is irregular. TLS technology can obtain the three-dimensional structure of the tree; thus, it can be a tool to measure crown volume. In this paper, we regarded a layer of the crown as the prism whose base area was the area of this layer and whose height was 0.5 m. The crown volume was approximately the accumulation of all prisms through the following expression:

$$V = \sum_{n=1}^{k} S \times H \tag{2}$$

$$k = L/H \tag{3}$$

where V is the crown volume, S is the base area of the prism of this layer, H is the prism's height (0.5 m in this study), and L

is the crown length. Fig. 6 shows the segments of the crown.

Fig. 6 Segments of crown

4 RESULTS AND ANALYSIS

4.1 Clear bole height and DBH

We compared the clear bole height and DBH with field measurements. The clear bole height yielded a high coefficient of determination ($R^2 = 0.97$, $p = 0.01$), and the Root Mean Square Error (RMSE) was 0.21 m. DBH had a low coefficient of determination ($R^2 = 0.79$, $p = 0.01$) compared with the clear bore height. However, DBH had a small error with an RMSE of 1 .07 cm. Fig. 7(a) and Fig. 7(b) show the regression results of the clear bore height and DBH, respectively.

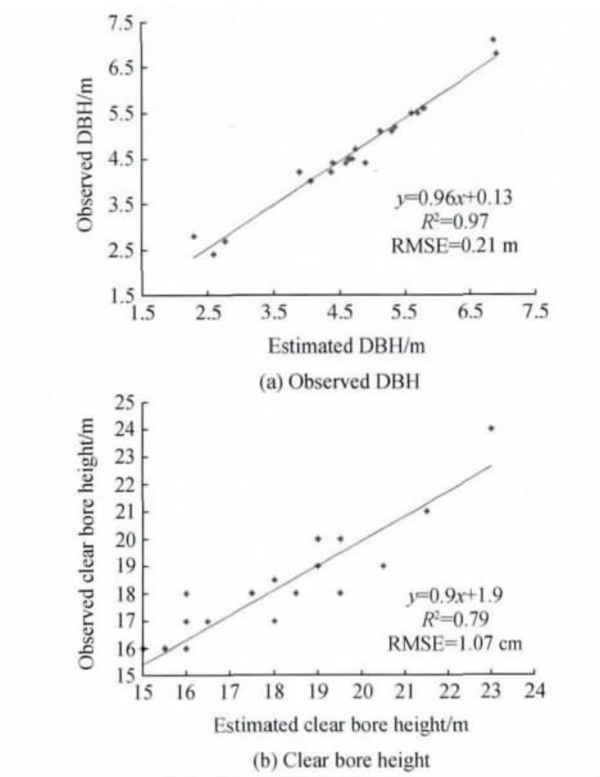

Fig. 7 Estimated versus observed DBH and clear bore height

4.2 Regression between crown volume and other p arameters

A regression model was established between crown volume and other parameters, such as crown width, crown length, the length of a crown filled with leaves, tree height, and DBH. The model excluded variables such as tree height and crown height. The model had a high coefficient of determination ($R^2 = 0.96$), and RMSE was 2.64 m^3. The regression function is

$$y = 3.56x_1 + 1.47x_2 + 1.045x_3 \quad (4)$$

where x_1 is the crown width, x_2 is the crown length, and x_3 is the DBH.

4.3 Analysis

Compared with field-measured data, the result of DBH estimated by Hough transformation yielded a small error. Some DBHs were underestimated. Data checking revealed that these trees were far from the scan station and that the error resulted from blocking by other trees.

This paper estimated clear bole height precisely. The important point of this paper was to detect the vertical profile of the trunk, which was based on the position of one layer. The study area was located in an artificial forest, and the shrub had little i nfluence on position detection. Thus, we assumed that all the detection positions were inside the trunk. The clear bole height estimated by this method had a small error and a strong relationship, indirectly showing that the position was estimated precisely. In structurally heterogeneous forest environments, however, the result would be influenced by leaves and shrubs.

In the real world, the crown is irregular. Thus, we segmented the crown into many layers, and the greater the number of layers, the higher the accuracy. Voxels are means to represent a three-dimensional space by a regular grid. The voxel-based method can reduce the density of TLS scan points and the number of point sets of the convex hull algorithm. Quickhull's average case complexity is considered to be $O(n \times \log(n))$, whereas in the worst case, it takes $O(n^2)$. The best condition e merges if the point set is divided in a balanced manner. The l ocation of voxels in one layer of the tree had a well-proportioned distribution. The quickhull algorithm is suitable for extracting the outline of crowns.

We calculated crown volume starting from the clear bore height. Crown volume was influenced by crown length and crown width. The regression result showed little relevance b etween crown volume and crown length but a good relation with the length of a crown filled with leaves because the most part was the volume of the crown filled with leaves rather than the branches of the P. bungeana trees. Crown volume was related to crown shape. For one tree species, the crown shape is similar to that of other trees but different from that of other tree species. Thus, tree structure should be described. The TLS scan point data have potential for the extraction of tree structure p arameters and build the relationship between easily obtained and hard-to-obtain parameters.

5 CONCLUSION

We selected 20 P. bungeana trees as the experiment materials and estimated the position and DBH of trees by Hough transformation. On the basis of tree position, the vertical profile of the trunk was extracted. The clear bole height was then estimated from the vertical profile of the trunk. Finally, the crown was sliced into several layers from the clear bore height to the tree top, and the crown width and crown volume were calculated. The main conclusions are as below.

(1) As a result, the DBH values were underestimated for those trees far from the scan station. Generally, the DBH values and positions determined were precise.

(2) We extracted the clear bole height from the vertical p rofile. The result showed the desired accuracy by R^2 and RMSE values of 0.97 m and 0.21 m, indicating that the method was suitable for extracting clear bole height from a homogeneous f orest.

(3) The quickhull algorithm was suitable for extracting the outline of the crown.

(4) A strong relation was found between crown volume and other tree structure parameters, such as crown width, the length of a crown filled with leaves, and DBH. TLS has the potential to construct a single-tree structure model.

The superiority of TLS is obtained by extracting the vertical structure of the tree without damage. TLS is convenient for the continuous observation and dynamic monitoring of forests and for modeling the three-dimensional structure of trees. The shadow generated by other trees influences the accuracy of single-tree parameters extracted in the forest area. The scan station should be designed reasonably to obtain accurate parameters in the forest area. More research is needed to extract the p arameters of heterogeneous forests.

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用地基激光雷达提取单木结构参数——以白皮松为例

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摘 要: 以白皮松(Pinus bungeana Zucc)为研究对象，针对地基激光雷达TLS扫描的3维点云数据在单株木垂直方向的分布特征，提出了一种基于体元化方法的树干覆盖度变化检测方法，获取单木枝下高; 然后根据获取的枝下高引入2维凸包算法获取垂直方向分层树冠轮廓，并计算树冠体积和冠幅; 同时获取的单木参数还有胸径与树高。结果表明: 单木枝下高的估测精度较高，R^2 与 RMSE 分别为 0.97 m 和 0.21 m; 胸径估测结果的 R^2 与 RMSE 分别为 0.79 cm和 1.07 cm; 采用逐步线性回归方法建立单木树冠体积与其他单木参数的相关关系，模型变量包括冠幅、叶子填充树冠长度和胸径，样本数为20，模型的 R^2 与 RMSE 分别是 0.967 m^3 和 2.64 m^3。本文方法能较准确地估测枝下高，TLS 数据具有对树冠结构3维建模的潜力。

关键词: 地基激光雷达，体元化，2维凸包，枝下高，树冠轮廓，树冠体积

中图分类号: S757　　文献标志码: A

引用格式: 刘鲁霞，庞勇，李增元，徐光彩，李丹，郑光. 2014. 用地基激光雷达提取单木结构参数——以白皮松为例. 遥感学报，18(2): 365 -377

Liu L X, Pang Y, Li Z Y, Xu G C, Li D and Zheng G. 2014. Retrieving structural parameters of individual tree through terrestrial laser scanning data. Journal of R emote Sensing, 1 8(2): 365 - 377 [DOI: 10.11834/jrs.20143091]

1 引 言

森林调查信息是森林经营管理的基本依据，可持续的森林管理需要更多的森林调查信息，不仅包括对森林未来的规划，也包括对森林历史资料的记录(Koch 等，2006)。然而对树高、树冠基部高、胸径和冠幅等传统森林参数的调查，需要大量的人力、物力。近年来，光学遥感技术使用航空照片与卫星影像替代或补充了一些传统的森林调查，使用光学遥感技术能够获取大区域森林生长因子和生态、环境信息(Lefsky 等，2002)，然而光学遥感技术在获取森林3维结构参数上能力有限(Kwak 等，2007)。激光雷达(LiDAR)技术是一种主动遥感技术，近年来，机载激光雷达 ALS 和地基激光雷达 TLS 在林业上的应用越来越广泛，并成为森林调查的一种重要手段(Nesset，1997; Tesfamichael 等，2009; García 等，2010; Kelbe 等，2012; Seidel 等，2012)。尤其是 TLS 能提供大量高质量的3维点云，TLS 提供了一种快速、有效、自动的探测，如树的位置、株数、胸径、树高和树冠形状等森林基本调查因子的方式。

近几年研究人员探索了基于 TLS 数据的森林结构参数提取方法，包括单木参数(如树干和胸径)、树冠结构特征、森林结构参数的提取算法等(Bienert 等，2006，2007; Strahler 等，2008; Moorthy 等，2011)。Aschoff 等人(2004)使用不规则三角网格(TIN)方法把地面点插值生成 DTM，然后将点云数据高度进行归一化至同一平面，对归一化后的点云数据分层，把每层点云数据投影至水平面上生成2维栅格图像，最

收稿日期: 2013-04-17; 修订日期: 2013-08-29; 优先数字出版日期: 2013-09-06
基金项目: 国家高技术研究发展计划(863 计划)(编号: 2012AA12A306); 国家重点基础研究发展计划(973 计划)(编号: 2013CB733404)
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后采用 Hough 变换和圆拟合的方式获取树位置和胸径。李丹等人(2012)采用一种改进的 Hough 变换和垂直向点云连续性检测方法提取复杂林分环境下单木位置、胸径和树高。Hopkinson 等人(2004) 利用地基激光雷达提取树位置、树高、胸径、树密度和材积等森林参数,并与样地实测数据相比较,结果显示由于树冠的遮挡和采样分布问题导致树高低估。熊妮娜等人(2007)使用地基激光扫描数据获取油松单木树冠体积,得出油松胸径、树冠、树高与树冠体积有很好的相关关系。Pfeifer 等人(2004)利用地基激光扫描数据重建了单木树干、主枝和树冠等单木结构。Jung 等人(2011)结合 ALS 与 TLS 获取树高、树冠基部高、冠幅、树冠体积等树冠结构参数,结果表明,结合两种数据可以有效提高例如树高、树冠基部高、冠幅和树冠体积等森林生长因子的估测精度。

体元化(voxel)方法是一种简单有效的方法,可以把高密度的大量地基激光点云按体元抽稀处理,设置好适合的尺寸大小,既降低了大量 3 维点云数据的复杂性又有效保存了目标物(树木)的真实信息。很多研究都用到了体元化的方法。Hauglin 等人(2013)用基于体元的方法和传统的异速生长方程估测的树木枝生物量,使用 TLS 数据获取的精度比使用异速生长方程获取的精度稍高,同时提取的参数还有树冠尺寸。李丹等人(2012)在其研究中把树干处某层按格网分开,以该层各格网含回波点数对格网赋值,生成 2 维栅格灰度影像,在此基础上提取胸径。García 等人(2011) 使用 TLS 数据获取森林冠层燃料参数,他把整个林分中的激光点按一定尺寸体元化,获取冠层基部高和燃料隔离层的高度。Zheng 和 Moskal(2012a,2012b,2012c) 采用体元化方法获取了单木和林分有效叶面积指数、叶面积指数空间变化和叶方向。

本研究主要基于体元化方法对树干部分和整株树进行垂直分层覆盖度检测,获取枝下高和树冠长度;利用树冠部分的体元数据,基于 2 维凸包算法获取树冠在垂直方向上轮廓分布,采用棱柱累加法获取树冠体积。

2 实验区和数据

2.1 实验区概况

实验区位于中国林业科学研究院内白皮松人工林,地理坐标为(40°00′18.16″N,116°14′32.51″E)。白皮松(*Pinus bungeana* Zucc)原产于华北山地。1928 年春用 3 年生苗造林,面积为 0.57 ha,株行距为 1.67 × 1.67 m,现存活立木 838 株。曾开展过土壤改良和疏伐等科学研究工作。它是中国栽植最早、树龄最长、面积最大和保护最好的白皮松人工林,具有科学研究和历史保存价值。

2.2 实测数据与 TLS 数据获取

实测数据包括挑选出的 20 棵树,测量每棵树胸径和枝下高,单株木的胸径使用围尺进行测量,枝下高使用激光测高仪进行测量。

外业使用的地基激光雷达系统为 Riegl VZ-400,该仪器采用 3 ns 的 1550 nm 红外激光束快速扫描机制,提供快速、非接触的数据获取。该仪器技术参数见表 1。

表 1 Riegl VZ-400 技术参数

参数类型	参数值
扫描距离/m	600(对反射率为 90% 的物体)
测量精度/mm	5
测量分辨率/mm	3
激光发射频率/(点/s)	300000
扫描视场范围	100° × 360°(垂直 × 水平)

2011 年 6 月 10 日对白皮松林进行了两个测站扫描,两个测站间相互重叠度大于 50%。

2.3 TLS 数据预处理

采用李丹等人(2012)论文中对 TLS 数据预处理方法对白皮松林 TLS 数据进行预处理。首先是“飞点”去除和强度过滤,去除了偏差值大于 25 的点云数据,并滤除了强度低于 1000 的噪点。然后对两站数据进行配准。本研究采用粗配准和精配准两种方式来配准数据。把全站仪测量的反射片全球坐标导入到 RiSCAN 软件中,两站都向全球坐标配准,保证所有站在同一坐标系下,然后利用目视观察和手动调整的粗配准方式调整第二站点云相对于第一站点云的位置。接下来利用精配准方式来实现第二站到第一站点云的配准:首先生成第一站和第二站的矢量型数据(polydata),然后以两站的反射片数据和 polydata 为基础,锁定第一站,按照具体给定的条件实现第二站到第一站点云的精配准(李丹 等,2012)。TLS 数据提取森林和单木参数都是基于高程归一化后点云数据,这能有效去除地形

对树木高度的影响,使植被点的高度值为相对于地面的高度值。由于本研究区地势平坦,地面高程差别很小,TLS 数据点密度很大,所以采用一种简单的局部最小值法提取地面点,对植被点云数据进行高程归一化处理。

3 研究方法

数据预处理后,采用如图 1 所示的技术流程进行单木参数的提取。

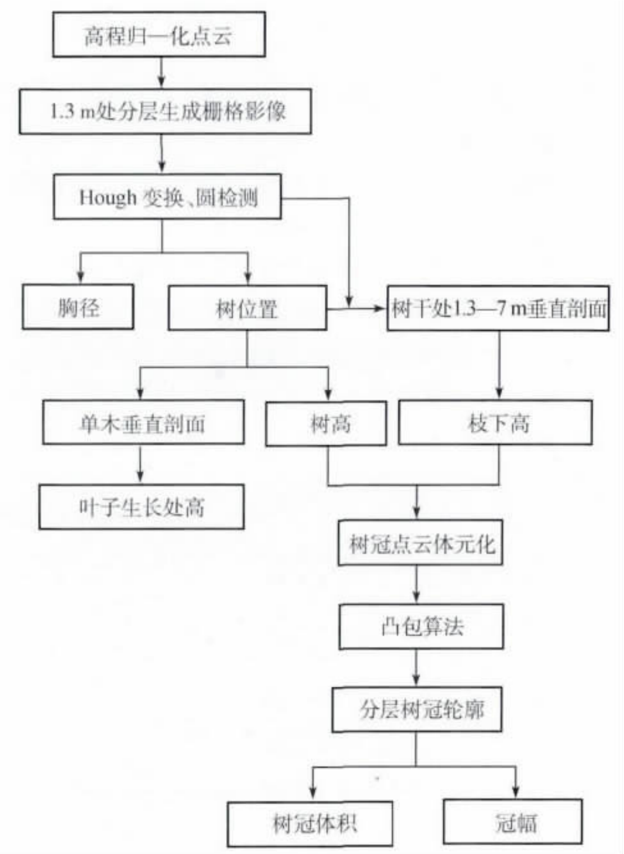

图 1 基于地基激光雷达数据的单木参数提取流程

3.1 单木位置和胸径

单木位置提取是单木参数提取的基础,准确识别单木位置之后,可以在其基础上进行胸径、树高及树冠结构参数的提取。本文采用 2 维 Hough 变换和圆拟合的方法来识别单木,获取单木位置和胸径。

首先在 1.3 m 处截取层厚度为 10 cm 的点云数据,然后将该薄层数据生成分辨率为 0.5 cm × 0.5 cm 的栅格灰度影像,像素灰度值根据该体元(10 cm × 0.5 cm × 0.5 cm) 内包含的回波点数 n 确定,如果 $n > 2$,把 n 赋为该像素的值,否则该像素赋值为 0。

然后对灰度影像利用 Hough 变换进行圆检测。检测半径从 5 cm 开始,到 25 cm 结束,步长为 0.5 cm。对于每棵树 1.3 m 胸径处,会检测出很多圆,取圆外扩和内缩 3% 处点云,并计算点云个数 n 和这些点到圆心距离的标准差 s。检测完所有给定半径后,开始确定单木位置。判断标准是: 选取 $2r/n$最小时的位置作为结果,当 $2r/n$ 存在多个结果时,从中选取 s 为最小值时对应的位置作为结果。

3.2 单木枝下高

枝下高位置是树木主干与树冠的分割点,对枝下高一般是测量离地面最近的明显大枝的高度,枝下高即为树木的主干高度。如果树木从 1.3 m 胸径处以下分叉,则认为是两棵树,1.3 m 以上分叉认为是枝干,枝下高大于 1.3 m。获取单木位置后,可以在其基础上检测不同高度处树干的干径和圆心位置。

对于每株树,取出该树 1.3—7 m 的点云数据。从 1.3 m 处开始对点云数据水平分层,单层厚度为 10 cm。采用 Hough 变换和圆拟合方法得到该层树干圆心与半径。以获取的圆心为圆心,提取半径为 $2r$ 范围内点云数据(r 为每层树干处拟合圆的半径) ,将该薄层数据体元化,体元尺寸为 5 cm × 5 cm × 10 cm,若体元内回波点个数 $n > 2$,则认为该体元被覆盖。

遍历所有层,得到各层的覆盖体元个数,如图 2 (a) ,即为树干处垂直剖面。

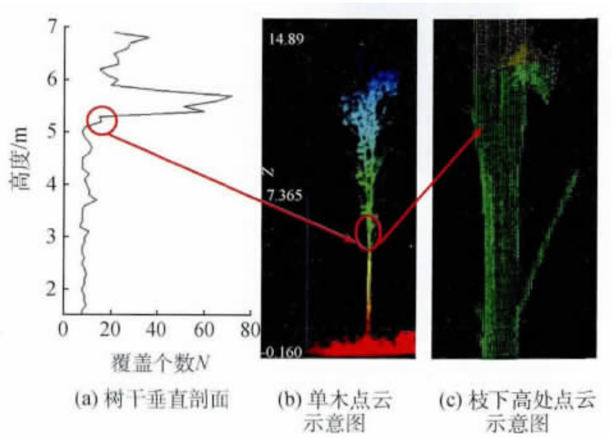

图 2 树干处垂直覆盖度变化检测方法示意图

如图 2(a) 所示,在树干处点云分布比较集中,而且各层的覆盖值变化不大,到枝下高处,覆盖度明显变大,根据这一特点,可以得到枝下高位置。覆盖值在较小枝处也会明显变大,变化幅度小于大枝处,而且小枝一般很短,覆盖值在变大后很快又变回到树干处水平,根据这个特点,可以有效去除

小枝对检测枝下高的影响。

3.3 树叶垂直分布

仍是以体元化方法,获取整棵树在垂直空间上的覆盖情况。体元大小为 10 cm×10 cm×10 cm,若体元内点个数大于 2 则该体元被覆盖。图 3(a) 为整棵树垂直剖面。

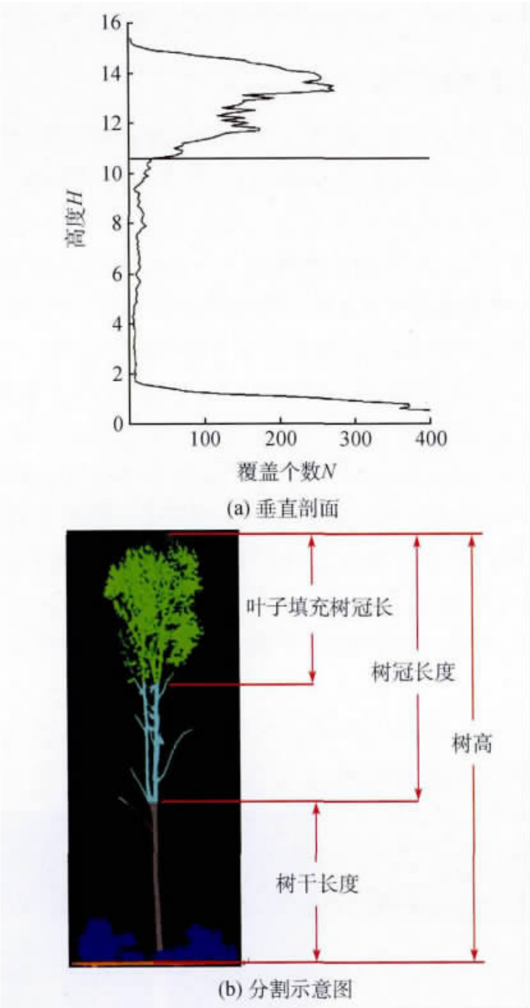

图 3 单株树垂直剖面与分割示意图

树高是单木范围内最高点。因为白皮松下部枝条很少长叶子,在此处计算两种树冠长度。一种是定义上的树冠长度,即树高减去枝下高;一种是叶子填充树冠长度,即树高减去树叶开始处高度。如图 3(a),覆盖值在 10.6 m 急剧增大,说明从这个地方开始分布大量叶子,如图 3(b),绿色部分长度即叶子填充树冠长度。以此处位置和枝下高位置,把单株树分成 3 部分。第 1 部分为地面至枝下高处,第 2 部分枝下高至叶子开始分布处,第 3 部分是叶子开始分布处至树顶。如图 3(b) 所示,用不同颜色表示这 3 部分结构。

3.4 树冠轮廓、冠幅及树冠体积

点集 Q 的凸包(Convex hull) 是指一个最小凸多边形,满足 Q 中的点或者在多边形上或者在其内(汪嘉业 等,2011)。本文采用 2 维凸包的快速算法获取树冠外轮廓。

凸包的快速算法主要思想是:点集 Q 的凸包是取决于凸包边界附近的点;逐步丢掉凸包内部的点,只关注凸包附近的点,从而提高算法的效率。可以分解为以下几个步骤:

(1) 找到 X 轴中坐标最小和最大的点,这两个点是凸包顶点的一部分。

(2) 这两个点连成的直线把点集一分为二,分别进行递归处理。

(3) 在直线两侧找出离直线距离最远的点,这样每一边都可以形成一个三角形。

(4) 去除三角形内部的点。

(5) 重复步骤(3)、(4),继续寻找距离三角形另外两条边(不包括原始的那条线) 距离最远的点。

(6) 对每个新形成的边进行递归,直到没有点留在三角形内部,当选择出的顶点组成凸包时,递归结束。

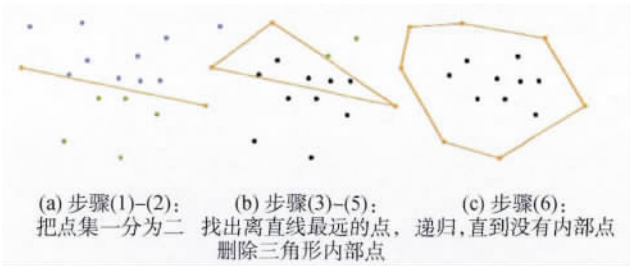

图 4 快速凸包算法示意图(Wikipedia,2012)

从枝下高处至树顶,重新对数据体元化,体元尺寸为 10 cm×10 cm×0.5 m,若体元内点个数大于 2 则该体元被覆盖。获取每层被覆盖体元位置,采用 2 维凸包的快速算法获取每层树冠外轮廓。

图 5 是树干在某一层处覆盖情况,黑色菱形框为被覆盖体元位置,红色框则是这些点组成点集的凸包顶点,即该层树冠的外轮廓顶点。

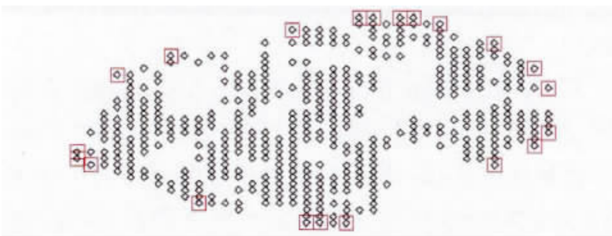

图 5 树冠外轮廓示意图

提取出每层树冠轮廓后，根据任意多边形面积计算公式计算树冠在每个水平层的投影面积

$$S = \frac{1}{2}\sum_{k=1}^{m}\left(x_k y_{k+1} - x_{k-1} y_k\right) \quad (1)$$

式中，m 是顶点个数，x_k 和 y_k 分别是第 k 个顶点的坐标，需要注意的是顶点的计算顺序是沿初始顶点逆时针选择。把所有层的树冠轮廓顶点在地面投影，重新计算这些点集围成的凸包顶点和凸包面积即树冠的冠幅。

树冠体积测量的传统方法是将树冠近似为一个规则的几何体。但现实中树冠形状一般都是不规则的。因为 TLS 能获取树木的 3 维空间点阵数据，所以利用分层思想，把树冠近似为多层棱柱体累加表示，棱柱的底即为该层树冠外轮廓围成多边形，棱柱的高是分层高度。树冠体积即这些棱柱体积累加和。

$$V = \sum_{n=1}^{k} S \times H \quad (2)$$

$$k = L/H \quad (3)$$

式中，V 是树冠体积，k 是树冠层数，H 是层高，L 是树冠长度，S 是该层树冠面积。图 6 直观显示了树冠的 3 维结构。

图 6　树冠分层示意图

4　结果与分析

4.1　胸径与枝下高估测

表 2 给出了 20 棵单木的胸径和枝下高估测结果，包括单木参数的回归方程、决定系数 R^2 和 RMSE。从总体上看，枝下高估测精度较高，实测和估测枝下高呈很好的线性关系。TLS 估测的胸径与实测的胸径与枝下高估测结果相比相关性较小。

图 7(a) 和图 7(b) 分别是枝下高与胸径回归结果。可以看出，对枝下高的估测结果优于对胸径的估测结果。

表 2　估测单木胸径和枝下高的统计回归结果

	回归方程	R^2	RMSE
枝下高估计	$y = 0.96x + 0.13$	0.97	0.21 m
胸径估计	$y = 0.9x + 1.9$	0.79	1.07 cm

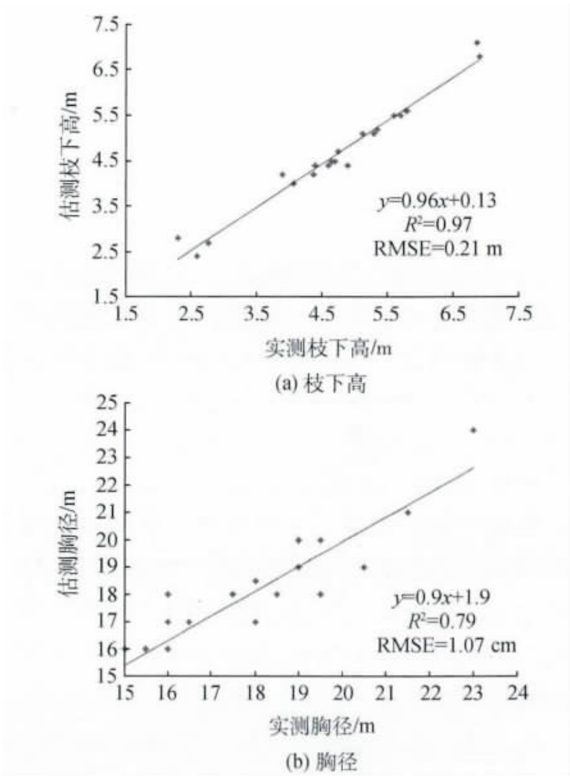

图 7　枝下高和胸径估测结果

4.2　单木树冠体积与其他单木参数回归结果

采用逐步线性回归方法建立单木树冠体积与其他单木参数的相关关系，输入变量为冠幅、实际树冠长度、叶子填充树冠长度、树高和胸径，进入模型的变量有冠幅、叶子填充树冠长度和胸径。表 3 给出了 20 棵单木的树冠体积和冠幅、叶子填充树冠长度和胸径的回归结果。

表 3　单木树冠体积统计回归结果

	回归方程	R^2	RMSE
树冠体积估计	$y = 3.56x_1 + 1.47x_2 + 1.045x_3 - 21.39$	0.96	2.64 m^3

注：x_1 为冠幅，x_2 为叶子填充树冠长度，x_3 为胸径。

4.3　分析

Hough 变换估测胸径与实测胸径相比，结果偏差较小，有个别估测值偏低。研究发现这些数据距离扫描站点较远，由于其他树木的遮挡，在树干部分激光点云分布不全。

本文方法的前提是对垂直方向上每层树干圆心位置估测准确。关键点是沿树干检测覆盖度,因而对白皮松林枝下高的估测精度较高。试验区为人工林,灌木对 Hough 圆检测的影响较小,所以假设所有检测到的圆心位置都在树干内部。结果表明,采用此方法估测的枝下高位置与实测值偏差较小,获取的树干垂直剖面与树干处实际点云分布一致,这也说明了 Hough 圆检测对树干圆心位置检测准确。对于林分结构复杂,林下灌木茂密的森林,Hough 圆检测的精度以及树干周围灌木会影响枝下高检测精度。

现实中的树冠是不规则的,所以分层获取树冠外轮廓来计算树冠体积,分层越多,计算的树冠体积越接近于真值。采用体元化方法降低需要计算的点数,把一个体元内的所有激光回波点看作一个整体,这样大大降低了凸包算法里需要计算的点数。快速凸包算法的最好时间复杂度为 $O(n\log n)$,最好情况均衡出现在每次划分中。最坏时间复杂度为 $O(n^2)$,只在极端情况下出现。树冠内部的体元位置点分布相对均匀(图5),选择快速凸包算法每次对凸包的划分都相对均衡,因此快速凸包算法适合提取树冠外轮廓。

树冠体积与其他单木参数的回归结果表明,树冠体积与树冠长度没有相关关系,而是与树叶填充树冠长度有关。白皮松下部枝叶较少,主枝结构也较为收敛,树木上部枝叶较多,树冠也蓬松,整个树冠结构类似一个下部和顶部细、中上部粗的“陀螺”形状,如图6。从叶子开始大量增加处,树冠的投影面积开始增加,整个树冠的下部分对树冠体积的贡献不大,所以本实验区内白皮松树冠体积与枝下高没有必然相关关系,而是与树叶填充树冠长度具有相关关系。树冠虽然是不规则的,但是同一树种的树冠结构相似并与其他一些树种具有可分性。利用地基激光雷达可以建立容易提取的单木参数(如胸径、枝下高、树高和冠幅)与不易测量的单木参数(如树冠体积等)的相关关系,所以地基激光雷达具有建立树木树冠3维结构模型的潜力。

5 结 论

以白皮松为研究对象,从获取的地基激光雷达数据中选择20棵单木作为实验材料。采用 Hough 变换、圆拟合方式获取单木胸径和位置。在单木位置基础上获取树干在垂直各层中的圆心位置,采用垂直向覆盖度检测方法获取枝下高位置。以枝下高位置为基础获取树冠在垂直方向上的外轮廓,并计算树冠体积。主要结论如下:

(1)利用 Hough 检测和圆拟合方法提取单木位置和胸径,与实测结果相比,估测结果精度较高,个别偏差较大的结果出现在被遮挡树干处。

(2)采用树干垂直向覆盖度检测方法获取枝下高,结果表明,该方法对实验区内白皮松人工林枝下高估测精度较高。

(3)快速凸包算法适合树冠轮廓提取。

(4)本实验区白皮松人工林树冠体积与冠幅、叶子填充树冠长度、胸径具有很好的相关关系。地基激光雷达具有建立树木树冠3维结构模型的潜力。

采用地基激光雷达对森林调查研究,最大的优势在于地基激光雷达在获取单木参数的同时,没有对树木造成任何损伤,方便进行树木的连续观测和森林的动态监测研究和树木3维结构进行建模。然而由于树木间相互遮挡影响单木参数获取精度。需要根据林分条件合理布设测站。如何获取林分结构复杂林分内单木参数并提高获取精度有待进一步研究。

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