Automated Low-cost Terrestrial Laser Scanner for Measuring Diameters at Breast Height and Heights of Forest Trees

Pei Wang 1,*, Guochao Bu 1, Ronghao Li 1, Rui Zhao 1

1 Institute of Science, Beijing Forestry University, No.35 Qinghua East Road, Haidian District, Beijing, China; wangpei@bjfu.edu.cn
* Correspondence: wangpei@bjuf.edu.cn; Tel.: +86-10-6233-8136

Abstract: Terrestrial laser scanner is a kind of fast, high-precision data acquisition device, which had been more and more applied to the research areas of forest inventory. In this study, a kind of automated low-cost terrestrial laser scanner was designed and implemented based on a two-dimensional laser radar sensor SICK LMS-511 and a stepper motor. The new scanner was named as BEE, which can scan the forest trees in three dimension. The BEE scanner and its supporting software are specifically designed for forest inventory. The experiments have been performed by using the BEE scanner in an artificial ginkgo forest which was located in Haidian district of Beijing. Four 10m×10m square plots were selected to do the experiments. The BEE scanner scanned in the four plots and acquired the single scan data respectively. The DBH, tree height and tree position of trees in the four plots were estimated and analyzed. For comparison, the manual measured data was also collected in the four plots. The tree stem detection rate for all four plots was 92.75%; the root mean square error of the DBH estimation was 1.27cm; the root mean square error of the tree height estimation was 0.24m; the tree position estimation was in line with the actual position. Experimental results show that the BEE scanner can efficiently estimate the structure parameters of forest trees and has a good potential in practical application of forest inventory.

Keywords: laser scanning; terrestrial laser scanning; low-cost; diameter at breast; tree height; tree position

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1. Introduction

Laser scanning is a surveying method which can measure the distance between the point the laser scanner located and the point on the object illuminated by a laser light. In the past decades, laser scanning technology have been widely used in various fields, such as mapping [1,2], photographing [3]; surveying [4] and so on. The laser scanning systems on airborne and spaceborne have been also used to acquire the point cloud data of large areas of forest to make the forest inventory [5], [6] [7].

Recently, the terrestrial laser scanning (TLS) has been used to acquire the data of forest in local area [8] [9]. TLS data could describe the forest in details with very high accuracy even to the level of millimeter. Without doubt, TLS data has the potential to make the forest inventory in a very high precision. More and more experiments were carried out to estimate the attributes of the forest trees, such as diameter at breast height (DBH), tree height, tree crown, leaf area index and biomass etc [9] [10] [11] [12]. Among these studies, one focus was the accurate estimation of the structure parameters, such as DBH, tree height etc.
TLS could acquire large amounts of scanning data with very high speed. Manually processing the data is very time-consuming. So automated processing the point cloud data becomes a trend. Many methods have been proposed to automatically estimate those structure parameters [11] [13] [14] [15] [16].

But there are still problems on the forest applications of the TLS data. One problem is that the terrestrial laser scanners used in the forest inventory are mostly expensive commercial equipment. The high price increases the cost of widely using TLS data in the forest applications. The other problem is that those expensive scanners are common equipment which are not limited to forestry. And they are lack of specialized processing software in forest inventory.

Therefore automated low-cost terrestrial laser scanners designed for the forest inventory were needed. Some work has been done some on this area. David Kelbe designed a low-cost terrestrial laser scanner with SICK LMS-151 to reconstruct the 3D tree stem models and estimate the DBH and tree position [17]. Xinlian Liang designed a personal laser scanning (PLS) system with FARO Focus3D 120 for forest mapping and ecosystem services [18]. They estimated the DBH and tree position in the experiments. Darius S. Culvenor designed an automated in-situ laser scanner for monitoring forest leaf area index [19].

This paper describes an automated low-cost terrestrial laser scanner for measuring the DBH, tree height and tree position of the local forest. The scanner described in the paper is composed of a SICK LMS-511 sensor and a stepper motor. The scanner was used in the scanning of four small plots. The estimating results of the plots were analyzed and discussed to demonstrate the potential of the automated low-cost terrestrial laser scanner.

2. Materials and Methods

2.1. Instruments Description

The goal of this study was to develop an automated low-cost terrestrial laser scanning system for measuring DBH, tree height and tree position. The developed system is named the BEE scanner, which is composed of two main parts, hardware and software. By selecting and developing the key components of the hardware, such as the laser scanning sensor and the platform, the cost of the system was below 10,000$. The laser scanning sensor implements the emission and the reception of the laser light. In this study, a two-dimensional laser scanning sensor was used. The platform implements the rotation of the laser scanning sensor and the communication between components. A stepper motor was used to rotate the laser scanning sensor to fulfill the three-dimensional scanning.

By considering the performance and price of the laser scanning sensor, we chose the SICK LMS-511 laser scanning sensor which was manufactured by SICK company. Table 1 lists the technical specifications of the SICK LMS-511 laser scanner. The laser scanning sensor employs a Class1 laser that operates in the near infrared part of the spectrum at 905nm. The angular step-width could be preset at several values, such as 0.1667°, 0.25°, 0.333°, 0.5°, 0.667° and 1°. The scan speed also could be preset at serval values, such as 25Hz, 35Hz, 50Hz, 75Hz and 100Hz. The angular coverage of the laser scanning sensor is up to 190°, from -5° to 185°. The laser scanning sensor's power requirements are supplied by a 24V DC supply. The laser scanning sensor can measure echoes from the object’s points. The measured range and intensity data can be recorded remotely via an Ethernet interface or a RS232 interface to the external computer.

| Performances          | Specifications       |
|-----------------------|----------------------|
| Measurement Distance(m)| 0.7–80               |
| Supply Voltage(V)     | 24DC±20%             |
| Accuracy(mm)          | ±12                  |
| Laser Wavelength(nm)  | 905                  |
The laser scanning sensor was mounted on a rotating platform which is set horizontal to the ground. And the scanning laser sensor was perpendicular to the ground so that the angular coverage is 190° in the vertical direction. The platform implements 360° scanning in the horizontal direction by using a motor which is also supplied by 24V DC. Therefore the field of view of the BEE scanner is 360° ×190°.

A specific software was developed for controlling the BEE scanner, receiving the data from the scanner, estimating the structural parameters of trees automatically and displaying the results. The specific software contains three modules: ScanController module, Display module and TreeStructureExtract module, as shown in Figure 1. The ScanController module controls the components of the BEE scanner to work together harmonically, receive and record the measured data on a laptop computer. The Display module could demonstrate the 3D effect of the measured data. And the TreeStructureExtract module could automatically detect the trees in the scene and measure the DBH, height and position of the trees.

![Figure 1. The scheme map of the BEE scanner.](image)

The BEE scanner was mounted on a tripod in the field measurement, and connected to a laptop computer, as shown in Figure 2. The BEE scanner was equipped with 24V DC battery pack to supply the laser scanning sensor and the stepper motor. And a solar battery also was provided as a standby.
2.2. Study Area

The study area is located in a man-made mixed plantation forest in the Haidian District of Beijing (37.7° S, 144.9° E), Figure 3(a). The forest trees are mainly ginkgo trees and a small amount of pine trees, Figure 3(b). The planting space between trees is about 1.6m in North-South direction, and 2.8m in West-East direction. Some trees died and were removed, then their locations were vacant. The stem density of the forest is about 0.2 trees/m². The mean and standard deviation are 12.11cm and 2.37cm for DBH and 8.43m and 0.78m for tree height. The experiment was carried out in March 2015 when the ginkgo trees are in leaf-off period. In the forest, four 10m×10m square plots were selected to do the scanning experiments.

Figure 3. (a) The study area located in Haidian district of Beijing (37.7° S, 144.9° E); (b) Picture of the field site.
2.3. Data Acquisition

Four 10m×10m square plots were selected to be scanned in the experiments. The scan position was selected near the center of each plot considering a good field of view, which could reduce the shadowing effects. The BEE scanner was mounted on a tripod which was placed on the selected positions. The rotating speed was set one degree per second so that the BEE scanner could scan the 360° scene in six minutes. When the BEE scanner started working, the dataset was transferred to the laptop computer and recorded. A single scan was performed in each plot.

For comparison, DBH of each tree in the four plots was tape-measured and recorded. Tree height could be deduced according to the distances and angles to the top and bottom of the tree, which were acquired by using the handle rangefinder of Bushnell. Tree heights were also calculated and recorded. And each tree in the plots was numbered and was drew its relative position in the plot. The above manual measured data would be used for the consecutive data processing and the comparison with the estimated values.

3. Methods

When the BEE scanner was settled down in the plot, scan was started by using the specific software. The system would run step by step as shown in Figure 4. A large amount of data including the horizontal angle, the vertical angle, the intensity data and the range data of each scanning point was got by the computer. The calculated point cloud data was used to detecting the trees in the plot and fitting the local ground plane of each tree. Then the DBH, tree height and tree position were estimated consecutively.

![Flowchart](image)

**Figure 4.** The flowchart of the data acquiring and processing of the BEE scanner.

3.1. Acquiring the Scanning Data

The SICK LMS-511 is a kind of two-dimensional laser scanning sensor which could scan the contour of the measured objects by using the time of flight of the laser pulse. The slant range $R$ and the intensity value $I$ of each measured point were provided to the user. Meanwhile the user could calculate the vertical angle $\theta$ of each point according to the preset vertical angular step width which is set to 0.1667° in the experiments. When the SICK LMS-511 was placed vertically and rotated by the stepper motor, the horizontal angle $\varphi$ of each point can be acquired by counting the steps of the stepper motor at a certain speed of rotation. Thus, there is a set of information $(R, I, \theta, \varphi)$ for each measured point.

Assuming that the position of the SICK sensor is in the position with the coordinates $(0, 0, 0)$ in the three-dimensional space, the coordinates $(x, y, z)$ of each point could be calculated by using a set of information $(R, \theta, \varphi)$ according to the simple spatial geometrical relationships. For example, when the measured point is in the first quadrant, the coordinates were calculated by
\[ x = R \cdot \cos(\theta) \cdot \cos(\varphi) \]
\[ y = R \cdot \cos(\theta) \cdot \sin(\varphi) , \]
\[ z = R \cdot \sin(\theta) \]

In this way, the point cloud data of the whole scene could be constructed in three-dimensional space. These measured points could also be projected into a cylinder with their range values or intensity values. Then the range map and the intensity map could be provided to the user as the auxiliary data for processing and analysis.

3.2. Trees Detection

Because the plots are only 10m×10m in size and the ground is relatively flat, the single slice method was used to detect the trees in the point cloud data. We obtained the point cloud transect at 1.3m height by slicing the point cloud data with ±5 cm height. Then the point cloud transect was projected into a plane and clustered by using the horizontal angle and the range [20]. If a cluster of points are consistent with the distribution of the circumference, it means a tree may be detected [10]. Each cluster of points would be used to fit a circle. The specific software can provide a variety of circle fitting methods, such as Gauss-Newton method, Pratt’s method[21] and Taubin’s method[22]. In order to ensure the efficiency, we used the Pratt’s method to fit the circle. The center point of the circle was seemed to be a tree position when the fitted diameter was in a reasonable range.

In practice, when we measured the four plots, the thickest stem and the thinnest stem in each plot could be roughly estimated by taking a look. And the rough values could be used as the upper limit and the lower limit respectively. So a tree position was defined only if the fitted diameter is between the upper limit and the lower limit. If the fitted diameter is out of the range, the circle fitting was thought to use the outliers, and the stem detection was defined failed.

3.3. Ground Fitting

In a large area, the ground may be fluctuated. And this will affect the judgement of the breast height. So the local ground plane should be fitted first before estimating the DBH. According to the acquired tree position mentioned above, we drew a cylindrical space in the point cloud data. The diameter of the cylinder is four times of the diameter of the tree. In the cylindrical space, the point cloud data was extracted with the lowest height of about 10cm thickness. Usually the extracted point includes the ground points and the points at the bottom of the trunk. In a local area, the ground is relatively flat. So the local ground plane was fitted by using RANSAC method in the experiment. If the plane tilts more serious, the breast height will be corrected. Otherwise project the center point of the fitted circle into the fitted ground plane, and the height of the projected point would be the local zero point for the estimation of the tree.

3.4. DBH, Height and Position Estimation

Based on the results of stem detection and local ground plane fitting, the breast height which is 1.3m height could be confirmed. According to the confirmed breast height, the point cloud transect was re-sliced and used to estimate the DBH by using the Pritt circle fitting. So the new center point of the circle was got, and the point’s projected position on the local ground plane was defined the local zero-height point and the position of the tree. Because the trees in the plots are growing straightly, the tree height was defined that the distance between the local zero-height point and the highest point in the above mentioned cylindrical space.

4. Results

4.1. Scanning Data
Since the measuring range of the laser scanning sensor can be up to 80 meters, the point cloud data of a large area will be obtained in a single scan. A field measurement of single scan is shown in Figure 5. As shown in the figure, the point cloud data around the scanner is with the higher density than the point cloud data far away from the scanner. The density varied because of the diffuseness and the shadowing effects of laser light. Obviously the trees are almost planted in lines from the north to the south and from the east to the west.

![Figure 5. Point cloud data of a single scan acquired by using the BEE scanner.](image)

In the study, four single scans were performed in the four plots respectively in the field experiments. In each single scan, a square plot with the size of $10m \times 10m$ was extracted from the whole single scan. The center point of the plot is the position of the BEE scanner. The point cloud data of four plots were shown in Figure 6.

![Figure 6. (a) and (b) show point cloud data of single scan.](image)
Figure 6. Point cloud data of the four plots. (a) Plot 1; (b) Plot 2; (c) Plot 3; (d) Plot 4.

Based on the dataset of each plot, the BEE scanner could get not only the point cloud data, but also the range data and intensity data. Taking the plot1 as an example, the range map and the intensity map of plot1 were calculated and shown in Figure 7. The intensity value of the points in the plot1 was mapped to a range of 0-255. The color of intensity map represents the different value of intensity. The color of range map represents the distance between the scanner and the measured point. It was demonstrated that the slant range is between 0.40m and 7.06m.
4.2. Detecting Results

According to the detecting method described in section 3.2, the point cloud data in each plot was tested and some trees were detected. Taking the plot 1 as an example, the detected result was shown in Figure 8. As shown in the figure, there was a group of points belonging to the local ground below each detected tree. And the ground points were extracted by using the cylindrical space mentioned in section 3.2.

![Figure 8. The detected trees of the plot 1.](image)

The results of the stem detection are reported in Table 2. The number of trees and the stem density were also listed in Table 2. As shown, the stem density was from 0.14 stems/m² to 0.22 stems/m². The correct detection means that the detected tree was right in the place. The false detection means that the detected tree did not exist. And the omission means that the tree existed but has not been found.

The detection rate is the ratio of the correct detection and the number of trees. The highest detection rate was 100% in plot 1, and the lowest detection rate was 86.36% in plot 3. Table 2 shows that there are 69 trees in the four plots. Among these trees, 64 trees were detected and 5 trees were missed. Therefore, the overall detection rate was 92.75%. Among these missed trees, three trees did not appear in the point cloud data of the plot because of the shadowing effects. The other two trees were missed because of the detecting algorithm. The low stem density, thresholds of diameter and the less branches in the point cloud transect contributed to the zero value of false detection.

| Plot | Number of Trees | Correct detection | False detection | Omission | Stem density (stems/m²) | Detection rate |
|------|-----------------|-------------------|-----------------|----------|------------------------|----------------|
| 1    | 16              | 16                | 0               | 0        | 0.16                   | 100%           |
| 2    | 14              | 13                | 0               | 1        | 0.14                   | 92.86%         |
| 3    | 22              | 19                | 0               | 3        | 0.22                   | 86.36%         |
| 4    | 17              | 16                | 0               | 1        | 0.17                   | 93.75%         |

4.3. Estimating DBH
The estimating error between the tape-measured DBH and the estimated DBH was shown in Figure 9. There are 49 error values positive, accounting for 76.56%. That is to say, in general the DBH was overestimated in the experiment.

![Figure 9. The DBH error between the tape-measured DBH and the estimated DBH.](image)

The scatter plot of the tape-measured DBH and the estimated DBH was shown in Figure 10(a), and residues of the fitting results were shown in Figure 10(b).

![Figure 10. (a) Scatter plot; (b) DBH residues.](image)
The bias and the RMSE values of the DBH estimating results were listed in Table 3. The bias and RMSE were calculated as described in Liang’s paper [18].

| Plot   | Bias (cm) | Bias% | RMSE | RMSE% |
|--------|-----------|-------|------|-------|
| DBH    | 0.64      | 5.32  | 1.27 | 10.52 |

4.3. Estimating Heights and Positions

The bias and the RMSE values of the tree height estimating results were listed in Table 4. In the four experimental plots, the ginkgo trees are artificially planted at the same period. Most of the ginkgo trees are about 8 meters high. In the experiment, the tree heights were obviously underestimated.

| Plot   | Height (m) | Bias | Bias% | RMSE | RMSE% |
|--------|------------|------|-------|------|-------|
| Height | -0.08      | -5.92| 0.24  | 2.77 |

The estimated tree positions of the four plots were shown in Figure 11 respectively. The blue triangles in Figure 11 represent the position of the BEE scanner. The black points represent the detected tree positions. The estimated tree position is in good agreement with the actual position.
5. Discussion

In this paper, we designed and implemented a low-cost 3D laser scanner (called BEE) and also developed the supporting software to capture the point cloud information of trees. The BEE scanner is portable and automated, and designed for forest inventory. Considering the performance of the laser scanner, the BEE scanner was designed for scanning small plots and estimating the tree parameters, such as DBH, tree height, tree position. The BEE scanner could also be used to scan a larger area forest by multiple single scans. In the field measurement, the BEE scanner could give the results quickly which could be verified on site.

In this study, the correct detection rate is 92.75%, which is a higher value. There are several reasons attributing to the higher correct detection rate. One reason is the smaller size of the plot. The BEE scanner is placed in the middle point in the plot which is 10m × 10m in size. This insurances that the point cloud density is high enough to describe the trees in detail relatively. The other reason is the smaller angular step-width in horizontal direction which means that points used to detecting trees would be with high density to improve the detection rate and DBH’s estimation accuracy. There is another reason that the lower stem density which is 0.1725 stems/m² and the regular inter-tree spacing are good help to reduce the shadowing effects. The shadowing effects is one of the common troubles in the forest scanning even in our small size experimental plots. There are three missing trees because of the shadowing effects, and two missing trees because of the detecting algorithm. To simplify the algorithm and ensure the efficiency, a simple detecting algorithm based on a single scan and a single slice was used in the study. But the small size of plot could reduce the passive impact to a certain extent.

The experimental results of DBH estimation shows that the RMSE is 1.27cm and the bias is 0.64cm in the study. The accuracy of the DBH estimation is reasonable and acceptable. The BEE scanner is composed of low-cost sensors and the accuracy of the sensor is not as good as the expensive terrestrial laser scanners. And the BEE scanner was assembled by several parts, so the accuracy of the whole system is not only affected by the sensor, but also by the other parts. But the results is in line with the analysis by Pueschel [23] and Bu [20] that DBH estimation accuracy is not sensitive to the scanner parameter settings, but sensitive to the coverage of tree stems and point density. When the points used to estimate is less, the result of DBH estimation is seriously affected by several individual outliers. In the experiment, large deviation of DBH estimation also occurred in trees with thin stem.

The tree height estimation and the tree position estimation in the experiment also gave good results by using the simple methods. Because of the vertical angular step-width is relatively larger compared to the expensive scanners, the point density is lower in the vertical direction. So the tree tops were likely missed because of the thin and sparse branches. And the tree height estimation exists common underestimation. The bare ground made the local ground fitting simpler and more accurate, and this benefits the accuracy of tree height estimation and tree position estimation. The estimated tree positions were in line with the actual positions because of the small size of plots and the flat ground.

Besides the plot-level estimating results mentioned above, the BEE scanner can also provide the range map and the intensity map which could be used as auxiliary data for the processing and analysis. The BEE scanner has the advantages of low-cost and light weight, which will make it more practical and to be used widely in the fields of forest inventory. With the development of the laser sensors, the cost of the BEE scanner could be decreased further, and the performance of the BEE scanner could be increased further. And more analysis methods could be designed and tested based on the dataset acquired by the scanner.

6. Conclusions
Terrestrial Laser scanning is an efficient manner for acquiring the point cloud data of forest. The interested parameters such as DBH, tree height and tree position could be estimated based on the acquired data. As an automated low-cost scanner, the BEE scanner could also estimate these interested parameters accurately in the small plots. The analysis of the results shows that the BEE scanner has the potential to practical use in the fields of forest inventory.

In our future research, the BEE scanner will be used in more forest types with different tree species and different circumstances. More research work will be carried on based on the data acquired by using the BEE scanner. And the portability, miniaturization and automation of the BEE scanner also the focus of our research.

In general, the low-cost terrestrial laser scanner for forestry has a lot of room for improvement in hardware selection, scanning scheme, processing methods and measuring accuracy. This kind of scanner will have great potential in the applications of forest inventory.

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Author Contributions

Pei Wang: Hardware design, algorithm development, design of field experiment and data analysis. Guochao Bu: Hardware design, algorithm development, field measurement and data analysis. Ronghao Li: Field measurement and data analysis. Rui Zhao: Data analysis.

Conflicts of Interest

The authors declare no conflict of interest.

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