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Method of Measuring Tree Height and Volume Based on CCD SmartStation

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ABSTRACT

Forest stock volume is an important factor for evaluating the status of forest resources and management level of the forest. It is also an important index to evaluate the ability of the forest to reduce the risk of climate change. Standing timber volume is the basis for accurate assessment of forest stock volume. In order to quickly and accurately measure the volume of standing timber and solve the problems and shortcomings of the traditional measurement methods of volume, this paper presents non-contact and nondestructive method of measuring tree height and volume, which uses CCD as a measuring tool and takes measuring principle of close-range photogrammetry as a basis. The method obtains the photograph by the CCD camera and the exterior element, when the photograph is shot by the total station's goniometry and ranging function, and takes surface, which crosses the center of the tree and is perpendicular to the main optical axis of the camera, as the solution surface. Extracting coordinates of feature points of standing timber in the photograph, calculates diameter at any height of standing timber, which achieves measurement of height and volume of standing timber under the model of single-photo solution and multi-photo solution of correction and merging. In order to simplify the operational procedures of the field, through the observation of one pole and 160 standing timber, the optimal observation distance of this method is 15 m, and the optimal observation angle is 0°, and the accuracy of the single-photo mode is better than the multi-photo mode of correction and merging. The results show that the precision of tree height measurement method is 98.41% and the measurement accuracy of volume is 98.01%, which can meet the precision requirements of forestry investigation. This provides a new idea of data acquisition for the establishment of timber volume tables and forestry surveys, which is of some reference value.

INTRODUCTION

As one of the important global terrestrial ecosystems, forests have always been an important way for people to access resources, maintain a good ecological environment and mitigate the impact of climate change. Forest stock volume is not only an important factor in evaluating the status of forest resources and the level of forest management, but also an important indicator to evaluate the ability of forests to reduce the risk of climate change. Therefore, the stock volume has been one of the main factors in forest surveys (Haibin 2016, Feng 2015, Liu 2014, Wang 2014, Guendehou 2012). Forest stock volume is the sum of the volumes of all standing trees per unit area of forest (Vibrans 2015, Berger 2014, Zeng 2015). Acquiring accurate standing timber volume is the basis for accurate assessment of forest stock volume and also the focus of tree research for a long time.

The traditional timber volume measurement method is also called trunking analysis method, that is, after cutting the standing tree, doing the trunk analysis, but the method has the disadvantages of time-consuming and labour-intensive, destroying the forest and so on. Correspondingly, some researches have proposed to establish the non-destructive estimation method of wood volume, such as high-elevation method, positive-type number method, experimental shape number method, shape point method and so on (Cao 2015, Feng 2015). However, due to the cumbersome operation, many restrictions and low measurement accuracy and other unfavourable factors, the use of these methods are limited. Therefore, scholars at home and abroad hope to establish a method of the non-destructive, rapid and accurate method to acquire the timber volume. Among them, the representative studies include scanning and modelling of standing timber acquiring timber volume based on three-dimensional laser scanner, volume calculation by angle and distance measurement of the electronic theodolite and total station, volume measurement of monocular CCD digital camera and so on. However, these methods also have their limitations. For example, 3D laser scanners are expensive and cumbersome to operate; electronic theodolite and total station measurement volume method need long hours of foreign work and intensive work. CCD digital camera method needs to place the calibration scale or the help of artificial measurement (Deng 2007, He 2016, Vonderach 2012, Feng 2003, Wang 2013, Abramo 2007, Tompalski 2014, Yu 2016, Zhao 2014, Jiao 2013, He 2012, Straub 2011).

In order to sum up the advantages of the above method, this paper presents a nondestructive, rapid and accurate method for measuring height and volume of standing tree by using a CCD SmartStation. In the method, the exterior elements are obtained by the goniometry and ranging measurement functions of the CCD SmartStation. The mode of single-photo photography and multi-photo correction and merging are adopted to obtain the tree height and volume factor of the standing tree by the principle of close-range photogrammetry. The method has the advantage, which is cheaper than the 3D laser scanner, and has a simple operation. Compared with the traditional method, the method reduces the working time and the workload in the field. In addition, the method can be operated by a single person without additional manual assistance, which achieves the true sense of the non-contact measurement. Table 1 compares the current method of measuring timber volume with the method proposed in this paper (Cao 2015, Cao 2013, He 2013).

THE PRINCIPLE OF PRECISE MEASUREMENT OF STANDING TREE OF CCD SMARTSTATION

Systematic calibration of CCD SmartStation: When photogrammetric post-processing is carried out, precisely obtaining the exterior elements of the photograph directly affects the accuracy of the measurement results. There are mainly two kinds of systematic errors in the CCD SmartStation systems, which are, respectively, optical distortion error of CCD lens and offset error between CCD lens center and total station center space position. In order to improve the measurement accuracy, two systematic errors need to be eliminated or reduced (Liu 2016, Feng 2015).

In this paper, DLT linear transformation method is used to calibrate the optical distortion of CCD lens. Through the principle of space resection of the single photograph, by using the ground control point and the corresponding pixel coordinates, iteratively solve the CCD extra ranging ele-

Table 1: Comparison and analysis table of measurement method of a variety of timber volume.

Measurement methods of standing timber volume	Instrument prices and labour costs	Work efficiency
Method of 3D laser scanners	Instrument prices are high (60~150 million yuan), at least two people are needed to operate.	Field workload is large; equipment is heavy and not easy to transport; internal work is complex, and it requires professional software; measurement of a tree needs about 20 minutes in average, precision is high.
Measuring method of monocular CCD digital camera	Instrument prices are low (0.1~0.8 million yuan), two people are needed to operate.	Field workload is small, and the equipment iseasy to carry. Office workload is moderate. The aver age time for measuring one tree is about 5 min utes, and the measurement accuracy is moderate.
Method of electronic theodolite	Instrument prices are low (0.3~0.8 million yuan), two people are needed to operate in cooperation	Field workload is large; human works are needed for the auxiliary measure of the diameter of the chest, it is not suitable for continuous operations; internal work is tedious, people should distin guish and organize data string; measurement of a tree is about 15 minutes in average, accuracy is high.
Method of TotalStation	Instrument prices are medium (30~80 thousand yuan), one person is needed to operate.	Field workload is large. It requires the continu ous work of the human eye and makes people tired easily. It is not suitable for continuous op eration; office work is moderate; measurement of a tree is about 12 minutes in average, accuracy is high.
Method of CCD SmartStation	Instrument prices are medium (30~80 thousand yuan), one person is needed to operate.	Field work is small. It doesn't need the assistance of other personnel, and operation is continuous; office workload is moderate; the measurement of a tree is about 5 minutes in average, accuracy is high.

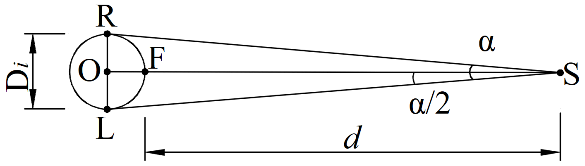


Fig.1: Relations diagram of observational distance and angle of CCD SmartStation.

ments at the moment of shooting, make the simultaneous solution of the coordinate with position and attitude of the instantaneous total station. The translation and rotation offsets relative to the total station can be obtained. The CCD SmartStation used in this paper is calibrated to obtain the space attitude offset parameter (0.09 cm, 11.50 cm, 0.04 cm, 2°07'03", -0°24'45", 0°16'30"), error in the unit weight is 2.90×10^{-7}. The CCD SmartStation is a connection of rigid body, which means that the space attitude offset is constant during the operation. Therefore, it is only necessary to perform a calibration before the operation.

The principle of tree measurement of the single-photo of CCD SmartStation: When using CCD super-station measurement, the instrument required to be strictly flat, at this moment, the rotation angle κ around the Z-axis has a very small value, κ can be regarded as zero within the allowable range of error, the direction of the main optical axis is the direction of zero when taking photographs, that is, the rotation angle around the Y-axis is zero. Therefore, it is considered that there is only an inclination ω rotating the X-axis at the moment of photography. With the set coordinate *m* of the photograph space as (*u*,*v*, *-f*), object-space coordinates of photographic centre S as (0,0,0) and the object-space coordinate of target point M as (X_M, Y_M, Z_M), it can be known that the coordinate of the object space point to be measured M is calculated as follows:

$$\begin{cases} X_M = \dfrac{Z_{\mathrm{M}}}{f\cos\omega - v\sin\omega}u \\ Y_M = \dfrac{Z_{\mathrm{M}}}{f\cos\omega - v\sin\omega}\left(v\cos\omega + f\sin\omega\right) \end{cases} \quad ...(1)$$

As shown in Fig. 1, CCD SmartStation is used to measure the included angle α between the left edge L and the right edge R that are from the projection center S to a certain diameter of standing timber, and the horizontal distance d from the instrument to F at α/2 of tree trunk. Record the vertical angle ω of the instrument while taking the photograph. The plane that intersects the center of the tree and is perpendicular to the main optical axis of the camera is used as the solution surface. Extracting the coordinates of the left and right edges of the standing timber at any height in the photograph. The formulas (2)-(4) are used to calculate the distance Z_M from the projection center S to the center O of the tree, the height H_i of standing timber at any height and the diameter D_i at the corresponding height.

$$Z_{\mathrm{M}} = d + \frac{d \cdot \tan\dfrac{\alpha}{2}}{1 - \tan\dfrac{\alpha}{2}} \quad ...(2)$$

$$D_i = \Delta X = \frac{Z_M}{f\cos\omega - v_i^L\sin\omega}\left(u_i^R - u_i^L\right) \quad ...(3)$$

$$H_i = \Delta Y = \frac{Z_M}{f\cos\omega - v_i^L\sin\omega}(v_i^L\cos\omega + f\sin\omega) - \frac{Z_M}{f\cos\omega - v_0^L\sin\omega}(v_0^L\cos\omega + f\sin\omega) \quad ...(4)$$

In the formula, $\left(u_i^L, v_i^L\right)$, $\left(u_i^R, v_i^R\right)$ are the coordinates of the photograph point of left and right edge at some height of the trunk. $\left(u_0^L, v_0^L\right)$, $\left(u_n^L, v_n^L\right)$ are the coordinates of the photograph point at the left edge of the ground diameter and the treetop.

The tree height H is calculated as:

$$H = H_n - H_0 \quad ...(5)$$

The classic piecewise partitioning method is used to calculate the stand volume V

$$V = \frac{\pi}{12}\sum_{i=1}^{n}\left(H_i - H_{i-1}\right)\left(D_{i-1}^2 + D_{i-1}D_i + D_i^2\right) \quad ...(6)$$

In the formula, $i = 1,2,...,n$, D_0 is round diameter, $D_{n=0}$

Merging photography measurement of multi-photo of CCD SmartStation: Due to the complex environment of woodland, it often encounters difficult conditions, especially when it is closer to the standing tree or when the standing wood is higher, it cannot be shot all at once. Therefore, it needs to change the angle to shoot multiple times to obtain the pictures of the standing wood at different heights to ensure that there is a certain degree of overlap between the pictures. By making inclination correction on the obtained photographs one by one, the photographs are uniformly corrected to be horizontal shots, and the photographs are spliced together to obtain an photograph containing the complete information of the tree.

Due to the inclination correction of the picture, it is considered that the picture after being merged is equivalent to the picture taken by the camera in an upright position, that is, $\omega=0$. At this time, height H_i at any place of standing trees can be obtained, and calculation formula of diameter D_i at the corresponding height is:

Fig. 2: Real product photo of CCD SmartStation.

Fig. 3: CCD main interface of precise measurement software of standing tree based on CCD SmartStation.

$$D_i = \Delta X = \frac{Z_M}{f}\left(u_i^R - u_i^L\right) \quad ...(7)$$

$$H_i = \Delta Y = \frac{Z_M}{f}(v_i^L - v_0^L) \quad ...(8)$$

Under stitching mode of multiple photographs, the method of calculating the height and volume of the standing tree is similar to the calculation method in the single-photo mode, and it is not explained here.

MATERIALS AND METHODS

Experimental preparation: The CCD SmartStation system used in this experiment consisted of CCD lens (DSC-QX100, Sony of Japan, effective pixels: 20.2 million), total station (NTS-362R, South Surveying Instruments Co., ranging accuracy is 2 + 2 ppm, angular accuracy is 2") and tablets (iPad mini 3, Apple USA) preinstalled with Play Memories Mobile software (Zhao 2010, Zhang 2005). Among them, the CCD lens photograph size is 5472 × 3648 pixels, the sensor size is 13.2 × 8.8 mm and the pixel size is 2.41 μm. In order to make the system stable, the CCD SmartStation system uses hard steel materials to make the connection, which not only fixes the spatial position of the CCD lens and the total station, but also ensures that the lens of the total station can be inverted vertically. Picture of real products of CCD SmartStation is shown in Fig. 2. According to the measurement principle, using Microsoft Visual Studio to develop a CCD SmartStation precision measuring software of standing tree, the software interface is shown in Fig. 3.

Experimental design: When using this method for precise measurement of standing wood, the observation distance affects the field of view of the photograph, which in turn affects the imaging distortion and pixel resolution, inclination affects the imaging distortion, whereas irregularities of standing timber affect the measurement of the trunk diameter. Therefore, in order to verify the performance and accuracy of measuring tree system of the CCD SmartStation, the experiment is divided into two parts: (1) Without considering the influence of shape of the standing timber, analyze the impact of distance, inclination and photography mode on the measurement accuracy, when using this method to measure tree height and volume; (2) The influence of various instability factors on the measurement results, such as irregular shape of standing timber, stem diameter, and tree height, is introduced into the actual measurement situations, and the accuracy and stability of this method in actual field measurement are verified.

First, when verifying experiment (1), in order to reduce the error caused by stem-shaped irregularity of standing timber, a comparatively-selected truncated cone-shaped electric pole was selected as a simulation object for standing wood. The pole size was Φ150 mm × 6 m, its tip diameter 150 mm, the root diameter 230 mm and pole length 6 m. As the bottom of the pole was buried underground, the actual height and root diameter of the ground have changed. A diameter caliper was used to measure the root diameter close to the ground several times in different directions, taken the average value as 22.2 cm, used the total station's hanging height measurement function to measure the height of the pole on the ground several times and taken the average as 5.470 m. Volume formula of the circular truncated cone was used to calculate the volume of pole as 0.1504 m^3, and the above measurements were taken as the pole of the standard data.

The operation steps of experiment (1) are as follows:

(1) The inclination of view of the experimental CCD lens is about 45°. After repeated deduction and testing, the instrument from the pole is less than 6.3 m. The entire pole cannot be completely shot by a single picture. In order to ensure that the degree of overlap is 30%, when the instrument is less than 3.8 m from the pole, the pole

cannot be fully shot by two pictures . In order to be able to complete the shoot of the pole above the ground, this experiment chooses the nearest distance of about 3 m, each time it was increased to about 1 m to shoot, and total of 20 stations were set up.

(2) In the site whose distance is 6.900 m ~ 21.338 m, based on the ability to complete the shooting pole, when shooting at each station, take the level as standard, press 5° increments (or decrements) to adjust the tilt for shooting, pole height and volume solution are achieved by self-developed precise measurement software of standing timber based on CCD SmartStation .

The operational steps of experiment (2) are:

(1) Select standing timber whose trunk is circular and less coarse, make 3 times hanging height measurement by using Total Station, take average value as the standard value of tree height, make 3 times measurement by using method of volume measurement of Total Station, and take the average value as the standard value of standing timber volume;

(2) For the selected stands, the field data are acquired on the same side of the Total Station measuring standing timber by using any of the photogrammetry models. The tree height and product volume are calculated in the developed precise measurement software of standing tree based on CCD SmartStation.

Evaluation method of observation accuracy: When estimating precise measurement method of standing tree based on CCD SmartStation, take the tree height and volume data from the tree height and volume calculated as standard value, compare it with the tree height and volume values measured by the CCD super-station, calculate the absolute error *e,* relative error δ', average relative error $\overline{\delta'}$, relative error absolute value δ, relative error absolute value average $\overline{\delta}$ and measurement accuracy *P* between the two by formulas (9)-(14).

$$e = V_m - V_s \quad ...(9)$$

$$\delta' = \frac{V_m - V_s}{V_s} \times 100\% \quad ...(10)$$

$$\overline{\delta'} = \frac{\sum_{i=1}^{n} \delta'}{n} \quad ...(11)$$

$$\delta = \frac{|V_m - V_s|}{V_s} \times 100\% \quad ...(12)$$

$$\overline{\delta} = \frac{\sum_{i=1}^{n} \delta}{n} \quad ...(13)$$

$$P = 1 - \overline{\delta} \quad ...(14)$$

In the formulas (9)-(14), V_m is the measured value of CCD SmartStation; V_s is the calculated standard value corresponding to V_m.

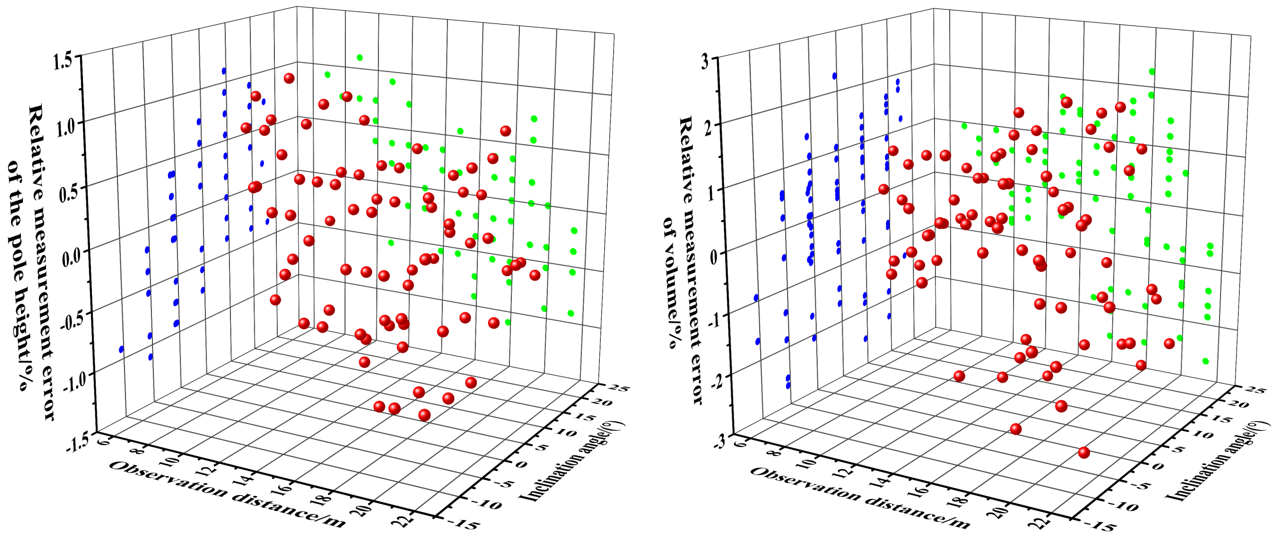
RESULTS AND DISCUSSION

The impact of distance and inclination of the measurement accuracy: During the experiment, a total of 110 shots were taken, of which 75 shots were taken in the single photogrammetric model, and 35 shots in correction and stitching photography measurement mode. The distance between the instrument and the pole in the monolithic operation mode ranges from 6.900 m ~ 21.338 m, and the inclination ranges from -10°~18.5°. The distance between the instrument and the pole in the multi-photo mode ranged from 2.892 m ~8.878 m, and the range of variation was -20° ~ 40°.

With the increase of the measuring distance, the relative error of the pole height measurement decreases at first (from 1% to 0) and then increases (from 0 to -1%), and the relative error of the volume measurement gradually increases. As the measured inclination increases, the relative error of the rod height and volume measurements decreases first (from -1% to 0) and then increases (from 0 to 1%) (Fig. 4).

The absolute error of pole height measurement range is -0.06 m ~ 0.06 m, the relative error range is -1.10% ~ 1.10%, the average relative error is -0.03%, the absolute value of relative error is 0.46%, and the measurement accuracy is 99.54%. The range of absolute error of the measurement results of the electric pole is -0.0040 m^3 ~ 0.0034 m^3, the relative error range is -2.66% ~ 2.26%, the average relative error is -0.04%, the absolute value of the relative error is 0.97%, and the measurement accuracy is 99.03%. The measured distance is negatively correlated with the error of the pole height measurement. The reason may be that the lens distortion cannot be completely corrected. As the measuring distance increases, the influence of the lens distortion gradually decreases, but the resolution of the photograph decreases. As the edge of the pole is misused, random errors in picking up feature points in the software increase. The measurement inclination angle is positively correlated with the error of pole height and volume measurement. The reason may be that the error of the photograph inclination correction increases with the shooting angle.

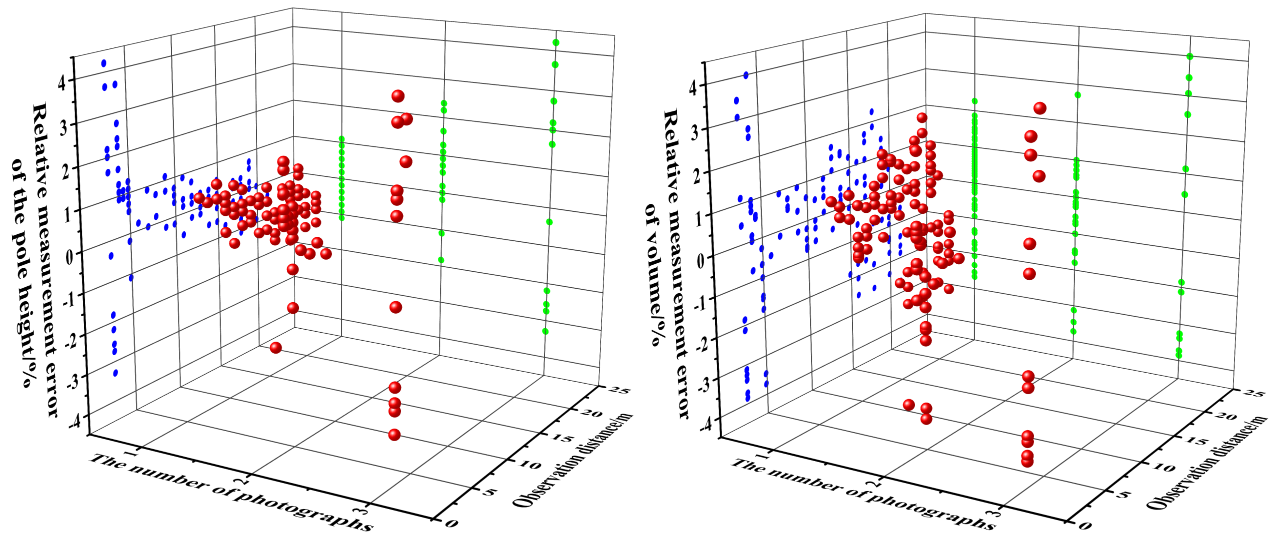
After experimental verification, when the distance measurement of CCD SmartStation used in the experiment is less than 20 m, the edge point of object-place is more clear. Therefore, it is recommended that the measurement distance should not be larger than 20 m, and when the observation distance is 15 m, and the observation angle is 0°, the data obtained will be in higher accuracy.



a. Pole height measurement results b. Volume measurement results

Note: The X-axis is the distance L (m), the Y-axis is the dip angle (°), and the Z-axis is the measurement relative error (%) of the rod height H and the volume V in turn.

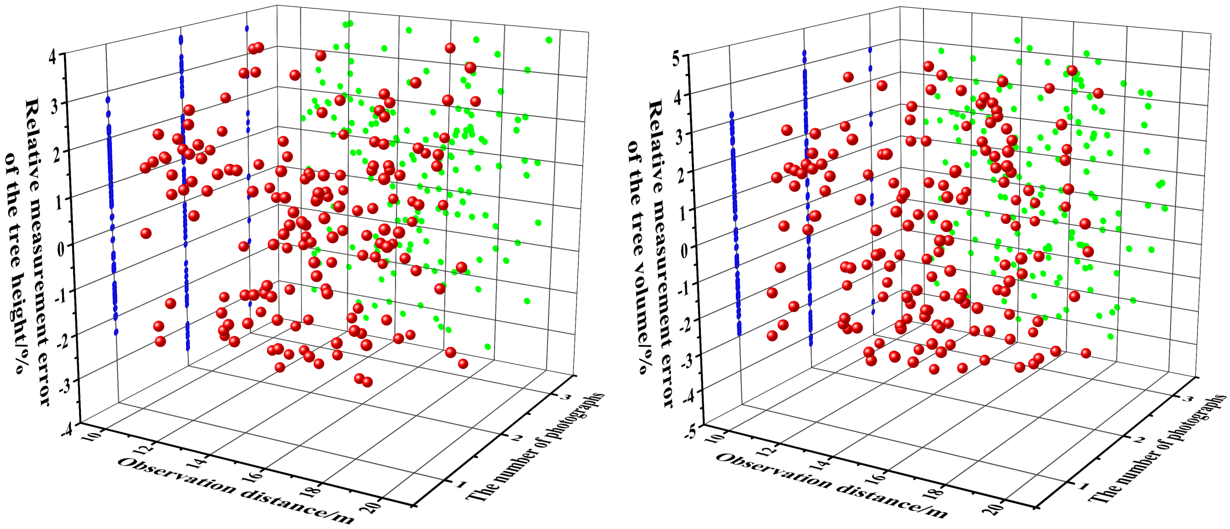
Fig. 4: The impact of distance and inclination on the single photogrammetry results.



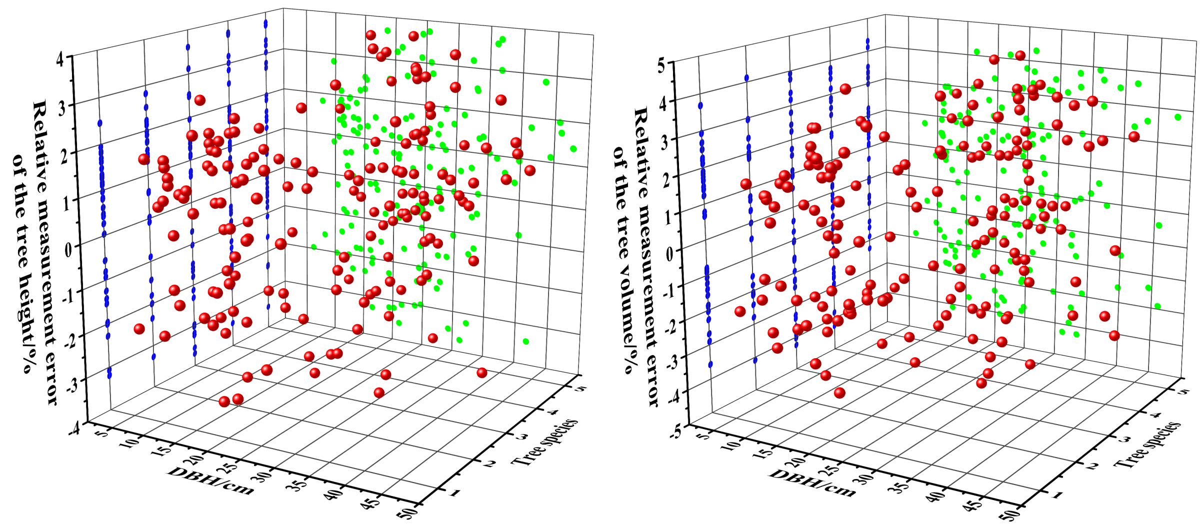
a. Pole height measurement results b. Volume measurement results

Fig. 5: The impact of single photo and multi-photo correction and merging on the photogrammetry results. Note: The X-axis is the number of photographs P (pieces), the Y-axis is the distance L (m), and the Z-axis is the measurement relative error (%) of the pole height H and volume V in turn.

The impact of photography mode on measurement accuracy: A total of 35 groups of merging measurements were obtained. Among them, 23 groups obtained from 2 photographs were merged and 12 groups obtained from 3 photographs were merged. Through the analysis of the experimental results of single and multiple corrective merging photogrammetry modes, it can be seen that as the number of photographs increases, the measurement precision of the pole height and volume decreases (Fig. 5). The precision of pole measurement of the single photo is 99.54%, and the accuracy of the volume measurement is 99.03%. The precision of poles measurement of the two photographs merging is 99.02%, and the precision of volume measurement is 98.87%. The precision of poles measurement of the three photo merging is 97.39%, and the accuracy of the volume measurement is 97.26%.



a. Impact of observation distance and observation mode on tree height measurement error
b. Impact of observation distance and observation mode on volume measurement error



c. Impact of DBH and species on tree height measurement error

d. Impact of DBH and species on volume measurement error

Fig. 6: Impact of DBH, tree species, observation distance and observation mode on standing tree error. Note: In the figure (a) and (b), the X axis is the observation distance (m), the Y axis is the number of photographs, and the Z axis is the measurement relative error (%) of tree height and volume;): In the figure (c) and (d)The X-axis is the diameter at breast height (cm), the Y-axis is tree species (1,2,3,4,5 respect Arborvitae, Pinus tabulaeformis, Populus trichocarpa, Ginkgo biloba and Populus tomentosa), Z axis respects tree height and volume measurement of relative error (%).

Accuracy analysis of measurement of standing timber: In order to verify the accuracy and stability of this method in the field measurement of standing timber, a total of 160 standing trees were selected for the measurement. Among them, 34 were oriental arborvitae, 24 were pine, 32 were fast-growing poplar, 35 were ginkgo and 35 were poplar. The information of standing timber is given in Table 2. Taking measurement of the total station as the standard value, through the experimental results of comparative analysis, the absolute error range of tree height of 160 standing timber is -1.01 m ~ 1.124 m, the relative error range is -3.70% ~ 3.75%, the average relative error is 0.28%, the mean of absolute value of the relative error is 1.59%, the range of absolute error of volume is -0.0373 m^3 ~ 0.0556 m^3, the relative error range is -4.25% - 4.31%, the average relative error is 0.11%, and the mean of absolute value of relative error is 1.99%.

The measurement and analysis of 160 standing trees are carried out by measurement experiment of field standing

Table 2: Information of experiment of standing wood.

Factor of standing timber	Minimum	Maximum	Mean	Standard deviation
Diameter at breast height (cm)	6.2	47.8	22.33	9.36
Height of timber (m)	5.661	31.15	15.772	6.78
Volume of timber (m^3)	0.0108	1.5286	0.3729	0.3439

wood. The measurement precision of tree height and volume are 98.41% and 98.01% respectively. Through the analysis of the results of the measurement accuracy of 5 tree species and three kinds of photographs (Fig. 6), we can get the different diameters at breast height, tree species and observation distance. There is no significant difference between the accuracy of using CCD and TotalStation in the same direction. As the number of photographs increases, the measurement accuracy decreases. The reason for such a result may be that the photograph will be distorted when the photograph is corrected for tilt, resulting in a decrease in resolution. In addition, there is merging error in the photograph merging, with the increase in the number of photographs, merging error increases. However, in general, the method of measuring the accuracy of standing wood can meet the requirement of the table for measuring the height and volume of standing wood.

Optimum observation method of factor of standing timber of CCD SmartStation: According to the measurement of a pole simulating standing wood, the relative error between the tree height and volume measurement has a negative correlation with the observation distance, and has a positive correlation with the observation inclination. As the observation distance and inclination increase, the measurement precision decreases first and then increases. The relative error of measurement results and observation distance and observation inclination are carried out by linear regression respectively, after analyzing the error reason, the optimal observation distance is 15 m, and the optimal observation angle is 0°. The relative error of tree height and volumetric measurement increases with the number of photographs merging, so the photography model should give priority to monolithic photogrammetry.

Based on the above analysis, when the method for measuring the volume of standing timber of a CCD SmartStation is used in a specific application, priority should be given to increasing the observation distance when conditions permit, followed by adjusting the observation angle and finally increasing the number of photographs.

CONCLUSION

In this paper, a non-contact method for measuring height and volume of standing timber based on CCD SmartStation is proposed. Through distance and angle measurement function of the total station, it can accurately obtain the outer orientation elements when the CCD lens takes the picture. By using the principle of the single-piece solution in the close-range photogrammetry, two kinds of photogrammetry modes of the single photo and multi-photo for tree height and volume measurement are obtained. In the field operation, this paper recommends measuring mode of single photo photogrammetry, which takes 15 m as observation distance and 0° as the observation angle. When office calculation, it is recommended to use the software of CCD SmartStation precision measuring software of standing tree developed in this paper, which can reduce the workload and improve the work efficiency. After the program is implemented and verified by experiments, the measurement accuracy of tree height of this method is 98.41%, and the volume measurement accuracy is 98.01%. Compared with the existing methods, the method has the advantages of low price, simple operation, small work load in the field, single operation, no additional manpower assistance and so on. However, this method also has some limitations. It can not get better measurement results when the standing wood is multi-stem, or the shelter is serious. Also, when measuring wood working operations, the average of the measurements should be taken in 2 to 3 directions as the measurement result. Overall, the use of a CCD SmartStation for precise measurement of standing timber is a new way to reduce the working hours in the field. It provides a reference for the establishment of timber volume tables and forestry surveys.

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