

Article

Discovering Tree Architecture: A Comparison of the Performance of 3D Digitizing and Close-Range Photogrammetry

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Abstract: Accurate measurement of tree architecture is vital for understanding forest dynamics and supporting effective forest management. This study evaluates close-range photogrammetry (CRP) using TreeQSM (v2.4.1) software, reconstructing 3D tree structures in both deciduous and coniferous species and comparing its performance to the Fastrak 3D digitizing method. CRP proved less labor-intensive and effective for estimating parameters like tree height, stem diameter, and volume of thicker branches in small trees. However, it struggled with capturing intricate structures, overestimating volumetric values and underestimating branch lengths and counts. Mean relative root mean square errors for height, diameter at 0.3 m height, volume, and branch count were 34.19%, 69.9%, 107.87%, and 142.03%, respectively. These discrepancies stem from challenges in reconstructing moving objects and filtering non-woody elements. While CRP shows potential as a complementary method, further advancements are necessary to improve 3D tree model reconstruction, emphasizing the need for ongoing research in this domain.

Keywords: Fastrak Polhemus; close-range photogrammetry; crown architecture; 3D reconstruction; tree morphology



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1. Introduction

Measuring forest attributes using laser scanning, unpiloted aerial vehicles, and other remote sensing techniques has recently become a trend. These methods allow researchers to detect, for example, dead trees, bark beetle infestations, or to perform forest inventory on large scales in a very short time [1]. However, to understand the forest as a whole superorganism, it is essential to understand each tree and its individual architecture [2]. To accurately assess tree growth, it is possible to understand and define growth as the net production of foliage, the increment in branch thickness or length, and the export of photosynthates to the trunk. Growth is understood as a result of five interacting processes: leaf development, branching, the production of new woody tissue, branch elongation, and gradual dieback [3]. The morphology of tree branches can be described by the spatial distribution of branch segments or the curvature of the entire branch profile under its own weight, and these processes together create the tree's architecture, where the partitioning of biomass between branch growth and export to the trunk is controlled by the phenology of shoot (branch) growth [4]. One of the new approaches to measuring three-dimensional tree architecture at the branch level is the use of a 3D digitizer (3SPACE FASTRAK, Polhemus (Company: NEUROSPEC AG, Stans, Switzerland Version: 1.0)) in combination with custom DiplAmi software for data control and acquisition [5]. This method was successfully applied by Sinoquet and Rivet for the architectural description of young walnut trees with

satisfactory visual comparisons to photographs [6]. Here, the authors investigated the relationship between topological and geometric variables in individual trees. The study found a correlation mainly with the characteristics of the parent shoot from the previous year, though it focused on adult walnut trees using 3D digitization technology rather than smaller plants [6]. The digitization of smaller plants has been addressed in several other studies, which generally concluded that 3D models can reveal differences in structure and development between individuals under varying environmental conditions [7,8]. The data can provide important information on branch morphology, the spatial distribution of leaf area, and fruits, which is consistent with previously obtained results in other studies [9]. In 2005, research by Cardillo (2005) [10] focused on the response of cork oak seedlings to a light gradient during their first growing season. The seedlings were grown with different mesh filters and watered to full soil capacity. The response to different light levels was assessed in terms of morphology and growth, measuring heights, diameters, photosynthetic apparatus dimensions, and biomass both above and below ground. The greatest morphological plasticity was observed in leaf size, which increased to 5.8 cm² in shade compared to 1.8 cm² in full sunlight [11].

A key trend in current research is tracking carbon fixation by individual trees, as this measurement accurately captures not only crown growth but also its spatial distribution. This can reveal whether more carbon is sequestered on the southern or northern side of the tree and whether the tree stores more carbon in its canopy at a younger or older age. To obtain such data, describing the architecture of a tree at a fine level, several methods may be considered appropriate [12,13].

In the proposed study, the Fastrak Polhemus Magnetic Digitizer and digital photogrammetry will be used. Both methods can provide the 3D structure of trees at a certain accuracy level, which will further be evaluated [14].

The Magnetic Digitizer directly provides 3D coordinates of manually detected features, making it a very precise measuring tool [15]. The manufacturer of the Fastrak reports an error of 0.7 cm for XYZ positions depending on the distance from the magnetic field source [16]. However, the accuracy of the measurement is primarily affected by the methodology and errors caused during manipulation with the device. The errors that may cause larger errors in the outcome appear due to human error, unwanted metal objects in the vicinity of the Fastrak Digitizer or weather conditions, mainly rain or wind.

Compared to the Fastrak Digitizer, close-range photogrammetry will be evaluated as an alternative to the method. Photogrammetry has emerged as a compelling alternative for reconstructing tree structures [17]. By utilizing stereo photography and algorithms like Structure from Motion (SfM) and Multi-View Stereo (MVS), photogrammetry leverages information from one or more 2D images to create virtual 3D point clouds. This technique allows for the efficient capture of complex scenes or tree architectures, providing precise measurements of parameters such as diameter at breast height (DBH) and height, often with accuracy comparable to manual methods [9,18,19]. Furthermore, in comparison to the Fastrak Digitizer, photogrammetry is generally less influenced by weather conditions, making it a cost-effective option for faster and larger-scale assessments. However, the impact of wind-caused movement of the scanned trees is an important obstacle in the precise close-range photogrammetric reconstruction, as the SfM algorithm expects the objects to be static. A study by Yun et al. [20] demonstrates how this issue with tree movement could be handled in the case that LiDAR data are used, highlighting the usage of wood–leaf classification algorithms, space colonization algorithms and others, leading to digital models of tree volume and leaf area even in the case of wind-suppressed trees. However, the algorithm might not be appropriate for the detailed reconstruction of tree architecture at a fine level, as it was primarily used for another reason in the cited study.

Also, it needs to be verified in some future work whether the used algorithms are able to work properly in the case of photogrammetric data, in case the tree point cloud is too incomplete.

The photogrammetric data in this study are evaluated using TreeQSM software, which offers automated ways for creating Quantitative Structure Models (QSMs) of trees based on point clouds and delivers a wide range of tree parameters in a single processing run [21,22]. Originally, the software was intended to be used for LiDAR data evaluation, but in the proposed study, photogrammetric point clouds of small trees will be used, as it may be possible to reconstruct small trees well. The QSM creation relies on fitting 3D cylinders into the point cloud, trying to copy the structure of a tree as well as possible while coping with noise and gaps in the point cloud [23]. Alternatives to the TreeQSM method include the SimpleTree [24] and AdQSM [25] programs, which claim to incorporate certain improvements over TreeQSM. All these software tools employ similar Quantitative Structure Modelling algorithms; however, TreeQSM is frequently used as a benchmarking method, and its code appears to be actively maintained. For these reasons, TreeQSM will be utilized in the present study. For estimating less detailed parameters, such as lengths or angles, skeletonization algorithms may also be employed [26]. However, compared to TreeQSM, these algorithms provide only a fraction of the detailed information that TreeQSM is capable of delivering.

The proposed study aims to build upon the above-mentioned findings by comparing the accuracy of measurements obtained from the Fastrak Polhemus system and close-range photogrammetry. The strengths and limitations of each method will be investigated, particularly regarding user-induced errors and external factors like wind and rain that may affect measurement accuracy, as well as the properties of the scanned features, namely small trees.

The results of our study could enhance the existing knowledge of forest ecosystem dynamics and architecture, providing valuable insights for future research and detailed tree reconstruction practices. By emphasizing the potential of both photogrammetry and the Fastrak Polhemus system, we aim to contribute to the development of more efficient and precise methodologies for analyzing tree architecture.

2. Materials and Methods

2.1. Study Area

The study area, an ornamental garden called “Libosad”, is located in the “Suchbát” region of Prague city in the Czech Republic at coordinates $50^{\circ}8'25''\text{N}$, $14^{\circ}22'25''\text{W}$, within the campus of the Czech University of Life Sciences in Prague (Figure 1).

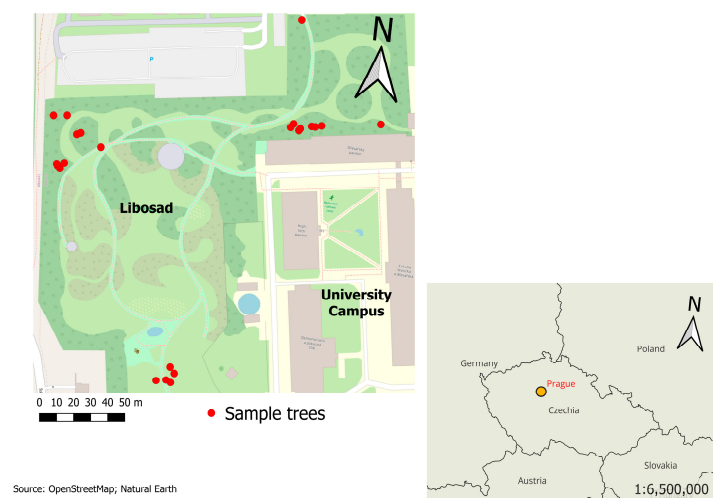


Figure 1. Research area within the Czech University of Life Sciences.

2.2. Data Collection

For this study, a total of 30 trees were selected, consisting of 15 deciduous and 15 coniferous species, with a maximum height of approximately 2.5 m. The trees were selected to represent a variety of growth forms, ranging from simple structures with only a few main branches to complex structures characterized by numerous small, intertwined branches or even additional vegetation. This diversity was chosen to ensure that the algorithms used in the study were tested against a wide range of structural scenarios.

2.2.1. Fastrak Digitizer Data Collection

The selected sample trees were processed using the Fastrak Polhemus magnetic digitizer (NEUROSPEC AG, Stans, Switzerland, software version 1.0) to generate detailed 3D models of the trees. This device is renowned for its precision in capturing the overall architecture of trees, especially in instances where parts of the tree overlap. The Digitizer records point positions with a manufacturer-stated accuracy of 0.08 cm and branching angles with a precision of 0.15° across the X, Y, and Z coordinates, making it one of the most reliable methods for such measurements [16,27]. However, the method may be limited by the reach of the magnetic field, whose source needs to be less than three meters from the recorded object, making it hard to collect information about higher spots, although it is theoretically possible after replacing the magnetic field source. Similarly, the method requires the operator to touch the object with a stylus. These aspects exclude the practical and rational use of this method for large trees.

The output models are provided in a Cartesian coordinate system, with the origin located at the source of the magnetic field. To ensure precise and comprehensive measurements of the crown architecture, it is crucial to position the tree within the magnetic field generated by a designated generator during the measurement process. The first measurement is taken at the base of the trunk, followed by a point at the start of the first branches, capturing a segment or section of the trunk. This process continues sequentially up to the tree's apex. The same method is applied to first-order branches, with subsequent measurements taken for all higher-order branches. In this study, particular focus was placed on measuring these branches to achieve a detailed and accurate representation of the tree's structure (see Figure 2).

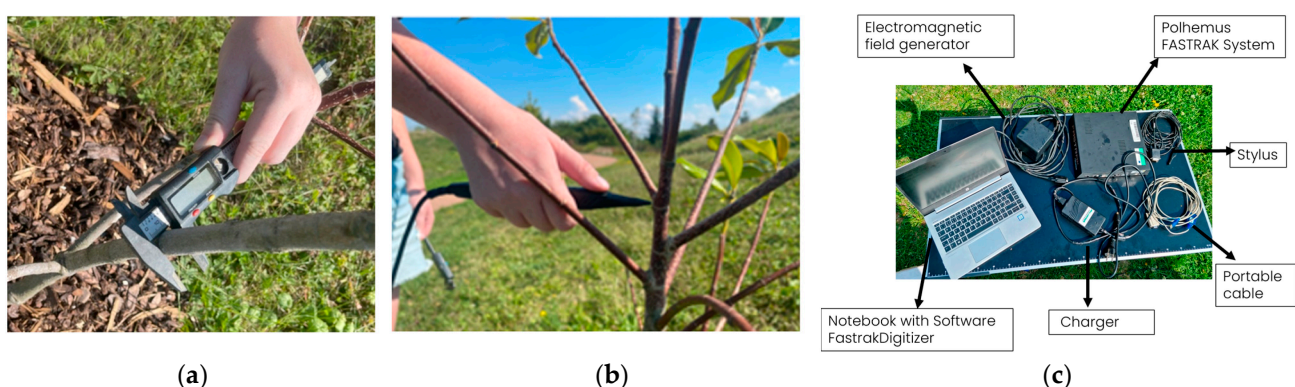


Figure 2. Fastrak Polhemus usage: (a) thickness measurement, (b) stylus and (c) whole device.

2.2.2. Photogrammetric Data Collection

In order to reconstruct selected trees, smartphone (iPhone 12 Pro or iPhone 14 Pro) images had to be acquired. Both smartphones were used to acquire 12 Mpx images, which is possible on iPhone 14 Pro, thanks to pixel binning in its quad-pixel sensor [28]. The imagery was mostly obtained in the morning times or during cloudy days in winter months, in leaf-off conditions for the deciduous tree species. The photoshoot times had to be selected

with consideration of the windy conditions in the study area, as the object's movement in the wind causes significant issues with photogrammetric 3D reconstruction later [29]. The time periods were also chosen to avoid direct sunlight on the target trees. These factors help to reduce the undesirable effects of sharp lighting, strong shadows, and branch occlusions.

However, despite these precautions, the lighting conditions during data acquisition were not optimal in some cases, where the photos were taken while a nearby building cast shadows over the examined trees, simulating diffused light conditions. However, this was not equivalent to the true diffused light seen on cloudy days. As a result, the optimal lighting conditions were not achieved in these cases, and the ISO and shutter speed settings may have been negatively impacted. Although most of the collected JPEG images were captured at the lowest possible ISO of 32 and a relatively fast shutter speed of around 1/215 s, suggesting generally good lighting during the shoot, some adverse effects may still have occurred. The process itself was conducted using the LensBuddy (v60) app [30], which allows the user to preset parameters for sequential imaging.

In the case of this study, the image was taken approximately every second, and the number of images per tree ranged from 349 to 909, depending on tree size, complexity, and light conditions.

Before images of every tree were taken, paper markers for scaling and referencing, exported from Agisoft Metashape software (v2.0.4) [31], had to be placed around each tree, as depicted in Figure 3. Most of the markers were placed vertically or horizontally on the ground around a tree, but there were also smaller markers placed on some of the tree's branches, especially in cases where multiple tree crowns touched. Afterwards, each tree was captured in photos while the camera copied a circular trajectory consisting of four or five circles, depending on the complexity of the examined tree. The first circle provides information on the general habitus of the tree and the location of the markers, while the remaining parts of the trajectory aim to get a closer view of the parts of the tree, such as the bottom, central, and terminal parts of its stem. If possible, closer details were captured along the main branches or inside the crown.



Figure 3. Paper markers used for photogrammetry in simple and complex conditions.

2.3. Data Analysis

2.3.1. Fastrak Digitizer Tree Reconstruction

To accurately assess the structural characteristics of each branch segment, a specific mathematical expression was developed to enable the summation of lengths for each branch and order separately. This detailed approach is crucial for generating precise three-

dimensional models of tree architecture, which in turn enhances our understanding of tree health, growth patterns, and responses to environmental changes.

The formula used to calculate the length L of a branch segment is expressed as:

$$L = \sum_{n=i} \left(\sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2} \right) \quad (1)$$

In this equation, L represents the total length of the branch, n denotes the number of segments within the branch, and i corresponds to the rank order of the branch. The coordinates $[x_1, y_1, z_1]$ and $[x_2, y_2, z_2]$ define the starting and ending points of each segment. This formulation enables a comprehensive evaluation of the geometric structure of the branches, contributing to a deeper understanding of how tree morphology affects light capture and carbon sequestration.

To further assess the volume of these branch segments, an additional mathematical expression was employed, which is critical for estimating biomass and assessing structural integrity. The volume V of each segment is calculated using:

$$V = \frac{\pi}{4} \cdot \frac{d_0^2 + d_n^2}{2} \cdot L \quad (2)$$

Here, V indicates the volume of the segment, with d_0 representing the diameter of the initial segment and d_n reflecting the diameter of the subsequent segment. Once again, parameter L denotes the length of the segment. This method provides valuable insights into the physical dimensions of tree branches, supporting the modelling of canopy structure and enhancing the accuracy of biomass estimates, particularly through the application of remote sensing techniques.

By using this approach, researchers can gain a deeper understanding of the relationships between tree structure, light interception, and carbon storage, which is critical for ecological and environmental studies.

2.3.2. Photogrammetric Tree Reconstruction

The processing of collected images was conducted in Agisoft Metashape software (v2.0.4) [31] and followed the basic steps, such as marker detection, visual control of detected markers, camera alignment, its optimization, dense cloud generation, color calibration and dense point cloud filtering.

The settings for camera alignment were set for the highest possible accuracy. Generic preselection and adaptive camera model fitting were disabled. The Reference preselection option was set to Estimated. Also, the dense point cloud was created using ultra-high quality with no filtering. The setting for point confidence calculation was enabled, as point confidence values are very valuable features for further point cloud editing and filtering.

Filtering of the dense point cloud was necessary, as the original data were excessively noisy and unsuitable for analysis in their initial form. Therefore, filtering based on point confidence, color, or shape was performed using CloudCompare software (v2.13.2) [32]. In most cases, the removal of outlying points or point clusters was successfully done using the Connected Components function. For evergreen tree species, attempts were made to remove the organs of the assimilation apparatus from the scans, primarily using HSV color composition or geometrical features, as described by Hackel et al. [33]. The geometrical features described in the latter study were also used for the semi-automatic segmentation of trees from the terrain. In many cases, the shapes of tree branches were clearly incorrect, with diameters often overestimated. Additionally, some branches may have appeared multiple times in the scan, likely due to tree movement caused by wind, leading to co-registration errors. Automated filtering of these points proved to be impossible, so they

were either slightly filtered using the Connected Components function or left unfiltered for rationalization of the process. The results of this filtering can be seen in Figure 4.

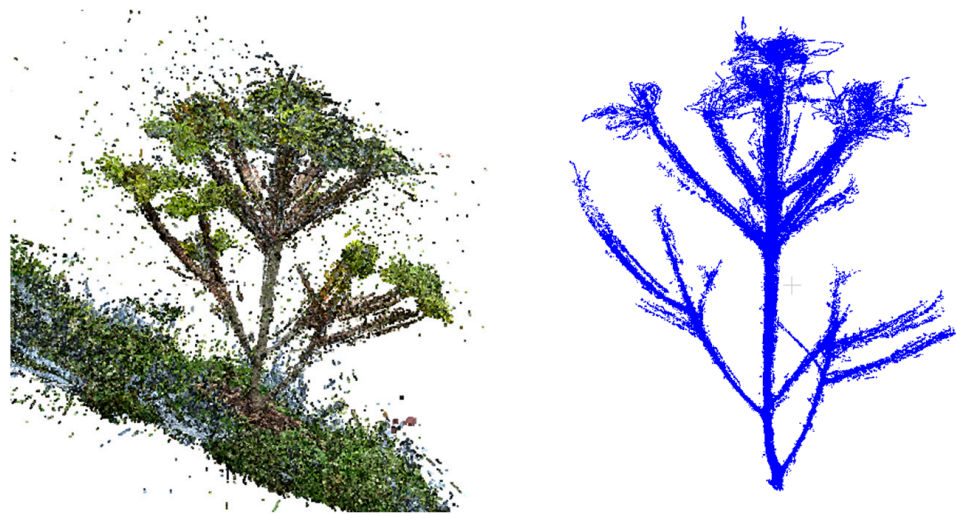


Figure 4. Unfiltered and filtered CRP point cloud of a small tree.

The filtered dense point clouds were subsequently imported into TreeQSM (v2.4.1) software, which is utilized in the following steps of the workflow. TreeQSM is capable of generating Quantitative Structure Models (QSMs) of individual trees based on their point clouds. The resulting models provide information on diameters, volumes, branch counts, branch angles, stem taper curves, and various other aspects of tree architecture. For this study, each tree was evaluated ten times by the program, as the process has stochastic elements, and outputs can vary even with the same input. Repeating the procedure multiple times increases the reliability of the final mean values, as recommended by the software's authors [21].

2.3.3. Comparison of Both Methods

Statistical evaluation was conducted using R software (v1.0) and Python (v3.10) [34,35]. Scatterplots were used to visually represent the data obtained by both methods, as shown in the results section. A more detailed analysis was conducted using paired *t*-tests and effect size (Cohen's *d*) computations. The paired *t*-test was applied to paired observations of each parameter obtained from photogrammetry and Fastrak measurements. While this test determines whether any observed discrepancies are statistically significant, it does not primarily quantify the magnitude of these discrepancies. Therefore, Cohen's *d* was also calculated to assess the effect size and provide a measure of the practical significance of the differences.

These graphs and statistical parameters effectively highlight the differences between the two measurement methods. The RMSE and rRMSE were calculated for each parameter, including height, DBH, volume, and total branch count, to assess accuracy. To ensure transparency, all results were analyzed without the removal of extreme values.

The structural comparison of the two types of 3D models was conducted using the Cloud-to-Cloud Distance function in CloudCompare software (v2.13.2) [26], following the methodology used by Jafari et al. [36].

3. Results

In the final analysis, data obtained through close-range photogrammetry (CRP) were compared with those from the precise Fastrak Digitizer method. A visual representation can be seen in Figure 5. Table 1 presents the modelling accuracies for several parameters

of deciduous and coniferous trees, evaluated using mean absolute error (MAE) and relative root mean square error (rRMSE) values. The results highlight notable differences in photogrammetric performance between the two tree types, capturing the limitations of the photogrammetric workflow.

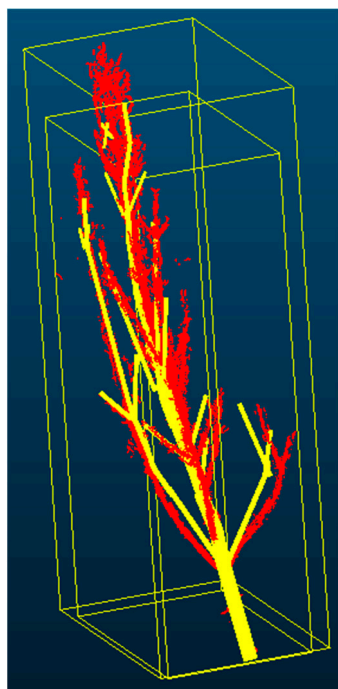


Figure 5. Visual tree structure comparison. Red color: CRP point cloud. Yellow color: Fastrak 3D model.

Table 1. Mean absolute error and rRMSE of CRP in the estimation of studied parameters.

	Deciduous Trees		Coniferous Trees	
	MAE	rRMSE [%]	MAE	rRMSE [%]
Height [m]	0.48	34.19	0.49	37.19
D ₀₃ [cm]	1.38	87.00	1.79	58.81
Length [m]	21.56	123.47	32.79	102.27
Volume [dm ³]	11.58	73.91	20.07	115.39
Number of branches	109.18	145.87	147.27	131.40

Tree height for both deciduous and coniferous trees was measured with similar error levels despite photogrammetric structure-from-motion (SfM) reconstructions encountering challenges with the finer, more mobile structures of deciduous trees compared to conifers. This was surprising, as the quality of deciduous-tree point clouds was subjectively worse than the quality of conifer-tree point clouds. The mean absolute errors for stem diameter at 0.3 m above ground reflect issues related to stem occlusion from dense needle-covered branches, which also contributes to inaccuracies in the estimated volume, total length of woody components, and the number of branches. These parameters appear to be reconstructed with higher accuracy for deciduous trees in leaf-off conditions.

The proposed study examined not only the parameters shown in Table 1 but also more detailed parameters related to the finer structures of tree architecture. General results for these additional parameters are presented in Table 2. As indicated, certain parameters, particularly those involving small structures, were not accurately reconstructed using photogrammetry.

Table 2. Results of paired *t*-tests (*p*-value) and the measure of effect size for deciduous, coniferous and all species together. Bold *p*-values refer to the non-rejected null hypothesis. Single-underlined effect size values refer to underestimation ($d < -0.2$), and double-underlined values refer to overestimation ($d > 0.2$).

Parameter	Paired <i>t</i> -Test (<i>p</i> -Value)			Effect Size (Cohen's <i>d</i>)		
	All	Deciduous	Coniferous	All	Deciduous	Coniferous
D ₀₃	0.332	0.234	0.853	0.180	<u>0.321</u>	0.049
H max	0.756	0.754	0.511	−0.057	0.083	−0.174
L branches	0.395	0.043	0.494	0.158	<u>0.574</u>	−0.181
L total	0.741	0.369	0.003	0.065	<u>0.539</u>	−0.234
L branch. 1st	0.187	0.511	0.049	−0.246	0.174	−0.555
L branch. 2nd	0.828	0.105	0.581	0.040	<u>0.448</u>	−0.146
L branch. 3rd	0.002	0.015	0.048	<u>0.629</u>	<u>0.718</u>	<u>0.558</u>
L branch. 4th	0.652	0.032	0.386	0.083	<u>0.616</u>	−0.231
L trunk	0.028	0.369	0.003	−1.090	−0.527	−11.369
N branch. 1st	0.000	0.050	0.001	−0.780	−0.554	−1.068
N branch. 2nd	0.180	0.546	0.148	−0.251	0.160	−0.396
N branch. 3rd	0.004	0.002	0.312	<u>0.565</u>	<u>1.006</u>	<u>0.271</u>
N branch. 4th	0.000	0.007	0.004	<u>0.771</u>	<u>0.817</u>	<u>0.877</u>
N branch. total	0.826	0.011	0.316	0.040	<u>0.755</u>	−0.268
V branch. 1st	0.018	0.030	0.270	−0.458	−0.622	−0.296
V branch. 2nd	0.103	0.846	0.106	<u>0.308</u>	0.051	<u>0.446</u>
V branch. 3rd	0.004	0.075	0.025	<u>0.566</u>	<u>0.496</u>	<u>0.649</u>
V branch. 4th	0.007	0.102	0.008	<u>0.536</u>	<u>0.470</u>	<u>0.806</u>
V branches	0.423	0.307	0.278	0.148	−0.273	<u>0.291</u>
V total	0.448	0.021	0.956	−0.141	−0.671	0.015

3.1. Comparison of Tree Heights

Estimates of tree height using the Fastrak system and photogrammetry were compared for deciduous and coniferous trees separately (Figure 6).

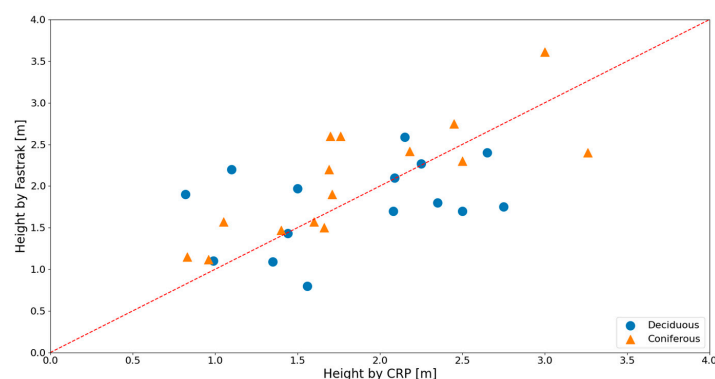


Figure 6. Comparison of tree heights measured by Fastrak and CRP on two tree types.

For all species studied, photogrammetry demonstrated success in estimating tree heights comparable to those measured by the Fastrak method. However, the effect size analysis in Table 2 reveals a slight underestimation of coniferous tree heights, which is also evident in the basic statistical summary of the selected trees shown in Table 3.

Table 3. Description of tree heights observed by Fastrak and CRP methods.

	Deciduous Trees		Coniferous Trees	
	CRP	Fastrak	CRP	Fastrak
Mean height	1.84	1.79	1.85	2.08
Standard deviation	0.63	0.51	0.71	0.69
Minimum height	0.82	0.80	0.83	1.12
Maximum height	2.75	2.59	3.26	3.61

3.2. Comparison of D_{03}

Estimates of tree diameter at 0.3 m above ground obtained through the Fastrak system and close-range photogrammetry (CRP) were compared for both deciduous and coniferous trees, as shown in Figure 7. Consistent with the findings presented in Table 2, CRP successfully estimated diameters at this height; however, the scatterplot in Figure 7 reveals some visible discrepancies between the two methods. For deciduous trees, the effect size ($d = 0.32$) and sample means ($\mu_{\text{CRP}} = 3.59$ cm; $\mu_{\text{Fastrak}} = 2.82$ cm) suggest a tendency for CRP to slightly overestimate diameter compared to the Fastrak system. Despite this observed difference, the paired t -test ($p = 0.23$) indicates that the difference is not statistically significant.

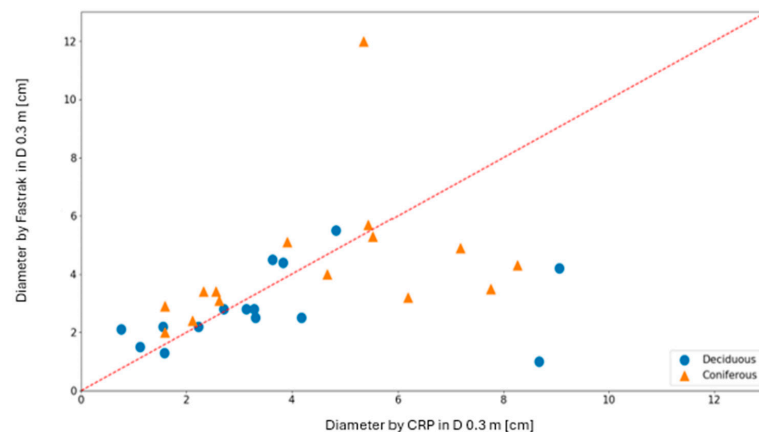


Figure 7. Comparison of stem diameters at 0.3 m height (D_{03}) measured by Fastrak and CRP.

Additionally, the basic descriptive statistics for the sample are presented in Table 4, providing a broader context for understanding the sample variation and distribution of measurements across the observed trees.

Table 4. Overall description of the diameter at 0.3 m height observed by both compared methods.

	Deciduous Trees		Coniferous Trees	
	CRP	Fastrak	CRP	Fastrak
Mean D_{03}	3.59	2.82	4.48	4.35
Standard deviation	2.44	1.29	2.28	2.38
Minimum D_{03}	0.76	1.00	1.59	2.00
Maximum D_{03}	9.06	5.50	8.27	12.00

3.3. Comparison of Tree Volume

Figure 8 provides a comparison of the estimated volumes for deciduous and coniferous trees. The CRP method demonstrated a high level of accuracy in estimating the volume of coniferous trees, with a p -value of 0.96, supporting the null hypothesis that there is no significant difference between CRP and the reference measurements. However, for deciduous trees, the null hypothesis was rejected ($p = 0.021$), indicating a significant underestimation by the CRP method, with an effect size of -0.67 . This suggests a moderate discrepancy in the volumetric assessment of deciduous trees when using photogrammetry.

These results pertain to the overall volume estimation of all woody components. A more detailed analysis focusing on the thinner, more intricate structures of the trees will be discussed in the subsequent sections, providing further insights into the limitations and accuracy of the CRP method for these finer architectural details.

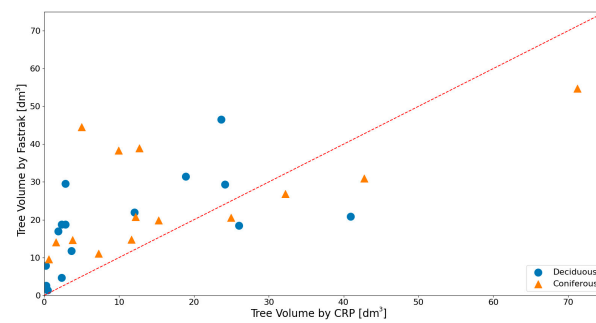


Figure 8. Comparison of total tree volumes measured by Fastrak and CRP.

3.4. The Detailed Volume of Each Branching Order Comparison

The volumetric estimates of branches across hierarchical levels (1st to 4th order) offer valuable insights into the accuracy of photogrammetry when applied to complex tree structures. Notably, for the thickest branches (1st order), the CRP method demonstrated accurate reconstruction primarily for coniferous trees ($p = 0.27$), while overall, the volumes of 1st-order branches tended to be underestimated, as indicated by the negative effect size values and as illustrated in Figure 9a.

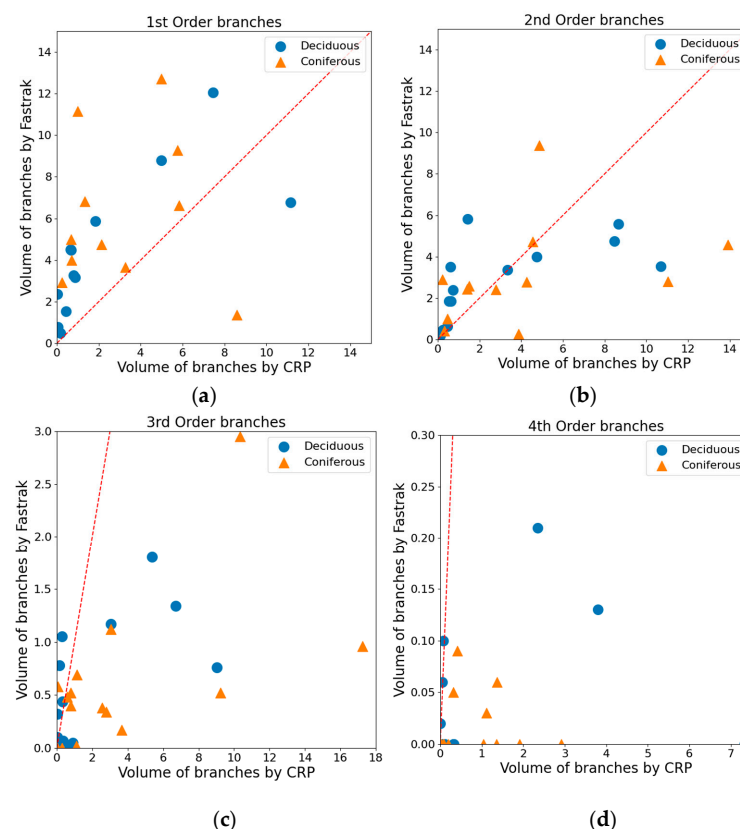


Figure 9. Difference in branch volume based on branching order. (a) shows the case of 1st branching order, (b) depicts 2nd branching order, (c) shows the 3rd order and (d) views the case of 4th branching order. Positive difference values suggest overestimation of the CRP method.

Conversely, an overestimation trend was observed for both 3rd- and 4th-order branches. However, a statistically significant similarity between CRP and Fastrak estimates was only achieved for deciduous trees at these branching levels. This disparity may be attributed to the challenges of detecting and filtering coniferous branches in point clouds, where dense foliage and needle structures complicate accurate volume estimation.

For 2nd-order branches, the CRP method performed consistently well across both tree types, with p -values exceeding the significance threshold of $\alpha = 0.05$, suggesting that these mid-sized branches were reconstructed accurately by photogrammetry.

These results may also be influenced by inaccuracies in branch lengths and counts, as detailed in Table 2, which will be discussed further in the next section.

3.5. Comparison of the Length and the Number of Branches

The error in branch volume estimation could, among other factors, be influenced by the number of detected branches and their actual lengths. Similar to the volume results, these parameters were assessed through hypothesis testing using paired t -tests.

Encouragingly, for 2nd-order branches, the CRP method yielded satisfactory results, successfully detecting branches whose counts and lengths closely matched those measured by the Fastrak method. However, for other branching orders, the results showed statistical significance in some instances, though no consistent pattern emerged across either deciduous or coniferous trees. A detailed summary of the paired t -test outcomes is provided in Table 2, whereas the comparison of the observed values is provided in Figures 10 and 11.

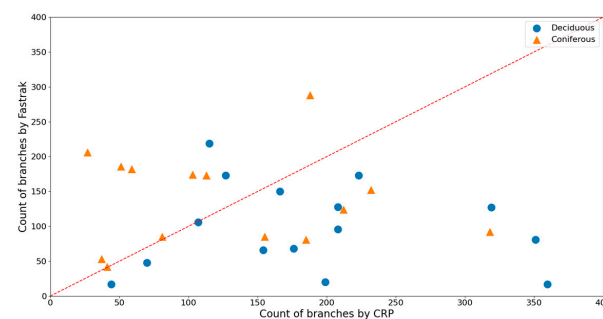


Figure 10. Comparison of the estimated total numbers of branches.

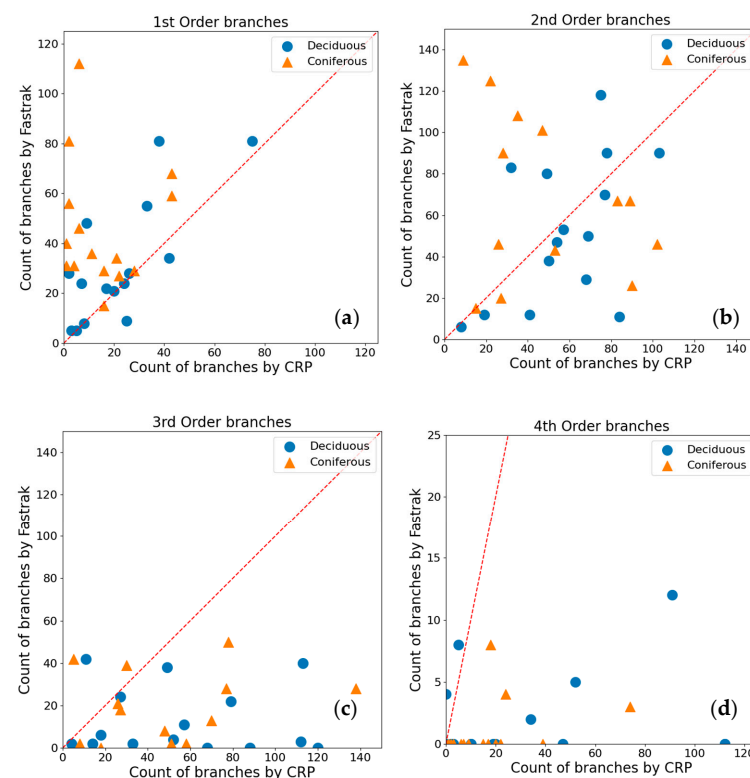


Figure 11. Difference in branch counts based on branching order. (a) shows the case of 1st branching order, (b) depicts 2nd branching order, (c) shows the 3rd order and (d) views the case of 4th branching order. Positive difference values suggest an overestimation of the CRP method.

Effect size analysis indicates that the CRP method generally overestimates both the number of detected branches and their lengths. This tendency toward overestimation highlights potential limitations in CRP accuracy, particularly as branch complexity increases.

3.6. Comparative Analysis of Structural Variability in 3D Models

Visual comparison of the produced models lacks the objectivity needed to assess model accuracy accurately. Human perception readily distinguishes tree parts, often leading to an overestimation of similarity among 3D models (see Figure 5). To provide a more objective analysis, a cloud-to-cloud distance comparison was conducted, yielding insights into the structural variability and complexity of deciduous and coniferous trees. These findings have valuable implications for ecological modelling and structural analysis of tree crowns.

A comparative analysis of 3D models generated for deciduous and coniferous trees revealed significant differences in spatial parameters between models produced by the Fastrak Digitizer and photogrammetric methods. For deciduous trees (Table 5), maximum distances of points to the reference model ranged from 1.54 cm to 79.86 cm, with average point distances spanning 1.43 to 21.26 cm. In contrast, coniferous trees showed greater variability, with maximum distances reaching up to 115.23 cm and average distances from 5.30 to 25.23 cm, indicating a more complex crown structure that poses challenges in reconstruction. Standard deviations for coniferous trees (Table 6) ranged from 1.73 to 22.55, suggesting a larger dispersion in point distances. These values indicate how much the parameters of branch length, tree height and others were influenced by the limitations of close-range photogrammetry, leading to over- or underestimation of volume calculations.

Table 5. Comparison of cloud-to-cloud distances in centimeters between 3D models of deciduous trees. The maximal error indicates the maximal possible systematical error.

Deciduous				
No.	Maximal Distance	Average Distance	Standard Deviation	Maximal Error
1	36.32	3.02	3.67	0.84
2	22.10	1.43	2.25	0.82
3	28.46	3.03	3.34	0.83
4	16.10	2.58	1.99	0.93
5	78.40	21.26	15.13	0.76
6	59.63	11.62	12.12	0.89
7	79.86	11.98	12.56	0.85
8	13.41	2.09	1.44	0.73
9	22.30	4.93	3.78	0.43
10	1.54	1.51	1.61	0.27
11	14.07	2.20	2.21	0.42
12	14.24	1.79	1.64	0.62
13	32.98	5.36	4.79	0.45
14	35.96	6.45	5.40	0.69
15	28.95	4.99	3.94	0.94

Table 6. Comparison of cloud-to-cloud distances in centimeters between 3D models of coniferous trees. The maximal error indicates the maximal possible systematical error.

Coniferous				
No.	Maximal Distance	Average Distance	Standard Deviation	Maximal Error
1	28.35	5.30	3.82	0.85
2	16.26	3.68	2.59	1.06
3	32.20	6.77	4.23	0.89
4	13.29	2.58	1.73	0.65
5	49.51	10.44	6.82	0.90
6	55.68	12.88	9.56	0.69

Table 6. *Cont.*

No.	Maximal Distance	Coniferous			Maximal Error
		Average Distance	Standard Deviation		
7	115.23	25.23	22.55		1.10
8	59.66	10.21	9.42		0.99
9	14.71	3.87	2.66		0.32
10	21.36	5.23	3.40		0.62
11	60.67	19.03	12.15		0.59
12	46.59	10.21	7.43		0.92
13	42.92	8.23	7.2		0.58
14	38.36	7.47	6.11		0.38
15	34.60	6.99	6.15		0.55

4. Discussion

Nowadays, studying the architecture of woody plants, especially in young specimens, is becoming increasingly important because of the desire to understand tree growth [37]. This raises the question of whether photogrammetry can achieve the same level of accuracy as Fastrak Polhemus technology. While Fastrak Polhemus is known for its minimal measurement errors when assessing young trees, its time requirements in the field may not always be optimal [38,39] and the average time required during this study was approximately 45 min for field data collection and 30 min for data evaluation per 1-m-tall tree. However, the time consumption increases with the complexity of the crown or branching structure. Consequently, close-range photogrammetry emerges as a promising alternative. Its use demonstrated a significant reduction in human time consumption. Image acquisition requires approximately five minutes, and manual processing of the point cloud in the computer circa 20 min. However, the computer processing time for photogrammetric reconstruction could extend up to three hours, in complex scenes, while the Quantitative Structure Modelling (QSM) calculation requires about 15 min of time, depending on the number of iterations performed in order to improve the statistical reliability of the final QSM. The image-processing time could however be further reduced by implementing novel algorithms as improved Harris+SURF described by Zhu et al. [40].

The analysis focused on the results of paired *t*-tests and effect size values for four key measurement accuracy indicators: tree height, $D_{0.3}$ (Diameter at 0.3 m height), volume, and number of branches.

Height and tree stem diameter measurements showed the greatest consistency between the two methods, while the largest discrepancies were observed in the estimation of individual branching order parameters, such as volume or count of branches. These significant errors likely appeared due to branch occlusion caused by the tree's assimilation apparatus, making it challenging to capture accurate photographs of the thin tree structures and inner parts of the tree crown. Additionally, the removal of assimilation organs in the 3D models led to the loss of some woody parts, as illustrated in Figure 12 or Figure 4. The complexity of effectively removing surrounding cloud points, especially in conifers, further impacts measurement accuracy. Deciduous trees present challenges, too, as their greater movement in wind conditions complicates the photogrammetric reconstruction of top shoots. This movement not only decreases confidence in the 3D point cloud data but also generates substantial noise, leading to the loss of thin branches during filtering due to their already low reconstruction confidence. These and some more factors are also mentioned in other studies and are a common issue with photogrammetry [21,34,35], and the impacts were numerically summarized in the comparative analysis of the proposed study. The presence of persistent noise introduces errors in branch count and length estimations, as the TreeQSM program interprets this noise as actual data [41]. It is very likely that the reduction in these impacts would dramatically improve the performance of the photogrammetry.

Practically, in outdoor conditions of a forest or park, these influences might only be reduced by the acquisition of a larger number of images in better light conditions, especially from angles revealing the inner architecture of a tree crown. Nonetheless, a proper workflow needs to be used to successfully use the Structure-from-Motion algorithm for point cloud creation. Some co-registration issues of the photogrammetric point clouds might be successfully solved by using other algorithms, less prone to errors due to object movement, such as Non-Rigid Structure from Motion (NRSfM) or Optical Flow [42,43]. These algorithms have not yet been tested for estimating parameters in forest environments or individual tree measurements.

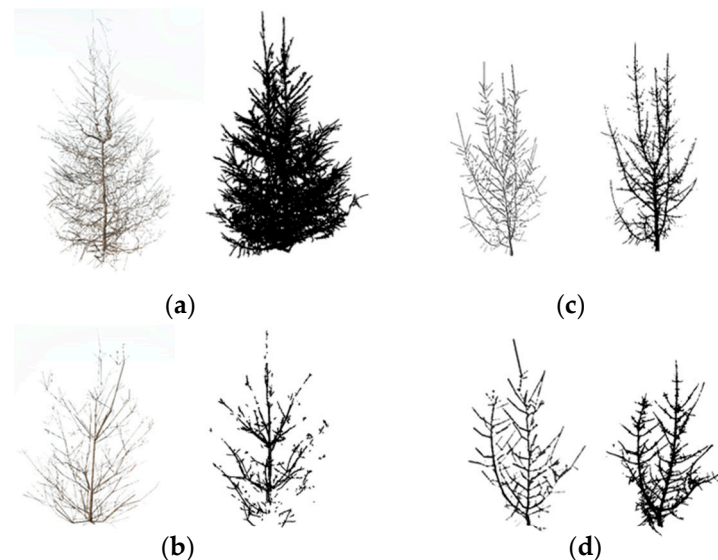


Figure 12. Visualization of Fastrak (left) and CRP (right) 3D models for coniferous (a,b) and deciduous trees (c,d).

Studies comparing remote sensing methods for tree architecture reconstruction are rare nowadays, and compared to the few available studies, e.g., Miller et al., the relative performance can be observed. Miller et al. manually measured 30 potted trees and compared the data to photogrammetric 3D reconstructions. The 3D model dimensions were also measured manually using Agisoft PhotoScan (v2.0.4.) software. Using these methods, height was measured with an rRMSE of 3.74%, DBH with an rRMSE of 9.6%, branch volume with an rRMSE of 47.53% and total volume with an rRMSE of 18.53% [17]. Very similar results were also shown in a study by Morgenroth and Gomez [44]. These results show significantly better performance than those of the proposed study. On the other hand, the methodology of the two latter studies required a large amount of manual labor, and the photoshoot conditions were more convenient. In the proposed study, the workflow consisted of automatically performing dimension estimations provided by TreeQSM software, and the trees were grown naturally in the soil without the possibility of being replaced with a more appropriate space with less wind and fewer obstacles. The main source of error in the presented study is likely the fact that during manual measurement of tree dimensions in a 3D model, a person can accurately estimate where branches begin and end, even in a very sparse point cloud. In contrast, when using software, this ability is lost, and the result depends on the density of the point cloud, which is negatively affected by the previously mentioned phenomena.

Similarly, tiny structures, as in the proposed study, were also examined in a study by Koeser et al. [45]. This study computed the volume of tree roots and also used CRP for this purpose. The rRMSE in the estimates was 12.3%, and the results suggested that photogrammetry is suitable for these purposes.

Other published studies usually aim to estimate forest inventory attributes of mature trees, mostly DBH and height of mature trees. Comparing these results with the results achieved in the proposed study should justify the methods used, even though the results indicated improvements are necessary. In a study by Surový et al. [27], data from 20 mature trees were evaluated using CRP, and the final RMSE for the trunk DBH was 1.87 cm. Similarly, Mokroš et al. [18] achieved DBH estimates with an rRMSE of less than 2%.

In contrast, our study found an RMSE for the diameter of deciduous trees at 1.38 cm and coniferous trees at 1.79 cm, corresponding to relative errors of 87% and 58.8%, respectively. Although these results are worse than those in the mentioned studies, it is important to consider that our study focused on small trees, with often strongly occluded stems and more complex architecture, and the overall task was more demanding. A view of the results achieved on small trees in contrast to mature trees implies that the larger the objects are, the better the obtained results.

Ground-based photogrammetry is potentially highly accurate for measuring trunk diameter and tree height. However, this method tends to be less precise for volume measurements. The type of tree also plays a significant role in measurement accuracy. The results of this study indicate that the reconstruction of deciduous and coniferous trees encounters distinct challenges, each specific to the tree type. For deciduous trees, lengths and volumes were estimated more accurately, likely due to their simpler branching patterns and crown structure. In contrast, coniferous trees, despite their more complex branching and denser crowns, exhibited higher accuracy in branch count estimates using photogrammetry. However, these structural complexities in conifers made it more challenging to accurately measure other parameters, such as volume.

It is strongly advised to pay attention to the aspects that decrease the quality of photogrammetry, as these are likely the main issues in this topic, as mentioned earlier in the text. Possibly, different scanning methods, like TLS or MLS, with sufficient resolution may be appropriate for this task but have not been sufficiently tested in this field so far [20].

Authors of the proposed study believe that these results may bring more awareness to the topic of tree architecture reconstruction, and further research on the 3D data analysis will be performed with a particular aim on easy-to-use and more automated processing.

5. Conclusions

The comparison of close-range photogrammetry (CRP) with the precise Fastrak digitizing method for measuring various tree parameters reveals that photogrammetry faces notable challenges in accurately estimating parameters of smaller, intricate tree structures. These challenges likely stem from difficulties in photogrammetrically reconstructing moving objects and effectively filtering out non-woody elements. Fastrak has proven to be a reliable tool for complex and detailed measurements, while CRP, despite its limitations, has demonstrated success in reconstructing certain parameters for small trees, such as tree height, stem diameter, and the length and volume of thicker branches.

Photogrammetry shows a tendency to overestimate volumetric values while generally underestimating branch lengths and counts, particularly for coniferous trees. The overall mean relative root mean square errors (rRMSEs) observed for height, diameter of stem (D_{03}), volume, and branch count were 34.19%, 69.9%, 107.87%, and 142.03%, respectively. These findings suggest that current photogrammetry-based modelling methods for trees lack precision in certain areas, highlighting the need for further algorithmic improvements to enhance 3D model reconstruction and estimation accuracy.

As a result, Fastrak remains the preferred method for detailed and highly accurate tree parameter measurements, especially where fine structural details are essential.

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