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Research on the Evaluation Model of Fruit Tree Leaf Area Index Based on LiDAR

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Abstract:
In the process of variable application, acquiring canopy structure parameters of fruit trees is crucial. Traditional manual measurement of these parameters is time-consuming and not conducive to online acquisition. This study presents a method for measuring leaf area index of fruit trees using LiDAR. Six simulated fruit trees with varying leaf area indexes were tested, and real-time collection of canopy data was conducted. The point cloud side view of scanned fruit trees was compared with the contour of simulated fruit trees. When the operation speed was below 1.5 m/s, The point cloud side view of fruit trees closely matched the actual fruit tree contour at less than 1m/s operation speed. It was observed that the point cloud obtained under the same leaf area index was inversely correlated with the operating speed. Mathematical models were developed using Origin to fit the relationships among operation speed, point cloud data, and leaf area index, yielding a coefficient of determination of 0.93. This demonstrates the feasibility of analyzing fruit tree leaf area index using point cloud data. In field tests, the maximum relative error was 12.5% under orchard 0peration speeds (0.5-1 m/s). This method enables real-time measurement of canopy leaf area index, providing technical and model support for variable spray decision-making in orchards.

Keywords: fruit tree canopy, LiDAR, Leaf Area Index (LAI), point cloud, operation speed.

INTRODUCTION

The accurate acquisition of canopy structure parameters of fruit trees is essential for effective spray parameter control and execution [1]. Traditional methods, such as picking fruit tree leaves, are efficient but can cause irreversible damage. In recent years, various non-contact measurements have been explored, including microwave radar [2], HD X-ray scanning [3], optical sensing [4], ultrasonic sensing [5], stereo vision [6], and LiDAR [7]. However, due to spatial resolution and lighting conditions in orchards, only ultrasonic and LiDAR sensing methods are widely recognized. Ultrasonic sensing method calculates the canopy width by measuring the distance between the outer boundary of the crown and each sensor, and then calculates the surface area of the crown region and the total volume of the crown [8]. However, it is greatly affected by the diffusion of the ultrasonic beam, leading to significant measurement errors.

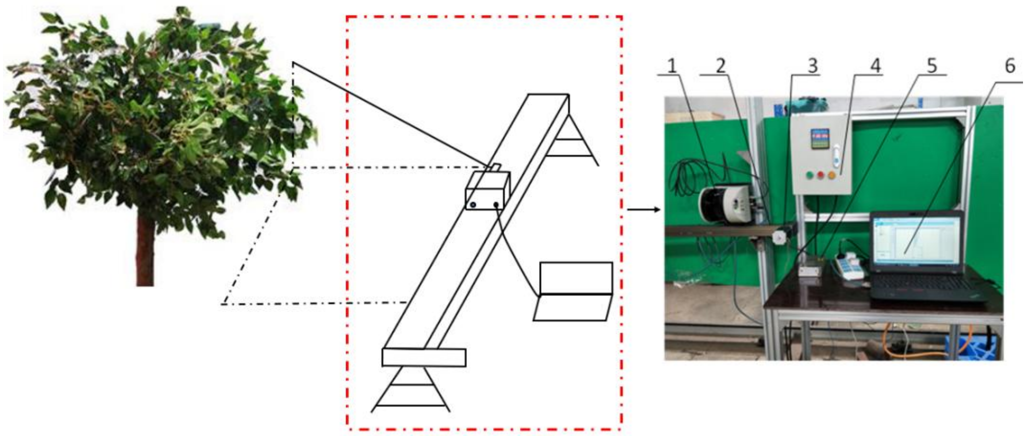
LiDAR offers high accuracy and speed, reconstructing 3D point clouds into precise fruit tree structures [9]. Investigating the relationship between LiDAR point clouds and canopy structure parameters is crucial. Yu, et al. [10] utilized laser sensors to extract laser cloud information of canopy and calculated the crown volume of fruit trees by slice accumulation. The results showed a relative error of approximately 5% between laser measurement and manual measurement. Zhang, et al. [11] projected the three-dimensional structure point cloud of trees collected by LiDAR and calculated the crown volume through volume calculation of the platform. Such studies often overlook the irregular structure and porous parts of the canopy, leading to significant errors in calculating the volume of sparse branches and leaves. However, parameters related to leaf area of fruit tree can accurately reflect the leaf density, becoming a hot topic in variable-rate application research. Zhang, et al. [12] used LiDAR sensors to study the relationship between laser points density and leaf density, and established a relationship model between laser points and different canopy using different fitting functions, with model determination coefficients all greater than 0.9. Zhou, et al. [13] studied leaf density and LAI models using reflections and echoes from airborne LiDAR, validating the effectiveness of LiDAR in assessing leaf area index. Sanza, et al. [14] used LiDAR to research the correlation between laser point clouds and measured LAI in trellised orchards, with a fitting coefficient $R^2 = 0.87$. The above studies overlook the impact of LiDAR moving speed on point cloud acquisition. Based on this, Li, et al. [15] studied the effect of different operating speeds of spraying vehicles on point cloud acquisition under indoor conditions, but lacked evaluation of its applicability in actual orchard environments.

The operating speed and actual orchard environment have significant impacts on the acquisition of laser point clouds and the evaluation of leaf area parameters. Currently, there are no relevant reports on comprehensive studies regarding these factors. In this study, we designed a laser radar testing system capable of accurately and real-time measuring the leaf area index of fruit tree canopies. By collecting laser point cloud distribution of fruit tree canopies through laser radar sensors, we calculated the number of laser points. We analyzed the influence of operating speed on the geometric shape and number of laser points of fruit tree point clouds and established a leaf area index evaluation model. Through field experiments, we evaluated the applicability of the model, aiming to provide a more accurate measurement of the LAI of canopy and thereby offering a basis for variable-rate spraying decisions in orchards.

MATERIALS AND EXPERIMENTAL PLATFORM

Experimental Platform

To accurately investigate the relationship between the laser point clouds and canopy structure data, a laboratory test platform was constructed as depicted in Figure 1. The platform comprises a LiDAR scanning sensor (SICK LMS5100), linear guide rail, motor, control cabinet, power supply, and upper position machine. The LiDAR sensor's technical specifications include a measuring range of 20m, scanning angle range of -45° to 225°, angular resolution of 0.25°/0.5°, and scanning frequency of 25Hz/50Hz. These parameters enable the sensor to capture point cloud of canopy. However, since the sensor can only achieve in-plane scanning, the three-dimensional spatial sweep of the two-dimensional plane laser is accomplished by mounting the LiDAR sensor on a linear guide rail.



1: LiDAR sensor; 2: linear guide rail; 3: motor; 4: control cabinet; 5: power supply; 6: upper position machine

Figure 1. Test platform of point cloud

Fruit Trees

To explore the relationship between the point clouds scanned by the laser sensor and the LAI, simulated fruit trees were utilized. The height of the tree stem was set at 2m, and various numbers of simulated leaves (900, 800, 600, 450, 250, 100) were artificially inserted, as depicted in Figure 2.

Figure 2. Simulated tree of different leaf number

To further verify the applicability of indoor research results in field conditions, experiments were conducted in the orchard. Five fruit trees with dense foliage were selected, and the trees were divided into two categories. Trees 2 and 4 had a high similarity in branch and leaf appearance to the simulated fruit tree, while trees 1, 3, and 5 had larger branch bifurcations and certain differences in appearance compared to the simulated fruit tree, as shown in Figure 3.

Figure 3. Canopy with different leaf area index

METHODS

Principle of Laser Point Cloud Measurement

The LiDAR sensor utilizes laser pulses for non-contact detection and scanning of target objects. The control system rotates the laser transmitter, returning distance information to the signal processor at fixed angular intervals (angular resolution). This data is converted into a polar coordinate form laser scanning surface, containing distance and angle information, completing a single scan. The LiDAR sensor continuously emits laser pulses at a specific scanning frequency and angle. When these pulses encounter the canopy target, they return distance values representing the distance traveled by the laser beam from its emission point to the point of impact. The principle of point cloud generation is illustrated in Figure 4.

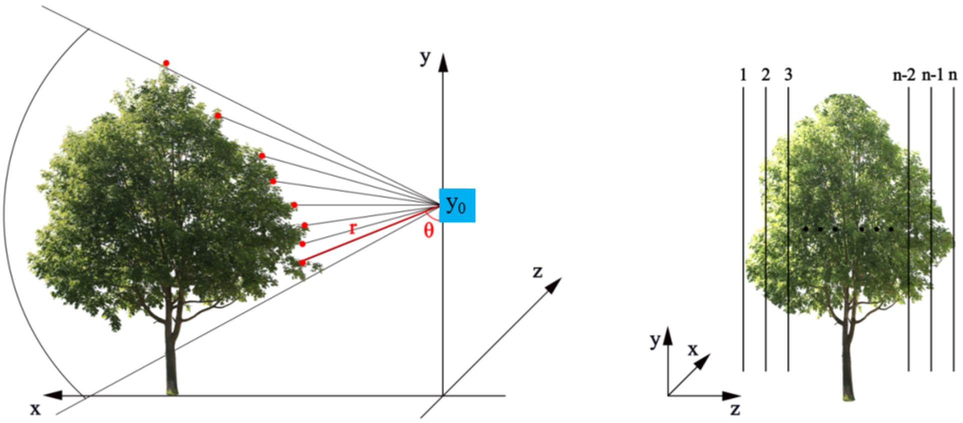


Figure 4. Schematic diagram of point cloud measurement

The initial position of the sensor was set as X=0, Y=y_0, Z=0 (y_0 is the height of the center of the canopy). Basic data such as the angle θ, distance r and the time t_i from laser scanning were recorded. Each laser point in polar coordinates (r_i, θ_i) is transformed into Cartesian coordinates (X_i, Y_i) according to equations (1) to (2). Meanwhile, as the laser scanning proceeds, the slider on the linear guide rail starts moving at a constant speed v. The Z-coordinate is calculated according to equation (3).

$$x_{ij} = r_{ij} \sin\theta \tag{1}$$

$$y_{ij} = y_0 - r_{ij} \sin\theta \tag{2}$$

$$Z_i = v \cdot t_i \tag{3}$$

where, x_{ij} is the x-coordinate corresponding to the j-th point of the i-th scan, y_{ij} is the y-coordinate corresponding to the j-th point of the i-th scan, r_{ij} represents the distance value corresponding to the j-th point of the i-th scan, and j represents the j-th scanning point starting from the initial scanning angle. The obtained x, y, and z values are assigned to matrices X, Y, and Z, respectively.

$$X=[x_{ij}];\ Y=[y_{ij}];\ Z=[z_i] \tag{4}$$

Where, i =1, 2, 3, 4 …, n, $j = \theta0, \theta0 + \theta', \ldots, \theta0 + n\theta'$. The scanning resolution of the laser radar is set to 0.5°, with a scanning frequency of 50Hz. The operating speeds are successively1.7 m/s ,1.5 m/s,1 m/s,0.5 m/s and 0.3 m/s. Based on equations (1) to (3), the spatial coordinates of each laser collision point are calculated. Then, the MATLAB software's scatter function is used to generate a 3D point cloud map of the scanning area. After eliminating non-target points related to the environment, a 3D point cloud map of the simulated fruit tree is obtained. Rotating the perspective of the 3D point cloud map changes it into a side view from the frontal direction.

Leaf Area Index Calculation Methods

Using a measuring tape, the tree height and width were measured. Starting from the tree trunk as the central point, boundary points were marked at every 45° direction using plumb line. Eight points were marked counterclockwise starting from 270°. The distances from the central point to each of these points were measured using a measuring tape. Using mapping software, the boundary points were drawn according to their actual dimensions. A spline curve was used to connect these boundary points to form a closed area. The area of the corresponding surface was then measured, which represents the maximum breast height diameter section area. Ten leaves from different positions were randomly selected, and the area of each leaf was manually measured using the grid method with a minimum grid unit of 1 mm^2. The average area of the 10 leaves was calculated as a single leaf for the tree. The LAI was calculated using Formula (5) based on these manual measurements. The corresponding leaf area indices were 6.06, 5.45, 4.15, 3.69, 2.05, and 1.48.

$$LAI = \frac{N \cdot S}{A} \tag{5}$$

Where, LAI is the leaf area index of canopy. A is the maximum cross-sectional area of the fruit tree trunk, measured in square meters (m^2). N is the total number of fruit tree leaves. S is the average leaf area of fruit trees, measured in square meters (m^2).

Model Research Methodology

The operational speed of the laser sensor significantly impacts the acquisition of point clouds, consequently affecting the geometry and number of point cloud images of canopies.

To validate the effect of operational speed on the point cloud geometry of fruit trees, point cloud geometry was obtained by scanning at different forward speeds of orchard tractors in a laboratory environment. The LiDAR sensor had a scanning angle resolution of 0.5 and a scanning frequency of 50 Hz. Six simulated fruit trees with varying leaf area indexes were selected as examples, with leaf area indexes ranging from 1.48 to 6.06. The tree height was fixed at 2.0 m, and the maximum diameter during height was 1.2 m. Since the laser sensor is mounted on the tractor for operation, and considering that the field operation speed of orchard tractors mostly ranges between low speeds of one and two gears (approximately 5 km/h), different operational speeds tested were 0.3 m/s, 0.5 m/s, 1 m/s, 1.5 m/s, and 1.7 m/s.

Point cloud counts at different LAI (ranging from 1.48 to 6.06) were recorded at different speeds to examine the influence of operational speed on point clouds,

Ultimately, a mathematical model incorporating operational speed, point cloud number, and LAI is constructed to accurately acquire the LAI in the orchard environment.

Model Evaluation Method

Based on the acquired point cloud data, the LAI of each fruit tree is calculated. Three measurements are taken each time, and the average is computed as the result for comparison with actual measured results. The relative error (E) is used to evaluate the accuracy of the prediction model, calculated as shown in equation (6):

$$E = \frac{|LAI_1 - LAI_2|}{LAI_1} \tag{6}$$

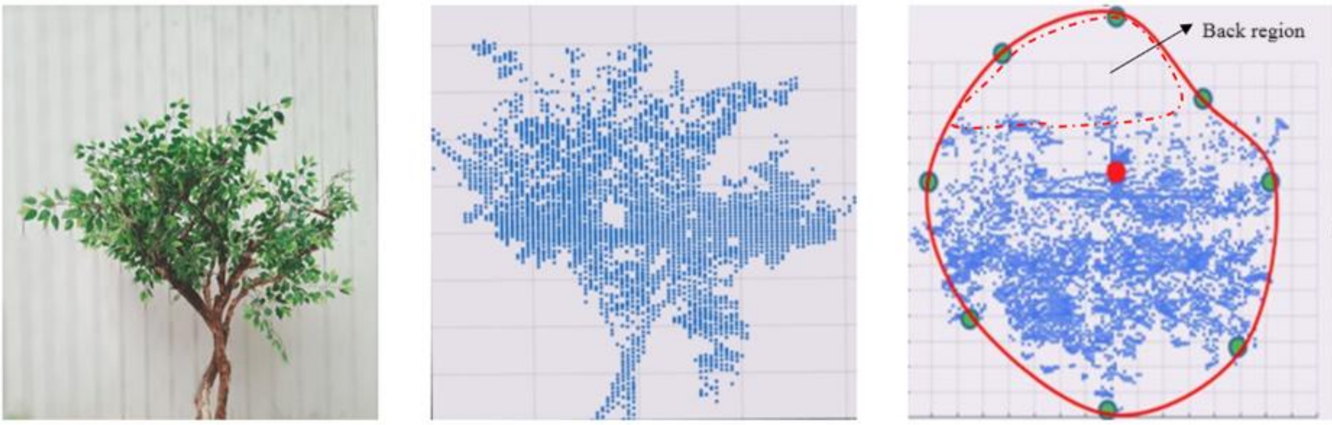
Where E represents the magnitude of the relative error, LAI_1 is the LAI measured manually, and LAI_2 is the average LAI measured by the model.

RESULTS AND ANALYSIS

Model Feasibility Analysis

Figure 5a depicts a simulated fruit tree with a leaf area index of 6.06, a tree height of 2.0 m, a maximum breast diameter of 1.2 m, and a total leaf count of 1000. Figure 5b shows the point cloud of the simulated tree under laboratory conditions with a scanning frequency of 50 Hz, a laser scanning forward operation speed of 0.3 m/s and a scanning angle resolution of 0.5°. Figure 5c displays a top-down view of the point cloud of the simulated tree, indicating the positions of the tree trunk center (red dot) and 8 boundary points (green dots), with the red curve representing the boundary curve of the fruit tree.

A comparison of the geometric shapes between Figure 5a and Figure 5b reveals that the geometric features of the fruit tree point cloud scanned by the laser sensor are consistent with the actual spatial geometric characteristics of the fruit tree. From Figure 5c, it can be observed that there are few laser points on the backside under high leaf area index, as shown in Figure 5c. This is primarily because during single-sided scanning, the rear portion is occluded by the front canopy, resulting in the laser beam being unable to penetrate the front canopy to generate laser points. However, the contour features and canopy density characteristics of the front half of the fruit tree can still be accurately obtained. The decision-making process for variable-rate spraying during fruit tree variable application often relies on semi-side fruit tree characteristic information for calculation. Therefore, utilizing the number of laser points to calculate the LAI provides practical significance for decision-making regarding the dosage of variable spraying during fruit tree variable application.



a: Simulated fruit trees; b: Side view; c: Top view

Figure 5. Simulation fruit tree and point cloud image

Influence of Operation Speed on the Geometric Shape of Fruit Tree Point Clouds

Figure 6 shows the side views of point clouds at operation speeds of 0.3 m/s, 0.5 m/s, 1 m/s, 1.5 m/s, and 1.7 m/s, with six simulated fruit tree point cloud images arranged from left to right in increasing order of leaf area index. The side view of the point cloud effectively reflects the geometric shape of the fruit tree point cloud. When the leaf area index is the same, a faster operation speed results in fewer points in the obtained point cloud, leading to a blurrier representation of the geometric shape of the fruit tree in the side view.

At lower operation speeds (0.3 m/s ~0.5 m/s), the side views of the point cloud images clearly depict the geometric shape of the tree. The number of points obtained from scanning decreases as the operation speed increases, as shown in Figures 6a and 6b. When the operation speed reaches 1.0 m/s, the geometric shape of the fruit tree point cloud starts to become blurry but still reflects the overall shape of the fruit tree, as shown in Figure 6c. At an operation speed of 1.5 m/s, only the point cloud of the fruit tree with a leaf area index of 6.06 exhibits a clear geometric shape, as depicted in Figure 6d. When the operation speed reaches 1.7 m/s, none of the scanned point cloud images accurately represent the geometric shape of the fruit tree, as illustrated in Figure 6e. Therefore, when the operation speed exceeds 1.5 m/s, the suitability of the laser sensor's scanned fruit tree outline becomes poor.

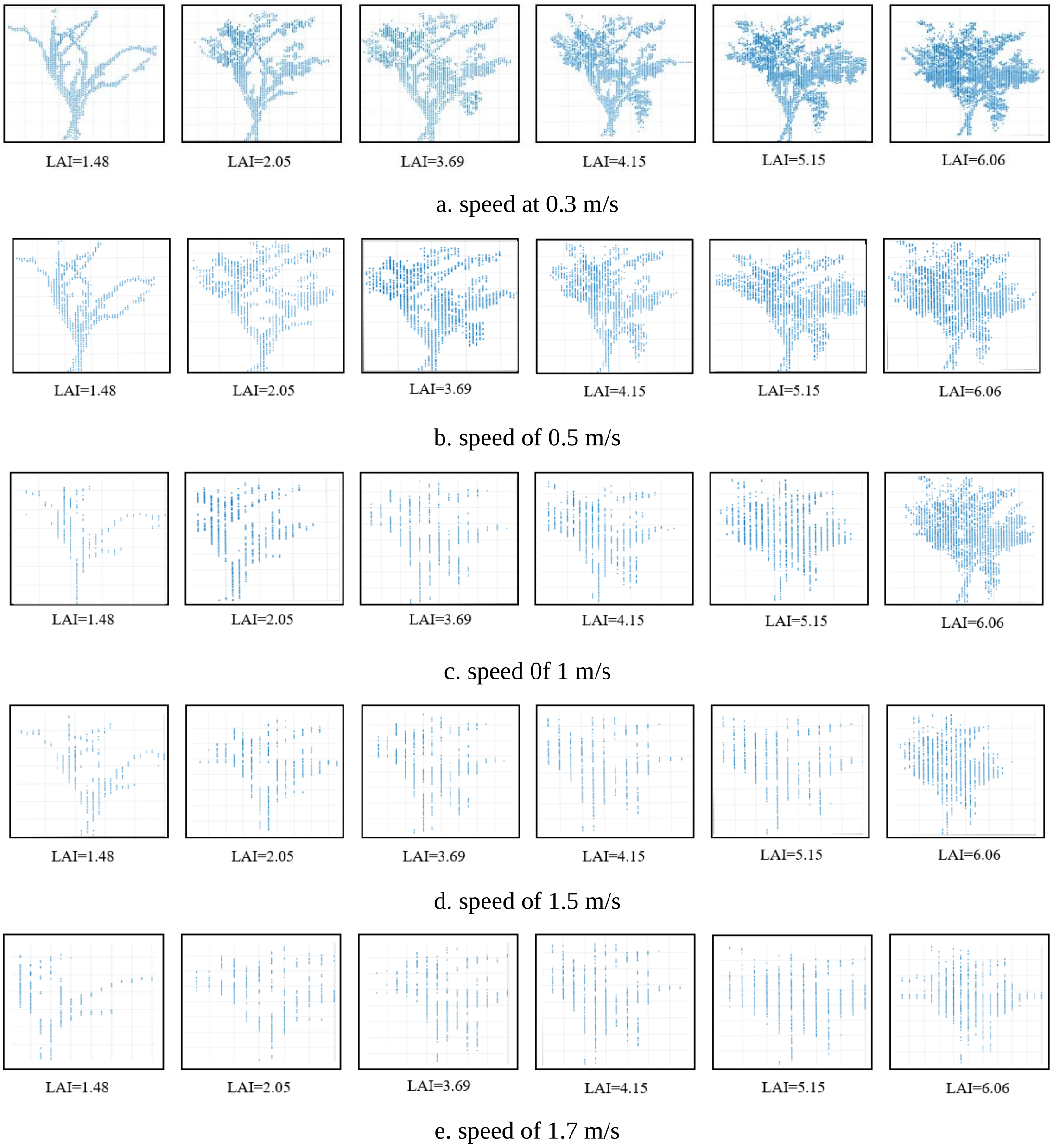


Figure 6. Point cloud side views at different operation speed

The Impact of Operating Speed on Point Cloud Count

Figure 7 reflects the relationship between operating speed and the number of point clouds obtained through scanning. It can be observed that, under the same leaf area index, the number of point clouds is negatively correlated with the operating speed. This is because as the operating speed of the LiDAR increases, the morphology of the scanned fruit tree canopy becomes more blurred, resulting in fewer point clouds obtained. Additionally, it can be observed that when speed is 0.3 m/s, and the LAI are 1.48, 2.05, and 3.69, the number of point clouds increases by 69.9%, 103.8%, respectively. While for LAI of 4.15, 5.45, and 6.06, the increase is 19.6%, 4.8%, respectively. This is because in cases of lower leaf area indices, the number of fruit tree leaves is fewer, and the LiDAR can scan most of the leaves. With the increase in leaf area index, the additional leaves mostly fall within the LiDAR's scanning range. However, as the leaf area index increases to a certain extent, the fruit tree canopy begins to enter a closed state, with more significant occlusion of branches and leaves. At this point, further increasing the leaf area index results in the LiDAR being unable to penetrate the canopy as effectively, leading to a plateau in the increase in the number of point clouds

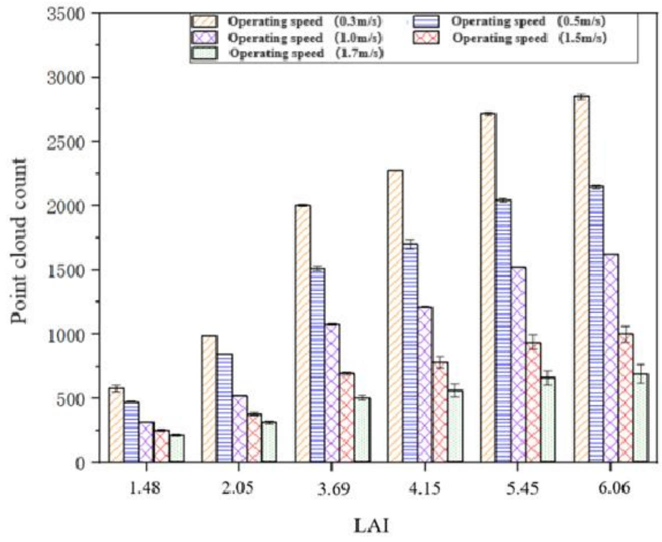


Figure 7. Effect of operating speed on point cloud under different leaf area index

LAI Evaluation Model Construction

In order to investigate the relationship between operation speed, number of point clouds and LAI. A surface fitting was performed using Origin software, as shown in Figure 8. A LAI evaluation model was constructed, the coefficient of determination (R^2) improved to 0.93. The model is represented by the following equation:

$$LAI = 1.984 - 4.973 \cdot m + 0.000841 \cdot n + 2.403 \cdot m^2 + 0.003914 \cdot m \cdot \mathrm{n} \tag{7}$$

Where, LAI is the leaf area index. *m* is the operation speed, m/s. *n* is the number of point clouds.

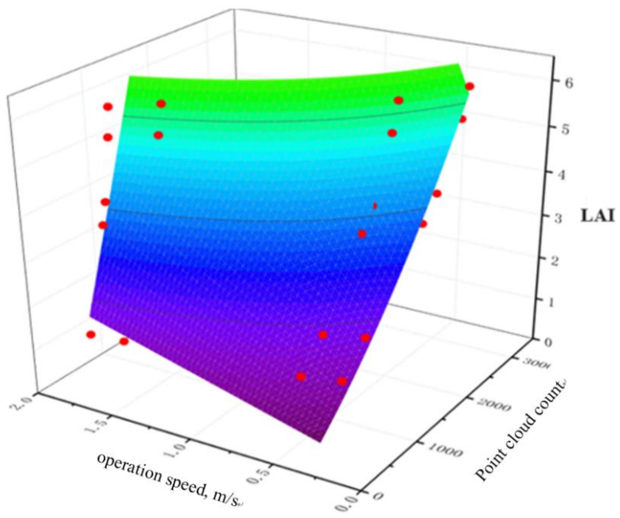


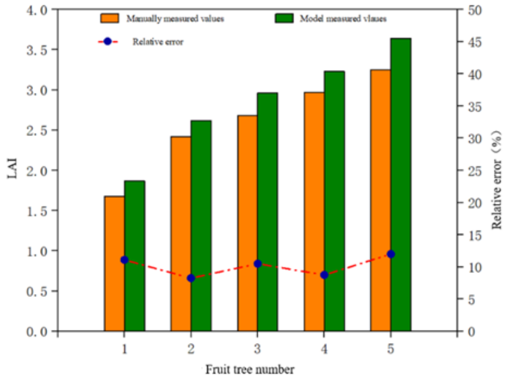
Figure 8. The fitting surface map of operation speed, point cloud, and leaf area index

FIELD APPLICATION

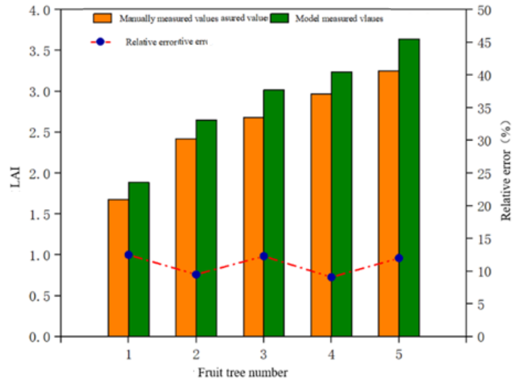
To elucidate the practical applicability of the established model, the Leaf Area Index (LAI) measured manually and by the model under different operating speeds were compared, as shown in Figure 9. During the model experiment, it was found that due to the differences between actual fruit trees and simulated ones, there were discrepancies between the manually measured LAI and the model-estimated LAI. Trees 2 and 4, with higher similarity in appearance to the simulated fruit tree, exhibited smaller relative errors in LAI under various operating speeds. However, Tree 1, with a larger branching angle, differed significantly from the simulated fruit tree, resulting in the largest relative errors consistently appearing in Tree 1. This indicates that the accuracy of the model during actual field operations is also influenced by the contour of the canopy of field fruit trees.

When the tractor's forward speed was 0.3 or 0.5 m/s, the maximum relative error between manual and model measurements was only 12.5%. At a forward speed of 1.0 m/s, for canopies with different LAI, the maximum relative error was 6.4%, indicating the highest accuracy of the model, as shown in Figure 9c. However, when the tractor traveled at relatively higher speeds in the field (forward speeds of 1.5 and 1.7 m/s), the model exhibited larger relative errors, with maximum relative errors of 31.7% and 42.2%, respectively. Excessive speed can lead to significant errors in LiDAR sensor scanning of tree contours, as extensively illustrated in the indoor experiments mentioned earlier. Although the relationship model under different driving speeds was determined through multiple indoor experiments, the complexity of the field environment introduces certain errors into the model.

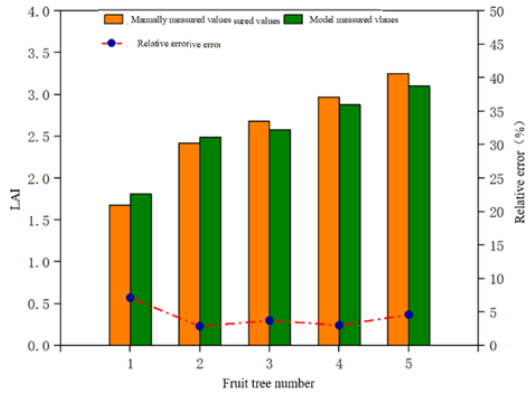
Therefore, the model is suitable for operating speeds around 1 m/s. Too low speeds are influenced by non-target environmental factors, resulting in an excessive number of point clouds. Conversely, excessively high operating speeds cause machinery vibrations, leading to a decrease in model accuracy.



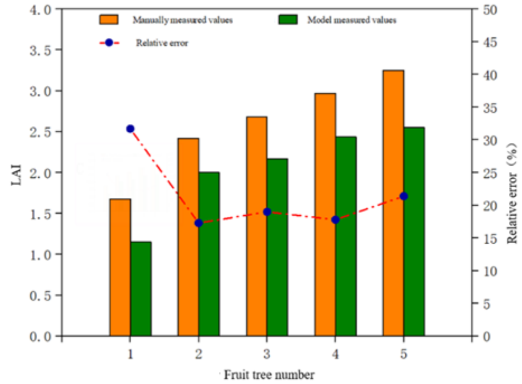
a. speed at 0.3 m/s



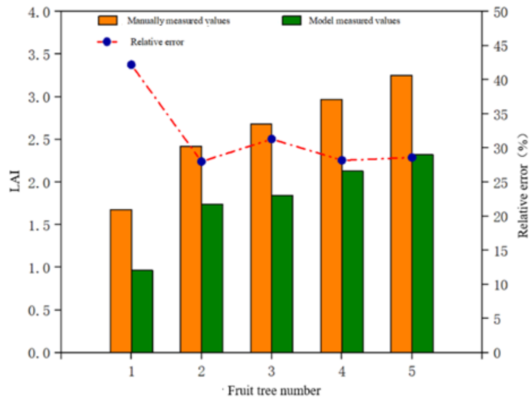
b. speed at 0.5 m/s



c. speed at 1 m/s



d. speed at 1.5 m/s



e. speed at 1.7 m/s

Figure 9. Analysis of model accuracy under different operation speed

CONCLUSION

A method for testing LAI of fruit tree canopies based on LiDAR technology is proposed. Using a LiDAR sensor, tests were conducted on simulated fruit trees with six different LAI values under laboratory conditions. Additionally, the relationship between operating speed, point cloud number, and LAI was fitted using Origin software to validate the feasibility of this method. Furthermore, the applicability of the model was further verified through field experiments.

Operating speed significantly affects both the geometric shape of fruit tree point clouds and the acquisition of point cloud numbers. When the operating speed exceeds 1.5 m/s, there is a noticeable difference between the side view of fruit tree point clouds and the real trees, which fails to meet practical application. Additionally, operating speeds exceeding 1.5m/s lead to a decrease in model accuracy and stability. Furthermore, as the LAI increases, under different operating speed conditions, the laser cannot penetrate the canopy effectively due to obstruction, resulting in an inability to obtain more point cloud numbers. Consequently, the increase in point cloud numbers gradually levels off.

A fitting model for operating speed, point cloud number, and LAI was constructed, with a coefficient of determination of 0.93. This indicates that the model can be used for measuring the LAI of fruit tree canopies. Field experiment results demonstrate that the higher the similarity between the actual fruit tree contour and the simulated fruit tree contour, the higher the accuracy of the model. The optimal field operating speed is 1.0 m/s, with minimal relative error, and the maximum relative error is only 7.14%.

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