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ORIGINAL ARTICLE

Drone-Based Three-Dimensional Photogrammetry and Concave Hull by Slices Algorithm for Apple Tree Volume Mapping

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Abstract

Purpose Apple tree volume is an important factor in apple quality control and spraying strategies. The measurement is a laborious task because of the complex structure of the apple tree. This study developed a technology for accurately estimating the apple tree volume from unmanned aerial vehicle-based multi-view three-dimensional reconstruction data using a novel concave hull by slices algorithm.

Method The CloudCompare software was used to preprocess the 3D data and extract a single tree. The 3D point cloud data of the tree were divided into truncated cone-type small slices of a specific thickness. The area of each slice was calculated using the proposed concave hull by slices algorithm. The tree volume was calculated by summing the volume of slices. The proposed method was verified on ten apple trees by comparing the results obtained using the proposed method with those calculated by two existing methods.

Results The proposed method provided the most accurate tree volume, while avoiding the influence of gaps and holes in the tree. The mean absolute percentage error (MAPE) and root mean squared error (RMSE) were 8.07% and 0.55 m^3, respectively.

Conclusion These results indicate that the concave hull by slices method can be used to calculate the tree volume from 3D point cloud data more effectively. Tree volume mapping was achieved by combining the tree volume with the tree position.

Keywords Concave hull by slices · Oblique photogrammetry · Three-dimensional reconstruction · Tree volume mapping

Introduction

Apple trees are cultivated worldwide and more than 87 million tons of apples are produced each year (FAOSTAT, 2019). Fertile planting land and high-quality orchard management are necessary to ensure the stable and increased production of apples (Qi et al., 2021). The volume and exterior structure of the canopy of apple trees are significant markers for determining their growth and biological characteristics (Wang et al., 2004). Fruit producers can estimate the amount of nutrients required by trees and the quantity of fruit produced throughout the fruiting period based on the canopy volume. Moreover, canopy volume is closely related to water evaporation. These factors have a direct influence on the operation and economic benefits of an apple orchard. Therefore, automated measurement of the canopy volume of apple trees is critical for managing orchards.

The traditional manual measurement of tree canopies focuses on the extraction of important parameters, including tree height, diameter at breast height, and crown diameter. However, this task is labor-intensive, time-consuming, and imprecise. Extracting these tree parameters from remote sensing data has been considered as an effective method for acquiring tree features (Dalponte et al., 2018, Yin et al., 2015). Jing et al. (2012) developed a method that uses multiscale filtering and segmentation to extract high-quality single-tree crown maps from multispectral aerial imagery. This method can provide large-scale crown map information based on two-dimensional (2D) data without crown volume. Recently, light detection and ranging (LiDAR) (Jimenez-Berni et al., 2018), ultrasonic sensors (Gangadharan et al., 2019), and infrared photoelectric sensors (Yin et al., 2021)

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have been used for three-dimensional (3D) data collection and canopy structure estimation of trees. Three-dimensional data, which can directly describe the geometrical characteristics of tree crowns, can be utilized to estimate crown volume. With the development of oblique photogrammetry and the structure from motion (SFM) algorithm, research on unmanned aerial vehicle (UAV)-based multi-view photogrammetry and 3D point cloud-based tree model processing has been widely conducted. Gülci (2019) built a 3D canopy model using UAV-based photogrammetry technology to estimate the number, height, and canopy coverage of trees. Based on oblique photogrammetry, Qi et al. (2021) combined deep learning-based segmentation to obtain the 3D point cloud of a single fruit tree and estimated the volume of the tree canopy. UAV-based oblique photogrammetry with point cloud data processing has become the most popular method for estimating individual tree volume.

Volume estimation from the 3D point cloud of apple trees is efficient and labor-saving. A commonly used method for calculating tree canopy volume is 3D convex hull-based geometric calculations (Yan et al., 2019). Korhonen et al. (2013) used the 3D convex hull technique to extract tree crown volume from airborne laser scanning data. The results showed that the LiDAR-based estimates were highly correlated with field-measured tree crown volumes. Colaço et al. (2017) used a 3D alpha shape algorithm to calculate the crown volume from LiDAR data. They concluded that their proposed method provides more accurate crown volumes than the 3D convex hull method. However, gaps within the crown are difficult to exclude. Thus, volume calculation methods generally overestimate the tree volume, especially the 3D convex hull algorithm.

Therefore, the major goal of this study was to develop a novel concave hull by slices method to estimate the canopy volume of apple trees more accurately using a 3D point cloud reconstructed by UAV-based multi-view photogrammetry. The specific objectives were to (1) obtain images of orchards using a UAV-based multi-camera system and make 3D reconstruction of apple trees; (2) develop a concave hull by slices method to calculate the tree canopy volume and calculate the tree volume and position; (3) compare the proposed method with existing methods, and (4) create a map of tree volume.

Materials and Methods

Data Collection

The experimental site of this study was located in the National Institute of Horticultural and Herbal Science, Rural Development Administration, Jeonju City, Republic of Korea, with the geographical coordinates of 127.02°E and 35.82°N as shown in Fig. 1. A total of 235 apple trees in six rows were selected for this study. These apple trees were trained using a vertical axis system and maintained in a narrow pyramidal shape with a dominant central leader. The apple trees were spaced at 4 m between tree rows and 2 m between trees in a row.

Three Sony α5100 cameras (Sony Corporation, Tokyo, Japan) with a 24 MP (6,000 × 4,000 px), CMOS APS-C sensor (23.5 × 15.6 mm), and 20 mm f/2.8 lens were mounted on a DJI S1000 drone (DJI Sciences and Technologies Ltd., Shenzhen, China) with RTK-GPS to acquire images of the apple trees (Fig. 2a and Fig. 2b). The angle between the center camera and oblique camera was 45° so that the system could capture a larger area with side information of the apple trees. The flight height of the drone was set to 10 m. The ground sampled distance (GSD), which is the distance between pixel centers measured on the ground, of the center camera was approximately 2 mm to create a high-resolution 3D point cloud. To improve the accuracy of triangulation, the forward and side overlap ratio was set to 80%. The flight path planning of the drone with a flight speed of 1.5 m/s, a GSD of 2 mm, and an overlap ratio of 80% was configured using UgCS software (SPH Engineering, Latvia) as shown in Fig. 2c. The ground control points (GCPs) and checking points (CPs) were evenly distributed in the field (Fig. 2d). The original 3D point cloud reconstructed by multi-view images was calibrated using the GCPs and the accuracy of the 3D point cloud was verified using the CPs. The positions of the GCPs and CPs were measured using a TDR-3000 RTK-GPS (MBC & SYNEREX, Seoul, Republic of Korea) and then converted from the World Geodetic System (WGS) 84 coordinate system into the European Petroleum Survey Group (EPSG): 5186, which is the Korea 2000/Central Belt 2010 coordinate system. The experiment of capturing tree images using the drone was conducted on August 18, 2020, on a sunny day with low wind speed. Accordingly, the international organization for standardization (ISO), which is a camera setting that can brighten or darken a photo, and the shutter speed of the camera were set to 200 and 1/250 s, respectively, to ensure that a high-quality image was captured using the UAV. Right after capturing the tree images using the UAV, a Velodyne 16 LiDAR (Velodyne LiDAR, California, USA) mounted on a mobile robot was used to scan each tree in the same experiment field and generate 3D point clouds (Fig. 2e). The LiDAR measurement could directly record the real geometry characteristic of the trees and thus was used as the reference data because the ground truth of the canopy volume was difficult to obtain manually.

3D Reconstruction Process of Orchard

The SFM algorithm, which is a photogrammetric range imaging technique for estimating three-dimensional

Fig. 1 Experimental field in the apple orchard

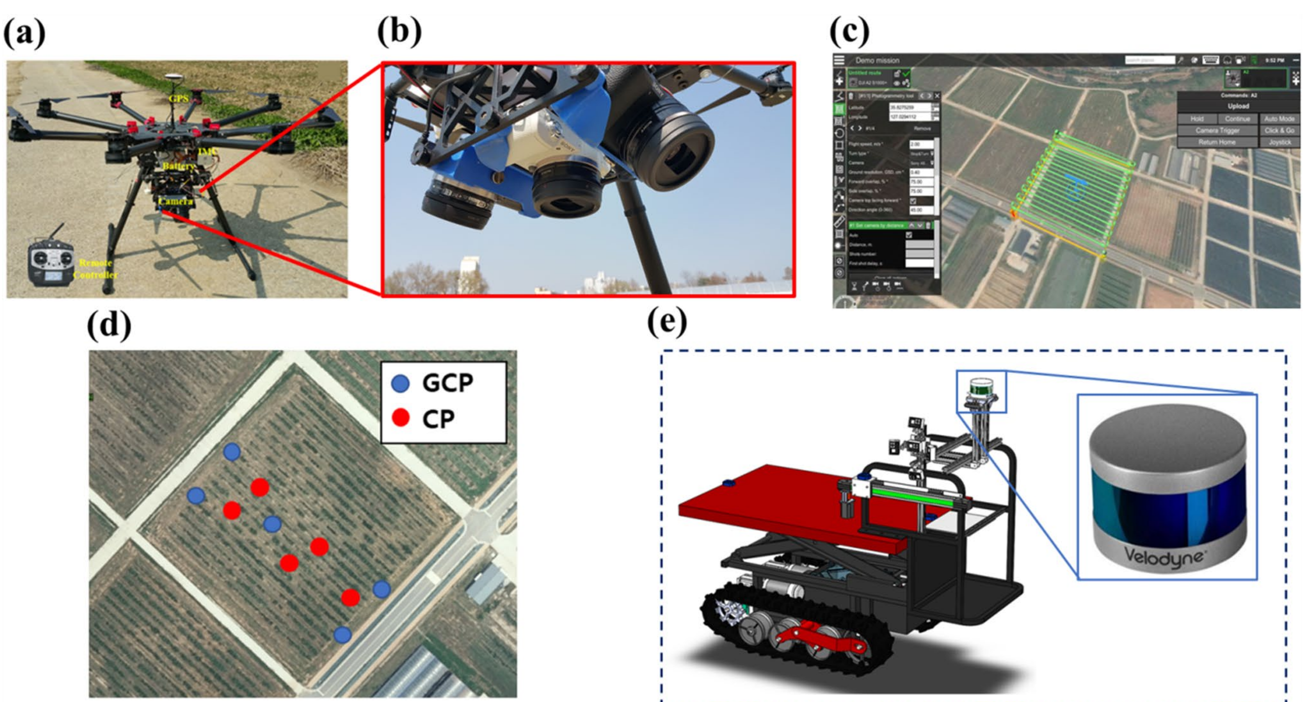

Fig. 2 UAV-based image collection system. **a** DJI drone and Sony cameras; **b** multi-camera platform; **c** ground control station software (UgCS) for flight path planning; **d** GCPs and CPs distribution; **e** Velodyne 16 LiDAR mounted on a mobile robot platform

structures from two-dimensional image sequences, was used to create 3D point cloud from multi-view images. First, the scale-invariant feature transform (SIFT) algorithm (Lowe, 2004) was used to detect the characteristic points that were stable under different viewpoints and lighting conditions. Additionally, a descriptor was produced for each point depending on the nearby neighborhood (Fig. 3b). The descriptors were then used to identify similar points across the images and to match the image pairs (Fig. 3c). The image geometry adjustment algorithm and calibration of the GCPs were used to calculate the camera position and orientation to generate a sparse 3D point cloud (Fig. 3d). Finally, a dense reconstruction of the orchard could be performed using multi-view stereo (Kuhn et al., 2017) as shown in Fig. 3e.

To verify the accuracy of the 3D reconstruction and canopy volume of the proposed algorithm, reference data were collected using a Velodyne 16 LiDAR. A high-performance algorithm called LeGO-LOAM (Shan and Englot, 2018) was used to generate a 3D point cloud of the orchard using LiDAR data (Fig. 4a) and individual trees could be extracted from the 3D point cloud (Fig. 4b). The tree volume was calculated by dividing the tree into slices, manually extracting the tree boundary of a slice, and then accumulating the area of the irregular polygon of each slice (Fig. 4c). The volume calculated from the LiDAR data was used as the reference data.

Volume Calculation Algorithm

Several methods for the segmentation of individual trees using 3D point cloud data have been developed (Lin et al., 2010; Wang et al., 2016). In this study, we focused on developing an algorithm to estimate the tree volume. The extraction of a single apple tree was conducted manually using CloudCompare (2021), which is an open-source software package for 3D point cloud processing including statistics computation, resampling, and automatic segmentation. The principal method used in this study involved four main steps (Fig. 5): (1) extraction of 3D point clouds of individual trees generated from the image; (2) calculation of tree volume using the proposed concave hull by slices algorithm; (3) comparison of the results obtained using the proposed algorithm with the existing methods, and (4) mapping of the volume of apple trees.

Due to the irregular edges of the canopy and the large number of pores, a traditional 3D convex hull algorithm, which calculates a volume by constructing a 3D convex geometry of an outer surface of 3D point clouds of a tree canopy, cannot effectively exclude canopy void gaps (Fig. 5). However, the slice-based volume calculation method can reduce the estimation error of tree volume. For discrete points on a sliced plane, the convex hull method is a commonly used method for calculating the plane area. However, the boundary polygon generated by the convex hull cannot

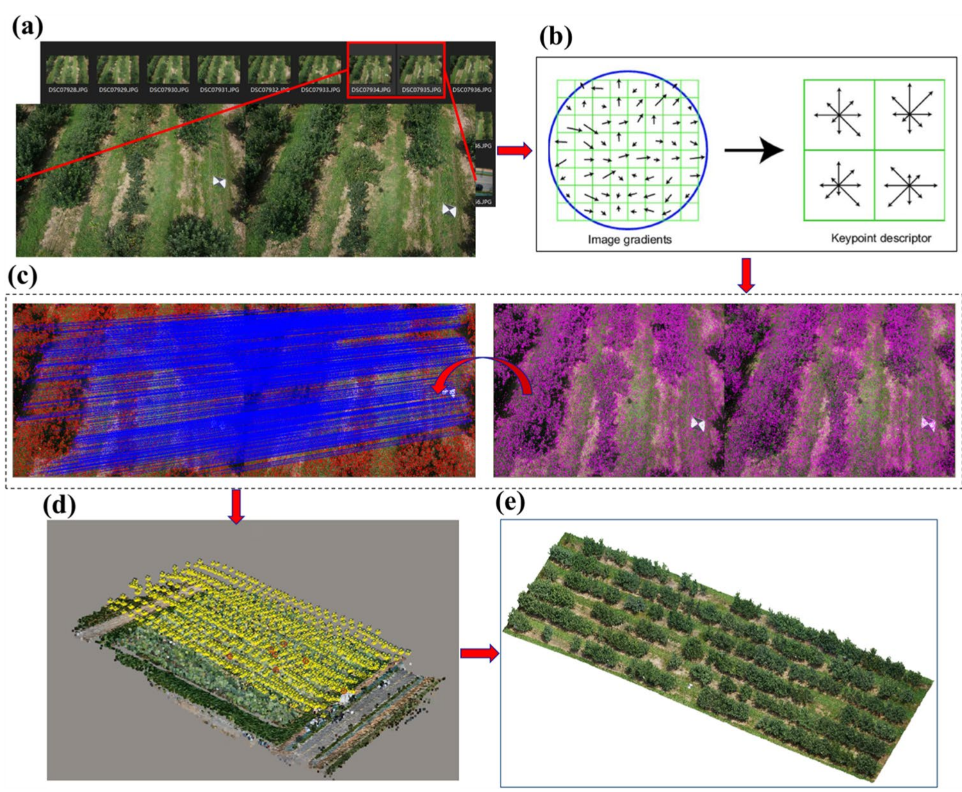

Fig. 3 3D reconstruction of the orchard. **a** 2D image set; **b** SIFT algorithm; **c** feature point extraction and image pair matching; **d** aerial triangulation and bundle adjustment; **e** dense 3D point cloud of the orchard

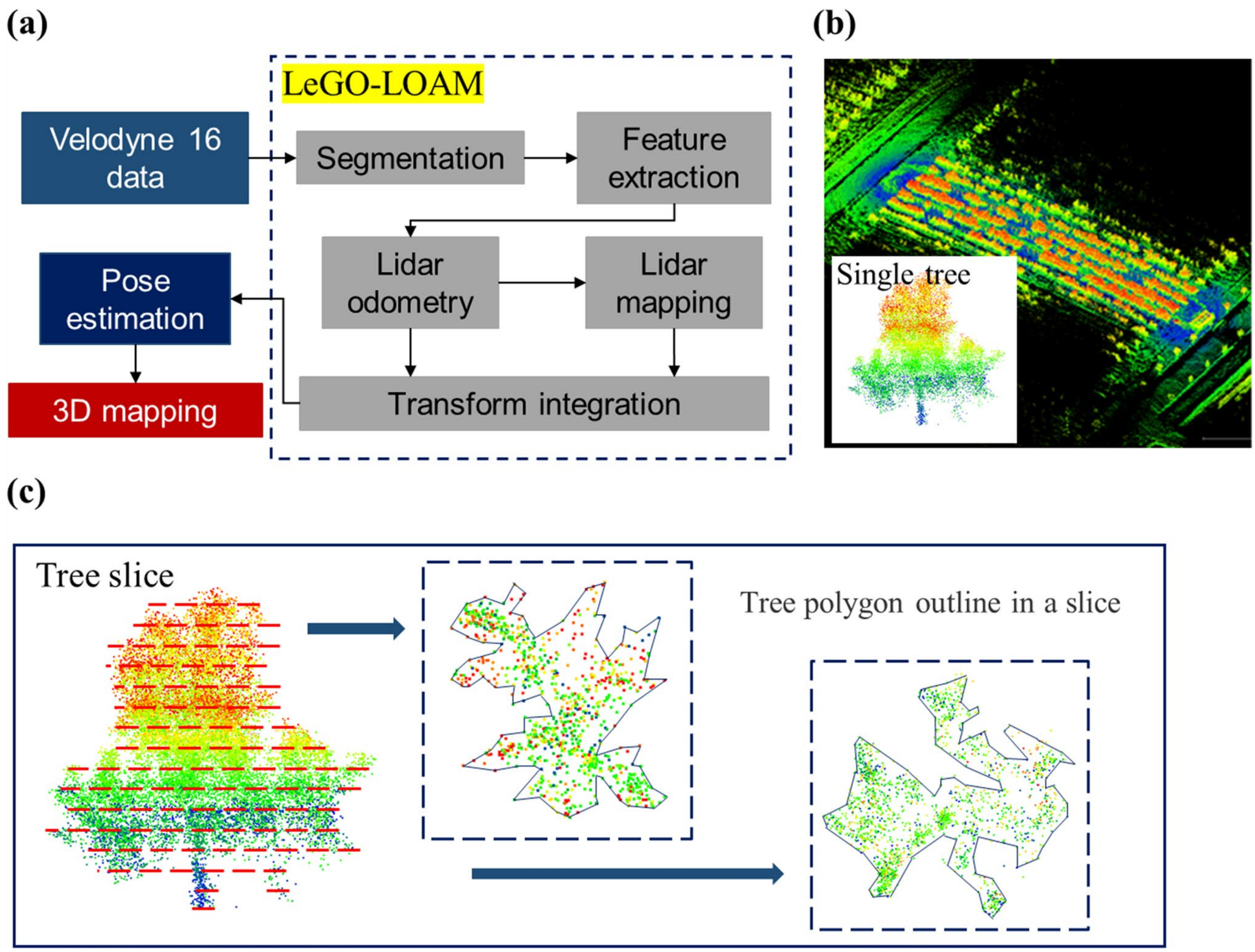

Fig. 4 3D mapping of LiDAR data in apple orchard. **a** LeGO-LOAM algorithm for 3D mapping of LiDAR data; **b** 3D mapping of orchard and individual tree of LiDAR data; **c** tree slice of LiDAR data and extraction of tree polygon outline in a slice

entirely represent the contour of the discrete points. This is particularly obvious in the point cloud of a tree. To further reduce the influence of holes and gaps in the tree crown, a novel iterative incremental concave hull-based volume calculation method was developed. The following steps were used in the concave hull method to sum the areas of the point cloud of the tree crown slices and then calculate the tree volume (Fig. 6):

Step 1: The 3D point cloud of the canopy was stratified at equal intervals of Δh from the bottom to the top and each layer was stored as an independent unit.
Step 2: The 3D point cloud after stratification was projected onto the ground plane.
Step 3: The outer contour was constructed for each layer of the point cloud using the traditional convex hull algorithm (Fig. 6b).
Step 4: The edge length threshold of the outer contour was set as L_{limit}. A circular region was built using an edge that was larger than the threshold. The points in the circle were considered as candidates for new contour vertices and vectors were drawn between each candidate point and the endpoints of the diameter. The candidate point for which the angle between the vectors was maximum would be the new contour vertex as shown in Fig. 6c.
Step 5: The final contour could be obtained by repeating step 4 until the edges of the contour were lower than the threshold L_{limit} (Fig. 6d–6f).
Step 6: Once the proposed concave hull was generated, the vertices of the contour were arranged counterclockwise. For the vertex coordinates $(x_1, y_1), (x_2, y_2), \ldots, (x_i, y_i), \ldots, (x_n, y_n)$, the area of the concave hull was calculated using Eq. (1):

$$S_j = \frac{1}{2}\sum_{i=1}^{n-1}(x_i y_{i+1} - x_{i+1} y_i) \tag{1}$$

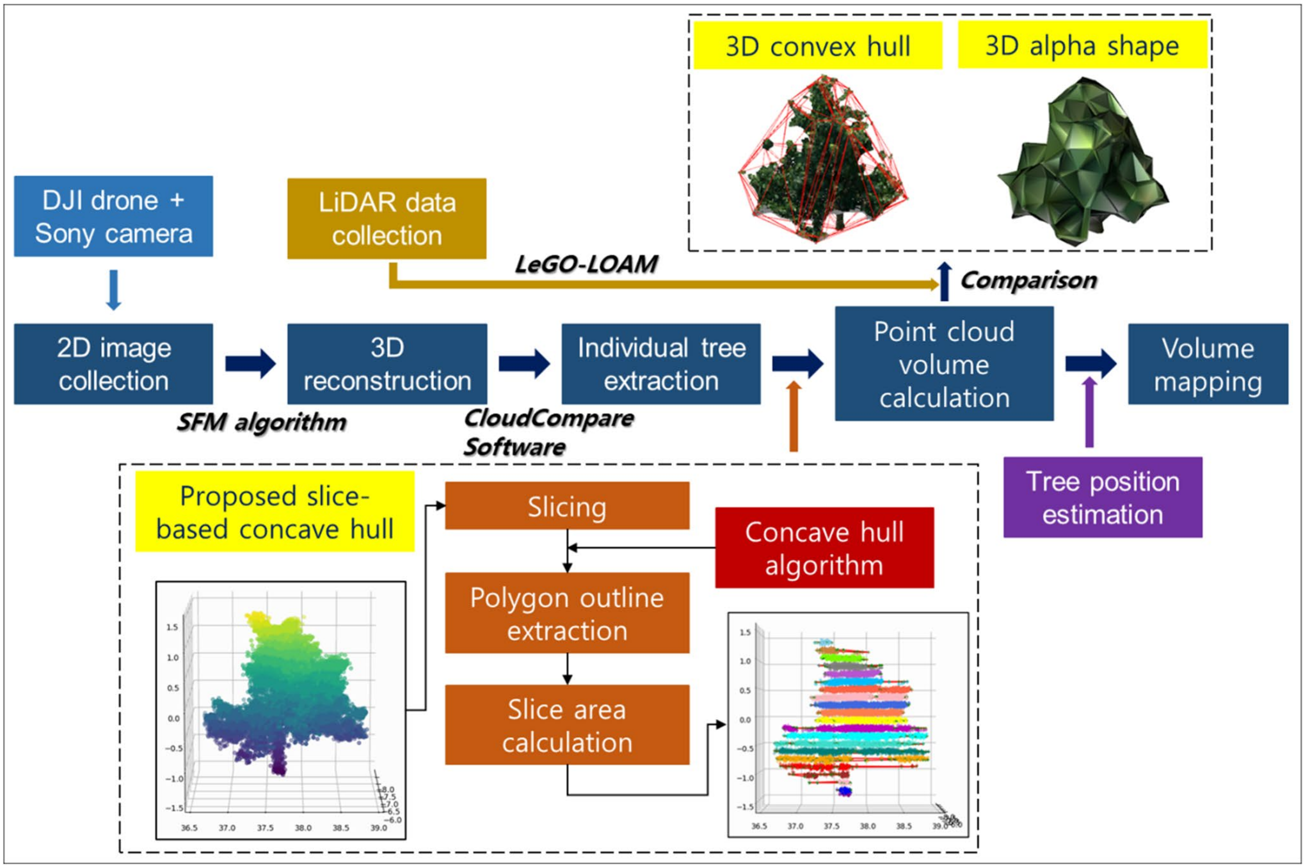

Fig. 5 Block diagram of the proposed volume estimation method

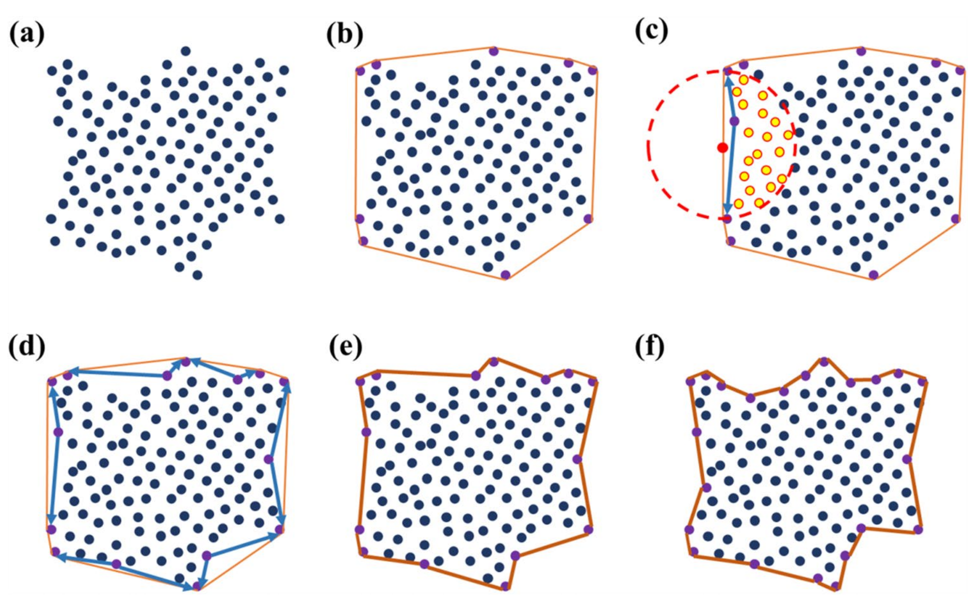

Fig. 6 Principle of the proposed concave hull algorithm. **a** Points of each layer projected on a plane; **b** outer contour generated by the convex hull method; **c** selection of the candidate points in the circle; **d** new boundary points; **e** new outer contour after one iteration; **f** final outer contour

where S_j is the area of the j th crown point cloud slice, (x_i, y_i) is the coordinate of the i th vertex of the concave hull generated by the proposed concave hull algorithm in each slice, and n is the number of concave hull vertices.

Step 7: Two adjacent slices were used to construct an irregular polygonal block. The volume of the block was calculated using Eq. (2):

$$V_j = \frac{1}{3}(S_j + \sqrt{S_j S_{j+1}} + S_{j+1})\Delta h \quad (2)$$

where V_j is the block volume of the j th crown point cloud slice.

Because the 3D point cloud of the tree crown was divided into N layers, the total volume (V) of the tree was calculated by summing the volumes of all slices using Eq. (3).

$$V = \sum_{j=1}^{N} V_j \quad (3)$$

Tree Position Estimation

To map the tree volume, the tree position must be calculated. Calibration with GCPs before dense 3D reconstruction can convert the coordinates of the 3D point cloud to the EPSG: 5186 coordinate system so that each 3D point of the tree has GPS position information. The polygon outline of the apple tree could be obtained by projecting the 3D point cloud of the entire tree on the ground plane and executing the proposed concave hull algorithm as shown in Fig. 7a. The tree position was calculated using the center of gravity of the irregular polygon using Eqs. (4) and (5).

$$C_x = \frac{1}{6A}\sum_{i=0}^{n}\left(x_i + x_{i+1}\right)\left(x_i y_{i+1} - x_{i+1} y_i\right) \quad (4)$$

$$C_y = \frac{1}{6A}\sum_{i=0}^{n}\left(y_i + y_{i+1}\right)\left(x_i y_{i+1} - x_{i+1} y_i\right) \quad (5)$$

$$A = \frac{1}{2}\sum_{i=0}^{n-1}\left(x_i y_{i+1} - x_{i+1} y_i\right) \quad (6)$$

where (C_x, C_y) is the center of gravity of the irregular polygon, (x_i, y_i) is the coordinate of the i th vertex of the irregular polygon generated by the proposed concave hull algorithm, n is the number of vertices, and A is the area of the irregular polygon.

The tree position was thus obtained in 3D space (Fig. 7b).

Statistical Analysis

To validate the performance of the proposed volume calculation and tree position estimation, the mean absolute percentage error (MAPE) was computed between the estimation obtained by the proposed algorithm (E_i) and the ground truth from the reference data (R_i) using Eq. (7).

$$MAPE = \frac{100}{n}\sum_{i=1}^{n}\frac{\left|E_i - R_i\right|}{R_i} \quad (7)$$

where n is the number of samples.

Results and Discussion

Tree Volume Estimation

The volume of 10 sample trees was in the range of 3.33 to 8.08 m^3, which was measured by LiDAR measurement by accumulating slice area and considered as the ground truth. The tree volume estimated by the proposed method was compared to that estimated by two conventional methods: the 3D convex hull method and the 3D alpha shape method. The mean volumes calculated by the proposed method, the 3D convex hull, and the 3D alpha shape were 5.50 ± 1.53, 7.67 ± 2.41, and 5.71 ± 1.96 m^3, respectively, as shown in Table 1. The proposed method provided the most similar results to LiDAR measurement. Through Duncan's multiple-comparison test, the significant differences among the four methods were examined. There was no significant difference among the LiDAR measurement, the proposed method, and the 3D alpha shape method at a 5% significance level. However, the 3D convex hull method showed a

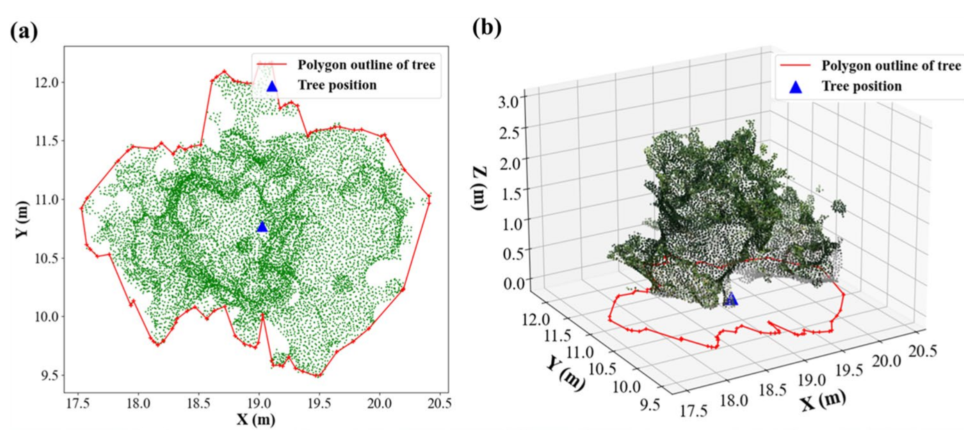

Fig. 7 Tree position calculation. **a** Concave hull in the projected ground plane and the tree position as the center of gravity of the polygon outline; **b** visualization of the tree position in 3D

Table 1 Comparison of tree volume estimation using different methods

Tree number	Tree height (m)	Tree volume (m^3)			
		LiDAR measurement[a]	Proposed method[a]	3D convex hull[b]	3D alpha shape[a]
Tree 01	3.03	3.43	3.66	4.95	4.10
Tree 02	3.18	8.08	8.16	11.83	9.17
Tree 03	2.87	5.36	5.21	6.81	4.94
Tree 04	2.59	3.33	3.57	4.88	3.03
Tree 05	3.23	6.24	6.01	9.90	7.76
Tree 06	2.86	3.53	3.11	4.65	2.68
Tree 07	3.09	4.56	6.07	6.54	5.75
Tree 08	3.34	6.16	5.99	8.68	6.00
Tree 09	2.90	6.86	6.78	10.58	6.82
Tree 10	2.89	5.84	6.42	7.85	6.83
Min		3.33	3.11	4.65	2.68
Max		8.08	8.16	11.83	9.17
Mean		5.34	5.50	7.67	5.71
Std		1.52	1.53	2.41	1.96

[a,b]: significant difference in Duncan's multiple-comparison test at a 5% significance level

significant difference from the others. The 3D convex hull method calculates the volume by constructing a 3D convex geometry of the surface of the 3D point cloud of the tree canopy. This overestimated the tree volume by including gaps between tree leaves. The performance of the 3D alpha shape method was similar to that of the proposed method. However, the volume estimation of the 3D alpha shape method was lower than that of the LiDAR measurement for small trees. In the 3D reconstruction process of the 3D alpha shape method, cloud points of the tree canopy could be excessively removed, which could cause an underestimation of tree volume in small trees.

The linear regressions of tree volume estimation between the LiDAR measurement and the proposed method, the 3D convex hull method, and the 3D alpha shape method are shown in Fig. 8. The proposed method shows good agreement with the LiDAR measurements ($R^2 = 0.88$, MAPE = 8.07%). The 3D convex hull method presents the highest MAPE, 42.78%. This method overestimates the tree volume and the overestimation error increases as the tree size increases. The 3D alpha shape method shows better performance ($R^2 = 0.87$, MAPE = 14.47%) than the 3D convex hull method. The tree volume is underestimated in small trees and is overestimated in large trees. The method for tree volume estimation proposed in this study shows higher performance than the other two conventional methods.

Tree Position Estimation

The positions of the 235 apple trees in six rows were calculated. A 30 cm threshold was used in the proposed concave hull algorithm to obtain the projected contour. The tree position obtained by the center of gravity of the tree polygon outline was determined as shown in Fig. 9a. To verify the accuracy of the position estimation, five apple trees in each row were selected to compare the tree position calculated by the proposed algorithm with the measurement of RTK-GPS. The mean error of all the estimations was approximately 18 cm (Fig. 9b). The position error was influenced by bundle adjustment (Mouragnon et al., 2006) in 3D reconstruction and polygon outline estimation in the proposed position estimation algorithm. The accuracy of 3D reconstruction can be verified by the error of GCPs and CP_S as shown in Table 2. The mean error of the CPs was approximately 6 cm, so that the precision of the 3D model was at the centimeter level. Excluding the error of 3D reconstruction, the accuracy of the position estimation algorithm was approximately 10 cm, demonstrating the good performance of the proposed algorithm for tree position estimation. Compared to the estimation of the tree position based on the position of the extracted trunk, the proposed method is simple and easy because it simply projects the 3D point cloud onto the ground plane and then calculates the center of gravity of the tree polygon outline. The proposed method could even determine the tree position when the tree truck could not be detected due to dense foliage. Meanwhile, the position information can be projected on an orthographic image (Fig. 9c) and a Google map (Fig. 9d).

Mapping of Tree Volume with Tree Position

The proposed method for tree volume estimation was applied to an apple orchard. The measured volumes of individual trees were displayed together with the tree positions on

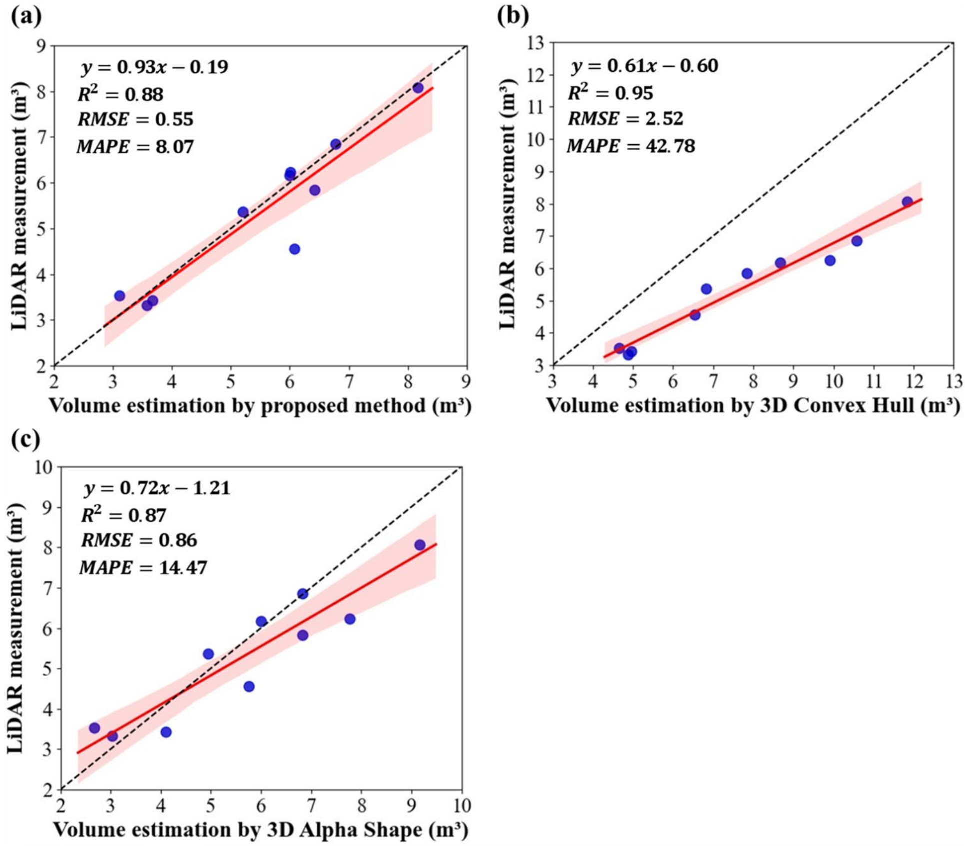

Fig. 8 Linear regression of tree volume estimation. **a** LiDAR measurement and proposed method; **b** LiDAR measurement and 3D convex hull method; **c** LiDAR measurement and 3D alpha shape method. Shading area indicates a 95% confidence interval

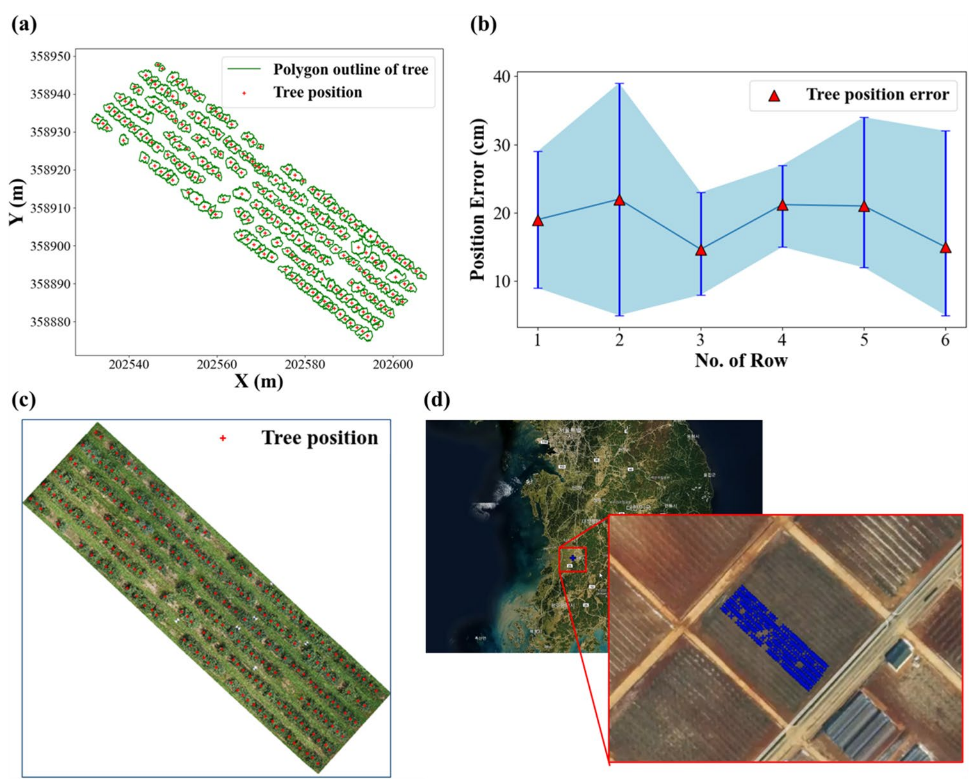

Fig. 9 Tree position estimation and mapping. **a** Tree position estimation of all apple trees in the orchard; **b** error of the tree position in each row; **c** tree position masking on the orthographic image; **d** tree position masking on a Google map

Table 2 Error of GCPs and CPs in 3D reconstruction

GCP	Error (cm)	CP	Error (cm)
GCP01	9.02	CP01	4.80
GCP02	2.85	CP02	12.39
GCP03	4.59	CP03	2.09
GCP04	4.14	CP04	4.71
GCP05	5.15	CP05	7.27
Mean	5.15	Mean	6.25
Std	2.08	Std	3.48

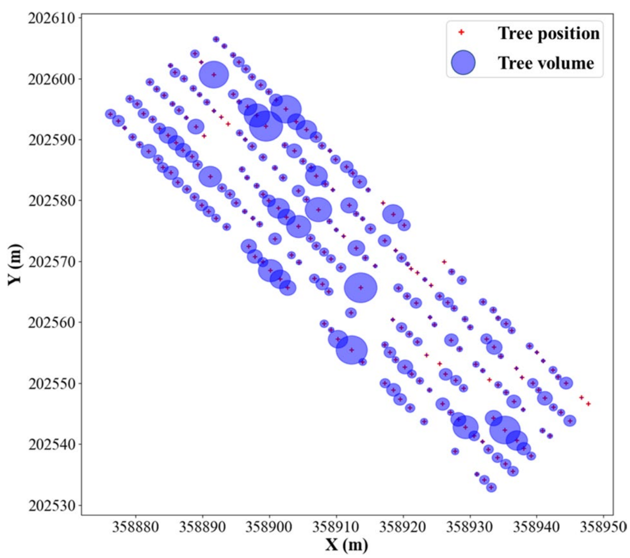

Fig. 10 Mapping of the 3D volume with the tree position

a map (Fig. 10). The tree volume throughout the orchard varied widely. Tree volume maps can be used to efficiently manage orchards. A map generated periodically during the leaf growing season can provide useful information for estimating the yield potential. In addition, a geo-referenced tree volume map can be used for the variable-rate spraying of chemicals. The nozzles of a sprayer can be controlled based on tree volume, which can reduce the use of chemicals and help achieve environmentally friendly sustainable agriculture.

Conclusions

The UAV-based multi-camera system can generate a highly accurate 3D point cloud using oblique photogrammetry technology. To apply the generated 3D point cloud data to calculate tree volume, a novel concave hull by slices algorithm was developed. To validate this algorithm, the volumes of 10 apple trees were calculated using the proposed algorithm and the results were compared with those of two existing methods. The results indicated that the proposed concave hull by slices algorithm was the best suited algorithm for calculating the volume of individual trees using a 3D point cloud. Finally, tree volume mapping was performed by combining volume data with the tree position estimation. A geo-referenced tree volume map can be a useful tool for yield potential estimation in orchards and variable-rate spraying of chemicals.

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Declarations

Conflict of Interest The authors declare no competing interests.

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