第35卷第2期
2016年4月

红外与毫米波学报
J. Infrared Millim. Waves

Vol. 35, No. 2
April, 2016

文章编号: 1001－9014(2016)02－0177－08 **DOI**:**10.11972/j.issn.1001－9014.2016.02.010**

Extraction of crown volume using triangulated irregular network algorithm based on LiDAR

GONG Yin-Xi[1,2], YAN Fei[1], FENG Zhong-Ke[1,*], LIU Yun-Feng[2], XUE Wen-Xing[2], XIE Fei[3]

(1. Beijing Forestry University, BeiJing 100083, China;
2. Research and Development Center, The First Institute of Photo-Grammetry and Remote Sensing,
State Bureau of Surveying and Mapping, Xi'an 710054, China;
3. The First Institute of Geographical information System and Mapping, State Bureau of Surveying and Mapping, Xi'an 710054, China)

Abstract: To improve the precision and effectiveness of crown-volume measurement and calculation, the authors have analyzed the characteristics of existing methods for processing the point cloud and have proposed a crown-surface reconstruction algorithm using a triangulated irregular network and voxel-based volumetric algorithms. This algorithm, after reconstructing the surface of the point-cloud crown, can extract the crown volume. This paper compares classic Delaunay grid-construction results with those from the proposed algorithm using a visualization method and carries out algorithm complexity analysis. These efforts have confirmed that the method presented in this paper is better than the traditional algorithm from the viewpoints of grid-construction accuracy and efficiency. This research, examined 30 trees in the study area. T-LiDAR was used to obtain point-cloud data for the crown. The classical manual dendrometric method, the point-cloud measurement method, the classical Delaunay algorithm, and the method proposed in this paper were used to calculate crown volume, and the results were compared. The four methods showed a good correlation ($R^2 > = 0.831$), while the improved Delaunay method presented in this paper achieved good precision, good stability, and the least calculation time. The results of these experiments proved that the proposed algorithm has a considerable advantage in crown-volume extraction from point clouds (especially from T-LiDAR data). The combination of the proposed algorithm with T-LiDAR data could extract crown properties such as surface area and biomass quickly and precisely.

Key words: crown volume, terrestrial LiDAR, triangular irregular net, point-cloud data
PACS: 42.68.Wt, 42.62.-b

改进的三角网构网算法用于 LiDAR 树冠体积提取

巩垠熙[1,2]，闫飞[1]，冯仲科[1,*]，刘云峰[2]，薛文星[2]，谢飞[3]

(1. 北京林业大学,北京 100083;
2. 国家测绘地理信息局第一航测遥感院,陕西 西安 710054;
3. 国家测绘地理信息局第一地理信息制图院,陕西 西安 710054)

摘要:在分析现存点云处理方法的特性后,通过改进三角网构网算法的算法机制,提出了一种基于空间分割的分块优先级机制的三角网表面重建算法,用于重构树冠表面,实现树冠体积的准确提取.通过可视化方法对比了多种算法的点云构网效果,以实验区选定的30棵树为研究对象,利用 T-LiDAR 获取树冠点云数据,通过人工方法、传统算法和本文的改进算法计算树冠体积,对这些结果进行了对比分析.分析发现:四种方法之间均显示出较好的相关性($R^2 > = 0.831$),其中所提出的改进 Delaunay 方法拥有理想的精度,较好稳定性和最少的耗费时间.实验结果表明,提出的算法在点云(尤其是 T-LiDAR 数据)树冠的体积提取中具有很大的优势.结合 T-LiDAR 数据还可以实现树冠表面积和生物量等树冠因子的高精度快速提取.

关 键 词:树冠体积; T-LiDAR;三角网;点云数据
中图分类号:S771.8, TP79, TP391.41 **文献标识码**:A

Received date: 2015－03－12, **revised date**: 2015－12－15 **收稿日期**:2015－03－12, **修回日期**:2015－12－15
Foundation items:Supported by National Natural Science Foundation of China (41371001)

Biography:GONG Yin-Xi (1986-), male, Tianshui, China. Ph. D. Research area involves "3S" Technology Integration and Application. E-mail: top_speed2@163.com

[*] **Corresponding author**:E-mail:fengzhongke@126.com

Introduction

The crown is an important fundamental factor indicating the productivity of trees. It influences and reflects the health status of trees[1]. In addition, the crown plays a very important role in the tree nutrient absorption, photosynthesis, and water preservations[2]. Crown volume, as one of the most difficult tree parameters to be calculated[3], is also among the most important factors indicating the biological characteristics and ecological functions of the crown. It influences directly the photosynthetic efficiency of the tree, which in turn influences forest productivity[4]. Current forest inventories based on allometric relationships with standard measurements of heights and diameters at breast height (DBH) generally lead to large errors, especially in commercial volume estimates[5]. 3D laser scanning technology, with its increasing power and decreasing cost, can be used as a technical means to perform high-precision measurement and quick construction of an object's spatial structure. This technology is highly helpful in obtaining detailed information at the tree or plot scales[6]. This information can be used to model quickly and in great detail the tree structure in a forest, based on which the factors and structural parameters of individual trees, e. g., the stem shape and quality, crown dimensions, branch biomass, and leaf-area index (LAI) of each tree, can be extracted quantitatively[3,7-8].

Many studies have been performed using T-LiDAR to study the structural parameters of forests and single trees, including detecting tree trunks in point clouds and determining diameters at breast height (DBH) using shape-recognition techniques[9-10]. This technique has also been used to determine the complex geometry of forest-canopy structural parameters (canopy cover, gap fraction, leaf-area ratios, foliage distribution, and biomass) more rapidly than with conventional techniques. This has been achieved by using the Echidna® prototype or by inserting a point cloud into a voxel grid (a voxel grid is a 3D space composed of adjacent cubic cells)[11-12]. Other authors have modeled tree structure to estimate tree growth and ecology by fitting cylinder sequences to the point cloud to determine trunk and branch geometry or by projecting point clouds into a voxel space[13]. These pioneering studies have demonstrated the potential of T-LiDAR scanning for accurate extraction of forest and tree information.

Because of the diversity and complexity of the crown shape, many methods are used to calculate crown volume. Some studies have used voxel methods and a *K*-dimensional tree algorithm using discretized cloud points in voxels to render discontinuous crown surfaces. The crown volume can be calculated by counting the effective number of voxels[14]. The advantage of this method is that it reduces distortion when processing T-LiDAR data and accommodates the simultaneous representation of interior and exterior T-LiDAR sensor readings[15]. However, this method cannot completely prevent the occultation of points inside the crown by external leaves and branches and requires much computing time to perform volume calculations[16].

Other studies have focused on using the Delaunay triangulation algorithm to generate a 3D tree-crown mesh model for ecological simulation[17-18]. This method progressively fits discrete point clouds to a continuous triangular mesh, covering the whole surface of the crown to generate a 3D model and to extract the crown factor. This approach is different from voxel-based region-growing methods; it can better restore details on the continuous surface of the object with less calculation time, while voxel-based region-growing methods are always slow and suffer from discretization artifacts[19-20]. Fernández-Sarría *et al.* compared the precision and efficiency of seven crown-volume extraction methods using point-cloud data, including the Delaunay triangulation algorithm and the voxel-based region-growing method. The results showed that the Delaunay-based crown-reconstruction algorithm (in this paper, it was called "flat sections") is precise and fast[16]. However, the classical Delaunay algorithm is generally sensitive to these factors and therefore lacks robustness[21-22]. One consequence of this is that the classical Delaunay algorithm commits more errors and consumes more time when used to model the crown surface using T-LiDAR data.

To extract the crown volume correctly and quickly from a large quantity of T-LiDAR point-cloud data, this research integrated the voxel-based method and Delaunay triangulation to propose a crown-surface reconstruction method based on a spatial division mechanism. This method obtains 3D dot-matrix data from a ground-based 3D laser scanning system. First, the point-cloud space is subdivided into tetrahedra, and every tetrahedron is screened. The characteristic points of the crown are reserved as constraints; then Delaunay triangulation is progressively applied to the tetrahedra. After local optimization, the triangulated irregular network (TIN) model is constructed for the crown surface; finally, the crown volume is calculated based on the TIN data.

This study considered four different crown-volume calculation methods. The research confirmed the advantage of the proposed method by comparing the efficiency and precision of the four methods. The proposed method was able to improve measurement precision and operating efficiency while achieving automated measurement and crown-factor calculation.

1 Experimental

1.1 Experimental platform

The experiment used T-LiDAR as the data source. The T-LiDAR system consisted of a ground-based 3D laser scanner, a power source, a digital camera, registration spheres, a support, and auxiliary equipment. It obtains the surface point-cloud data of an object by non-contact laser measurement. The experiment used a FARO Focus 3D ground-based laser scanner (manufactured by FARO), which is a single-reading system. The vertical scanning angle was 305°, the horizontal scanning angle was 360°, and the maximum resolution was 0.9 mm when the device is 10 m away from the target. This device is characterized by its wide range of vertical scanning angle, its high emission frequency, and its acquisition rate up to 976 000 pts/s , (http://wenku. baidu. com/view/669eb68ccc22bcd1 26ff0c72. html). It can scan an entire tree.

1.2 Field data collection

The study site was a temporary plot located in the northern section of the Miyun Reservoir in Miyun County near Beijing. The coordinates of the plot center were (40°29.946′ N, 116°49.049′ E). For the experiment, 30 trees were chosen in good growing condition and with little shading from the surrounding environment. At the same time, traditional manual measurement was conducted on these trees. The heights of the studied trees were between 5.67 m and 15.97 m, and the crown diameters measured between 5.69 m and 12.28 m.

To obtain multi-directional point-cloud information for the crown, scanning should be carried out from at least three stations for the same object[23]. Data from the three stations were aligned and merged by arranging registration spheres uniformly in the plot. The SCENE LT software was used to select and splice the point-cloud data. Using digital photos taken on-site, point-cloud data for the ground and for other non-target trees were eliminated manually. Thus, a complete set of point-cloud data for individual trees was obtained. Because human factors account for most errors in traditional crown-volume measurement[18], manual data collection and point-cloud measurement were used to extract the crown characterization factors (including height, diameter, and shape) to improve data precision. Manual collection used the traditional Height Finder and soft tape to measure crown height and diameter. SCENE LT was used for point-cloud data measurement. The precision reached centimeter scale.

1.3 Data pre-processing

Pre-processing of the point-cloud data included matching of data from different stations and the elimination of redundant data for the ground and other non-target trees. The pre-processing was done using SCENE LT in combination with visual recognition. The goal of matching the point-cloud data was to define an absolute coordinate system to align data from different stations. T-LiDAR could obtain the point-cloud data for the crown, but during data collection, the trunk was inevitably scanned into the point-cloud data. To obtain pure point-cloud for the crown, the point cloud was rotated and zoomed in Cyclone to eliminate the point-cloud data for the trunk. Consequently, the crown-surface model was determined, and the crown-volume data obtained.

2 Methods

Four methods were used to calculate the crown volume in this paper:

1) Classic Delaunay triangulated irregular network method: this method was applied to all the trees to construct the crown-surface model. Using the crown-surface model and the base model, the crown volume was extracted.

2) Spatial Division Delaunay method (SD Delaunay): this is an improved classic Delaunay triangulated irregular network method. It uses the same principles for crown-volume extraction as the classic Delaunay triangulated irregular network method. The difference lies in their grid construction effects.

3) Classic manual-dendrometric crown-volume calculation: using on-site measurements of the crown diameter, height, and shape, the crown was simulated as a regular geometric shape to calculate its volume.

4) Crown-volume calculation by point cloud: using software, the crown diameter, height, and shape were measured. The calculation principle was the same as that of the classic dendrometric crown-volume calculation.

The following discussion introduces the principles of each method in detail, with a focus on explaining the mechanism, improvements, and features of Spatial Division Delaunay.

2.1 Delaunay triangulated irregular network method

Delaunay triangulation is the most commonly used algorithm for fitting a crown surface by building a digital elevation model with discrete points. Its advantages are that it is more efficient than the method based on contour lines and that it reduces data redundancy compared with a regular mesh[24].

The calculation based on the triangulated irregular network requires two models: the crown-surface model and the base-surface model. The volume between the triangular units formed by the superposition of the two models is the crown volume. Thus, the TIN data for the crown surface are obtained. The principle of this process is shown in Fig. 1.

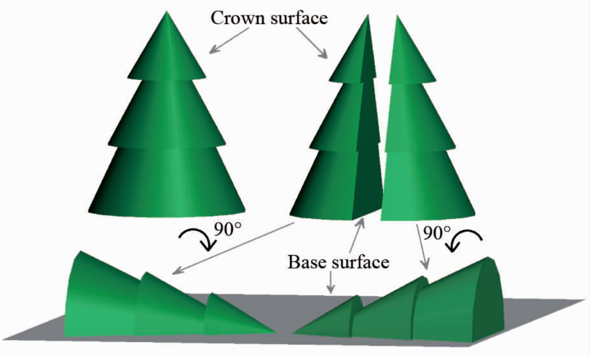

Fig. 1 Principle of the calculation of crown volume based on the TIN model

图 1 TIN 树冠模型体积计算原理

The left part is rotated by -90° along the X-axis, by 0° along the Y-axis, and by -90° along the Z-axis; the right part is rotated by 90° along the X-axis, by 0° along the Y-axis, and by 90° along the Z-axis. The principle of crown-volume calculation using a TIN model of the crown surface is: first, the surface points are projected onto the zero plane to obtain the coordinates of discrete points, or in other words, to transform 3D coordinates into 2D coordinates. Then the points on the zero plane are vertically connected to the surface points to obtain a large number of straight triangular prisms. The sum of the volume of all the straight triangular prisms is the crown volume. In addition, the triangular prisms formed by the TIN do not mutually intersect and are close to each other. Therefore, the summation can be represented by the following equation:

$$V = V_1 + V_1 + \cdots + V_i \cdots + V_n = \sum_{i=1}^{n} V_i \quad ,(1)$$

where V_i is the volume of each individual straight triangular prism. The sum V is the volume of the crown. A schematic diagram illustrating this principle is shown in Fig. 2. In Fig. 2, V_i represents the volume of each straight triangular prism, and the sum V is the crown volume.

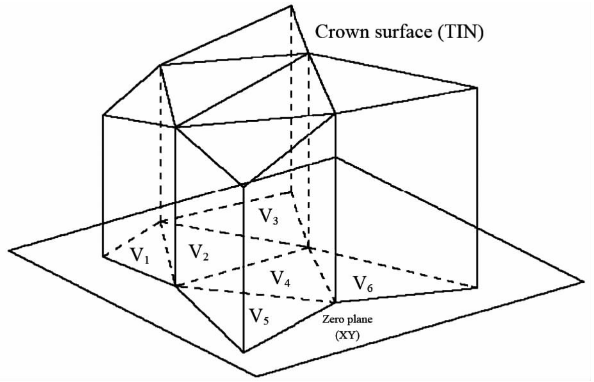

Fig. 2 Principle of volume calculation
图2 体积计算原则

2.2 SD Delaunay triangulated irregular network

The crown surface usually includes multiple clustered, unevenly distributed bulges and holes. It is more complex than the ground surface. The classical Delaunay algorithm is generally sensitive to these factors, and therefore twisting or knotting can be generated by this lack of robustness[21]. The algorithm presented in this paper establishes a spatial division mechanism, selects the point cloud of the crown using blocks, and reserves the characteristic points of the crown as constraints. Then a 3D local optimization procedure (LOP) is carried out over the point cloud representing the crown. This approach avoids the holes and errors of triangulation methods while effectively fitting the bulges and holes of the crown surface. The recognition of the crown surface thus becomes more accurate. 3D LOP is a commonly used method for optimization of a triangulated irregular network. It determines a parallelogram made up of two triangles with common sides. If the circumcircle of any triangle contains the third vertex of another triangle except the common points, the common side is interchanged. Ordinary T-LiDAR data are too massive for this procedure because the constructed network must search every point that falls into the mesh, and therefore the efficiency of the traditional Delaunay triangulation algorithm is low. In comparison, the SD Delaunay triangulated irregular network generation algorithm proposed in this paper has the advantage of selecting the point cloud by spatial division of point-cloud data, which reduces the number of unnecessary point clouds and improves calculation efficiency. To improve search efficiency in the point-cloud space, to specify the relation between data and objects, and to facilitate point-cloud data storage and network construction, the data structure of the traditional Delaunay triangulated irregular network was improved in this research[25]. The improved data structure involves points, baselines, and a mesh, as shown in Fig. 3.

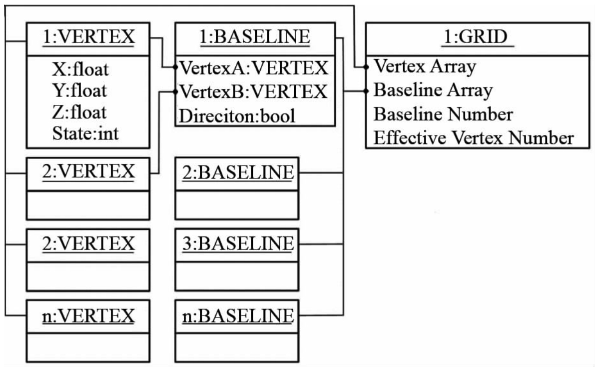

Fig. 3 Improved data structures and topological relations
图3 改进的数据结构和拓扑关系

2.3 Classic crown-volume calculation

In the traditional crown-volume calculation method, tree characteristics are usually collected manually in the field to calculate the crown volume using the crown diameter and height as parameters, and the crown is simulated as a regular geometric body. In this research, the crown diameter, height, and shape of 30 trees were collected using two methods: manual measurement and point-cloud measurement.

3 Results and discussion

3.1 Effectiveness analysis of the algorithm

Figure 4 shows a comparison of network-construction effectiveness for the same crown with an interval of 20 cm × 20 cm using the Delaunay algorithm proposed by Wei *et al.* [25] and the proposed algorithm.

Comparing Figs. 4(a) and (d), it is apparent that the Delaunay algorithm and the SD Delaunay algorithm are on the whole similar in triangulation effectiveness and that both reflect the surface shape of the crown in a relatively correct manner. After magnification of the crown surface, holes appear in the irregular parts of the crown surface when the Delaunay algorithm is used, as shown in Fig. 4(b). The presence of holes compromises the integrity of the triangulation network; as shown in Fig. 4(e), such phenomenon can be avoided when using the SD Delaunay algorithm. The triangulation network in Fig. 4(c) shows clustered overlapping in areas with large changes in the point-cloud distribution due to the irregular crown surface; Figure 4(f) shows that this situation can be improved greatly after the point-cloud data have been screened and divided using the SD Delaunay algorithm.

3.2 Calculation results for crown volume

In this paper, traditional manual measurement[22,26], point-cloud measurement[18], Delaunay triangulation (the algorithm described in Ref. 25), and the SD Delaunay algorithm were used to calculate the crown volume. The two triangulation algorithms were implemented using a VC++6.0 program, with an Intel E 5700 CPU and 4 GB DDR2 memory as the hardware configuration. The calculation performance and efficiency of

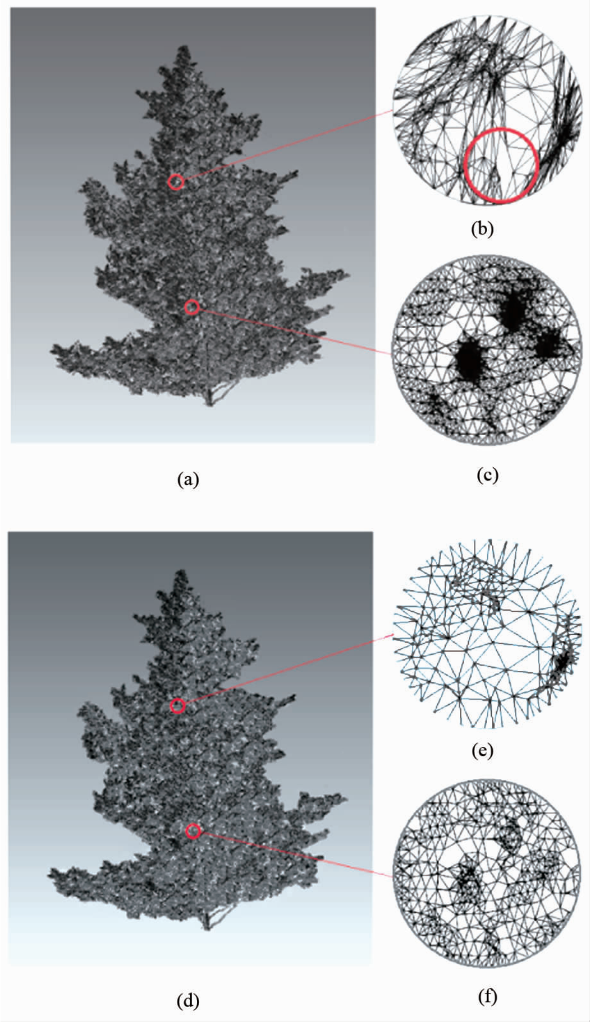

Fig. 4　Comparison of TINs for the crown for different algorithms (a) Overall result of Delaunay triangulation, (b) local result of Delaunay triangulation 1, (c) local result of Delaunay triangulation 2, (d) overall result of SD Delaunay triangulation, (e) local result of SD Delaunay triangulation 1, and (f) local result of SD Delaunay triangulation 2
图 4　不同算法构网结果对比(a)Delaunay 总体构网结果，(b)Delaunay 构网局部结果 1，(c)Delaunay 构网局部结果 2，(d)SD Delaunay 总体构网结果，(e)SD Delaunay 构网局部结果 1，(f)SD Delaunay 构网局部结果 2

different methods were analyzed. Figure 5 and Table 1 show a comparison of the results of crown-volume calculation using the four methods.

Table 1　Summary of calculated crown-volume results
表 1　树冠体积计算结果统计表

Method	Manual measurement Volume /m^3	Point-cloud measurement Volume /m^3	Delaunay Volume /m^3	SD Delaunay Volume /m^3
Mean	36.266	37.102	41.611	40.114
Max	110.073	113.364	143.478	138.321
Min	13.916	14.087	13.283	12.791
Stand. dev.	25.396	24.655	27.776	26.424
C. V	70.0%	66.5%	66.8%	65.9%

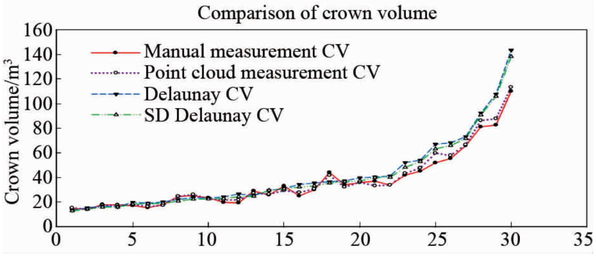

Fig. 5　Comparison of crown volume
图 5　树冠体积对比

The results in Table 1 show that the means of the two Delaunay methods are close to each other, and so are those obtained by the two dendrometric methods. This is due to a difference in the volume-calculation mechanism. The largest volume calculated was from the Delaunay method, and the results of the two Delaunay methods were slightly larger than those from the two dendrometric methods. This result originates from the nature of the dendrometric methods, which fit the crown as a regular geometric body and fail to guarantee accuracy in cases of irregular crowns. Meanwhile, some internal holes in the crown may be inevitably included in the crown volume, causing larger values with the two Delaunay methods. By comparing the coefficients of variation in Table 1, it is apparent that the results of manual measurement fluctuate greatly. This reflects the fact that human factors may interfere with manual measurement to a certain extent, causing large raw variance. Figure 5 shows the large variation in results obtained using these methods. From Fig. 5, it is also apparent that for relatively small values of crown volume, the results from the four methods differ only slightly, while the differences for large values are greater. This may indicate a more complex structure in larger crowns.

Comparing the volumes obtained using manual measurement and point-cloud measurement, as shown in Fig. 5 and Table 1, the standard deviation and coefficients of variation of the point-cloud measurement results were all lower than those for manual measurement. This can be explained by the fact that the point-cloud measurement has better accuracy and stability.

Comparing the volumes obtained using the Delaunay and SD Delaunay methods, as shown in Fig. 5 and Table 1, the mean volume calculated using SD Delaunay is evidently lower than that of classic Delaunay. This can be explained by the fact that SD Delaunay can better reflect the holes and bulges of the tree crown than the classic one, so that the real shape and surface of the tree crowns can be replicated. However, it is difficult for the classic Delaunay method to reflect the holes and bulges properly. As a result, when the volume is calculated, the holes are filled and the bulges are amplified, reducing the accuracy of the volume calculation.

This research has studied the correlations among different methods using linear regression models, as shown in Table 2. The correlation between any two methods was high. Analysis of the methods as applied to LiDAR data shows an R^2 greater than 0.95. When these methods were compared with dendrometric methods, the R^2 values were slightly lower (0. 831 ~0. 889). The lowest value (0. 831) was found between SD Delaunay and manual measurement. A good correlation was found between the dendrometric method and the Delaunay method, which also proves that the Delaunay method is highly suitable for crown-volume extraction.

Table 2 R^2 of crown volumes calculated by different methods
表 2 不同方法计算树冠体积的 R^2

Method	Delaunay	SD Delaunay	Manual measurement	Point-cloud measurement
Delaunay	–	0. 982	0. 845	0. 886
SD Delaunay	0. 982	–	0. 831	0. 889
Manual measurement	0. 845	0. 831	–	0. 927
Point-cloud measurement	0. 886	0. 889	0. 927	–

Figures 6 and 7 show the scatter plots relating the results of the Delaunay methods to those from the point-cloud measurement method. It is clear that the volumes of smaller crowns exhibit a more concentrated distribution than big crowns. This is explainable by the fact that a large canopy has a more complex shape and structure. All results have a good coefficient of determination (R^2). These good correlations between the Delaunay methods and the point-cloud measurement method have proved the reliability of both methods for crown-volume calculation.

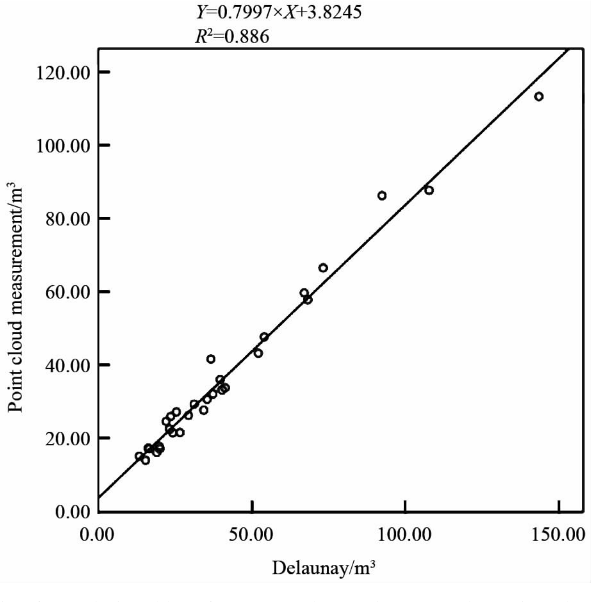

Fig. 6 Relationship of crown volumes between the point-cloud measurement method and the Delaunay method
图 6 点云测量法和 Delaunay 方法树冠体积计算的相关性

From the above analysis, it is apparent that the point-cloud measurement is more efficient among the dendrometric methods because it has good stability. Among the triangulation methods, SD Delaunay is better than Delaunay method due to its better precision (smaller mean volume) and stability (smaller coefficient of variation). The high correlation coefficient between SD Delaunay and the point-cloud measurements confirms SD Delaunay's effectiveness in measuring crown volume.

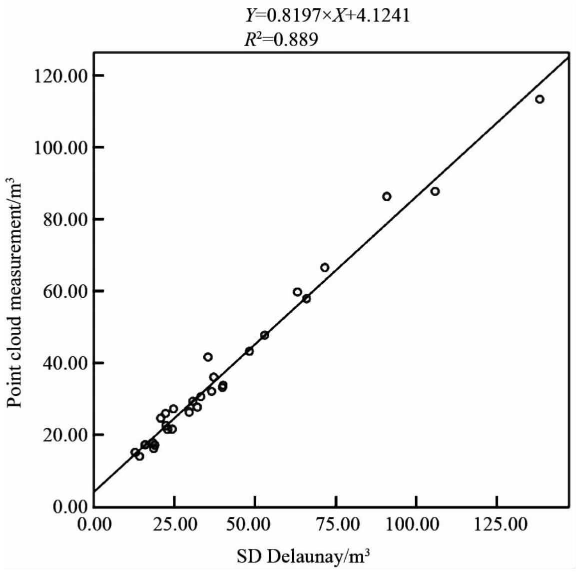

Fig. 7 Relationship of crown volumes between the point-cloud measurement method and the SD Delaunay method
图 7 点云测量法和 SD Delaunay 方法树冠体积计算的相关性

A statistical experiment was then conducted on the time consumption of the three different point-cloud measurement methods for measuring crown volume. Thirty trees were arranged from small to large and were divided into ten groups. The time consumptions for the crown-volume calculation were then compared, as shown in Fig. 8. The different time consumptions for the volume calculation using the digital elevation model were related to the complexity of the different triangulation network-construction algorithms.

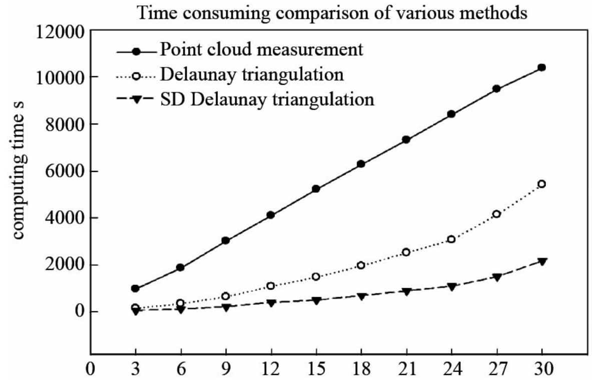

Fig. 8 Comparison of the time consumption of various methods
图 8 不同提取方法的耗费时间对比

According to Fig. 8, the time consumption of the various methods increased linearly with the number of trees. The time consumption of the SD Delaunay method increased slowly and showed high execution efficiency. Its time consumption was less than half that of the classic Delaunay method. The processing times increased markedly from the twenty-first tree onwards because the crown of this tree was unusually large. The time consumption of the two methods showed no significant difference for smaller crown sizes.

4 Conclusions

Based on point-cloud data for tree crowns collected by T-LiDAR, this research used the SD Delaunay method, an improved Delaunay triangulation growth algorithm, to construct a crown-surface model and then to calculate the crown volume. This algorithm improves the data structure of the classic Delaunay algorithm by fully considering the features of T-LiDAR point-cloud data and eliminates redundant data by reserving the characteristic points of tree crowns as constraints using a block mechanism. Local 3D LOP optimization is used to expand the cover gradually to the whole surface of the crown, thus achieving crown-surface reconstruction. The algorithm can avoid filling in or omitting some details of the crown surface, and also greatly increase the efficiency of the volume calculation. The resulting 3D crown-surface model is greatly superior to the classic Delaunay algorithm and provides a convenient method for crown-factor extraction.

To study the performance of SD Delaunay in calculating crown volume, this research has implemented four methods for calculating tree volume, with T-LiDAR point-cloud data used in three methods and manually collected crown data in one method. All four methods showed high correlations among each other. The volume calculated by the SD Delaunay method was much smaller than that calculated by the classic Delaunay method. The reason for this was that SD Delaunay could better reflect the holes and bulges of the crown and therefore achieved a higher precision of crown-surface restoration than the classic one. It can be inferred that SD Delaunay is better than classic Delaunay in estimating crown parameters such as surface area and biomass. This research also found that the crown-volume results showed only small differences among the various methods when calculating smaller crowns, but huge differences for bigger crowns. This occurs because the bigger the crown, the more complex is its shape. It was also apparent that classical dendrometric methods are more suitable for calculating the volumes of smaller crowns. By comparing the coefficients of variation of point-cloud measurement and manual measurement, it is clear that point-cloud measurement has higher precision and stability because it is better at reducing the errors that may be caused by manual measurement. The manual measurement results had the highest fluctuations, revealing their relatively low precision.

From a comparison of the calculation time of the three point-cloud methods, it is apparent that SD Delaunay possesses an absolute advantage, with a time consumption far smaller than that of point-cloud measurement and less than one-half that of classical Delaunay. The size of the tree crown is the decisive factor determining the processing time of the two triangulation methods, but it does not affect the processing time of the point-cloud measurement. This is attributable to the different volume-calculation mechanisms used by the various methods.

Generally, the SD Delaunay method has better stability, accuracy, and efficiency than the classic Delaunay method and is therefore more suitable for crown-surface reconstruction using massive point-cloud data (acquired by T-LiDAR). The combination of the SD Delaunay method and T-LiDAR provides a reliable basis for extracting crown parameters such as volume, surface area, and biomass more rapidly and precisely than before.

Acknowledgements

Financial support for this study was provided through National Natural Science Foundation of China (41371001). We are grateful to the undergraduate students and staff of the Laboratory of Forest Management and “3S” technology, Beijing Forestry University, and the great support from Beijing Municipal Bureau of Forest. A special thank is due to LI, from Tsinghua University for careful revision of English text.

References

[1][1] Alexander C. Delineating tree crowns from airborne laser scanning point cloud data using Delaunay triangulation[J]. *International Journal of Remote Sensing*, 2009, **30**(14): 3843 -3848.

[2] Amenta N, Bern M. Surface reconstruction by Voronoi filtering[J]. *Discrete & Computational Geometry*, 1999, **22**(4): 481 -504.

[3] Bienert A, Maas H G, Scheller S. Analysis of the information content of terrestrial laserscanner point clouds for the automatic determination of forest inventory parameters[J]. *Workshop on 3D Remote Sensing in Forestry*. 2006 ,**14**(15) ,1 -7.

[4] Bienert A, Scheller S, Keane E, *et al*. Tree detection and diameter estimations by analysis of forest terrestrial laserscanner point clouds [C]//ISPRS workshop on laser scanning. 2007: 50 -55.

[5] Brandeis T, Delaney M, Royer L, *et al*. Allometric equations for predicting Puerto Rican dry forest biomass and volume[J]. Proceedings of the Eighth Annual Forest Inventory and Analysis Symposium, 2006: 197 -202.

[6] Bréda N J J. Ground - based measurements of leaf area index: a review of methods, instruments and current controversies[J]. *Journal of experimental botany*, 2003, **54**(392): 2403 -2417.

[7] Chasmer L, Hopkinson C, Treitz P. Investigating laser pulse penetration through a conifer canopy by integrating airborne and terrestrial lidar[J]. *Canadian Journal of Remote Sensing*, 2006, **32**(2): 116 -125.

[8] Dassot M, Constant T, Fournier M. The use of terrestrial LiDAR technology in forest science: application fields, benefits and challenges [J]. *Annals of Forest Science*, 2011, **68**(5): 959 -974.

[9] Fernández-Sarría A, Martínez L, Velázquez-Martí B, *et al*. Different methodologies for calculating crown volumes of Platanus hispanica trees using terrestrial laser scanner and a comparison with classical dendrometric measurements [J]. *Computers and electronics in agriculture*, 2013, **90**: 176 -185.

[10] Garber S M, Monserud R A, Maguire D A. Crown recession patterns in three conifer species of the northern Rocky Mountains[J]. *Forest Science*, 2008, **54**(6): 633 -646.

[11] Hinsley S A, Hill R A, Gaveau D L A, *et al*. Quantifying woodland structure and habitat quality for birds using airborne laser scanning [J]. *Functional Ecology*, 2002, **16**(6): 851 -857.

[12] Hosoi F, Omasa K. Detecting seasonal change of broad-leaved woody canopy leaf area density profile using 3D portable LIDAR imaging[J]. *Functional Plant Biology*, 2009, **36**(11): 998 -1005.

[13] Husch B, Beers T W, Kershaw Jr, J A. *Forest mensuration*[M]. Wiley, 2002.

[14] Jupp D L B, Culvenor D S, Lovell J L, *et al*. Estimating forest LAI profiles and structural parameters using a ground-based laser called ‘Echidna® [J]. *Tree physiology*, 2009, **29**(2): 171 -181.

[15] Kint V, Aertsen W, Wouters J, *et al*. Stem and wood quality assess-

（下转第 189 页）

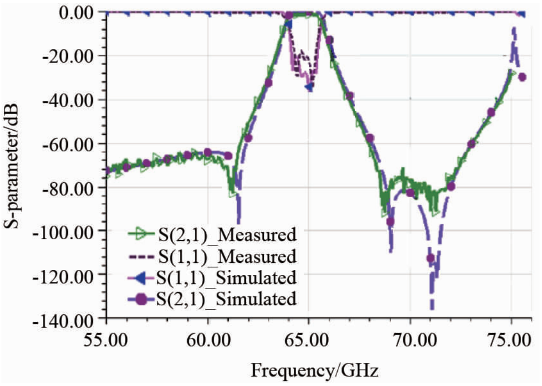

Fig. 16　Simulated and measured results of the BPF2
图 16　BPF2 的仿真与测试结果

shown in Fig. 16. Two TZs, which are individually resulted by the perturbing angles β_1, β_2 of notches, are located at 61.25 GHz and 68.6 GHz, respectively. The other TZs generated by the rotation angle $\alpha = 90°$ are located at upper stopband. The measured BPF2 has the expanded fractional bandwidth of 2.5%, 1.35 dB insertion loss of at center frequency of 64.8 GHz. The measured S_{11} is smaller than -20dB, and the out-of-band rejection is about 65dB.

4 Conclusion

This paper proposed a novel technique to design high selectivity BPFs with controllable transmission zeros, which does not need the sophisticated tuning screws for the filter tuning after fabrication. A small perturbation notch is provided for the filter application, which can be used to easily adjust the locations TZs to improve the selectivity of the filters. Two V-band filter prototypes have been designed, fabricated and measured. The experiment results confirm the good agreement with the simulated results, which shows that the proposed techniques are promising to design the compact and low cost mm-wave quasi-planar BPFs.

Acknowledgement

The authors appreciate the financial supported by Specialized Research Fund for the Doctoral Program of Higher Education of China, Grant No. 20120092110012, and the National Natural Science Foundation of China 61471118.

References

[1] Kudsia C, Cameron R, Tang W C. Innovations in microwavefilters and multiplexing networks for communications satellite systems [J]. *IEEE Trans. Microwave Theory Tech.*, 1992,**40**(6): 1133-1149.

[2] Guglielmi M, Molina R C, Melcon A A. Dual-mode circular waveguide filters without tuning screws [J]. *IEEE Microwave Guided Wave Lett.*,1992, **2**(11): 457-458.

[3] Tang H J, Hong W, Chen J, *et al.* Development of millimeter-wave planar diplexers based on complementary characters of dual-mode SIW filters with circular and elliptic cavities [J]. *IEEE Trans. Microwave Theory Tech.*, 2007,**55**(4): 776-782.

[4] Guglielmi M, Jarry P, Kerherve E, *et al.* A new family of all-inductive dual-mode filters [J]. *IEEE Trans. Microwave Theory Tech.*, 2001, **49**(10): 1764-1769.

[5] ZHAO Xing-Hai, SHAN Guang-Cun, ZHENG Ying-Bin, *et al.* MEMS rectangular waveguide filter at 140 GHz [J]. *Journal of Infrared and Millimeter Waves*(赵兴海, 单光存, 郑英彬, 等. 140 GHz MEMS 矩形波导滤波器. **红外与毫米波学报**), 2013, **32**(2): 165-169.

[6] Hong J S. *Microstrip filter for RF/microwave applications*[M]. New Jersey: Wiley, 2011, 2^{nd}, 193-231.

(上接 183 页)

ment in national forest inventories[J]. *Proc of the IUFRO Division*, 2009, **4**:1-5.

[16] Ku N W, Popescu S C, Ansley R J, *et al.* Assessment of available rangeland woody plant biomass with a terrestrial LIDAR system[J]. *Photogrammetric Engineering & Remote Sensing*, 2012, **78**(4): 349-361.

[17] Lin Y, Jaakkola A, Hyyppä J, *et al.* From TLS to VLS: Biomass estimation at individual tree level[J]. *Remote Sensing*, 2010, **2**(8): 1864-1879.

[18] Liu X, Gavrilova M L, Rokne J. Incorporating object-centered sampling and Delaunay tetrahedrization for visual hull reconstruction[J]. *The Visual Computer*, 2009, **25**(5-7): 381-389.

[19] Luo X. Study on measuring of forest based on 3D laser scanning measurement[J]. *Beijing Forestry University*. 2006, **2**(8):127-128.

[20] Maas H G, Bienert A, Scheller S, *et al.* Automatic forest inventory parameter determination from terrestrial laser scanner data[J]. *International journal of remote sensing*, 2008, **29**(5): 1579-1593.

[21] McDaniel M W, Nishihata T, Brooks C A, *et al.* Terrain classification and identification of tree stems using ground - based LiDAR[J]. *Journal of Field Robotics*, 2012, **29**(6): 891-910.

[22] Moorthy I, Miller J R, Berni J A J, *et al.* Field characterization of olive (Olea europaea L.) tree crown architecture using terrestrial laser scanning data[J]. *Agricultural and Forest Meteorology*, 2011, **151**(2): 204-214.

[23] Chun-li S, Peng H, Cheng-yi H, *et al.* The expatiation of delaunay algorithms and a promising direction in application[J]. *Science of Surveying and Mapping*, 2004, **29**(6): 68-71.

[24] Stoker J. Visualization of multiple-return Lidar data: Using voxels[J]. *Photogramm. Eng. Remote Sens*, 2009, **75**(2): 109-112.

[25] Vander Zande D, Stuckens J, Verstraeten W W, *et al.* Assessment of light environment variability in broadleaved forest canopies using terrestrial laser scanning[J]. *Remote Sensing*, 2010, **2**(6): 1564-1574.

[26] Waguchi Y. Accuracy and precision of crown profile, volume, and surface area measurements of 29-year-old Japanese cypress trees using a Spiegel relascope[J]. *Journal of forest research*, 2004, **9**(2): 173-176.

[27] Wei Y, Su X. Novel and fast mapping triangulation algorithm for unorganized points cloud[J]. *Optical Engineering*, 2008, **47**(11): 117205-117205-8.

[28] Xiong N N, Wang J, Luo X, *et al.* Measuring tree crown volume based on three dimension laser scanning and mapping system taking Pinus tabulaeformis as a case[J]. *Journal of Beijing Forestry University*, 2007, **29**(Suppl. 2): 61-65.