UAV-Based Acquisition of Structural Parameters for Populus euphratica: A Postprint

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Abstract

Rapid and accurate acquisition of forest structural parameters is of great scientific significance. By using a DJI Phantom 4 Pro drone to acquire canopy height models of a Populus euphratica forest sample plot in the lower reaches of the Tarim River through oblique photogrammetry and orthophotography, an adaptive window maximum algorithm was proposed for analysis and processing, obtaining structural parameters such as tree height, crown width, and tree number of Populus euphratica in the study area. Finally, ground-measured data were used to evaluate the accuracy of the aforementioned structural data. The results indicated that: (1) The computational performance of the adaptive window maximum algorithm was superior to that of the traditional fixed window maximum algorithm. (2) The accuracy of tree height, crown width, and tree number obtained through oblique photogrammetry was superior to that obtained through orthophotography. (3) Compared with measured values, the structural data obtained by oblique photogrammetry yielded R^2 values of 0.9002, 0.8403, and 0.9405 for tree height, crown width, and tree number, respectively, with root mean square errors of 0.4457, 0.6815, and 4.2500, demonstrating that consumer-grade drones can effectively acquire forest structural parameters at the individual tree scale.

Full Text

Preamble

Research on UAV-Based Acquisition Technology for Structural Parameters of Populus euphratica

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Abstract: Rapid and accurate acquisition of forest structural parameters holds significant scientific importance. Using a DJI Phantom UAV, this study obtained canopy height models of Populus euphratica forest plots in the lower Tarim River region through both oblique and orthophotogrammetry. An adaptive window maxima algorithm was proposed to analyze and process the data, extracting structural parameters including tree height, crown diameter, and tree count. Ground-based measurements were then used to evaluate the accuracy of these parameters. The results demonstrate that: (1) the adaptive window maxima algorithm outperforms the traditional fixed window maxima algorithm; (2) the accuracy of tree height, crown diameter, and tree count obtained via oblique photogrammetry is superior to that from orthophotogrammetry; (3) when comparing oblique photogrammetry data with measured values, the R^2 values for tree height, crown diameter, and tree count are 0.9002, 0.8403, and 0.9405, respectively, with root mean square errors of 0.4457 m, 0.6815 m, and 4.2500 trees. These findings prove that consumer-grade UAVs can effectively acquire single-tree-scale forest structural parameters.

Keywords: Populus euphratica; structural parameters; adaptive window maxima algorithm; UAV; oblique photogrammetry

Introduction

Forest structure information, such as canopy height, crown diameter, and tree count, plays a crucial role in hydrological, ecological, carbon cycle, and climate change processes. These data form the basis for forest biomass estimation and serve as important parameters in numerous terrestrial carbon cycle ecological models. Consequently, accurate and efficient acquisition of forest structural parameters holds major scientific significance. Traditional forest survey methods are time-consuming, labor-intensive, and costly for large areas, and some regions are often inaccessible for field investigations, limiting their broad application. Remote sensing technology offers a relatively low-cost, high-efficiency alternative. Polarimetric interferometric synthetic aperture radar, high-resolution optical satellite remote sensing, spaceborne LiDAR, multi-angle satellite remote sensing, and multi-source remote sensing have all proven effective for obtaining medium-to-low resolution, regional-scale forest structural parameters. However, acquiring single-tree-scale structural information using these technologies remains an unresolved challenge.

The rapid development of unmanned aerial vehicles (UAVs) in recent years has provided new technical means for obtaining forest structures. UAVs can capture ground images using conventional cameras and employ Structure from Motion (SfM) photogrammetry for 3D reconstruction to generate ground point clouds. Based on the derived digital surface model (DSM), digital elevation model (DEM), and canopy height model (CHM), forest structural measurements can be performed. Compared with airborne LiDAR technology, UAV image photogrammetry offers significant cost advantages while maintaining high accuracy. Both domestic and international researchers have actively explored UAV applications in vegetation surveys. Previous studies have primarily used expensive mapping-grade fixed-wing UAVs, which offer long endurance, large payload capacity, and high flight stability, often equipped with high-precision metric cameras and Real-Time Kinematic (RTK) devices. In contrast, lower-cost rotary-wing UAVs, particularly consumer-grade models, suffer from unstable aerial attitudes, lower camera resolution, uncalibrated cameras, and lower-precision onboard GPS. Nevertheless, their compact size, flexibility, and convenient takeoff/landing capabilities offer great potential for forest surveys. Research on consumer-grade UAVs for forest structure applications remains limited, and corresponding methodologies are lacking.

Furthermore, technical and algorithmic challenges persist in single-tree identification and crown diameter/tree height extraction from high-resolution imagery. Commonly used methods include multi-scale segmentation, watershed algorithms, local maxima, and seed point region growing. Multi-scale segmentation and watershed algorithms segment imagery to determine crown boundaries for single-tree identification, performing well with high-resolution satellite or UAV optical imagery but failing to effectively utilize height information. When using CHM data, local maxima and seed point region growing methods are more suitable, enabling simultaneous single-tree identification and extraction of tree height and crown information. The key to the local maxima method lies in selecting an appropriate window size to identify the grid value maximum (seed point) representing the tree crown apex. Window size significantly affects correct seed point identification—overly large windows may miss some maxima, while overly small windows generate incorrect extraneous points. One solution involves using dynamic windows to search for local maxima, though this approach relies heavily on the correlation between tree height and crown diameter, potentially introducing substantial errors in areas with poor correlation.

The Populus euphratica forest along the Tarim River represents typical forest resources in Xinjiang. The lower Tarim River region is an important ecological conservation and restoration area, where Populus euphratica structural information is vital for monitoring forest resources and guiding ecological protection and restoration in the Tarim River basin. Previous studies in this region have primarily employed ground survey methods, and overall, these efforts have not yet achieved efficient, automated acquisition of structural information such as tree height, crown diameter, and tree count across large areas. This study utilizes a consumer-grade rotary-wing UAV to conduct aerial photogrammetry of Populus euphratica forests in the lower Tarim River region, investigating effective UAV measurement methods and improving the regional maxima method for more efficient single-tree identification and extraction of tree height and crown diameter.

1. Study Area Overview

The study area is located in the lower reaches of the Tarim River in Xinjiang, within the river channel region between 40°25 59 –40°26 33 N and 88°01 07 –88°01 55 E, covering approximately 1.1 km^2. The regional environment features a warm temperate continental arid climate, with annual precipitation of about 55 mm in plain areas, resulting in scarce rainfall and sparse vegetation. Riparian forests dominated by Populus euphratica develop near the Tarim River, with virtually no understory vegetation. The surface soil consists of silty sand with high salinization. Tamarix chinensis shrublands, Lycium ruthenicum, Phragmites communis, and Alhagi sparsifolia are distributed in areas with higher groundwater levels, and the terrain is relatively flat.

Due to water cutoff in the lower Tarim River over many years, large-scale Populus euphratica decline and mortality occurred. Emergency water diversion measures implemented after 2000 have improved the situation somewhat. However, prolonged drought has created significant variation in Populus euphratica growth status, particularly in crown completeness, which differs substantially from normally growing forests and poses challenges for both aerial and ground measurements [Figure 1: see original paper].

2. Methods

2.1 Data Collection 2.1.1 Field Measurement Data

In October 2017, a field survey was conducted in the study area within a 100 m × 100 m plot, measuring tree height and crown diameter of 49 Populus euphratica trees and counting individual trees in sampling grids. The measurement methods were: (1) Tree height was measured from three different directions using a laser rangefinder' s height measurement function, with the average taken as the measured tree height; (2) Coordinates of each tree were recorded using the OruxMaps handheld mapping software and annotated on a 0.5 m ground resolution WorldView-2 multispectral imagery map for later comparison with UAV imagery; (3) Crown diameter was measured with a tape measure in four directions and averaged; (4) Using OruxMaps software with WorldView imagery as reference, Populus euphratica trees in each grid were counted and marked in the mapping software.

2.1.2 UAV Photogrammetry Data

The UAV used was the DJI Phantom 4 Pro, a consumer-grade quadcopter produced by DJI Innovations. Current UAV ground image acquisition methods primarily include orthophotography and oblique photogrammetry. Traditional orthophotography captures images vertically, while oblique photogrammetry—an emerging technology in international mapping—overcomes the vertical-only limitation by simultaneously acquiring images from multiple angles. Although five-lens cameras are typically used for UAV oblique photogrammetry, small UAVs have limited payload capacity and endurance. The DJI Phantom 4 Pro is equipped with a single camera, requiring multiple flights to complete both orthophotography and oblique photogrammetry. Without ground control points, flight missions were planned using the Altizure route planning software, comprising one vertical and four oblique flights. Specific flight parameters are shown in .

2.2 Technical Approach 2.2.1 Technical Route

This study first employed traditional ground surveys to obtain reference data, then used low-altitude UAV photogrammetry to acquire ground images, and applied software methods for automated data processing [Figure 2: see original paper].

2.2.2 UAV Data Processing

PIX4D Mapper software was used to process both orthophotography and oblique photogrammetry images through image matching, aerial triangulation, and point cloud generation to obtain dense point clouds for the study area. The dense point clouds were classified to derive ground and vegetation point clouds, which were then interpolated and rasterized to generate DSM, DEM, and CHM data. The processing results from oblique photogrammetry are shown in [Figure 3: see original paper].

2.2.3 Structure Extraction Algorithm

(1) Seed Point Identification. In the study area, the tree height-crown diameter regression equation $R^2 = 0.31$, indicating that the linear relationship between Populus euphratica height and crown size is not significant and unsuitable for direct use as a dynamic window. Therefore, this study proposes an "adaptive window local maxima algorithm." Building upon the fixed window local maxima algorithm, this method uses the lower limit of the predicted window from the tree height-crown size regression equation as a distance threshold, combined with judgment of height variation between seed points to improve seed point selection accuracy.

The specific method is as follows: First, a relatively small fixed window is used with the local maxima algorithm to generate an initial seed point set. Each seed point is processed sequentially. The shortest distance between the current seed point and other seed points is calculated, and seed points within the distance threshold are identified for further processing. The principle involves judging whether the elevation variation between two seed points exceeds a specified height threshold. If below the threshold, the points are considered to belong to the same tree, and the lower seed point is merged into the higher one; otherwise, they are considered different canopies and remain unmerged. This process continues until all seed points are processed, achieving an adaptive window effect [Figure 4: see original paper]. The final seed points represent individual tree apexes, and their quantity equals the tree count.

(2) Crown Diameter Extraction. After determining tree seed points, a region growing method is applied with the seed point pixel as the center, searching eight neighboring pixels in sequence. If neighboring pixel values fall within a

specified descent slope range, the region continues to grow until reaching the search boundary or exceeding the descent slope threshold. All qualifying neighboring pixels constitute the individual tree crown range, with crown diameter calculated geometrically.

3. Results and Analysis

All algorithms were implemented using Python.

3.1 Algorithm Analysis The adaptive window maxima algorithm and fixed window maxima algorithm (using 1.5 m, 2.0 m, 2.5 m, and 3.0 m windows) were applied to CHM data from oblique photogrammetry to generate Populus euphratica seed points, which were compared with tree count statistics from 25 sample plots [Figure 5: see original paper]. The R^2 values for fixed window algorithms varied widely from 0.7834 to 0.8261, indicating that appropriate window sizes must be selected based on regional conditions to achieve higher accuracy. In contrast, the adaptive window algorithm achieved the highest R^2 of 0.8341, demonstrating higher accuracy by reducing dependence on window size selection.

3.2 Comparison of Measurement Methods 3.2.1 Measurement Method Comparison
Using the adaptive window maxima algorithm, CHM data from both UAV orthophotography and oblique photogrammetry were processed to obtain tree height and crown diameter data. Compared with field measurements, both methods overestimated tree height and underestimated crown diameter. However, the mean, median, and data distribution of tree height and crown diameter from oblique photogrammetry were closer to measured values, indicating that oblique photogrammetry is more accurate than orthophotography [Figure 6: see original paper].

3.2.2 Structural Data Correlation Analysis
To precisely analyze the quality of tree height, crown diameter, and tree count data, coefficient of determination (R^2), mean relative error, and root mean squared error (RMSE) were calculated against measured data. For 49 Populus euphratica samples, oblique photogrammetry-derived tree height showed $R^2 =$ 0.9002 with measured values, with mean relative error of 5.400% and RMSE of 0.4457 m. Crown diameter from oblique photogrammetry (after removing samples with incomplete crowns) compared with 44 measured samples showed $R^2 = 0.8403$, mean relative error of 8.925%, and RMSE of 0.6815 m. Tree count per hectare from 25 statistical sample plots compared with measured values showed high accuracy with $R^2 = 0.9405$, mean relative error of 6.928%, and RMSE of 4.2500 trees [Figure 7: see original paper].

3.3 Error Analysis The observed results stem from combined measurement, algorithmic, UAV, and environmental factors.

3.3.1 Measurement Factors

Measurement difficulty varies. Tree height measurement targets are clear (the tree apex), yielding relatively consistent results with small differences from field data. In contrast, crown diameter is determined by a series of edge points, making precise determination more difficult. Populus euphratica crown boundaries are challenging to identify accurately, leading to lower consistency with measured values.

3.3.2 Algorithmic Factors

In areas with overlapping crowns, the algorithm is prone to seed point omission or incorrect merging, and crown growth algorithms may misidentify boundaries, causing erroneous tree height and crown estimates.

3.3.3 UAV Factors

(1) The DJI Phantom 4 Pro' s single-camera configuration requires multiple flights for oblique photogrammetry. With each battery providing only 20+ minutes of flight time, missions must be completed over several days, introducing varying solar illumination conditions that affect image brightness and clarity, subsequently impacting aerial triangulation quality. (2) The Phantom 4 Pro camera is non-metric with unknown interior orientation elements, causing image distortion. Although upgraded from previous models, its performance still lags significantly behind professional cameras.

3.3.4 Environmental Factors

(1) The desert edge location experiences frequent wind and sand weather, affecting image quality. (2) The study area' s silty sand soil with high salinization exhibits high reflectivity, creating strong specular reflection at certain angles that produces bright spots in imagery, potentially generating erroneous point cloud data or causing point cloud generation failure.

4. Conclusions

The rapid development of UAV technology provides diverse technical means for spatial mapping and resource surveys. However, UAV applications in arid region forest resources remain relatively scarce, the potential of consumer-grade UAV technology for forest resource surveys is not yet fully understood, and opportunities exist for improving UAV data processing algorithms. This study compared Populus euphratica structural parameters obtained from different consumer-grade UAV photogrammetry methods and processing algorithms with field-measured data, yielding the following conclusions:

(1) The fixed window maxima algorithm requires appropriate window size selection based on actual conditions to achieve satisfactory results, whereas the adaptive window maxima algorithm reduces constraints on window size settings and produces superior results. This algorithm can more effectively extract Populus euphratica structural parameters from CHM data.

(2) Both oblique and orthophotography overestimated tree height and under-

estimated crown diameter compared with field data. However, oblique photogrammetry achieved higher data accuracy than orthophotography.

(3) Using the adaptive window maxima algorithm with oblique photogrammetry data, the coefficients of determination (R^2) for tree height, crown diameter, and tree count compared with measured values were 0.9002, 0.8403, and 0.9405, respectively, with mean relative errors all below 9%. This demonstrates that combining these technologies can obtain high-precision, single-tree-scale forest structural parameters.

Although consumer-grade UAVs have inferior hardware compared with mapping-grade UAVs, reasonable flight measurement planning and advanced algorithms make it feasible to acquire Populus euphratica structural parameters using consumer-grade UAVs. This approach can replace some manual ground surveys, ensuring efficiency while effectively reducing investigation costs.

Future research should focus on developing more effective image processing algorithms based on UAV data to further improve the accuracy and efficiency of automated data extraction.

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Note: Figure translations are in progress. See original paper for figures.