Citrus canopy volume estimation using UAV oblique photography

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Abstract: The canopy volume estimation method based on UAV oblique photography combined with pointed cloud processing technology was proposed in this study. Navel orange trees with irregular crown and landscape trees with regular crown were used as research objects in the experiment. Based on the multi-angle aerial images acquired by oblique photography with a low-cost four-rotor UAV, the three-dimensional point cloud and True Digital Ortho Map (TDOM) of the target area were generated after 3D reconstruction. Then, processing and classification were taken successively to obtain the Canopy Height Model (CHM) of individual tree. The cone sum algorithm, the convex-hull algorithm and the trapezoid segmentation algorithm were employed to estimate crown volume of individual tree. For orange trees, the R^2 between the cone volume sum algorithm and manual volume measurement was 0.63 of orange trees, and it is higher than that by the other two algorithms. For the landscape tree, the convex-hull algorithm did best, and the R^2 was 0.89. The results show that UAV oblique photography technology could be used to extract the individual canopy parameters of citrus orchard and to meet the requirements of large-scale and low-cost orchard management.

Keywords: canopy volume estimation, oblique photography, Unmanned Aerial Vehicles (UAV), Canopy Height Model (CHM), point cloud
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1 Introduction

The citrus production area and planting area of China rank first in the world for a long time, but citrus orchards in China are still facing a low level mechanization and intelligent management for a long time. The acquisition and analysis of crop growth information are the basis of agricultural intelligent decision management. Canopy volume refers to the space occupied within the crown contour, which is a composite index representing the 3D space size of the crown. The size and structure of the crown have a critical impact on the nutritional demand, water transpiration and fruit setting capacity of the fruit trees. As an important basis for monitoring the growth status and estimating the biomass of trees, it also provides theoretical support for precision management of orchard, such as variable pesticide application, precise fertilizer application and fruit yield prediction[1-3]. Therefore, it is of great significance to measure the canopy volume of fruit trees rapidly for the precise management for individual plant.

It is difficult to accurately measure the citrus canopy volume[4] because the crown has the characteristics of complex structure and irregular shape. At present, the acquisition of geometry and structure information of fruit orchard mainly depends on manual measurement. The ruler-based measuring of the primary dimensions of the tree might produce incongruent results due to the subjectivity of the staff involved in the task, and to the fact that models decrease the data accuracy when treating the tree as a regular polygon or spheroid. The volume measurement of individual tree is time-consuming and labor intensive.

In order to obtain the required volume data accurately and efficiently, different equipment and methods were employed to measure the tree canopy volume. It mainly includes ultrasonic measurement method, total station measurement method, 3D vision technology and 3D laser scanning method. Combined with proposing corresponding data processing algorithms, the geometric parameters of trees can be obtained. Basing on the principle of ultrasonic distance measurement, the main problems of ultrasonic measurement method is that the results might be significantly affected by the plant leaf density[5,6]. The accuracy of crown volume obtained by total station measurement method is higher than that obtained by traditional manual measurement method and inferior to that obtained by 3D laser scanning method[7,8]. And the disadvantage of total station method is that the data cannot be visualized. The 3D vision technology[9] can measure canopy parameters, which is simple in implementation with low-cost and high accuracy. The application and development of the technology are limited by the varied working scene and heavy data acquisition work. The 3D laser scanning method with Light Detection and Ranging (LiDAR) provides relative high accuracy for volume measurement[10-13]. But the equipment is expensive

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and bulky, which greatly increased the complexity and cost of data collection[14]. Additionally, LiDAR does not include spectral and textural information[15,16].

With the development of UAV aviation technology, especially automatic navigation technology and oblique photography technology, aerial photogrammetry is shown to be a potential alternative given its low cost of operation in environmental monitoring, high spatial and temporal resolution, and high flexibility in image acquisition programming[17-19].

By processing the high resolution Digital Ortho Map (DOM) and Digital Surface Model (DSM) acquired by UAV, parameters such as crown width, tree height and tree number density are extracted[20,21]. And then, establish the inversion model between field truth and image extraction data to estimate crown traits. Díaz-Varela et al. used a fixed-wing UAV to obtain olive tree images and extracted the tree parameters from a DSM generated from the reconstructed high-density point clouds[22]. Cao et al. used UAV to collect images and produce DEM, DSM and DOM. Information about border trees was extracted on basis of maximum neighborhood filtration method. The results showed that the average relative error of individual tree height was 2.58%, and the extraction rate of tree number was above 95%[23]. Jensen et al. extracted the height of sparse mixed forest by using three-dimensional point clouds produced from UAV high-resolution images, whose results similar to those based on UAV-LiDAR[24].

The oblique photography is a potential alternative to measure the canopy traits because it could not only obtain high-resolution, high-overlap and multi-position images, but also reconstruct high-density point clouds. However, most of the studies were developed in the field of forestry and conducted at the stand scale; few of them set individual trees as the research object. The application of this technology in individual citrus tree with irregular shape is few reported. The research goals of this paper are (1) to evaluate the feasibility of UAV measurements as a high-throughput phenotyping tool of canopy volume in citrus orchard in comparison with traditional on-ground evaluation and use the 3D information in point clouds, and (2) to determine the algorithms suitable for extracting individual tree parameters, especially the canopy volume.

2 Materials and Methods

In this paper, using the high-resolution oblique photographs acquired by a digital camera mounted in a low-cost four-rotor UAV, the 3D point cloud of target trees was generated by structure from motion (SFM) algorithm[16]. Volumes of individual trees were estimated by segmenting normalized point cloud of CHM with three algorithms: cone volume sum algorithm, convex hull algorithm, and trapezoid segmentation algorithm. By constructing the technical framework of automatic extraction of extracting individual citrus tree volume, the optimal algorithms are explored. The approach of this paper is shown in Figure 1.

2.1 Study Sites

All the measurements were conducted in the citrus orchard (106°22'30″-106°23′30″E, 29°45'15"-29°45'40"N) of Citrus Research Institute, Chinese Academy Agricultural Sciences (CRI-CAAS), in Beibei District, Chongqing, China. The study area is located in the sweet orange industrial belt in the upper and middle reaches of Yangtze River, one of the dominant Citrus Industrial Belts in China. Newhall navel orange (*Citrus sinensis* L. Osbeck cv. Newhall), one of the most important and widely cultivated sweet orange variety in China, was chosen as the research object. Orange trees were planted in line with 4.0×4.0 m spacing to form its canopy. All plants were under unified and normal production management, e.g., fertilization, spraying and pruning.

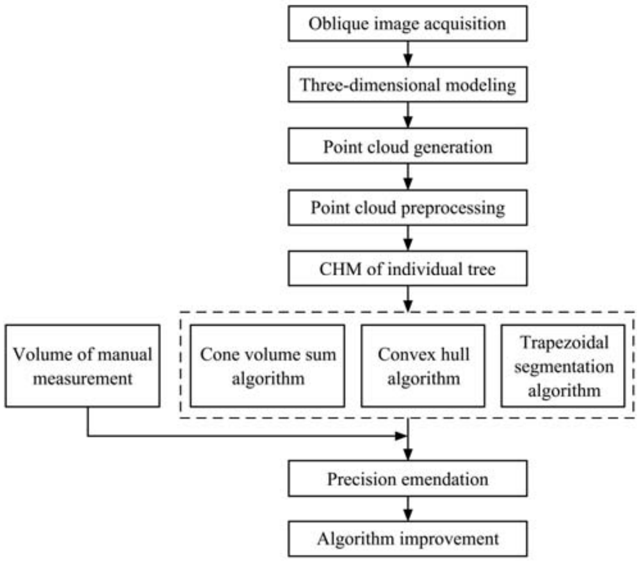


Figure 1 Flowchart of individual tree parameters estimation

In order to explore the feasibility and robustness of oblique photography and data processing algorithms, 6 plants with manual pruning regular shape were selected in this experiment.

2.2 Equipment and Image Acquisition

A Phantom 4 RTK UAV (DJI Co., Ltd., Shenzhen, China) equipped with a FC6310R digital camera (effective pixels: 20 Megapixels), and a built-in DJI onboard D-RTK, which provided precision data for centimeter-level positioning accuracy, was used in this study. There are two types of 3D oblique photography: double grid and multi-oriented. Using multi-oriented mode, the single nadir view flight path and four oblique paths are generated to create more accurate 3D models of the operation area.

The images were captured using multi-oriented mode on September 11, 2019. The gimbal pitch angle was set to 45° when collecting oblique photos. The flight was performed at 40 m altitude with the longitudinal overlap of 80% and the lateral overlap of 70%. Total 1,260 oblique optical photographs with ground resolution (GSD) of 0.86 cm were obtained. The parameters of the aerial photos were shown in Table 1.

Table 1 Parameters of collected photos

Parameters	Value
Photo size	5472×3648
Calibration focal length(Image center as origin) f_x	3663.2
Calibration focal length(Image center as origin) f_y	3656.35
main point offset C_x	–15.32
main point offset C_y	–3.05
Radial distortion correction coefficient K_1	–0.26597
Radial distortion correction coefficient K_2	0.11841
Radial distortion correction coefficient K_3	0.000632
Tangential distortion correction coefficient P_1	0.000291
Tangential distortion correction coefficient P_2	–0.04456

2.3 3D Modeling and Point Cloud Generation

The point cloud data of the citrus orchard was generated based on the overlapping UAV oblique photographs by the aerial triangulation (AT) using Bentley Context Capture (CC) v4.3 (Exton, PA, USA), with additional input data including POS data and a camera calibration model for the digital camera[25]. The original UAV oblique images of test site were divided into some rectangular blocks. And the images of each block is processed by performing interior orientation, measuring and transferring all of the tie points, checking points, performing a least squares bundle adjustment and other operations. The photos of each block were ortho-rectified and mosaicked to produce the point clouds called Digital Surface Model (DSM) and True Digital Ortho Map (TDOM).

The point clouds and TDOM were clipped according to the boundary of the sample plots. It had some noise points that need to be eliminated. Point cloud noise can be classified as high or low noise according to the relative positions of noise points to normal points. In the study, the point cloud obtained using the AT method had high noise caused by false image matching, and it was notably higher than the surrounding average elevation. The method for distinguishing the high noise involved calculating the median and standard deviation of all of the point heights in the neighborhood determined by a certain searching radius for each point. If the point was higher than the specified height difference of the surrounding points, it was judged as a high noise point, and then removed[26].

2.4 CHM Extraction

The point cloud data of a DSM includes ground points, as well as non-ground surface points of artificial buildings, and vegetation. Point cloud filtering serves to remove non-ground points and extract points that represent real ground[27,28]. In the study, the gradual densification algorithm was implemented using Terrasolid (Helsinki, Finland). It firstly seeks the lowest point in each grid cell, takes them as surface points, and uses them as initial seed points to generate a sparse Triangulated Irregular Network (TIN) model. Then, the initial TIN model was raised to achieve the final Digital Terrain Model (DTM). The iterative angle is the maximum angle between the line that connects the target point and the nearest vertex of the TIN model, and the local triangular plane of the TIN model. The smaller the iterative angle, the smaller the surface fluctuation of the point cloud. The iterative angle usually has a small set value of about 4° in flat areas, and a large value of about 10° in mountainous areas. The iterative distance is the distance from the target point to the local triangular plane, which helps to exclude low height objects from the TIN model. Its typical value is 0.5-1.5 m, and it was also dependent on flat to mountainous terrain features. If the iterative angle and the iterative distance were less than the specified values, the target point would be added to the TIN model. Each added point brings the TIN model closer to the real ground, with the process repeating until no new ground points found. The CHM data could be obtained by subtracting the DTM from the corresponding DSM without low vegetation[29].

2.5 Volume Extraction of Individual Canopy

2.5.1 Individual Tree Segmentation

After obtaining CHM, it was necessary to generate the point cloud data of each specific fruit tree for extracting the canopy volume of individual plant. The points of every tree were identified based on the TDOM. In order to improve the segmentation accuracy, depth was introduced to obtain more accurate contour of a single tree. Based on the point clouds of every canopy, the cone sum algorithm, the convex-hull algorithm and the trapezoid segmentation algorithm were employed to estimate crown volume of individual tree respectively.

2.5.2 Cone Volume Sum Algorithm

K.H. Lee et al. (2009) put forward the manual measurement method of subsection accumulation for the first time with the interval of 20 cm[30]. The basic idea of cone volume sum algorithm is discretization-accumulation. The point cloud of crown was cut into numerous slices in the elevation direction, and some micro segments were formed between the slices. When the slices were dense enough, the accumulation of micro segment volume can be regarded as canopy volume. The volume of crown point clouds can be calculated in the following four steps.

Step 1: Projection Slice

According to the elevation, the point cloud was reordered to form a series of height sets from the treetop to the foot. The points in the same set had the same height, then a series of tangent plane point sets were gotten, so-called slice in cone volume sum algorithm. The highest and lowest points were taken as the top and foot of the tree, so the height was the difference between them.

Step 2: Contour Profile Reconstruction

The two-dimensional point cloud extracted from the slice is scattered and disordered, which cannot reflect the profile information. If the farthest two points were found in the same plane, the ligature L divided the point cloud plane into two parts. Taking L as the coordinate axis, according to equation (1), the points were transformed from the space coordinate system to the rectangular coordinate system based on L, which was called L-coordinate system.

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} x \\ y \\ z \end{bmatrix} \times \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \times \begin{bmatrix} \cos\alpha & \sin\alpha & 0 \\ -\sin\alpha & \cos\alpha & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{1}$$

In the formula, the (x_A, y_A) was the coordinate of the point A has the minimum value of X on each plane, and α represented the angle between the L-axis and the x-axis in the original coordinate system, that is, the inclination angle of the line L. Its value was obtained through the inverse trigonometric function.

Based on the equation, the point cloud data in L-coordinate system was obtained as $|X_i|$, $|Y_i|$ and $|Z_i|$ were the coordinates of the i^{th} point of the L_x, L_y and L_z axis respectively. Then, it was necessary to connect the set of section points according to the original topological relationship of the model, that is, to reconstruct the two-dimensional contour of the section. In the field of two-dimensional topological reconstruction of scattered points, nearest neighbor search method was not suitable for multi contour and concave contour, while method based on α - shape strictly required uniform density of point cloud. The observation of the point cloud image shows that, influenced by the real tree shape of citrus fruit trees, the obtained point cloud has multiple contours and narrow concave contours, and the obtained point cloud were inhomogeneous.

Step 3: Area Calculation

The calculation of the cross-sectional area of the tree crown is actually the area of the closed graph formed by the connection of the boundary points on the plane. The three-dimensional point cloud of any specific elevation value of the tree crown is plotted on the plane composed of X-axis and Y-axis. The key and difficulty in this process is to obtain the precise outline of point clouds. Due to the natural growth of the canopy of citrus fruit trees, complex contour shapes are formed. The typical profile includes multi ring section, hole, etc.

By obtaining the plane coordinate information of each boundary point, the calculation of arbitrary cross-sectional area of the tree crown can be realized based on the equation (2).

$$S_i = \frac{1}{2} \times \begin{vmatrix} X_i & Y_i \\ X_{i+1} & Y_{i+1} \end{vmatrix} \quad (2)$$

Step 4: Volume Accumulation

The calculation of crown volume is actually to calculate the volume of segments between two layers after crown segmentation, and then accumulate and sum the volume of segments.

Firstly, the height of the tree was obtained by the difference of Z_{max} and Z_{min} as they were the Z of the top and bottom point respectively and the point data of single tree was divided into reasonable number of layers. The segment between two near layers was approximately composed of circular truncated cone and the volume of it could be calculated by the equation (3). Add the volume of all segmentation units and the result was approximately regarded as the total volume of tree canopy. In the formula, S_i, S_{i+1} are the area of two near layers respectively.

$$V_i = \frac{(\sqrt{S_i S_{i+1}} + S_i + S_{i+1}) \times \Delta_H}{3} \quad (3)$$

2.5.3 Convex-hull Algorithm

The convex hull of point set Q is a minimum convex polygon, which satisfies that the points in Q are either on or inside the polygon edge. That is, given a set of points in a two-dimensional plane, a convex hull is a convex polygonal type formed by connecting the outermost points, which can contain all the points in the set. For convex-hull algorithm[31], the disordered point cloud can be processed directly. The convex hull of 3D Delaunay triangulation was calculated and draw. The output volume parameter was the approximate volume of the canopy.

2.5.4 Trapezoid Segmentation Algorithm

In this work, we modified the cuboid segmentation method proposed by Chen et al[32], and called it as trapezoid segmentation algorithm. The former constructed cuboid elements just based on a single scanning point and resulted in calculation error. Similar to the cone volume sum algorithm, the fruit tree canopy points were divided into several small regular prisms and the canopy volume was the accumulation of unit volume based on the trapezoid segmentation algorithm. First, the point cloud was sorted from the highest points according to the elevation to get a series of planes. Then, the points of same layer were reordered and coordinately transformed according to the L-axis direction. In every plane from treetop to foot, every two adjacent contour points and their projection points on L were linked to form a trapezoid. The trapezoids were projected to the next near plane, and the regular prism units were generated. In practical terms, the bases length of trapezoids were the distances from contour point to coordinate axis, and the altitude was the distance of the contour point in the coordinate axis direction. The height of the prism was the elevation difference between the two planes. The canopy volume was calculated as the volumes sum of the prims.

2.6 Canopy Volume Measurement

The manual measurement method of crown volume is to select the approximate regular geometry to simulate the shape of the crown part. By manually collecting crown diameters and crown height, the volume of the whole crown can be calculated by applying empirical models.

Field truthing on the orange trees were carried out in the experimental orchard in mid-September, 2019. All of the trees were manually measured with a ruler. Three indexes were made in each tree: crown length diameter (D_1), crown width diameter (D_2, perpendicular to $D1$), crown height (H, perpendicular to D_1 and D_2). The crown volume (V) was calculated assuming a spheroid shape and applying the validated equation (4)[33].

$$V = \frac{\pi}{6} \times D_1 \times D_2 \times H \quad (4)$$

2.7 Evaluation of Canopy Volume Estimation

In order to select the best method to estimate canopy volume, the accuracy of the target plant structure parameters, height and volume of crown, were analyzed based on manual measurement and estimation volume. In this study, the coefficient of determination (R^2), root mean square error (RMSE) and relative root mean square error (rRMSE), average absolute error (ABE) and mean absolute value of relative error (MARE) were used to evaluate the feasibility of UAV and the accuracy of volume estimation of individual trees. The equations are as follows:

$$R^2 = 1 - \frac{\sum_{i=1}^{n} (\tilde{x}_i - \bar{x})^2}{\sum_{i=1}^{n} (x_i - \bar{x})^2} \quad (5)$$

$$RMSE = \sqrt{\frac{1}{n} \sum_{1}^{n} (x_i - \tilde{x}_i)^2} \quad (6)$$

$$rRMSE = \frac{RMSE}{\bar{x}} \quad (7)$$

$$ABE = \frac{1}{n} \sum_{i=1}^{n} (\tilde{x}_i - x_i) \quad (8)$$

$$MARE = \frac{1}{n} \sum_{i=1}^{n} \left| \frac{\tilde{x}_i - x_i}{x_i} \right| \quad (9)$$

In the formulas, x_i is the measured value, $\tilde{x}_i$ is the extracted value, and $\bar{X}_i$ is the measured average value.

3 Results

3.1 Citrus Canopy Volume

In the experimental orchard, some fruit trees on the edge were sheltered by buildings, fences, or roadside trees, were therefore abandoned. In addition, two trees have not yet fully developed a crown and were also not selected. Total 82 Newhall navel orange trees with irregular shape (marked with red circle in Figure 2) were selected in this study.

Figure 2 The experimental orange trees

The measured canopy volume results of two type trees were presented in Table 2. For the orange trees, the measured volume values covered 4.6511-21.2099 m^3, with $SD = 3.1691$ and $CV = 0.2316$. The number of volume <5, 5-10, 10-15, 15-20, >20 are 1 (1%), 4 (5%), 48 (59%), 27 (33%) and 2 (2%), respectively. The orange canopy trees are free to form irregular shapes, and its volume values change greatly. For the landscape trees, the measured volume values covered 2.7515-4.8049 m^3, with $SD =$

0.7835 and *CV*=0.2013. Landscape trees were planted scattered and trained up to form the subglobose canopy.

Table 2 Measured volumes of sample trees

Samples	Number	Range/m^3	Mean/m^3	*SD*	*CV*
Orange tree	82	4.6511-21.2099	13.6837	3.1691	0.2316
Landscape tree	6	2.7515-4.8049	3.8922	0.7835	0.2013

Note: *SD*, Standard deviation; *CV*, Coefficient of variation.

3.2 CHM Extraction

The 3D point cloud was generated by sequentially applying AT processing and 3D reconstruction to UAV-acquired oblique photographs. In order to remove high-noise, the median and standard deviation of all of the point heights in the neighborhood determined by a certain searching radius for each point were needed. Then, the neighborhood points were defined as a circle with a radius of 5 m, and the threshold of height difference was set to 0.5 m. Depth was applied to the point cloud, which increased the difference between the crown and the ground to facilitate the subsequent classification and individual tree crown segmentation.

To classify points into two categories-the crown and the ground, the gradual densification algorithm was implemented. The correct setting of angle and distance parameters is the basis of the optimum effect of the algorithm. As recommended by Lin et al.[34], the iterative angle and iterative distance in citrus orchard were set to 4°and 1.4m respectively in the algorithm for filtering non-ground points. After the above process, the points of trees were visualized (shown in Figure 3). A total of 69,271,130 and 2,950,892 points were ultimately obtained as the CHM of the Newhall Navel Orange trees and Landscape trees respectively. Taking the TDOM as reference, points of individual tree were segmented from the whole CHM by interaction method.

3.3 Evaluation of Canopy Volume

For 82 navel orange fruit trees and 6 landscape trees, the above three algorithms were employed to calculate the canopy volume, and the accuracy of the target plant structure parameters, height and volume of crown, were analyzed based on manual measurement and estimation volume. The results evaluation indexes of canopy volume estimation using above three algorithms were shown in Table 3. The average RMSE of navel orange trees was 2.56 m^3, and the rRMSE was no higher than 18.92%. The average RMSE of landscape trees was 0.28 m^3, and the rRMSE was no higher than 7.35%.

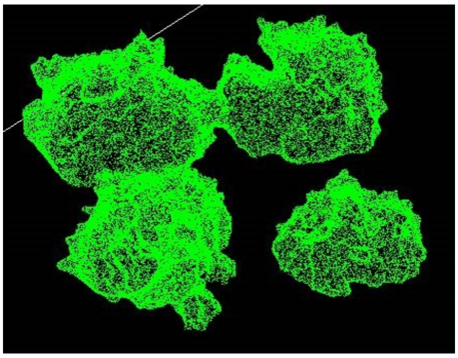
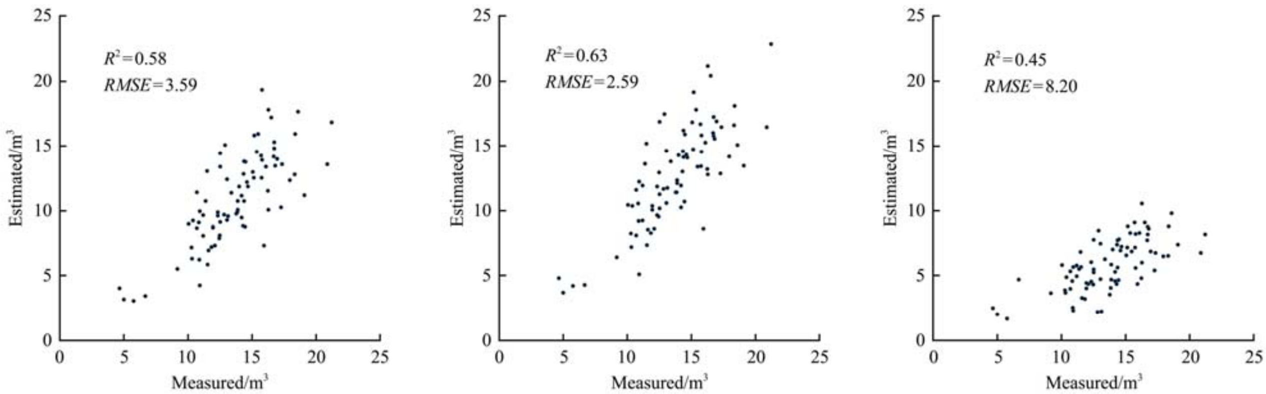


Figure 3 The point cloud of citrus canopies

Table 3 Evaluation indexes of canopy volume estimation using three algorithms

Tree type	Indexes	Cone volume sum algorithm	Convex hull method	Trapezoidal segmentation algorithm
Navel orange tree	RMSE/m^3	2.59	3.59	8.20
	rRMSE	18.92%	26.25%	59.90%
	ABE/m³	–0.82	–2.61	–7.76
	MARE	15.84%	23.20%	57.40%
Landscape tree	RMSE/m^3	0.44	0.28	1.77
	rRMSE	11.32%	7.35%	45.62%
	ABE/m³	–0.17	–0.16	–1.70
	MARE	10.52%	4.40%	43.09%

For the navel orange trees, the R^2 between the canopy volume estimation values using the cone volume sum algorithm and the manual measured values was 0.63, and it is higher than that by the other two algorithms (shown in Figure 4). For the landscape tree, the convex-hull algorithm did best, and the R^2 was 0.89. With the convex-hull algorithm and cone volume sum algorithm, the volume estimation accuracy of landscape trees is greater than that of navel orange trees. Moreover, for both the volume extraction of the two type trees, the performance of trapezoid segmentation algorithm was the worst. The results show that the convex-hull method is suitable for extracting individual tree parameter of landscape trees, and the cone volume sum algorithm is suitable for extracting individual tree parameter of navel orange tree.



a. Convex hull method b. Cone volume sum algorithm c. Trapezoidal segmentation algorithm

Figure 4 Scatter plots of measured volumes of navel orange trees VS estimated using three different algorithms

4 Discussion

4.1 Feasibility of Oblique Photography for Canopy Volume Estimation

One of the objectives of this study is to explore the potential of UAV oblique photography in accurately extracting canopy volumes of individual trees. Although airborne laser scanning (ALS) can more accurately estimate the vertical structure of forest in the range of canopy density, SFM is still a low-cost stand survey method [35]. What's more, in Terje Gobakken's study[36], when estimating height in young forest and mature forest on poor sites, the root mean square error (RMSE) values were slightly better using data from image matching compared to ALS. There is a rather high correlation between the volume values using UAV oblique photography and field measurement results, as R^2 are 0.89 (landscape trees) comparing with 0.63 (Navel orange trees). The results show that the point clouds acquired by UAV oblique photography have great potential in extracting the parameters of a single tree due to the density of point cloud data was high and each point has spatial coordinate information[37]. The high-resolution and high-overlap oblique images provide high-density point cloud data for calculating canopy volume and other parameters. Li et al[1] used a laser scanner mounted on a ground vehicle and designed the corresponding algorithm to extract the canopy volume of regular and irregular plants, however, this way was restricted by the geographical environment of the orchard. Digital aerial photogrammetry (DAP) is becoming an alternative data source for ALS data for three-dimensional characterization of forest structure. Compared with traditional aerial photogrammetry, oblique photography has higher extraction accuracy because it could collect more comprehensive canopy information. This work shows that it is feasibility to estimate the canopy traits and locate the canopy of the orchard trees on large scale using oblique photography, which can be used for orchard production management.

4.2 Accuracy Evaluation and Algorithm Comparison

We selected the cone volume sum algorithm, convex hull algorithm and trapezoidal segmentation algorithm for individual tree volume estimation. The results show that the convex-hull algorithm is suitable for individual landscape trees volume extraction with the highest accuracy (RMSE=0.28 m^3, rRMSE=7.35%, ABE=–0.16, MARE=4.4%), which may be because the crown is oval and cone-shaped and thicker foliage, and the point clouds acquired by oblique photography can be used to estimate the volume of landscape tree with dense leaf effectively. The cone volume sum method performs best in the individual tree extraction of navel orange trees (RMSE=2.59 m^3, rRMSE=18.92%, ABE=–0.82 m^3, MARE=15.84%). This is because the crown shape of navel orange tree is extremely irregular, and the branches and leaves are disordered and unevenly distributed. The convex hull method cannot eliminate the influence of them. But, for some navel orange trees with regular crown shape, the volume values estimated by convex hull method are close to the measured values, which is consistent with the results of landscape tree. For trapezoid segmentation algorithm, there are two reasons for its worst performance. First, there was a big disparity between the plane formed by trapezoid and the real contour of the slice. Second, although the slices are comparatively dense, there were still differences between sections. As a result, when the trapezoid was projected downward, some parts of the crown were less or over calculated.

Although the method has achieved relatively high extraction accuracy, there are still large errors compared with the actual results. In the canopy volume extraction in citrus orchard, many factors could have influenced the accuracy of the results. When acquiring optical photographs, the UAV attitudes and GPS accuracy would affect the geo-reference precision of the resulting data. While generating point cloud data, the image matching and AT processing might introduce some errors[38]. When producing DTM, the recommended iterative angle and iterative distance might cause some errors in filtering non-ground points. Some adjacent trees have so-called grafting phenomena (i.e., two adjacent branches intersect each other), which may lead to misclassification in segmentation. The observation error will inevitably be introduced due to the influence of tools and subjective factors. On the other hand, the calculation of the measured crown area uses the average length in the north-south and east-west directions as the diameter to calculate the circular area, which results in the measured area being larger than the actual canopy area.

Additionally, for the calculation of crown volume, the lack of fine-sampling manual measurements is often an important constraint, and the difference between the reference volume obtained by the empirical model and the real volume is inevitable. So it is necessary to select the appropriate model according to different tree shapes. Therefore, the extraction accuracy of individual tree heights and estimated individual tree canopy volume depended on the cumulative result of all of the errors incurred throughout the whole process.

5 Conclusions

In this present work, the feasibility of canopy volume estimation based on oblique photography using a low-cost four-rotor UAV was explored. The three-dimensional point cloud of target trees was extracted based on high-resolution images acquired by oblique photography of target trees with UAV. The gradual densification algorithm and threshold method were used to accomplish the work of classification of point cloud to obtain the CHM. For 82 Newhall navel orange trees and 6 landscape trees, individual canopy volumes were estimated by segmenting normalized point cloud of CHM using three algorithms: cone volume sum algorithm, convex-hull algorithm, and trapezoid segmentation algorithm. For landscape trees, the volume accuracy extracted by convex-hull method is higher than that by the other two algorithms. For navel orange trees, the cone volume sum algorithm performs best. This study shows that UAV oblique photography has good effect in terms of individual tree parameter extraction for citrus orchard management. Compared with three-dimensional laser scanner and ground-based LiDAR, UAV has lower price, higher efficiency and wider application prospects. The citrus canopy volume estimation based on UAV oblique photography is the result of the interaction of software and hardware, so further and systematic research is needed.

Author Contributions

Teng Wang: experimental design and conducting, data collection and analysis, paper draft and revision;

Jiacao Li and Lin He: data collection, and analysis

Lie Deng: research design, paper draft and revision;

Yongqiang Zheng: data analysis;

Shilai Yi and Rangjie Xie: materials contribution;

Qiang Lyu: research conception and design, final draft approval.

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Conflicts of Interest

The authors declare there is no conflict of interest.

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