TRANSACTIONS OF THE CHINESE SOCIETY FOR AGRICULTURAL MACHINERY
Vol. 47, No. 1, 2016

doi:10.6041/j.issn.1000-1298.2016.01.041

Measurement of Trees Crown Projection Area and Volume Based on Airborne LiDAR Data

Zhang Weizheng[1] Dong Shouyin[2] Wang Guofei[3] Qiu Zhengjun[1] Wu Xiang[1] He Yong[1]
(1. *School of Biosystems Engineering and Food Science, Zhejiang University, Hangzhou* 310058, *China*
2. *The Second Surveying and Mapping Institute of Zhejiang Province, Hangzhou* 310012, *China*
3. *Tianjin StarGIS Engineering Co., Ltd., Tianjin* 300384, *China*)

Abstract: Airborne LiDAR can obtain three-dimensional structural information of trees, get forest information by using points cloud classification and calculation method of crown projection area and volume. From the distribution of points cloud, the laser pulse formed once echo when encountered the bare ground and roof of the building, and the distribution of the generated points cloud were smooth and continuous. The laser pulse penetrated vegetation would appear multiple echoes, the distribution rules of the points would be destroyed, and the distribution were in an irregular shape such as cluster-like. First, the points cloud of ground were extracted by triangulated irregular network, then the points cloud of building were extracted by using planar-fitting filtering algorithm. Filter points cloud of building to get points cloud of forest, and the points cloud of forest were projected onto $x-y$ plane. The edges of points cloud of timber were extracted by using the angle method; its corresponding image was display; the area of polygon were calculated by using area algorithm; then the calculation of the projection area of crown was achieved, combine the formula to calculate crown volume. In the study area, 10 experimental districts were randomly selected to carry out the traditional manual measurement. The experimental results showed that the projection area and volume's correlation coefficient of the two measurement methods were 0.957 and 0.944, respectively. The proposed method was feasible to achieve the accurate extraction of forest information that extracts a wide range of tree crown projection area and crown volume rapidly and efficiently.

Key words: trees; airborne LiDAR; projection area; volume; triangulated irregular network; planar-fitting filtering algorithm

0 Introduction

With the deepening understanding of vegetation structure, vegetation function and ecological benefits, the acquisition and monitoring technology of projection area and the volume of forest canopy information get more and more attention by government departments and relevant industry[1]. These studies can detect the distribution of trees grow, study the distribution of trees to help municipal administration departments get access to accurate information timely, provide the basis for biomass calculations of trees and other vegetation, growth monitoring and management[2-4].

Traditional optical remote sensing technology was limited by vertical resolution, could only get a two-dimensional color information of trees, and the trees information could not be extract effectively[5-6]. Airborne light detection and ranging (LiDAR) technology was characterized by initiative, unrestricted from light and shadow and had a certain penetration through ground objects, its detection capabilities of spatial structure of vegetation and topography were strong, which could get the structural information of trees and had a significant innovation in remote sensing of forestry compared to other remote sensing data[7-12].

This paper uses the algorithm of points cloud classification and border search, calculation method of area and volume to achieve the extraction of projection area and volume of forest canopy based on the airborne LiDAR data, provides accurate data to support the research and monitoring of the forest region.

Received date: 2015-07-12 Accepted date: 2015-08-20
Supported by National Hi-tech Research and Development Program of China (863 Program) (Grant No. 2012AA101903)

Corresponding author: Qiu Zhengjun, Professor. E-mail: zjqiu@zju.edu.cn. Tel: +86-13082815578.

1 Research area and experiment system

The research area is located north of Jixian County in Tianjin City, while connecting the cities of Beijing, Tianjin, Tangshan and Chengde, the location is 117.40°E, and latitude is 40.05°N.

This research took Y－12 transport aircraft as flight platform according to LiDAR systems and regional characteristics, in order to ensure good flight results. As shown in Fig. 1a, this type of aircraft had oxygen systems, flight recorders and proximity warning devices, while suitable for a variety of environments and mountain plateau, etc., average ground speed of routes could be maintained at 230 km/h, the flight was stable and safe. In September 2013, the flight was starting when the weather was sunny, using ALTM－NAV flight control software was used to design route according to range, terrain elevation and slope of the experimental area. The flight altitude was about 800 m.


(a) Y－12 transport aircraft (b) ALTM Gemini LiDAR

Fig. 1 Acquisition system of LiDAR data

The ALTM Gemini system used in experiment including laser scanner, a direct geopositioning system and digital camera, as shown in Fig. 1b. The system used automatic multi-continuous pulse technology, it utilized the powerful capabilities of processing software HASHMap for the fast output of three-dimensional coordinate data. Parameters of the system were shown in Tab. 1.

Tab. 1 ALTM Gemini system parameters

Parameters	Value
Laser wavelength/nm	1 064
Elevation accuracy/m	0.1
Horizontal accuracy/m	1/5 500 × relative flying height
Maximum pulse frequency/kHz	166
Single pulse-echo times	4
Double-beam scattering angle/mrad	0.25,0.8
Scan angle/(°)	0 ～ 50
Strength/bit	12
Camera resolution/(pixels × pixels)	7 228 × 5 428
Pixel size/μm	6.8

2 Research methods

2.1 Extraction of ground, buildings and trees points cloud

To analyze the three-dimensional information of trees, firstly, the points cloud of trees should be extracted from the points cloud collected by airborne LiDAR. Steps were as follows: separate the ground points, extracte regular points cloud rules, analyze and calculate of the point cloud of forest.

2.1.1 Extraction of ground points cloud

(1) According to the given size set square grid, the lowest point in elevation was extracted from each grid as the ground seeds, and was added to the triangulated irregular network (TIN) for establishing the initial ground model. The grid should be greater than the maximum reference (trees or buildings) of point cloud data typically.

(2) Traverse TIN, calculate the distance d which was contained in each triangle triangulation to its plane. If d was smaller than the set threshold, then set this point as ground point, and add it to the ground point group. Repeat this step until the points satisfied the conditions were added to the triangle network, completed iteration[13].

Achieved extraction of ground points by the above steps, and filtered the ground points, the remaining were buildings points and trees points and other non-ground points, as shown in Fig. 2.

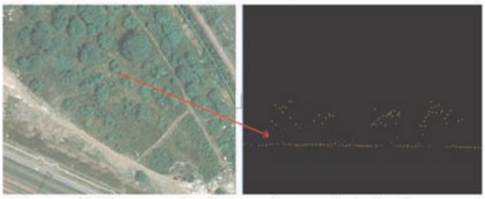
Fig. 2 Non-ground points after filtration ground points

2.1.2 Extraction of building points cloud

After filtering the ground points, the planar-fitting filtering algorithm was used to obtain the building points based on the characteristics of buildings and trees points cloud.

(1) Distribution of building and forest points cloud

From the distribution of points cloud in space, laser pulses encountered bare floor and roof of the building formed once echo, the distribution rule of generated points cloud were smooth and continuous[14]. While the laser pulses penetrated vegetation will appear multiple echoes, the generated points cloud were clustered, and the distribution were in irregular shape. The cross-sectional view of trees and buildings points cloud were shown as Fig. 3.



(a) Corss–sectional view of tress points cloud

(b) Corss–sectional view of tress and buildings points cloud

Fig. 3 Cross-sectional view of buildings and trees

(2) The planar-fitting filtering algorithm

In recent years, airborne LiDAR data were mostly filtered based on elevation mutations, commonly used morphological filtering, elevation texture analysis and topographic gradient filtering[15-16]. In this paper, planar-fitting filtering algorithm was used, which needed to set multiple parameters to fit the approximate plane, as schematically illustrated in Fig. 4.

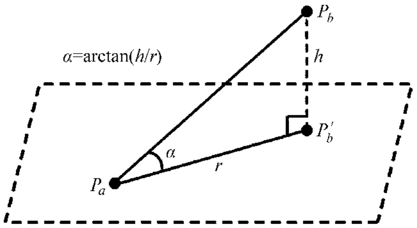


Fig. 4 Parameters illustration of planar-fitting filtering algorithm

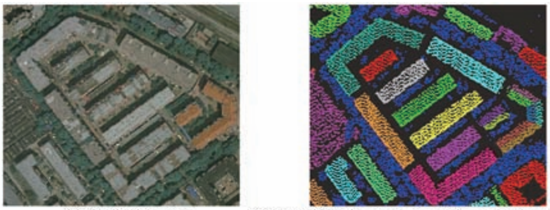
P_b' was the projection point of P_b to the P_a plane, r was the distance between P_b' and P_a, h was the height from P_b to P_a, α was the inclination from P_b to P_a plane. Set P_a as starting point, calculated the adjacent point P_b whether contained in fitting plane of P_a, the conditions to be met:

$$\begin{cases} r < r_t \\ |h| < h_t \\ \alpha < \alpha_t \end{cases} \tag{1}$$

Where r_t is distance; h_t is height difference; α_t is dip threshold.

P_a was the center for plane fitting. Calculate the r, h and α between P_a and its neighboring points. Classify as P_a fitting plane if conforming to the requirements of Eq. (1). Then set neighboring point of P_a as the center fitting the plane, fitted all the points met requirements to the fitting plane.

If the number of points meets the conditions was greater than the preset threshold parameter m, then it was classified to the other type of plane. The plane fitting results were shown in Fig. 5. As could be seen from the figure, the points cloud of building achieved a perfect fit, and the remaining points cloud of forest had been classified as non-planar.



(a) Optical image (b) Classification and extraction of points cloud

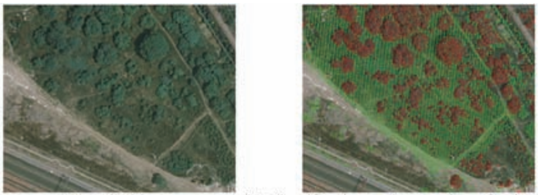
Fig. 5 Extraction of buildings points cloud

2.1.3 Extraction of forest points cloud

Filtering points cloud of buildings as shown in Fig. 5, the remaining part of the points cloud of forest were shown as Fig. 6.

Fig. 6 Points cloud of trees

The planar-fitting filtering algorithm was used for classification of points cloud of suburb forest, since there was no influence of the building, using this algorithm classified all forest points cloud as non-planar points, achieved the extraction of forest points cloud, as shown in Fig. 7.



(a) Optical image (b) Classification and extraction of points cloud

Fig. 7 Points cloud classification of suburb

Setting the parameters for each step was an important factor in achieving good classification results, according to the characteristic of classification data to set parameters.

2.2 Forest canopy projection area and volume calculations

After extraction of the points cloud of forest, according to the characteristics that trees in urban and rural were cross-distribution, each communication area as was set as an units, the crown projection area was calculated by using boundary search and polygon area calculation algorithm, and crown volume was calculated by using accumulating stratification method.

2.2.1 Projection area calculations

The canopy projection area of forest points cloud were constituted by the maximum cross-sectional data set, the specific steps: computing the projection of $x-y$ plane by forest points cloud; calculating the crown projection area by boundary search and polygon area calculation algorithm, and taking its result as the projected area of the forest canopy.

2.2.1.1 Boundary search method

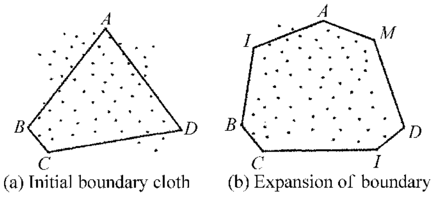
The boundaries of discrete target group were searched by using angle method based on vector data[17]. The laser points cloud were in uneven distribution, however, the average distance d' between the adjacent points met the certain requirements, and the length of the boundary line was related to average distance. Let $d'_{\max}$ was the maximum value of the boundary line, it must met

$$d'_{\max} = qd' \tag{2}$$

Where q is a coefficient, the higher value of q indicated a longer boundary line, the rougher of the border, and q was usually set between 4 ~ 10.

The coordinate of trees points cloud, which was projected onto the xy-plane, was (x_i, y_i), i was 1 ~ n. Boundary generation steps were as follows:

(1) Set the initial boundary. Find the extreme value of coordinates of the points set, get points A, B, C, D to constitute a convex polygon, as the initial boundary of points set, as shown in Fig. 8a, and save the initial boundary points list in counterclockwise order.



(a) Initial boundary cloth (b) Expansion of boundary

Fig. 8 Boundary generation process

(2) Extension of the boundary. Taking order along the edge (AB side) in list, search for a point I in its left, try to make sure the angle between the point and edge AB was the minimum, as shown in Fig. 8b. If point I is found, add it to the list, and use AI, IB to replace AB. Traverse each edge, search boundary point I, J and M that met the conditions, then connect them to the original polygons. Repeat this step, the border continued to expand, after the completion of traversing, the boundary had been extended to the convex hull.

(3) Calculate the maximum length of the boundary line. Calculate the area S of convex hull polygon according to convex hull point set, and compute the density of points set, i.e.

$$\rho = n/S \tag{3}$$

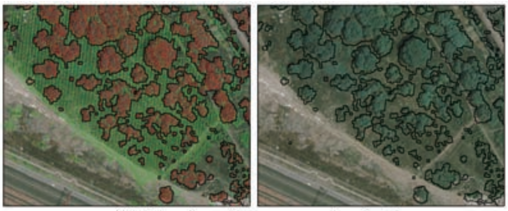
Where n is the number of points surrounded by convex hull.

The average distance between adjacent points was calculated as follows

$$d' = \frac{1}{\sqrt{\rho}} \tag{4}$$

and then calculate $d'_{\max}$ based on the Eq. (2).

(4) Contraction of the boundary. Traverse the list, if the length of edge was longer than $d'_{\max}$, find the largest angle between the edge and point J in its right, add the point J to the list, and realize that two edges could replace one edge. Traverse one loop, find the qualified border point, and establish a new polygon. Repeat this step, the boundary continued contraction inwardly. The results were shown in Fig. 9, and display the contour of forest points cloud on CCD image, and achieve the extraction of forest canopy.


(a) Extraction of trees canopy in suburbs

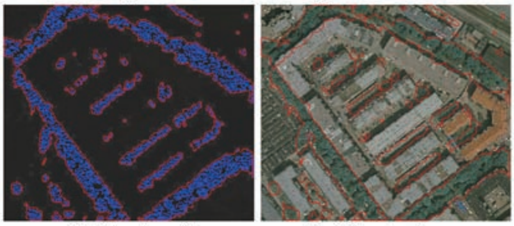

(b) Extraction of trees canopy and buildings in urban

Fig. 9 Extraction of trees canopy

2.1.1.2 Polygon area calculation method

The boundary points of each connected region were successively connected into line, then constitute a plurality of polygons, take a polygon with n vertices for example, select a point as the start point optionally, as shown in Fig. 10.

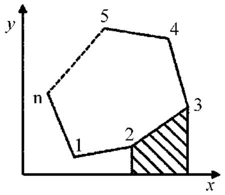


Fig. 10 Area calculation for polygon

The polygon area constituted by n points[21]:

$$S = \left| \sum_{i=1}^{n} \frac{1}{2}(x_{i+1} - x_i)(y_{i+1} - y_i) \right| \qquad (5)$$

Where $x_{n+1} = x_1$, $y_{n+1} = y_1$.

The sum of polygon area of each connected region was calculated, that was the projection area of the forest canopy.

2.2.2 Canopy volume calculation model

In this paper, volume was calculated based on the actual distribution and edge extraction of forest canopy, the algorithm was as follows: extracting points cloud of forest canopy according to the different characteristics of urban and suburban regions. Stratified crown points cloud into slice from the bottom at regular intervals, calculated polygon area by border search and polygon area calculation method, calculated the area of each piece slice, set the adjacent sections as a table body approximately, used the calculation formula of volume table to get the crown volume, i. e.

$$V = \sum_{m=1}^{p-1} (S_m + \sqrt{S_m S_{m+1}} + S_{m+1}) z/3 \qquad (6)$$

Where S_m, S_{m+1} are m, $m+1$ layer slice area, m^2; z is adjacent sections space, m; V is crown volume, m^3; p is slice layers.

The sum volume of each connected region was the volume of the trees canopy.

3 Result analysis

3.1 Extraction accuracy of forest points cloud

The extraction of trees were shown as Fig. 9a, the red points cloud were trees, the extraction of forest information had been completed with closed curve. Fig. 9a showed the edge information on CCD image, it could been seen that the edges were not perfectly match the image of trees, because the CCD images were corrected, but were not orthophotos, the images had a certain inclination, while the data of LiDAR points cloud were accurate rendering forest location. Fig. 9b also has the same problem, since the complex and diverse of urban feature, combined with the optical image could be seen parts of points were misclassificated, the surface shape of points cloud which was complex was misclassifying forest.

While minimizing the workload, in order to ensure the accuracy of verification, selected 500 points on the image randomly to artificial determine whether trees, and compared with the classification results.

The classification error contained leak points and multisection points error, as shown in Tab. 2, the classification of forest points cloud was better, the leakage points and multisection error were within 3.4%; while the leakage and multisection error of ground points were within 9%, the classification effect was relatively poor.

Tab. 2 Error of classification results

	Select points	Leakage points	Leakage error/ %	Multisection points	Multisection error/%	Total error/ %
Trees points	323	11	3.4	8	2.5	5.9
Ground points	177	13	7.3	16	9.0	16.3

The points cloud of forest had a certain height and in clustered distribution, with respect to the ground points cloud which had significantly different, and easier to distinguish, so the extraction forest points cloud were better.

3.2 Canopy projection area and volume compared with manual measurements

Compared the laser measurement method based on LiDAR points cloud with traditional manual measurement methods. Ten experimental districts were randomly selected to carry out the traditional manual measurement, the points cloud of forest were projected onto $x-y$ plane, then the border search and polygon area formula were used to calculate the crown projection area. While artificial measuring of the projection area of the canopy in the ground, the projection of an individual tree crown were seen as an ellipse, the length of the major axis and the minor axis were the lengths of crown's two vertical direction, in order to calculate the projection area of a single tree, and then sum of each individual tree within the region was calculated to get the projection area of the forest canopy. The area A_1 was LiDAR laser measurement result, and area A_2 was manual measuring result, as shown in Fig. 11.

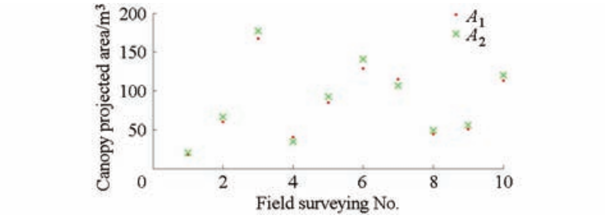


Fig. 11 Canopy projection area by laser and manual measurement

Using the proposed method to achieve the canopy volume measurement based on 3D laser points cloud; and getting the canopy height and crown width by artificial measurement, selecting volume formula as shown in Tab. 3 according to tree species canopy to estimate the volume.

Tab. 3 Formulas for calculating volumes of different crown geometries

No.	Canopy shape	Volume formula
1	Cylinder	$\frac{\pi x^2 y}{4}$
2	Conic	$\frac{\pi x^2 y}{12}$
3	Spherical	$\frac{\pi(3xy^2-2y^3)}{6}$
4	Hemispherical	$\frac{\pi(3xy^2-2y^3)}{12}$
5	Ball fan	$\frac{\pi(3y^3-y^2\sqrt{4y^2-x^2})}{3}$
6	Ovate	$\frac{\pi x^2 y}{6}$

The volume V_1 of LiDAR laser measurement and volume V_2 of manual measurement were shown in Fig. 12.

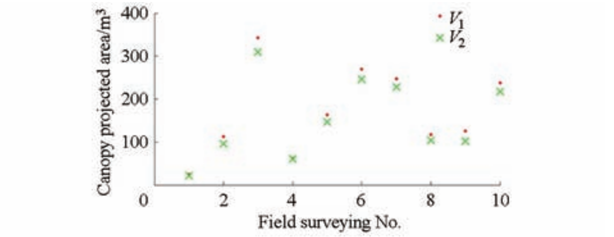


Fig. 12 Canopy volume by laser and manual measurement

The average measurement error of canopy projection area of laser and manual measurement were within 6%, and the correlation coefficient was 0.957; the average error of canopy volume by laser measurement and manual measurement were less than 8%, the correlation coefficient was 0.944, reached the practical requirements.

3.3 Effect of season on forest growth

Forest canopy shape and foliage volume in different seasons affected the acquisition of airborne LiDAR data directly, which presented challenge to the adaptability of this method. In this paper, the experimental data collected in the vigorous growth period of vegetation, if in the winter or when tree species had rare leaves, would require a lot of practical work to verify the proposed method. Furthermore, the growth status of trees may affect the results, which also needs to explore in the subsequent study.

4 Conclusions

In order to achieve rapid and efficient extraction of the projection area and volume of a wide range of forest area, this paper got the three-dimensional structural information of trees by airborne LiDAR, used points cloud classification algorithms to filter the ground and buildings points cloud, achieved the extraction of forest points cloud in urban. The angle method was used to search boundary, and then it was displayed on the corresponding CCD images. Canopy projection area and volume of each connected region was calculated with polygon area formula and volume calculation algorithm. Ten experimental districts were randomly selected to carry out the traditional manual measurement, compared the proposed LiDAR measurement method and manual measurement method, the average leakage and multisection error were both within 8%. High-quality data sources were provided for the precision quantitative of vegetation canopy and estimation of biomass. The proposed method has high precision and large measuring range, which has broad application prospects in the forestry, and will contribute to relevant government departments for efficient scientific management and rational decision-making.

References

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

[2] Chen Zhiyuan. Application of remote sensing in the survey of forest resources [J]. Inner Mongolia Forestry Investigation and Design, 2010 (3): 59-61.

[3] Næsset E. Practical large-scale forest stand inventory

using a small-footprint airborne scanning laser [J]. Scandinavian Journal of Forest Research, 2004, 19(2): 164-179.

[4] Andersen H E, McGaughey R J, Reutebuch S E. Estimating forest canopy fuel parameters using LIDAR data[J]. Remote Sensing of Environment, 2005, 94(4): 441-449.

[5] Xu Xinliang, Zhuang Dafang, Zhang Shuwen, et al. Using RS and GIS technology to investigate urban green land cover[J]. Remote Sensing for Land and Resources, 2001(2): 28-32.

[6] Barr S, Barnsley M. Reducing structural clutter in land cover classifications of high spatial resolution remotely sensed images for urban land use mapping [J]. Computers and Geosciences, 2000, 26(4): 433-449.

[7] Pang Yong, Li Zengyuan, Chen Erxue, et al. LiDAR technology and its application in forestry [J]. Scientia Silvae Sinicae, 2005, 41(3): 129-136.

[8] Liu Qingwang, Li Zengyuan, Chen Erxue, et al. Extracting height and crown of individual tree using airborne LiDAR data[J]. Journal of Beijing Forestry University, 2008, 30(6): 83-89.

[9] Liu Feng, Gong Jianya. Individual trees recognition in dense forest based on airborne LiDAR[J]. Transactions of the Chinese Society for Agricultural Machinery, 2011, 42(7): 200-203, 209.

[10] Liu Feng, Tan Chang, Zhang Gui, et al. Estimation of forest parameter and biomass for individual pine trees using airborne LiDAR[J]. Transactions of the Chinese Society for Agricultural Machinery, 2013, 44(9): 219-224, 242.

[11] Xu Weiheng, Feng Zhongke, Su Zhifang, et al. An automatic extraction algorithm for individual tree crown projection area and volume based on 3D point cloud data [J]. Spectroscopy and Spectral Analysis, 2014, 34(2): 465-471.

[12] Shendryk I, Hellström M, Klemedtsson L, et al. Low-density LiDAR and optical imagery for biomass estimation over boreal forest in sweden[J]. Forests, 2014, 5(5): 992-1010.

[13] Guan Haiyan, Deng Fei, Zhang Jianqing, et al. Object based fusion and classification of airborne laser scanning data and aerial images[J]. Geomatics and Information Science of Wuhan University, 2009, 34(7): 830-833.

[14] Zeng Qihong, Xue Feng. LiDAR point cloud processing and 3D building reconstruction [D]. Shanghai: Shanghai University, 2009.

[15] Wu Jiguang. A method for detecting objects by fusing LiDAR data and images[J]. Journal of Capital Normal University, 2009, 30(4): 6-11.

[16] Zeng Qihong, Mao Jianhua, Li Xianhua, et al. Planar-fitting filtering algorithm for LiDAR points cloud[J]. Geomatics and Information Science of Wuhan University, 2008, 33(1): 25-28.

[17] Wang Yanliang, Liu Dengjie. Search discrete boundary of the target group [J]. Science of Surveying and Mapping, 2007, 32(5): 101-102.

[18] Qiu Zhengjun, Ying Xiafang, He Yong. A portable instrument for measuring field area based on GPS module [J]. Journal of Zhejiang University (Agriculture & Life Sciences), 2005, 31(3): 333-336.

[19] Fan Zhongmou, Feng Zhongke, Zheng Jun, et al. Tree crown volume calculation and prediction model establishment using cubic lattice method [J]. Transactions of the Chinese Society for Agricultural Machinery, 2015, 46(3): 320-327.

[20] Zhang Ning, Zhang Xiaoli, Ye Li. Tree crown extraction based on segmentation of high-resolution remote sensing image improved peak-climbing algorithm [J]. Transactions of the Chinese Society for Agricultural Machinery, 2014, 45(12): 294-300.

[21] Wei Xuehua, Wang Yongguo, Zheng Jun, et al. Tree crown volume calculation based on 3-D laser scanning point clouds data [J]. Transactions of the Chinese Society for Agricultural Machinery, 2013, 44(7): 235-240.

doi:10.6041/j.issn.1000-1298.2016.01.041

基于机载 LiDAR 数据的林木冠层投影面积与体积测量

张卫正[1] 董寿银[2] 王国飞[3] 裘正军[1] 吴翔[1] 何勇[1]

(1.浙江大学生物系统工程与食品科学学院，杭州 310058；2.浙江省第二测绘院航测与遥感三分院，杭州 310012；
3.星际空间(天津)科技发展有限公司，天津 300384)

摘要： 机载激光雷达系统能够采集反映林木三维结构的点云，利用点云分类及林木冠层投影面积和体积计算方法获得林木信息。通过不规则三角网法和平面拟合过滤算法分别提取地面和建筑物点云，并将建筑物点云过滤得到林木点云，将树冠点云投影到 $x-y$ 平面，采用角度法搜索边界，提取林木点云边缘，并在与其相对应的 CCD 影像上显示。利用任意多边形面积算法计算各个连通区域的面积，将它们求和得到冠层投影面积，通过台体的体积计算得到冠层体积。在研究区域随机选出 10 个外业样地进行传统的人工测量，实验结果表明，基于 LiDAR 的激光测量与人工测量测得的投影面积和体积的相关系数分别为 0.957 和 0.944。本文提出的方法准确有效，为高精度定量估算林木冠层生物量提供了依据。

关键词： 林木；机载 LiDAR；投影面积；体积；不规则三角网；平面拟合过滤算法

中图分类号： TN959.4；S758.4 **文献标识码：** A **文章编号：** 1000-1298(2016)01-0304-06

Measurement of Trees Crown Projection Area and Volume Based on Airborne LiDAR Data

Zhang Weizheng[1] Dong Shouyin[2] Wang Guofei[3] Qiu Zhengjun[1] Wu Xiang[1] He Yong[1]

(1. *School of Biosystems Engineering and Food Science*, *Zhejiang University*, *Hangzhou* 310058, *China*
2. *The Second Surveying and Mapping Institute of Zhejiang Province*, *Hangzhou* 310012, *China*
3. *Tianjin StarGIS Engineering Co., Ltd.*, *Tianjin* 300384, *China*)

Abstract: Airborne LiDAR can obtain three-dimensional structural information of trees and get forest information by using points cloud classification and calculation method of crown projection area and volume. From the distribution of points cloud, the laser pulse formed an once echo when encountered the bare ground and roof of the building, and the distribution of the generated points cloud were smooth and continuous. The laser pulse penetrated vegetation would appear multiple echoes, the distribution rules of the points would be destroyed, and the distribution was in an irregular shape such as cluster-like. First, the points cloud of ground were extracted by using triangulated irregular network, then the points cloud of building were extracted by using planar-fitting filtering algorithm. The points cloud of building were filtered to get points cloud of forest, and then the points cloud of forest were projected onto $x-y$ plane. The edges of points cloud of timber were extracted by using the angle method; its corresponding image was displayed; the area of polygon was calculated by using area algorithm; then the calculation of the projection area of crown was achieved. In the study area, 10 experimental districts were randomly selected to carry out the traditional manual measurement. The experimental results showed that the projection area and volume's correlation coefficient of the two measurement methods were 0.957 and 0.944, respectively. The proposed method was feasible to achieve the accurate extraction of forest information rapidly and efficiently which includes a wide range of tree crown projection area and crown volume.

Key words: trees; airborne LiDAR; projection area; volume; triangulated irregular network; planar-fitting filtering algorithm

---

收稿日期：2015-07-12 修回日期：2015-08-20

基金项目： 国家高技术研究发展计划(863 计划)项目(2012AA101903)

作者简介： 张卫正(1982—)，男，博士生，主要从事生物生长信息采集处理技术研究，E-mail：weizheng008@126.com

通信作者： 裘正军(1971—)，男，教授，博士生导师，主要从事农业信息化相关技术研究，E-mail：zjqiu@zju.edu.cn

引言

随着对植被结构、功能及生态效益认识的不断深入，林木冠层投影面积及体积等信息的获取与监测技术越来越受到国内外政府部门及相关行业的重视[1]。通过这些研究可以检测树木的生长分布情况，研究林木的分布规律，有助于市政管理部门及时、准确地掌握信息，为林木等植被的生物量计算、生长监测与管理提供依据[2-4]。

传统的光学遥感技术受到垂直分辨率的限制，只能获取林木的二维色彩信息，不能有效地提取林木信息[5-6]。机载激光雷达（Light detection and ranging，LiDAR）具有主动性、免受光照及阴影限制和一定的地物间隙穿透性等优点，对植被空间结构和地形的探测能力强，可以获取林木的三维结构信息，在林业遥感研究方面具有重大创新，相比其他遥感数据具有极大优势[7-12]。

本文在机载 LiDAR 数据基础上，利用点云分类及边界搜索、面积和体积计算方法实现林木冠层投影面积和体积的提取，以提供准确数据支撑区域的林木研究和监测。

1　研究区域及实验系统

研究区域位于天津市北部的蓟县，同时连接北京市、天津市、承德市和唐山市，地理位置是 117.40°E，40.05°N。

根据 LiDAR 系统和研究区域特点，飞行平台采用运 12 飞机，以保证良好的飞行效果。如图 1a 所示，该机型设有供氧系统、飞行记录仪和近地告警设备，同时适于高原和山地等各种环境，航线中平均地速可保持在 230 km/h，飞行稳定且安全性高。2013 年 9 月，选择天气晴朗少云的时间飞行，依据实验地区范围、地形高度和坡度等，采用 ALTM-NAV 飞行控制软件设计航线，飞行高度在 800 m 左右。


(a) 运12飞机　(b) ALTM Gemini激光雷达系统

图 1　LiDAR 数据采集系统

Fig. 1　Acquisition system of LiDAR data

实验采用包括激光扫描仪、直接地理定位系统和数码相机等的 ALTM Gemini 系统，如图 1b 所示。该系统采用全自动连续多脉冲技术，利用功能强大的激光雷达处理软件 DASHMap 快速输出三维坐标数据。系统的参数如表 1 所示。

表 1　ALTM Gemini 系统参数

Tab. 1　ALTM Gemini system parameters

参数	数值
激光波长/nm	1 064
高程精度/m	0. 1
水平精度	1/5 500 乘以相对航高
最高脉冲频率/kHz	166
单脉冲回波次数	4
双光束散射角/mrad	0. 25、0. 8
扫描角/(°)	0 ~ 50
强度/bit	12
相机分辨率/(像素 × 像素)	7 228 × 5 428
像素大小/μm	6. 8

2　研究方法

2. 1　地面、建筑物及林木点云提取

要对林木的三维信息进行分析，首先需要从机载 LiDAR 所采集的复杂地物点云中提取林木点云。步骤为：分离地面点，提取规则点云，林木点云的分析计算。

2. 1. 1　地面点的点云提取

（1）依据给定尺寸设定正方形网格，从每个网格中提取高程最低的点作为地面种子点，添加到不规则三角网（TIN），建立初始地面模型。通常网格应大于点云数据中最大参照物（林木或建筑物）。

（2）遍历 TIN，计算包含在三角网的各个三角形中的点与其平面的距离 d，若 d 小于设定的阈值则规定该点为地面点，加入到地面点集合。重复此步骤，直到满足条件的地面点都加入到三角网中，完成迭代[13]。

通过以上步骤实现地面点的点云提取，并将之过滤，剩余建筑物和树木等非地面点，如图 2 所示。

图 2　过滤地面点后的地面点点云

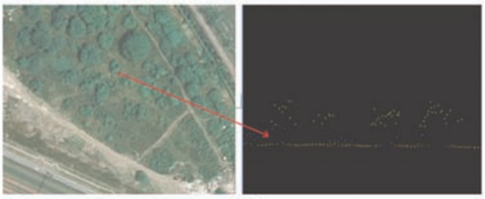
Fig. 2　Non-ground points after filtration ground points

2. 1. 2　建筑物的点云提取

过滤地面点后，通过分析建筑物和林木点云的特点，采用平面拟合过滤算法获得建筑物点云。

（1）建筑物及林木点云分布特征

从点云的空间分布规律来看，激光脉冲遇到光秃地面和建筑物屋顶形成一次回波，产生的点云分布规则，平滑连续[14]。脉冲穿透植被会出现多次回波，呈簇状等不规则形状分布。图 3 为林木和建筑



(a) 树木

(b) 建筑物及树木

图 3　建筑物和林木点云的剖面图

Fig. 3　Sectional view of buildings and trees

物点云的剖面图。

（2）平面拟合过滤算法

近年来，机载 LiDAR 数据多以高程突变为基础作滤波，常用的有形态学滤波法、高程纹理分析法和基于地形坡度滤波等[15-16]。本文利用平面拟合过滤算法，需要设置多个参数来拟合该近似平面，参数示意如图 4 所示。

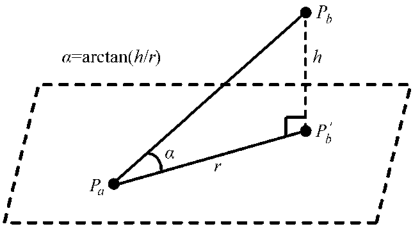


图 4　平面拟合过滤算法的参数示意图

Fig. 4　Parameters illustration of planar-fitting filtering algorithm

P_b'为 P_b到 P_a所在平面的投影点，r 为 P_b'与 P_a的距离，h 为 P_b与 P_a的距离高度，α 为点 P_b相对点 P_a所在平面的倾角。以 P_a点为中心起点，计算相邻点 P_b包含于 P_a的拟合平面，需满足条件

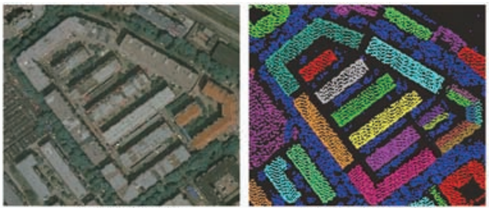
$$\begin{cases} r < r_t \\ |h| < h_t \\ \alpha < \alpha_t \end{cases} \tag{1}$$

式中　r_t——距离　　h_t——高度差

α_t——倾角阈值

平面拟合是以 P_a为中心点，计算该点与所有邻近点的 r、h 及 α，符合式（1）要求的，归入以点 P_a为中心点的拟合平面。再按顺序以 P_a的邻近点为中心拟合该平面，将满足要求的点全都包含到拟合平面内。

本算法中满足条件的邻近点数量大于预设的阈值参数 m，则归入某平面类。平面拟合结果如图 5 所示。从图中可看出建筑物点云已实现较好的拟合，剩下的林木点云已被归类为非平面。



(a) 光学影像　　(b) 点云分类提取

图 5　建筑物点云信息提取效果

Fig. 5　Extracted buildings points cloud

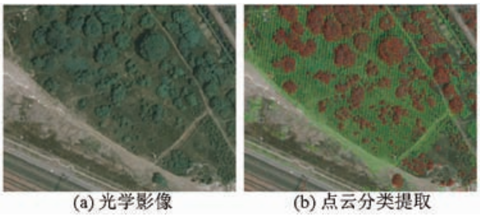
2.1.3　林木的点云提取

将图 5 中的建筑物点云过滤，所剩部分主要为林木点云，如图 6 所示。

图 6　林木点云

Fig. 6　Points cloud of trees

采用平面拟合过滤算法进行郊区林木点云分类时，因为没有建筑物的影响，采用该算法将林木全部归类为非平面点，同样实现了林木点云的提取，效果如图 7 所示。



(a) 光学影像　　(b) 点云分类提取

图 7　郊区林木点云分类

Fig. 7　Points cloud classification of suburb

各个步骤中参数的设定是实现良好分类效果的重要因素，依据分类数据的特征设定参数。

2.2　林木冠层投影面积及体积计算

完成林木点云的提取后，根据城区及郊区林木常有距离相近而产生交叉或粘连的生长分布特点，以连通区域为单位，通过边界搜索和任意多边形面积算法计算冠层投影面积，通过分割累加法计算冠层体积。

2.2.1　林木冠层投影面积的计算

林木冠层投影面积用最大横截面点云数据点集构成，具体步骤为：计算林木点云在 $x-y$ 平面投影；利用边界搜索和任意多边形面积算法计算投影面积，以此作为林木冠层的投影面积。

2.2.1.1　边界搜索方法

采用基于矢量数据的角度法搜索离散目标群的

边界[17]。激光点云分布不均，但相邻点间的平均距离 d' 满足一定的要求，边界线段的长度与平均距离有关。设 $d'_{\max}$ 是边界线段的最大值，满足

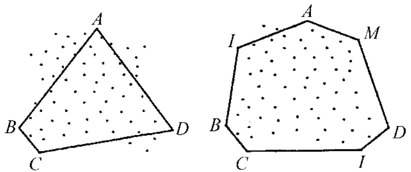
$$d'_{\max}=qd' \tag{2}$$

式中　q——系数

q 越大表明边界线段越长，边界越粗糙，通常为 4～10。

树木点云投影到 $x-y$ 平面的坐标为 (x_i,y_i)，i 为 1～n。边界生成步骤如下：

（1）设定初始边界。查找点集的坐标极值（点 A、B、C、D）并构成凸多边形，作为点集的初始边界，如图8a所示，保存为按逆时针方向排列的初始边界点链表。



(a) 初始边界　(b) 膨胀边界

图8　边界生成过程

Fig. 8　Boundary generation process

（2）边界扩展。按顺序沿链表的边（如 AB 边），在其左边搜索一个点 I，使该点与 AB 边的夹角最小，如图8b所示。若搜索到 I 点就把它加到链表中，实现 AI、IB 取代 AB。遍历各条边，搜索到符合条件的边界点 I、J 和 M，把它们连接到原有的多边形。重复该步骤，边界不断向四周扩展，完成遍历后，边界已经扩展为凸壳。

（3）计算最大长度的边界线段。根据点集的凸壳计算该凸壳多边形的面积 S，并计算点集的密度，即

$$\rho=n/S \tag{3}$$

式中　n——凸壳所包围的点的数量

计算相邻点的平均距离为

$$d'=\frac{1}{\sqrt{\rho}} \tag{4}$$

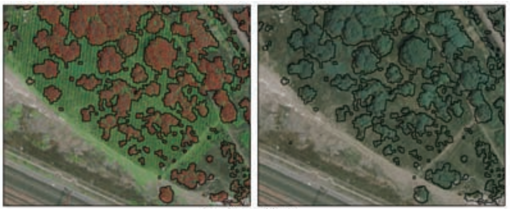
再依据式（2）计算 $d'_{\max}$。

（4）边界收缩。遍历链表，若边长大于 $d'_{\max}$，就在它的右边找到与该边夹角最大的点 J，把点 J 加到链表中，实现2条边替换1条边。遍历1周，发现符合条件的边界点，建立新的多边形。重复该步骤，边界不断向内收缩。效果如图9所示，并将林木区域点云的轮廓显示在CCD影像上，实现林木冠层提取。

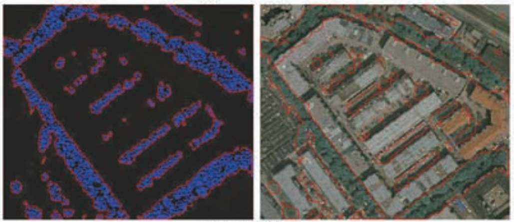
2.2.1.2　任意多边形面积方法

将各个连通区域的边界点分别依次连接成线，则构成多个多边形，以其中有 n 个顶点的多边形为例，任选一点作为起始点，如图10所示。

则由 n 点构成的多边形的面积[18]为



(a) 郊区林木



(b) 城区林木

图9　林木冠层信息提取

Fig. 9　Extraction of canopy trees information

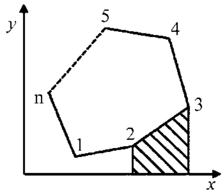


图10　多边形面积计算

Fig. 10　Area calculation for polygon

$$S=\left|\sum_{i=1}^{n}\frac{1}{2}(x_{i+1}-x_i)(y_{i+1}-y_i)\right| \tag{5}$$

其中　$x_{n+1}=x_1$　$y_{n+1}=y_1$

各连通区域的多边形面积之和即为林木冠层的投影面积。

2.2.2　冠层体积计算模型

本文结合林木的实际分布及边缘提取情况采用台体公式法计算冠层体积，具体算法如下：根据城区和郊区等不同区域林木点云特征确立林木冠层点云。从下向上等间隔的将冠层点云切片，通过边界搜索及任意多边形面积方法，计算每幅切片的面积，将相邻切片间近似地作为台体，采用台体体积累加公式计算冠层的体积，即

$$V=\sum_{m=1}^{p-1}\left(S_m+\sqrt{S_mS_{m+1}}+S_{m+1}\right)z/3 \tag{6}$$

式中　S_m、S_{m+1}——第 m、$m+1$ 层切片面积，m^2

z——相邻切片间隔，m

V——冠层体积，m^3

p——切片层数[11]

各连通区域的体积之和即为林木冠层的体积。

3　结果分析

3.1　林木点云及冠层提取精度分析

图9a为林木信息的提取，红色点云为林木，已经采用闭合曲线完成林木信息提取，图9a是检测的边缘信息在CCD影像上进行叠加，可以看到一部分

闭合边缘与影像上林木的边缘不是特别吻合，是因为 CCD 影像虽经过校正，但并不是真正射影像，图像会有一定角度的倾斜，而 LiDAR 点云数据是准确表现林木位置的。图 9b 也存在同样的问题，由于城区地物复杂多样，结合光学影像可以看出在中间部分有部分多分，将表面形状复杂的点云误分为林木。

在尽量减少工作量的同时，为了保证验证的精度，人工判定在图像上随机选取的 500 个点是否为林木，并与分类结果相比较。分类误差包含漏分误差和多分误差，如表 2 所示，林木点云的分类效果较好，漏分误差和多分误差均在 3.4% 以内；地面点漏分误差和多分误差均在 9% 以内，相对较差。

表 2 分类结果的误差

Tab. 2 Errors of classification results

	选取点数	漏分点数	漏分误差/%	多分点数	多分误差/%	总误差/%
林木	323	11	3.4	8	2.5	5.9
地面点	177	13	7.3	16	9.0	16.3

林木点云具有一定高度且呈簇状团聚分布，相对于较平整缓和的地面点云差异明显，更容易区分，因此林木点云的提取效果较好。

3.2 冠层投影面积及体积与人工测量结果比较

将本文基于 LiDAR 点云的激光测量方法与传统人工测量方法相比较。选取 10 个外业样地的树冠点云，将树冠点云数据投影到 $x-y$ 平面，再用边界搜索和任意多边形面积计算公式，获取树冠投影面积。人工测量树冠在地面的投影面积时，将单木树冠投影视为椭圆，其长、短轴的长度分别为树冠东西和南北方向的冠幅，以此求取单木投影面积，再对区域内各个单木面积求和得到林木冠层的投影面积。激光测量面积 A_1 和人工测量面积 A_2 如图 11 所示。

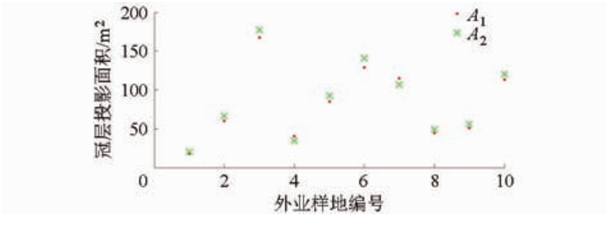


图 11 激光与人工测量冠层投影面积

Fig. 11 Canopy projection area by laser and manual measurement

采用本文方法，实现了基于三维激光点云数据的冠层体积测量；并利用人工测量得到的树冠高度和冠幅，依据树种的冠形选择表 3 中的体积公式估算冠层体积。

激光测量体积 V_1 和人工测量体积 V_2 结果如图 12 所示。

表 3 不同冠形冠层体积计算公式

Tab. 3 Formula for calculating volumes of different crown geometries

序号	冠形	体积计算公式
1	圆柱	$\frac{\pi x^2 y}{4}$
2	圆锥	$\frac{\pi x^2 y}{12}$
3	球形	$\frac{\pi(3xy^2-2y^3)}{6}$
4	半球形	$\frac{\pi(3xy^2-2y^3)}{12}$
5	球扇	$\frac{\pi(3y^3-y^2\sqrt{4y^2-x^2})}{3}$
6	卵形	$\frac{\pi x^2 y}{6}$

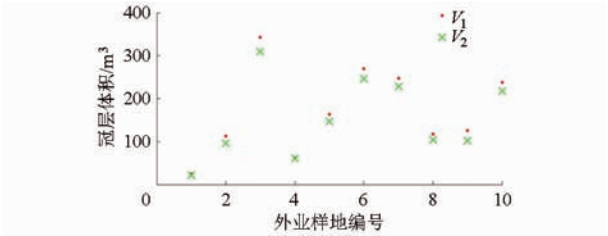


图 12 激光与人工测量冠层体积

Fig. 12 Canopy volume by laser and manual measurement

激光测量与人工测量的冠层投影面积的平均误差在 6% 以内，相关系数为 0.957；激光测量与人工测量的冠层体积的平均误差在 8% 以内，相关系数为 0.944，可以满足实际要求。

3.3 季节及林木生长状况的影响

林木在不同季节的树冠形态和树叶量对采集的机载激光雷达数据有直接影响[19-21]，这也对本方法的适应性提出了一定的挑战，本文实验数据的采集是在植被生长旺盛的时间段，若在冬季或者有些树种的树叶稀少时，需要进行大量的实践工作以验证本文方法。此外林木生长状况等对结果可能产生影响，也需要在后续研究中进行探讨。

4 结束语

为解决大范围的林木投影面积及体积难以高效快速提取的难题，本文采用机载 LiDAR 获取点云，利用点云分类算法，分别过滤地面和建筑物点云，实现了城区林木点云的提取。采用角度法搜索边界，并在相应的 CCD 影像上显示，用任意多边形面积算法和体积计算公式计算各连通区域的冠层投影面积和体积。在研究区域随机选出 10 个外业样地进行传统的人工测量，将基于 LiDAR 的激光测量与人工测量 2 种方法进行比较，平均漏分误差和平均多分误差均在 8% 以内，为植被冠层和生物量的高精度

定量估算提供了优质数据源，具有精度高、测量范围大等优点，将其引入到林业领域具有广阔的应用前景，有助于政府等相关部门进行高效合理地科学管理和决策。

参考文献

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

2 陈志远. 遥感在森林资源调查中的应用[J]. 内蒙古林业调查设计, 2010(3): 59-61.

3 Naesset E. Practical large-scale forest stand inventory using a small-footprint airborne scanning laser[J]. Scandinavian Journal of Forest Research, 2004, 19(2): 164-179.

4 Andersen H E, McGaughey R J, Reutebuch S E. Estimating forest canopy fuel parameters using LIDAR data[J]. Remote Sensing of Environment, 2005, 94(4): 441-449.

5 徐新良, 庄大方, 张树文, 等. 运用RS和GIS技术进行城市绿地覆盖调查[J]. 国土资源遥感, 2001, 13(2): 28-32.
Xu Xinliang, Zhuang Dafang, Zhang Shuwen, et al. Using RS and GIS technology to investigate urban green land cover[J]. Remote Sensing for Land and Resources, 2001, 13(2): 28-32. (in Chinese)

6 Barr S, Barnsley M. Reducing structural clutter in land cover classifications of high spatial resolution remotely sensed images for urban land use mapping[J]. Computers and Geosciences, 2000, 26(4): 433-449.

7 庞勇, 李增元, 陈尔学, 等. 激光雷达技术及其在林业上的应用[J]. 林业科学, 2005, 41(3): 129-136.
Pang Yong, Li Zengyuan, Chen Erxue, et al. LiDAR technology and its application in forestry[J]. Scientia Silvae Sinicae, 2005, 41(3): 129-136. (in Chinese)

8 刘清旺, 李增元, 陈尔学, 等. 利用机载激光雷达数据提取单株木树高和树冠[J]. 北京林业大学学报, 2008, 30(6): 83-89.
Liu Qingwang, Li Zengyuan, Chen Erxue, et al. Extracting height and crown of individual tree using airborne LiDAR data[J]. Journal of Beijing Forestry University, 2008, 30(6): 83-89. (in Chinese)

9 刘峰, 龚健雅. 基于机载激光雷达技术的茂密林地单株木识别[J]. 农业机械学报, 2011, 42(7): 200-203, 209.
Liu Feng, Gong Jianya. Individual trees recognition in dense forest based on airborne LiDAR[J]. Transactions of the Chinese Society for Agricultural Machinery, 2011, 42(7): 200-203, 209. (in Chinese)

10 刘峰, 谭畅, 张贵, 等. 长白落叶松单木参数与生物量机载LiDAR估测[J]. 农业机械学报, 2013, 44(9): 219-224, 242.
Liu Feng, Tan Chang, Zhang Gui, et al. Estimation of forest parameter and biomass for individual pine trees using airborne LiDAR[J]. Transactions of the Chinese Society for Agricultural Machinery, 2013, 44(9): 219-224, 242. (in Chinese)

11 徐伟恒, 冯仲科, 苏志芳, 等. 一种基于三维激光点云数据的单木树冠投影面积和树冠体积自动提取算法[J]. 光谱学与光谱分析, 2014, 34(2): 465-471.
Xu Weiheng, Feng Zhongke, Su Zhifang, et al. An automatic extraction algorithm for individual tree crown projection area and volume based on 3D point cloud data[J]. Spectroscopy and Spectral Analysis, 2014, 34(2): 465-471. (in Chinese)

12 Shendryk I, Hellström M, Klemedtsson L, et al. Low-density LiDAR and optical imagery for biomass estimation over boreal forest in sweden[J]. Forests, 2014, 5(5): 992-1010.

13 管海燕, 邓非, 张剑清, 等. 面向对象的航空影像与LiDAR数据融合分类[J]. 武汉大学学报: 信息科学版, 2009, 34(7): 830-833.
Guan Haiyan, Deng Fei, Zhang Jianqing, et al. Object based fusion and classification of airborne laser scanning data and aerial images[J]. Geomatics and Information Science of Wuhan University, 2009, 34(7): 830-833. (in Chinese)

14 曾齐红. 机载激光雷达点云数据处理与建筑物三维重建[D]. 上海: 上海大学, 2009.

15 Wu Jiguang. A method for detecting objects by fusing LiDAR data and images[J]. Journal of Capital Normal University, 2009, 30(4): 6-11.

16 曾齐红, 毛建华, 李先华, 等. 激光雷达点云平面拟合过滤算法[J]. 武汉大学学报: 信息科学版, 2008, 33(1): 25-28.
Zeng Qihong, Mao Jianhua, Li Xianhua, et al. Planar-fitting filtering algorithm for LiDAR points cloud[J]. Geomatics and Information Science of Wuhan University, 2008, 33(1): 25-28. (in Chinese)

17 王延亮, 刘登杰. 离散目标群的边界搜索[J]. 测绘科学, 2007, 32(5): 101-102.
Wang Yanliang, Liu Dengjie. Search discrete boundary of the target group[J]. Science of Surveying and Mapping, 2007, 32(5): 101-102. (in Chinese)

18 裘正军, 应霞芳, 何勇. 基于GPS模块的便携式农田面积测量仪[J]. 浙江大学学报: 农业与生命科学版, 2005, 31(3): 333-336.
Qiu Zhengjun, Ying Xiafang, He Yong. A portable instrument for measuring field area based on GPS module[J]. Journal of Zhejiang University: Agriculture & Life Sciences, 2005, 31(3): 333-336. (in Chinese)

19 樊仲谋, 冯仲科, 郑君, 等. 基于立方体格网法的树冠体积计算与预估模型建立[J]. 农业机械学报, 2015, 46(3): 320-327.
Fan Zhongmou, Feng Zhongke, Zheng Jun, et al. Tree crown volume calculation and prediction model establishment using cubic lattice method[J]. Transactions of the Chinese Society for Agricultural Machinery, 2015, 46(3): 320-327. (in Chinese)

20 张凝, 张晓丽, 叶栗. 基于改进爬峰法高分辨率遥感影像分割的树冠提取[J]. 农业机械学报, 2014, 45(12): 294-300.
Zhang Ning, Zhang Xiaoli, Ye Li. Tree crown extraction based on segmentation of high-resolution remote sensing image improved peak-climbing algorithm[J]. Transactions of the Chinese Society for Agricultural Machinery, 2014, 45(12): 294-300. (in Chinese)

21 韦雪花, 王永国, 郑君, 等. 基于三维激光扫描点云的树冠体积计算方法[J]. 农业机械学报, 2013, 44(7): 235-240.
Wei Xuehua, Wang Yongguo, Zheng Jun, et al. Tree crown volume calculation based on 3-D laser scanning point clouds data[J]. Transactions of the Chinese Society for Agricultural Machinery, 2013, 44(7): 235-240. (in Chinese)