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Development of a portable measuring device for diameter at breast height and tree height

Entwicklung eines tragbaren Messgerätes für Durchmesser in Brusthöhe und Baumhöhe

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Keywords: DBH, tree height, sensor, algorithm, simulation

Schlüsselbegriffe: DBH, Baumhöhe, Sensor, Algorithmus, Simulation

Abstract

The diameter at breast height (DBH) and tree height are significant parameters of tree growth. Conventional measurement and recording methods take considerable time collect information on tree growth; where an intelligent electronic device (IED) could increase efficiency. The main achievements documented in this paper are: (1) an IED to accurately and efficiently measure DBH and tree height was developed, (2) a simple algorithm to estimate the DBH by using high-precision Hall angle sensors was designed. (3) A convenient tree height measurement method using a high-precision laser ranging sensor and dip sensor was designed. (4) A simulation experiment to analyze the DBH and tree height measurement range of the device at different angles was designed. (5) A personal computer (PC) software application was developed to automatically store and upload DBH and tree height data. The simulation results showed that the maximum measurable DBH and tree height were 151.47 cm and

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65.94 m, respectively. This IED was used to measure eight types of trees to assess the accuracy of DBH and five types of trees to assess the accuracy of tree height measurements. Compared with diameter tapes, the DBH measurements had a -0.03 cm bias and 0.69 cm root mean square error (RMSE). Compared with calipers, the DBH measurements had a 0.16 cm bias and 0.46 cm RMSE. Compared with laser rangefinder, the tree height measurements had a 0.13 m bias and 0.45 m RMSE. The results showed that the new IED is an accurate and effective tool for measuring DBH and tree height.

Zusammenfassung

Der Durchmesser auf Brusthöhe (DBH) und die Baumhöhe sind wichtige Masszahlen des Baumwachstums. Konventionelle Methoden erfordern viel Zeit, um solche Daten zu sammeln und ein intelligentes elektronisches Gerät (IED) kann hier zu Effizienzsteigerungen führen. Diese Arbeit dokumentiert die folgenden Errungenschaften: (1) Es wurde ein IED zur genauen und effizienten Messung von DBH und Baumhöhe entwickelt. (2) Es wurde ein einfacher Algorithmus zur Schätzung des DBH durch den Einsatz hochpräziser Hallwinkelsensoren entwickelt. (3) Es wurde ein praktisches Verfahren zur Messung der Baumhöhe durch den Einsatz eines hochpräzisen Laserentfernungssensors und eines Neigungssensors entwickelt. (4) Es wurde ein Simulationsexperiment zur Analyse des DBH- und Baumhöhen-Messbereichs des Geräts unter verschiedenen Winkeln entwickelt. (5) Es wurde eine Persönliche-Computer-Softwareanwendung (PC-Softwareanwendung) zum automatischen Speichern und Hochladen von DBH- und Baumhöhendaten entwickelt. Vor dem Feldexperiment zeigten die Simulationsergebnisse des DBH- und Baumhöhenmessalgorithmus, dass die maximal messbare DBH und die Baumhöhe 151.47 cm bzw. 65.94 m betrugen. Mit diesen IED wurden acht Baumarten gemessen, um die Genauigkeit der DBH zu bewerten und fünf Baumarten, um die Genauigkeit der Baumhöhenmessungen zu bewerten. Im Vergleich zu Durchmesserbändern hatten die DBH-Messungen eine Verzerrung von -0,03 cm und RMSE von 0.69 cm. Verglichen mit Messschiebern hatten die DBH-Messungen eine Vorspannung von 0.16 cm und RMSE von 0.46 cm. Verglichen mit Laserentfernungsmessern wiesen die Baumhöhenmessungen eine Verzerrung von 0.13 m und RMSE von 0.45 m auf. Die Ergebnisse zeigten, dass das neue IED ein genaues und effektives Werkzeug zur Messung von DBH- und Baumhöhenwerten ist.

1. Introduction

DBH and tree height are the key tree growth attributes often measured in forest surveys (Yang *et al*. 2020; Mokroš *et al*. 2018). The two most common instruments used to measure DBH are girthing (or diameter) tapes and calipers (Cabo *et al*. 2018; Sievänen *et al*. 2014), and the Blume-Leiss altimeter (Lin *et al*. 2012) was developed to measure slope and tree height by trigonometric principles. Using conventional tools to measure DBH and tree height relies on manual data recording, which severely limits the efficiency and quality of forest surveys (Zhou *et al*. 2019). Improving the efficiency and quality of DBH and tree height data collection has become an important part of digital forest surveys. Therefore, a high-precision, efficient and convenient digital measuring device is needed (Sun *et al*. 2020).

Forest surveys have progressively developed with advances in sensor technology, microelectronic technology, remote sensing technology, machine learning, computer vision, and Internet of Things (IoT) technology (Zhou *et al*. 2019; Iizuka *et al*. 2020; Moe *et al*. 2020; Alcarria *et al*. 2020; Suciu *et al*. 2017). In recent years, electrical tools for measuring DBH and tree height, such as MD II electronic caliper (MD II Caliper, 2015), Swedish electronic measuring tape (Haglof and Helgum. 2008) and Japanese Forestry 550 (Forestry 550, 2015) have been developed; however, these devices or methods have limitations to some extent. For example, MD II electronic caliper and Swedish electronic measuring tape can only measure DBH, and Japanese Forestry 550 can only measure tree height, which do not satisfy the requirement of forest surveys to measure DBH and tree height simultaneously; moreover, they are expensive. Some devices and methods to measure DBH and tree height simultaneously have been developed. These include ground-based light detection and ranging (LiDAR, also known as terrestrial laser scanning (TLS)) (Béland *et al*. 2011; Srinivasan *et al*. 2015; Ye *et al*. 2020; Liang *et al*. 2016; Schilling *et al*. 2012; Fan *et al*. 2020), close-range photogrammetry (CRP) (Mikita *et al*. 2016; Surový *et al*. 2016), unmanned aerial vehicle (UAV) with digital aerial photographs (Dalla *et al*. 2020; Iizuka *et al*. 2018), total stations (Huang *et al*. 2015; Zhao *et al*. 2014; Yu *et al*. 2016) and smartphones with time of flight (TOF) cameras (Wu *et al*. 2019; Fan *et al*. 2018; Hyyppä *et al*. 2017; Tomaštík *et al*. 2017). Among them, the TLS, CRP and TOF camera methods require professional knowledge to handle complex point cloud data, while UAV- or total station-based methods are inconvenient for measuring DBH and tree height because the devices are large and heavy, and data processing on the devices is complex and time-consuming.

Therefore, for DBH and tree height measurements, there is an urgent need to develop a novel device with the following features: strong anti-environmental interference ability, low cost, ease of carrying, simple data processing and ease of operation. Recent developments in electronics and sensors have made this possible. Hall angle sensors, laser ranging sensors and dip sensors are important sensors widely used in instrument measurement and industrial automation. Among them, the Hall angle sensor is a noncontact sensor that is small in size, economical and durable, and has high accuracy. It is suitable for angle measurement scenarios where a narrow available space and high accuracy requirements are required. Combined with the trigonometric formula, it is feasible to use Hall angle sensors and special mechanical structures to measure the diameter of DBH, as the DBH is similar to a circle, as well as to use a laser ranging sensor and dip sensor to measure tree height.

In this study, we propose a simple algorithm to quickly calculate DBH and tree height with the help of a trigonometric function. Based on the algorithm and microelectronics, we also develop a device for measuring DBH and tree height for various tree species to evaluate its accuracy. Moreover, the device, equipped with a PC application, integrates the functions of measurement, uploading, and storage of DBH and tree height data, which will greatly reduce the labor intensity required for the forest survey.

2. System Design

2.1 Design of the Main Device

The mechanical structure of the new measuring device is designed with a control box, laser ranging sensor and folding ruler arm, as shown in Figure 1-a. Inside the control box, there are slots for display screens, charging ports, switches, buttons, lithium batteries and printed circuit boards (PCBs). The folding ruler arm is composed of two parts: the upper and lower arms are connected by a rivet, and the surveyor can manually adjust a fixing screw to fix the current state of the ruler arm. Figure 1-b shows that if the surveyor has not started or finished the measurement, the folding ruler arm can be fully closed. When the surveyor is working, the folding ruler arm can be fully extended to carry out the measurement work. After folding the ruler arm, the device is smaller and more delicate, which is more convenient for surveyors to carry during forest inventory. The total weight of the device is approximately 500 g.

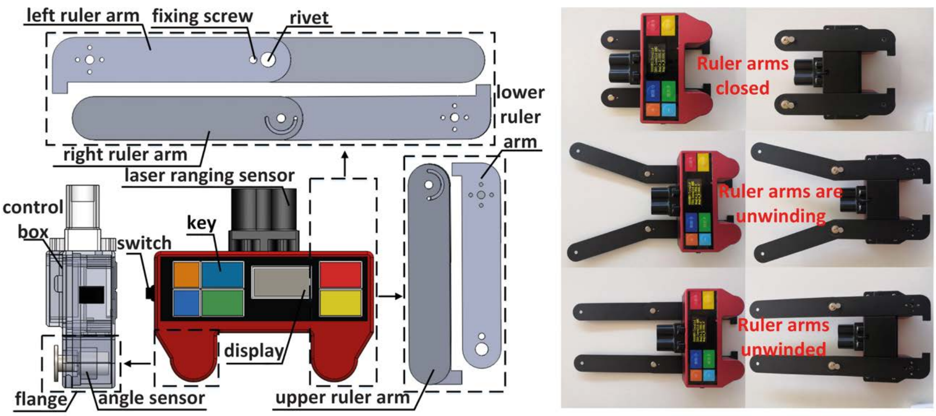

Figure 1: Design of the main device and its components.

Abbildung 1: Aufbau des Hauptgeräts und seiner Komponenten.

Figure 2 shows the structure of the PCB. It mainly consists of the main control module, power module, storage module, Bluetooth module, sampling module, and interaction module. The central processing unit centered at the main control module performs as the core to control other modules and gives real-time feedback on the information processed by other modules.

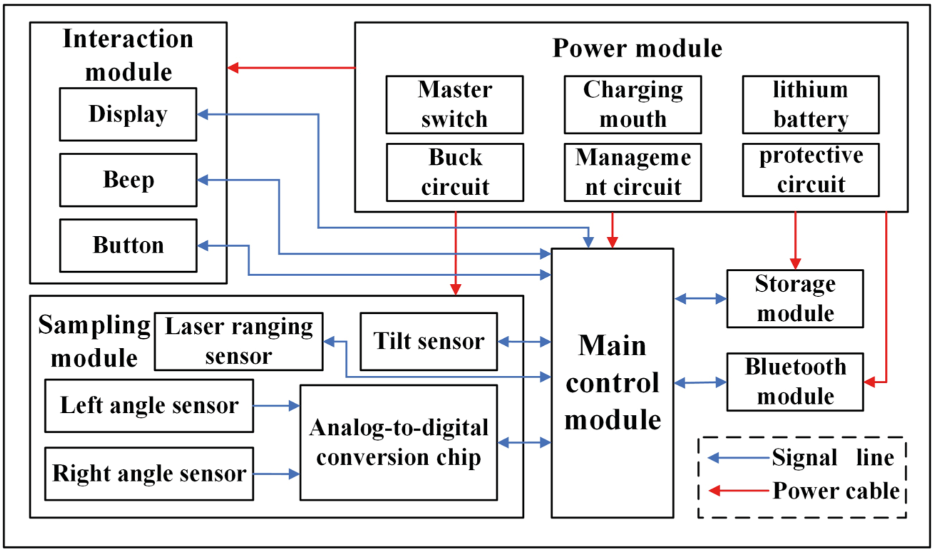

Figure 2: The structure of printed circuit board.

Abbildung 2: Aufbau der Leiterplatte.

2.2 Principle of angle calculation

The electromechanical sampling schematic diagram of the angle sensor is shown in Figure 3, where the angle limit card can ensure that the movement range of the two angles is between 0° and 90°.

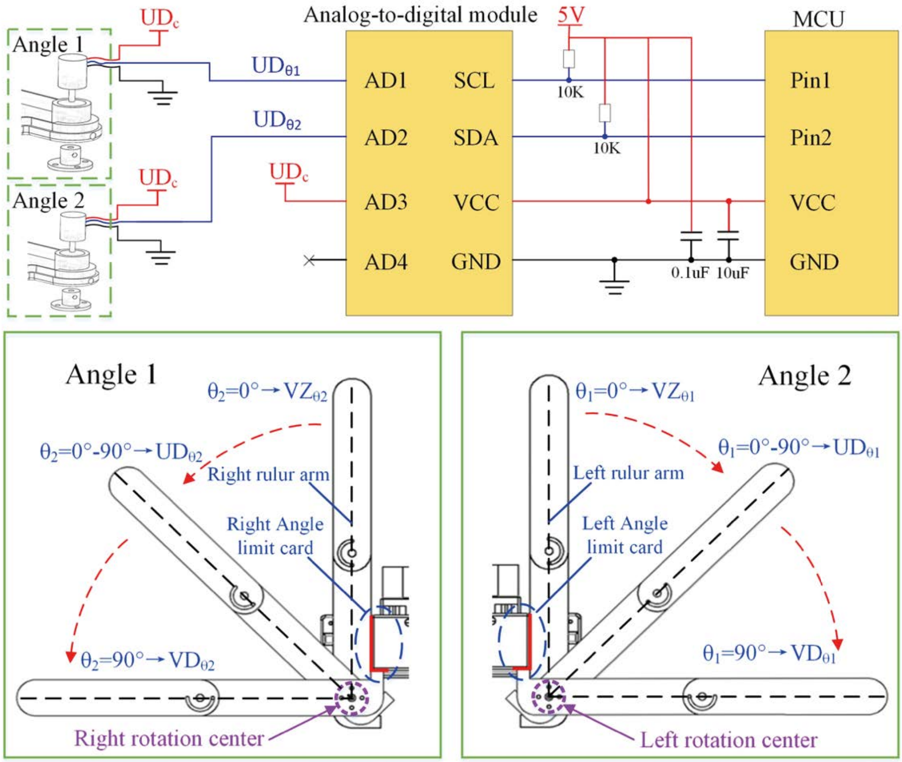

Figure 3: Electromechanical sampling schematic diagram of the angle sensor.

Abbildung 3: Elektromechanische schematische Diagramme des Winkelsensors.

According to the linear relation between the output voltage and angular displacement in the angle sensor, the calculation of θi is shown in formula (1).

$$\theta_i = \begin{cases} \dfrac{90^\circ}{VN_{\theta_i} - VZ_{\theta_i}} \times \left(UD_{\theta_i} \times \dfrac{VD_C}{UD_C} - VZ_{\theta_i}\right) & VZ_{\theta_i} < UD_{\theta_i} < VN_{\theta_i} \\ \dfrac{90^\circ}{VZ_{\theta_i} - VN_{\theta_i}} \times \left(UD_{\theta_i} \times \dfrac{VD_C}{UD_C} - VN_{\theta_i}\right) & VN_{\theta_i} < UD_{\theta_i} < VZ_{\theta_i} \end{cases} \tag{1}$$

where $UD_{\theta i}$ is the dynamic sampling value of the output voltage from the left angle sensor returning to the microcontroller, UD_C is the dynamic sampling value of the input voltages to the two angle sensors returning to the microcontroller, $VZ_{\theta i}$ is the reference value of the output voltage when the angle sensor is 0°, $VN_{\theta i}$ is the reference value of the output voltage when the angle sensor is 90°, and VD_C is the reference value of the input voltage of the two angle sensors. Among them, $VZ_{\theta i}$, $VN_{\theta i}$, and VD_C

are all obtained under initialization conditions and stored in the microcontroller as constants.

2.3 Principle of Laser Ranging

To minimize the influence of outdoor bright light on the ranging module, a laser ranging sensor with improved TOF technology is selected. Its measurement ranges from 0 to 40 m, covering most tree height measurements. Figure 4 shows the principle of laser ranging.

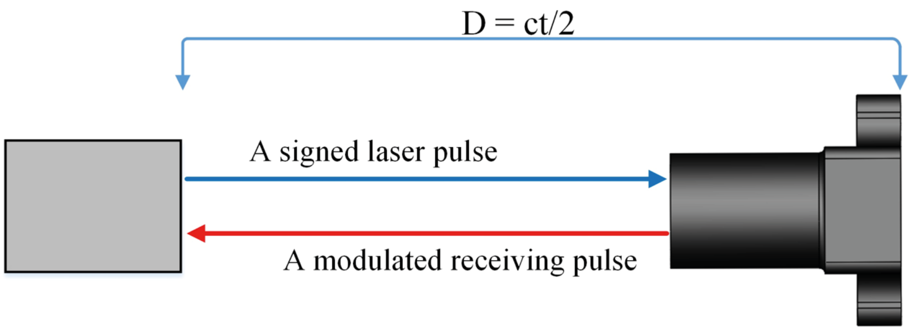

Figure 4: Principle of laser ranging.

Abbildung 4: Prinzip der Laserentfernung.

The distance between the sensor and the object can be accurately calculated by formula (2).

$$D = \frac{c \times t}{2} \quad (2)$$

where D is the distance between the object surface and the back end of the laser ranging sensor, c is the speed of light propagation in air, and t is the flight time between the object surface and the laser ranging sensor.

2.4 Design of Software Process

The software designed for the frontend device is divided into two main parts: DBH measurement and tree height measurement to enable the device to realize button control, angle calculation, laser ranging, dip acquisition, DBH calculation, tree height calculation and data management. As shown in Figure 5, the graphical user interface (GUI) designed on the host computer mainly enables users to perform device information reading, data analysis and data export so that the surveyor can process and analyze data more easily. The flow chart of the system is shown in Figure 6, which can be divided into the object layer, data layer, hardware layer, physical layer and software layer from top to bottom. The subprograms of the software layer include a human-computer interaction program for key input and display control, a sampling program for DBH and tree height information extraction, and a date management program for data storage and communication. After completing the tree measurement process, DBH and tree height data will be automatically synthesized into a line of comprehensive data to achieve the integration of measurements.

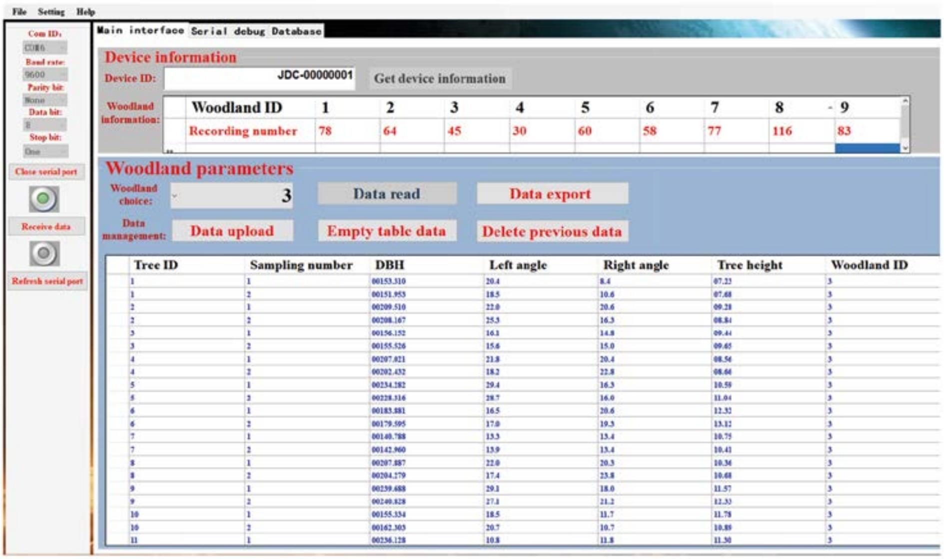

Figure 5: Host computer interface.

Abbildung 5: Interface des Host-Computers.

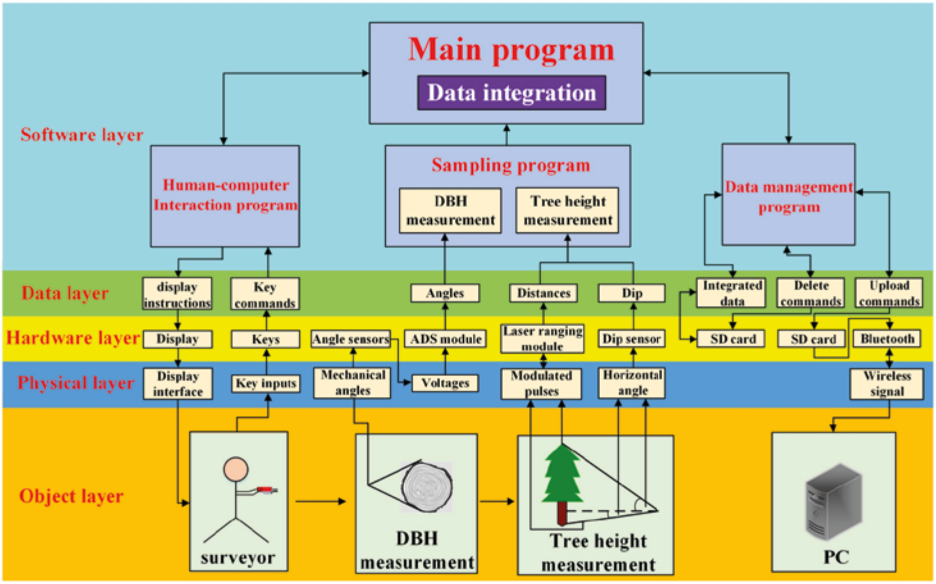

Figure 6: Flow chart of the system.

Abbildung 6: Flussdiagramm des Systems.

3. Material and Methods

3.1 Study Region

The test site chosen here is the suburbs of Hangzhou City, China (N 30°15′, E 119°43′). For DBH measurement, a total of 8 tree species (240 trees) were selected and measured. For tree height measurement, a total of 5 tree species (150 trees) were selected and measured. All measured tree species (dominated by artificial forest) are located on the campus of Zhejiang Agriculture and Forestry University, China. The DBH measured by diameter tapes varies from 10.84 to 44.44 cm, and the mean value varies from 17.48 to 33.04 cm (Table 1). The DBH measured by calipers (Haglöf brand, normal calipers) vary from 10.90 to 43.90 cm, and the mean value varies from 17.34 to 32.47 cm (Table 2, two measurements were made to obtain the mean value, and the measurement direction was vertical). The tree height measured by laser rangefinder (JETBEAM brand, AK-800W model, transponders are not needed) using 905 nano-laser technology vary from 5.03 m to 13.75 m with mean value varies from 7.73 m to 11.10 m (Table 3).

Table 1: Descriptive statistics of diameter at breast height (DBH) measured by diameter tapes.

Tabelle 1: Zusammenfassung der Durchmesser in Brusthöhe (DBH) gemessen mit Maßbändern.

Tree Species	Number of Trees	DBH (cm)			
		Mean	Max	Min	Standard deviation
Ginkgo biloba L.	30	19.30	26.41	14.08	3.08
Magnolia denudata Desr.	30	18.61	23.15	13.48	2.42
Cinnamomum camphora (L.) Presl.	30	18.35	23.34	11.66	3.05
Magnolia alba DC.	30	17.48	24.03	12.63	3.10
Platanus orientalis Linn.	30	21.61	27.27	12.92	3.55
Populus euramericana cv.'i-214'	30	33.04	44.44	24.96	5.47
Sapindus mukorossi Gaertn.	30	22.75	32.12	10.84	5.71
Liriodendron chinense (Hemsl.) Sargent.	30	27.01	38.60	16.36	5.11

Table 2: Descriptive statistics of DBH measured by caliper.

Tabelle 2: Zusammenfassung von DBH gemessen mit Kluppen.

Tree Species	Number of Trees	DBH (cm)			
		Mean	Max	Min	Standard deviation
Ginkgo biloba L.	30	19.18	25.20	13.80	3.01
Magnolia denudata Desr.	30	18.55	23.20	13.60	2.44
Cinnamomum camphora (L.) Presl.	30	18.07	23.00	11.80	2.81
Magnolia alba DC.	30	17.34	23.80	12.70	2.98
Platanus orientalis Linn.	30	21.54	26.70	13.10	3.55
Populus euramericana cv.'i-214'	30	32.47	43.90	24.50	5.38
Sapindus mukorossi Gaertn.	30	22.69	31.90	10.90	5.71
Liriodendron chinense (Hemsl.) Sargent.	30	27.02	39.00	16.30	5.16

Table 3: Descriptive statistics of tree height measured with Laser range finder.

Tabelle 3: Zusammenfassung der Baumhöhe gemessen mit Laser Distanzmesser.

Tree Species	Number of Trees	Tree height (m)			
		Mean	Max	Min	Standard deviation
Ginkgo biloba L.	30	9.54	12.32	7.40	1.42
Magnolia denudata Desr.	30	8.40	11.23	6.09	1.43
Cinnamomum camphora (L.) Presl.	30	7.73	10.67	5.03	1.30
Magnolia alba DC.	30	9.82	12.32	7.08	1.51
Platanus orientalis Linn.	30	11.10	13.75	8.10	1.49

3.2 Methods

3.2.1 Measurement Process Design

The diameter tapes and calipers for measuring DBH and the laser rangefinder for measuring tree height are implemented with conventional operations. The device adopted in this paper to measure DBH and tree height uses the following steps.

1. The number of sample plots in the main menu is set.
2. The surveyor records the DBH. If the trunk of the tree is irregular, the surveyor may need to change the contact position and take multiple measurements; finally, the average value can be automatically calculated. An example of a physical image of DBH measurement is shown in Figure 7-a.
3. The surveyor stands away from the tree at a distance close to the whole tree to record the tree height. A physical image of tree height measurement is shown in Figure 7-b.
4. After completing measurement of the DBH and tree height of each tree in turn at the target location, the DBH data and tree height can be uploaded to a PC application for statistical analysis.

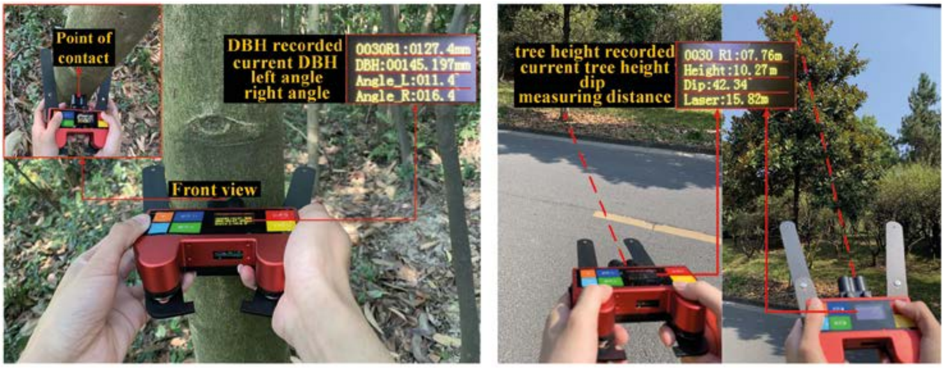

Figure 7: Pictures of field measurements.

Abbildung 7: Aufnahme bei Feldmessungen.

3.2.2 Measurement Algorithm Design of DBH

As shown in Figure 8, the maximum length of the control box is 14 cm, and the maximum width is 8.35 cm. Here, r1 and r2 are the rotation centers on the bearings of the two angle sensors, and the distance between them is recorded as W (W=9 cm). The vertical distance from the rotation centers to the front face of the laser ranging sensor is recorded as L (L=10.85 cm). The horizontal distances between the front face center of the laser ranging sensor and the two rotation centers are the same at 4.5 cm. The widths of the left arm and right arm are recorded as Z (Z=3 cm). The distances between the rotation centers and the arc top of the folding ruler arms are 25.5 cm. Note that the values of W, Z, and L are fixed mechanical structural values.

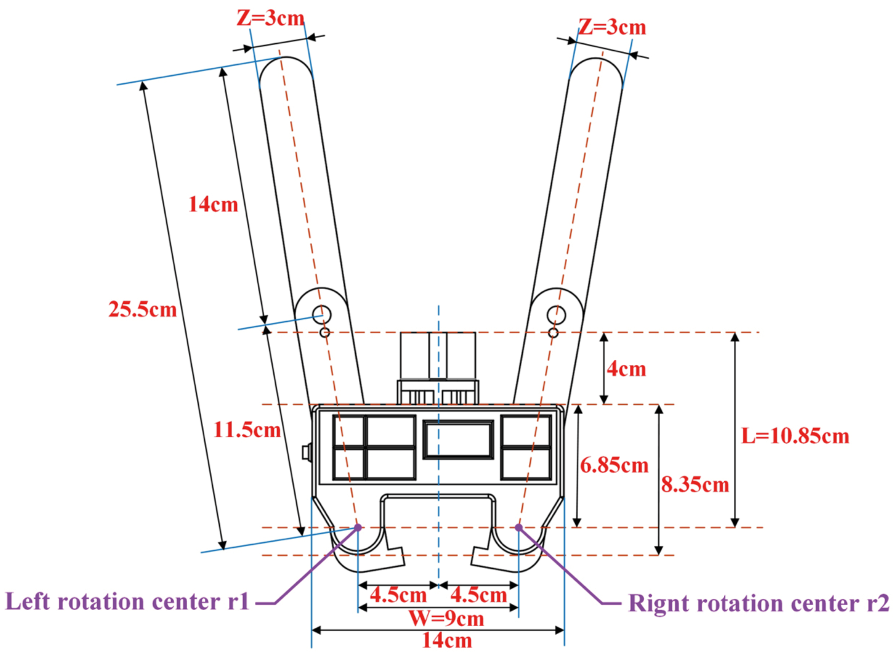

Figure 8: Overview of main mechanical structures.

Abbildung 8: Übersicht der Mechanischen Bauteile.

As shown in Figure 9, A, B and C are the points of contact between the device and the tree surface, which results in two arcs. As the cross section of the tree is not a standard circle, arcs BA and BC have different centers, O_1 and O_2.

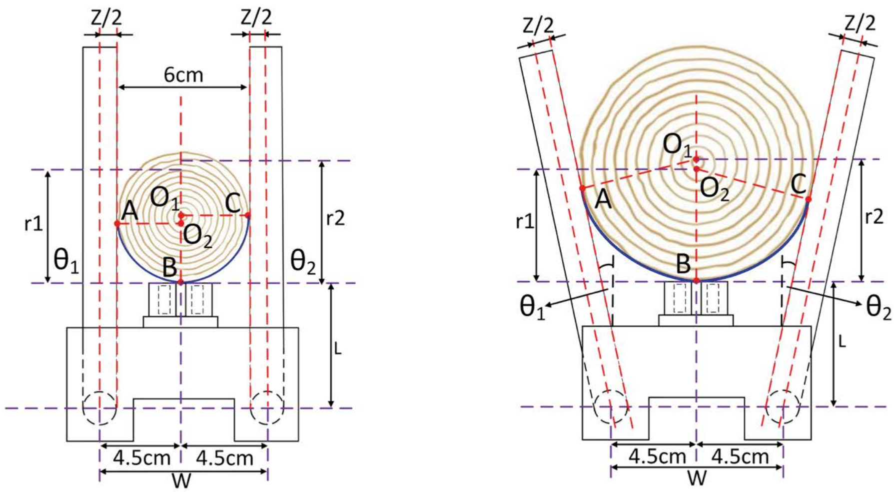

Figure 9: Measurement principle at different DBH sizes.

Abbildung 9: Messprinzip bei verschiedenen DBH-Größen.

Assume that the measured DBH is d. Measurement situations can be divided into two types: (1) $\theta_1 = \theta_2 = 0°$ (Figure 9-a) and (2) $0°<\theta_1<90°$ and $0°<\theta_2<90°$ (Figure 9-b). The DBH can be calculated by the following formula (3):

$$r_i = \begin{cases} \dfrac{W \times (1 - \frac{\theta_i^2}{2!} + \frac{\theta_i^4}{4!} - \frac{\theta_i^6}{6!}) + 2 \times L \times (\theta_i - \frac{\theta_i^3}{3!} + \frac{\theta_i^5}{5!} - \frac{\theta_i^7}{7!}) - Z}{2 \times (1 - \theta_i + \frac{\theta_i^3}{3!} - \frac{\theta_i^5}{5!} + \frac{\theta_i^7}{7!})} & 0° < \theta_i < 90° \\ \dfrac{S}{2} & \theta_i = 0° \end{cases} \quad (3)$$

And formula (4):

$$d = r_1 + r_2 \quad (4)$$

3.2.3 Measurement Algorithm Design of Tree Height

The tree height measurement relies on the laser ranging sensor and dip sensor to measure the distance and angle, respectively. When measuring, it is necessary to ensure that the whole tree is not blocked within the line of sight of the surveyor. First, the surveyor needs to aim the laser emitter at the bottom of the tree, and the ranging distance (L_S) and dip (α) will be recorded automatically at the moment (Figures 10-a and c). Then, the surveyor needs to aim the laser emitter at the top of the tree, and the ranging distance (L_D) and dip (β) will also be recorded (Figures 10-b and d). Note that the L_H (horizontal distance) from the measurement process is not required, it is not calculated. As shown in Figure 10-a, when the bottom of the tree is at a lower slope than the surveyor, the dip (α) ranges from -90° to 0° at this point. As shown in Figure 10-c, when the bottom of the tree is at a higher slope than the surveyor, the dip (α) ranges from 0° to 90° at this point.

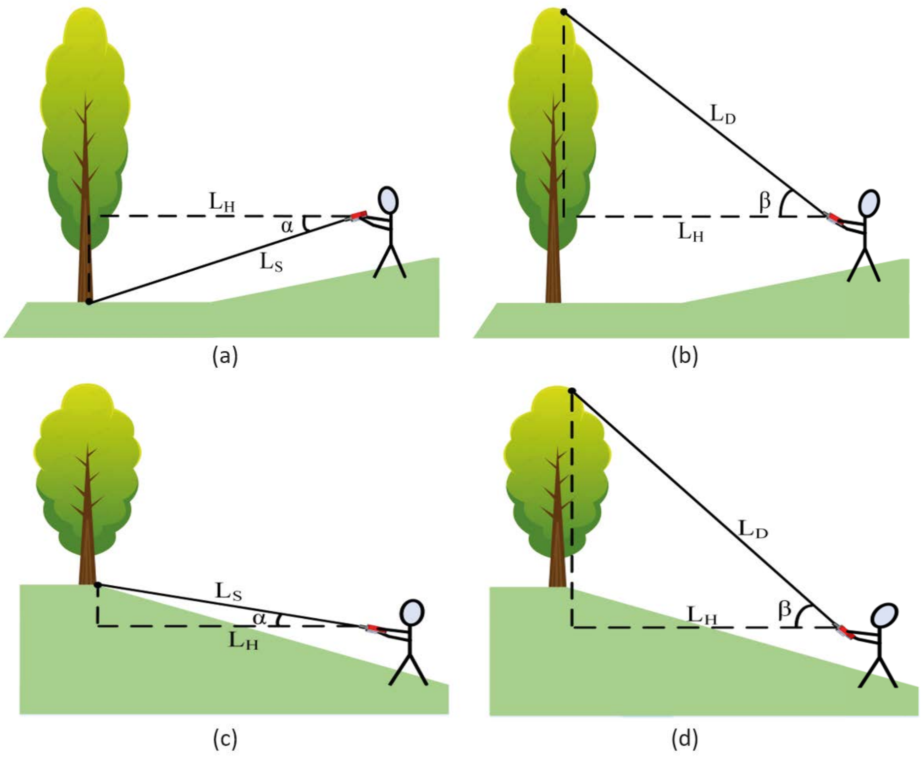

Figure 10: Measuring principles of tree height measurement.

Abbildung 10: Messprinzipien der Baumhöhenmessung.

Assume that the measured tree height is h. To realize the fast and accurate calculation of tree height, use Taylor's expansion in the following formulas:

$$h = L_D \times (\beta - \frac{\beta^3}{3!} + \frac{\beta^5}{5!} - \frac{\beta^7}{7!}) - L_S \times (\alpha - \frac{\alpha^3}{3!} + \frac{\alpha^5}{5!} - \frac{\alpha^7}{7!}) \quad (5)$$

3.2.4 Simulation Method of Measuring Range

The DBH measurement range can be simulated by changing the θ_1 value and θ_2 value. In terms of the special structural design of the device, as shown in Figure 11, the maximum DBH to be measured by the device is limited. After the calculation, arccosθ_1=arccosθ_2≈63.12°. To reflect the range of the device, the θ_1 value and θ_2 value were limited from 0° to 60°.

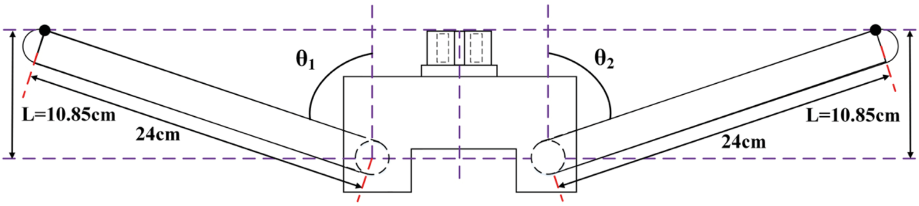

Figure 11: Display of measurement angle limit.

Abbildung 11: Darstellung der Messwinkelgrenze.

The tree height measurement range also requires simulation. After repetitive experiments, when the horizontal distance from the tree is between 8 and 15 m (Figure 10, L_H), the surveyor can obtain a better line of sight. Here, 10 m of the horizontal distance was used to carry out the simulation research. Because the maximum range of the laser ranging sensor is 40 m, there are limits on angles α and β. As shown in Figures 10-a and b, arccosα≈-75.52° and arccosβ≈75.52°, thus taking angle α from -70° to 0° and angle β from 0° to 70°. As shown in Figures 10-c and d, angle β is taken from 0° to 70° and α<β.

3.2.5 Accuracy Evaluation

The DBH data measured by diameter tapes or calipers and the tree height data measured by the laser rangefinder were used as reference values. The accuracy of the DBH and tree height measurements were evaluated by utilizing the bias following formulas (6), (7) and (8) and precision following formula (9).

$$Error = x_i - X_i \tag{6}$$

$$Bias = \frac{1}{n}\sum_{i=1}^{n}(x_i - X_i) \tag{7}$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - X_i)^2} \tag{8}$$

$$rel\ accuracy = 1 - \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x / X_i - 1)^2} \times 100\% \tag{9}$$

where x_i is the DBH or tree height measured value, X_i is the DBH or tree height reference value, and n is the number of measurements.

4. Results

4.1 Simulation Results

Table 4 showed that the maximum DBH that could be obtained under different combinations of θ_1 and θ_2 values was 151.47 cm.

Table 4: The maximum measurable DBH (cm) under different angle combinations.

Tabelle 4: Die maximal messbare DBH (cm) unter verschiedenen Winkelkombinationen.

Angle	0°	10°	20°	30°	40°	50°	60°
0°	6.00	8.83	12.79	18.64	27.98	44.48	78.73
10°	8.83	11.66	15.62	21.47	30.80	47.31	81.56
20°	12.79	15.62	19.57	25.43	34.76	51.27	85.52
30°	18.64	21.47	25.43	31.29	40.62	57.12	91.38
40°	27.98	30.80	34.76	40.62	49.95	66.45	100.71
50°	44.48	47.31	51.27	57.12	66.45	82.96	117.21
60°	78.73	81.56	85.52	91.38	100.71	117.21	151.47

The measurement situation shown in Figures 10-a and b and Table 5 indicated that the maximum tree height that could be obtained under different combinations of angles α and β was 65.94 m. With the measurement situation shown in Figures 10-c and d and Table 6, the maximum tree height was 32.97 m.

Table 5: The maximum measurable tree height (m) under different angle combinations (-70°≤α≤0° and 0°≤β≤70°).

Tabelle 5: Die maximal messbare Baumhöhe (m) unter verschiedenen Winkelkombinationen (-70°≤α≤0° und 0°≤β≤70°).

Dip	0°	-10°	-20°	-30°	-40°	-50°	-60°	-70°
0°	0.00	2.12	4.37	6.93	10.07	14.30	20.78	32.97
10°	2.12	4.23	6.48	9.04	12.19	16.42	22.90	35.09
20°	4.37	6.48	8.74	11.30	14.44	18.67	25.15	37.34
30°	6.93	9.04	11.30	13.86	17.00	21.23	27.71	39.90
40°	10.07	12.19	14.44	17.00	21.14	24.37	30.85	43.04
50°	14.30	16.42	18.67	21.23	24.37	28.60	35.09	47.27
60°	20.78	22.90	25.15	27.71	30.85	35.09	41.57	53.75
70°	32.97	35.09	37.34	39.90	43.04	47.27	53.75	65.94

Table 6: The maximum measurable tree height (m) under different angle combinations (0°≤β≤70° and α<β).

Tabelle 6: Die maximal messbare Baumhöhe (m) unter verschiedenen Winkelkombinationen (0°≤β≤70° und α<β).

Dip	0°	10°	20°	30°	40°	50°	60°	70°
0°	0.00	-	-	-	-	-	-	-
10°	2.12	0.00	-	-	-	-	-	-
20°	4.37	2.25	0.00	-	-	-	-	-
30°	6.93	4.81	2.56	0.00	-	-	-	-
40°	10.07	7.95	5.70	3.14	0.00	-	-	-
50°	14.30	12.19	9.93	7.37	4.23	0.00	-	-
60°	20.78	18.67	16.42	13.86	10.72	6.48	0.00	-
70°	32.97	30.85	28.60	26.04	22.90	18.67	12.19	0.00

4.2 Accuracy Assessment of DBH Measurement

The data measured by the device recorded as DBHIED were compared with the reference data recorded as DBHtape and DBHcaliper that were measured by diameter tapes and calipers, respectively. The results showed that the measured data were similar to the reference data (Figures 12). Compared with diameter tape data, the device had results with a mean bias of -0.03 cm and a mean RMSE of 0.69 cm (Table 7). Compared with the caliper data, the device presented results with a mean bias of +0.16 cm and a mean RMSE of 0.46 cm (Table 8). Figures 13 showed that when the DBH sizes increased, more variation in error was observed. The measured values were smaller than the reference values, indicating that our device underestimated the DBH compared to diameter tape (Bias in Table 7). For the caliper data, our measured values were larger than the reference values, indicating that our device overestimated the DBH (Bias in Table 8).

Table 7: Accuracy of the DBH measurements (compared with diameter tapes) in different tree species.

Tabelle 7: Genauigkeit der DBH-Messungen (im Vergleich zu Maßbändern) bei verschiedenen Baumarten.

Tree Species	Number of Trees	Bias(cm)	RMSE(cm)	rel accuracy(%)
Ginkgo biloba L.	30	-0.19	0.47	97.66
Magnolia denudata Desr.	30	-0.06	0.60	96.67
Cinnamomum camphora (L.) Presl.	30	+0.33	0.65	96.53
Magnolia alba DC.	30	-0.04	0.60	96.69
Platanus orientalis Linn.	30	-0.16	0.70	96.55
Populus euramericana cv.'i-214'	30	-0.12	1.06	96.67
Sapindus mukorossi Gaertn.	30	-0.23	0.64	97.33
Liriodendron chinense (Hemsl.) Sargent.	30	+0.24	0.76	97.19
Total	240	-0.03	0.69	96.92

Table 8: Accuracy of the DBH measurements (compared with calipers) in different tree species.

Tabelle 8: Genauigkeit der DBH-Messungen (im Vergleich mit Kluppen) bei verschiedenen Baumarten.

Tree Species	Number of Trees	Bias(cm)	RMSE(cm)	rel accuracy(%)
Ginkgo biloba L.	30	+0.13	0.39	98.05
Magnolia denudata Desr.	30	+0.06	0.42	97.80
Cinnamomum camphora (L.) Presl.	30	+0.28	0.48	97.55
Magnolia alba DC.	30	+0.14	0.38	97.93
Platanus orientalis Linn.	30	+0.07	0.44	97.90
Populus euramericana cv.'i-214'	30	+0.57	0.82	97.44
Sapindus mukorossi Gaertn.	30	+0.07	0.28	98.75
Liriodendron chinense (Hemsl.) Sargent.	30	-0.01	0.44	98.40
Total	240	+0.16	0.46	97.98

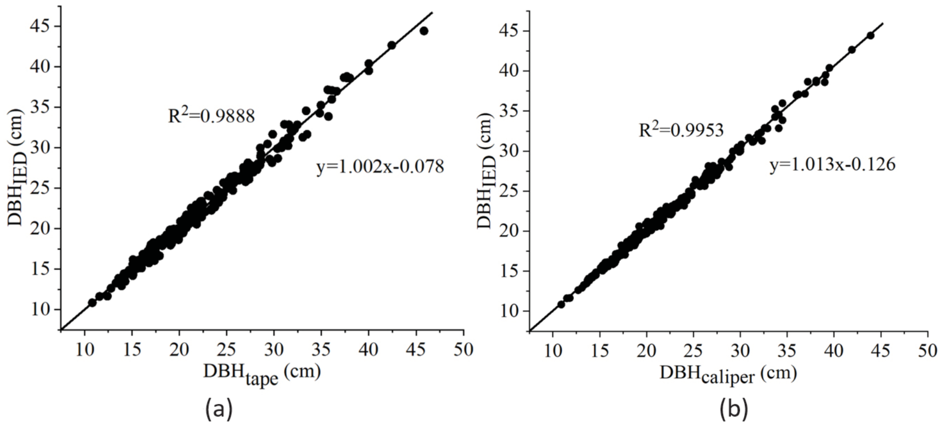

Figure 12: Scatterplot of DBH measurements with IED versus measurements using (a) diameter tape and (b) caliper.

Abbildung 12: Streudiagramm der IED Messungen des DBH gegenüber Messungen mit (a) Maßbändern und (b) Kluppen.

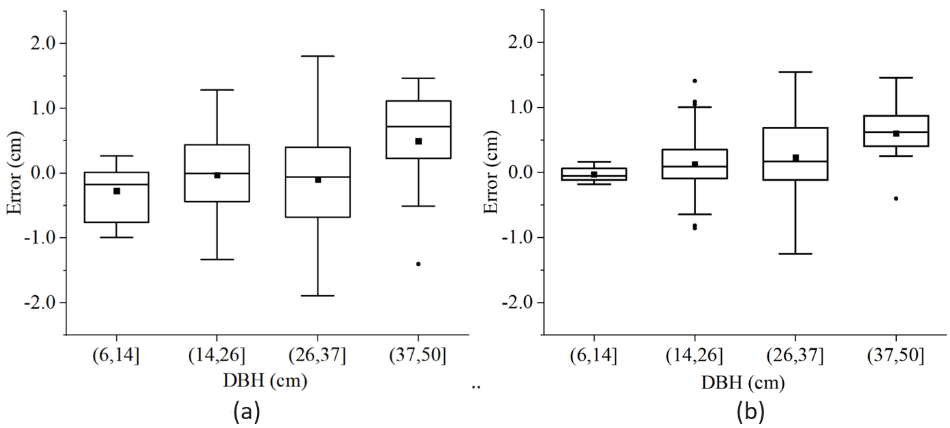

Figure 13: The errors of the measured DBH at different DBH sizes versus measurements with (a) diameter tape and (b) caliper.

Abbildung 13: Die Fehler des gemessenen DBH bei verschiedene DBH-Größen gegenüber Messungen (a) Maßbändern und (b) Kluppen.

4.3 Accuracy Assessment of Tree Height Measurement

The measurement data recorded as HIED were compared with the reference data recorded as Hlaser. Because surveyors might not be able to fully aim at the bottom and top of the tree during the measurement, tree height would be overestimated or underestimated, but the results showed that there was still a good correlation between the measured data and reference data (Figure 14). Compared with the reference data, the device presented results with a mean bias of +0.13 m and a mean RMSE of 0.45 m (Table 9).

Table 9: Accuracy of the tree height measurements in different tree species.

Tabelle 9: Genauigkeit der Baumhöhenmessungen bei verschiedenen Baumarten.

Tree Species	Number of Trees	Bias(m)	RMSE(m)	rel accuracy(%)
Ginkgo biloba L.	30	+0.16	0.49	95.14
Magnolia denudata Desr.	30	+0.13	0.38	95.77
Cinnamomum camphora (L.) Presl.	30	+0.07	0.40	95.14
Magnolia alba DC.	30	+0.14	0.47	95.06
Platanus orientalis Linn.	30	+0.15	0.53	95.27
Total	150	+0.13	0.45	95.28

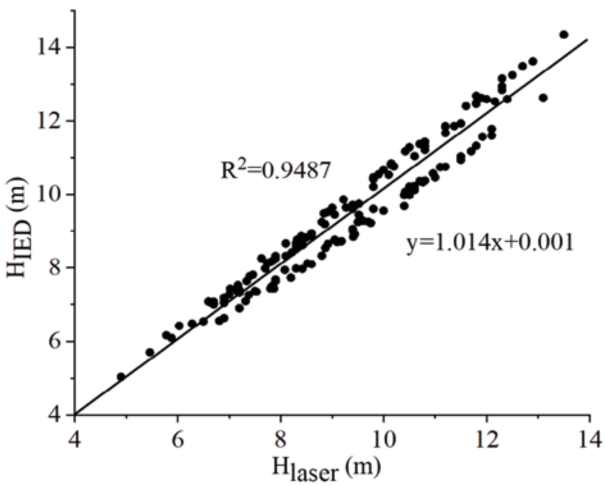

Figure 14: Scatter plot of measured tree height values.

Abbildung 14: Streudiagramm der gemessenen Baumhöhenwerte.

4.4 Efficiency of Measurement

To evaluate the efficiency of measurement, the times (including data recording and digitizing) required for traditional and device measurements were recorded. As shown in Table 10, using the device for measurements increased the efficiency by approximately 3 times.

Table 10: Comparison of work efficiency of selected measuring methods.

Tabelle 10: Vergleich der Zeitbedarfs ausgewählter Messmethoden.

Measuring method	Number of person	Total measuring time (min)	Total digitizing time (min)	Mean time per tree (s)
Diameter tape combined with laser rangefinder	2	180.15	32.89	62.66
Caliper combined with laser rangefinder	2	156.22	33.15	56.70
Device	1	63.61	0.00	20.24

5. Discussion and Conclusions

New devices and new methods to measure DBH and tree height have been developed in recent years. For example, the Swedish Haglöf company manufactured MD II electronic calipers (MD II Caliper. 2015) and electronic measuring tapes (Haglof and Helgum. 2008) for DBH measurement. The Japanese NIKON company developed Forestry 550 (Forestry 550. 2015) for tree height measurement. But, these devices could not measure both the DBH and tree height and needed to record data manually, and their cost were expensive. In addition, Fan *et al*. (Fan *et al*. 2020) used TLS and the Adtree method to estimate DBH and tree height and reported a bias of +0.38 cm and a RMSE of 1.28 cm for the DBH measurement and a bias of -0.76 m and a RMSE of 1.21 m for the tree height measurement. Mikita *et al*. (Mikita *et al*. 2016) used the combined aerial and terrestrial CRP method to estimate the DBH and tree height and reported a RMSE of 0.90 cm for the DBH measurement and a RMSE of 1.016 m for the tree height measurement. Huang *et al*. (Huang *et al*. 2015) relied on the total station and reported a RMSE of 0.369 cm for the DBH measurement and a RMSE of 0.06 m for the tree height measurement. Fan *et al*. (Fan *et al*. 2020) obtained a +0.33 cm bias and a 1.26 cm RMSE for the DBH estimations and a +0.63 m bias and a 1.45 m RMSE for tree height estimations using a mobile phone with a TOF camera and simultaneous localization and mapping (SLAM) technology in that study. Although the above devices and methods had high precision, they were not suitable for conducting forest surveys based on UAVs or total stations, considering convenience. TLS, CRP and TOF cameras required professional knowledge to handle complex point cloud data.

In this study, we report a novel device based on sensor and electronic technologies. Before the field experiments, we designed a simulation experiment to verify that the maximum measurable DBH and tree height could reach 151.47 cm and 65.94 m, respectively (Tables 4, 5 and 6). In the field experiment, compared with the diameter tape data, the DBH measurements had a mean bias of -0.03 cm and a mean RMSE of 0.69 cm (Table 7), and the measured values were smaller than the reference values, indicating that the device underestimated the DBH (Figure 13-a). Compared with the caliper data, the DBH measurements had a mean bias of +0.16 cm and a mean RMSE of 0.46 cm (Table 8), and the measured values were larger than the reference values, indicating that the device overestimated the DBH (Figure 13-b). There were variances in different tree species (Figures 12-a and b), and more variances were observed with the diameter tape data. Variability was attributed to multiple factors, but we speculated that the main factor was that the cross section of the tree was similar to an ellipse or superellipse. Nonetheless, the mean bias and RMSE were similar compared with conventional tools with different tree species (Tables 7 and 8), suggesting that the device and the calculation algorithm were accurate for DBH measurement. For the tree height measurement, compared with the laser rangefinder, the tree height measurements had a mean bias of +0.13 m and a mean RMSE of 0.45 m (Table 9). Although the results showed that the measured values were larger than the reference values, the tree height measured with the device still had good accuracy (Figure 14).

Even though our measurement method was based on the trigonometric function proposed by the mechanical structure, it was simple and effective and enriched the pool of tools for the ground measurements in forest surveys. Moreover, it was easy to carry and operate, data were automatically recorded and processed and the efficiency of measurement could be increased by approximately 3 times. Meanwhile, we developed a PC application that could be stably connected to the device for data upload, which was of great value for creating a database of DBH and tree height management and development.

In conclusion, the device could measure both DBH and tree height and had the advantages of low cost (approx €126), convenient carrying, automatic data recording and simple data processing, which made up for the deficiencies of the existing devices and methods and provided a new solution for forest surveys. However, there are still some limitations. It cannot measure the DBH and tree height greater than 151.47 cm and 65.94 m, respectively. At high stand densities, the occlusion of the surrounding trees has a great influence on tree height measurements. If the surveyor does not hit the bottom and top of the tree well, the tree height will be overestimated or underestimated, and the laser ranging sensor may still be affected by the environment. Therefore, further research is needed.

6. Further improvements

The device still needs to be improved. The measuring range can be further expanded by increasing the length of the ruler arm and selecting a laser ranging sensor with a larger measuring range. Adding a sight telescope allows the surveyor to better hit the bottom and top of the tree with the laser beam. Further research should focus on data measurement methods that will increase the overall accuracy to 100%.

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