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Tree architecture description using a single-image photogrammetric method

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Abstract: Tree architecture is thought to allow species to share available resources both above and below ground. The description of plant architecture is useful to model plant structure and function, as well as interactions with other species or generally with the environment. The aim of this study was to present a conceptual implementation of a simple photogrammetric method for the above-ground tree architecture description of leafless individuals growing under different conditions. The implemented method was single-image photogrammetry. The novel aspect is the heuristic assumption that tree's image is a projection onto a plane that cross-sections the stem base; which enables assessment of a set of the canopy attributes, with only one image involved. The method was tested in two ways: (1) in the field: in terms of its applicability to real trees, we used 31 plots with different terrain slope and tree density, in natural forest, in every case the target tree was European beech (*Fagus sylvatica* L.) which is known as a very plastic tree species, and (2) with virtual tree-like 3D models, created with L-system rules, to determine the accuracy of the method. Some of the traits measured or estimated with respect to the projection plane α are: the length of the trunk and branches (L), inclination of the tree main axis from the vertical (IA), crown width (CW), two opposite crown radius (CR), crown length (CL); and the external factors, like the terrain slope inclination (S) and number of trees competing for light (N). The advantages (e.g., low time consumption and low cost), difficulties (e.g., occlusion of tree tops) and accuracy in idealised conditions were described. The tree traits that can be measured using the proposed method are essential for estimating many ecological parameters. Our method allows reducing fieldwork time to a minimum and taking measurements of large numbers of plots daily when the environmental conditions are similar, even when they are taken by only one person. This method is very useful for conducting studies on a temporal scale (e.g., to record changes in the branching structure). Future research is needed to validate the method in different environments.

Key words: stand structure, biometry, Non-Destructive Method, plant morphology, above-ground biomass, *Fagus sylvatica* L.

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Introduction

Terrestrial photogrammetry as a method for architectural inventory

The term 'plant architecture' is frequently understood as a description of the form or growth pattern of an individual of a certain species growing in good conditions. The other meaning of this term is tightly connected with the geometry and the structure of individuals. The description of plant architecture is often used by scientists to model plant structure or different processes, as well as interactions with other species or generally with the environment. The architectural approach is crucial in understanding tree structure and function (Sievänen et al., 2014). However, to make progress in the field, empirical data are needed; low-cost, non-destructive and accurate acquisition of architectural data is still a concern (Bauwens et al., 2017).

In the last decades there has been a strong technological development in digital photography, making it easier and more affordable. Quality images of trees may be used for taking specific measurements by the means of terrestrial photogrammetry. Most of the existing image-based methods for tree traits analyses aim at measuring foliaged trees (Koike, 1985; Reche et al., 2004; Shlyakhter et al., 2001). Many of these methods use photogrammetry to identify and reduce the distortions of perspective and transform the image into an orthophotograph, which after recognizing the scale, can be used for measurement purposes (Grussenmeyer et al., 2002; Tommaselli & Reiss, 2005). The results are usually obtained from a combined set of images, as in Phattaralerphong et al. (2006). Few methods address the measurement of trees growing in dense stands (but see Koike (1985)); often, a special background screen is needed (e.g., in Reche et al. (2004)). The accuracy, cost and time-consumption of those methods are relatively low compared to the following methods for canopy variables assessment: the stratified clipping method (Monsi & Saeki, 1953), articulate arms (Lang, 1973), laser scanner (Ashcroft et al., 2014; Kaminuma et al., 2004; Parker et al., 2004; Tanaka et al., 1998; Walklate, 1989), ultra-sonic 3D digitaliser (Sinoquet et al., 1991), and 3D magnetic digitaliser (Polhemus Incorporated, 1993; Sinoquet et al., 1997).

The strong development of the laser scanning-related techniques (Calders et al., 2015; Hackenberg et al., 2014; Raumonen et al., 2015; Raumonen et al., 2013) has given the most impressive insights into the problem of tree branching system inventory. The image-based methods seem to be overshadowed by the laser-based ones (mainly terrestrial laser scanning, TLS), especially when the measurements from TLS undergo constant automatization (Hackenberg et al., 2014). Nevertheless, there is a huge gap in terms of cost, time consumption, accuracy and the number of possible features to be measured between the laser-based and sight-based (e.g., tangent-based) techniques, while the latter is still a very frequent praxis in forest science (Fleck et al., 2011). Therefore, a simplified photogrammetric (image-based) method may be the solution for many researchers who need a verifiable, repeatable, quick and low-cost method that allows useful approximations of trees' complex architecture.

The main aim and novelty of our study was to present a conceptual implementation of a single-image photogrammetric method for describing the above ground tree architecture of leafless individuals of large, canopy trees growing in various ecological conditions. A similar approach was proposed by Chi et al. (2016), however, the method was applied to only small, solitary tree, no camera tilt was considered and the purpose was to create a 3D model. On the contrary, in this study we focus on taking specific measurements. The procedure described here is based on a heuristic assumption that tree's image is a projection onto a plane (α) that cross-sections the stem base; a similar idea was proposed by Sinoquet et al. (1991) for maize description. This enables measurement of the extracted (digitized) features redundant space, with one digital image involved. The method is non-destructive, relatively simple, low-cost and accurate enough for many applications. It may be used by scientists to analyse different morphological features (e.g., number of branches, branch angles, internodes lengths, cavities) of studied tree/trees, also in terms of specific habitats for associated organisms (e.g., insects, lichens, birds, etc.) at different scales.

Methods

This section is divided into four subsequent parts, corresponding to the workflow of the method: (i) Data collection – presents the field work procedure, particularly, how to take the image of the target tree for further architectural analysis; (ii) Image transformation – describes the theoretic and practical aspects of turning a non-metric into a metric image (ortophotograph), including calibration with the use of a reference object; (iii) Digitisation (vectorization) – focuses on extracting the architectural data from the transformed image; (iv) Accuracy – explains the idea of using virtual 'trees' for the accuracy assessment. The procedure (ii)–(iii) is showed in detail at the example of a specific tree in the Appendix.

Data collection

We conducted a pilot study to test the capability of the photogrammetric method to describe real

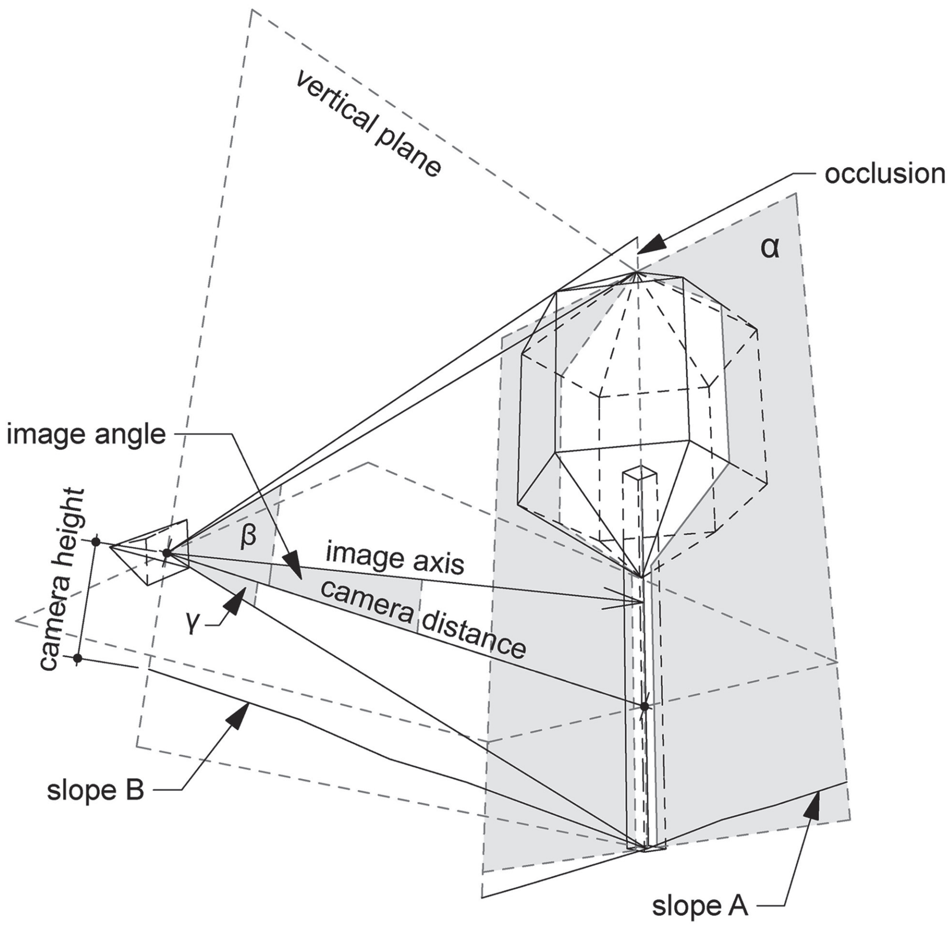

Fig. 1. Scheme of image and field measurement parameters. β and γ are the angles between the horizontal plane and the axes: pointing towards the tree top and tree base (respectively). α is the projection plane (test plane)

trees growing in various conditions. We used 31 mature beech trees (*Fagus sylvatica* L.) within a temperate natural forest (coordinates for the central point of the Ojców National Park: 50°12'25.0"N 19°49'03.2"E). The individuals were selected by systematic random method. The plots were of different slope inclination (min. = 1°; max. = 35°), tree density (min. = 6 trees/0.1 ha; max. = 27 trees/0.1 ha) and species composition (pure beech plots and mixed, mostly with silver fir *Abies alba* Mill.). The distance between target trees was not less than 200 m. All of the field and laboratory work was performed by following the described method.

To begin tree architecture analysis, one digital image in high resolution containing the whole tree is necessary (in our case, it was 3672 × 4896 pixels; DSC-HX20V camera). Digital cameras with low values of chromatic aberration, a wide viewing angle (e.g., 25 mm lens) and high-quality picture performance are especially useful. The projection plane (α) cross-sections the base of the tree, it is a vertical plane, perpendicular to the vertical plane containing the image axis (Fig. 1). When looking for the best location to take the image, it is necessary to find a place from which the target tree is well visible, in particular, there are no other trees directly in front or behind the target tree. Moreover, if the tree's horizontal crown projection is visibly elongated, it is best to set the plane α close to the longitudinal axis of the crown. Distance of the camera to the plane α and image angle (tilt) must be measured in the field; for that purpose a laser rangefinder with a built-in clinometer may be used. Additionally, we recorded the azimuth of the image axis with a compass. The digital camera used should be equipped with a level indicator so that the inclination angle of the camera line of sight would not deviate from the vertical plane (Fig. 1). The angles between the horizontal plane and the directions to the tree top and base (β and γ in Fig. 1) may be measured to compare the calculated tangent-based tree height with the image-based one.

Image transformation

The image transformation is based on the selected plane α (Fig. 1) and known location of at least four control points enclosed in that plane (see Appendix). Since α (in the images of trees) is a conceptual plane,

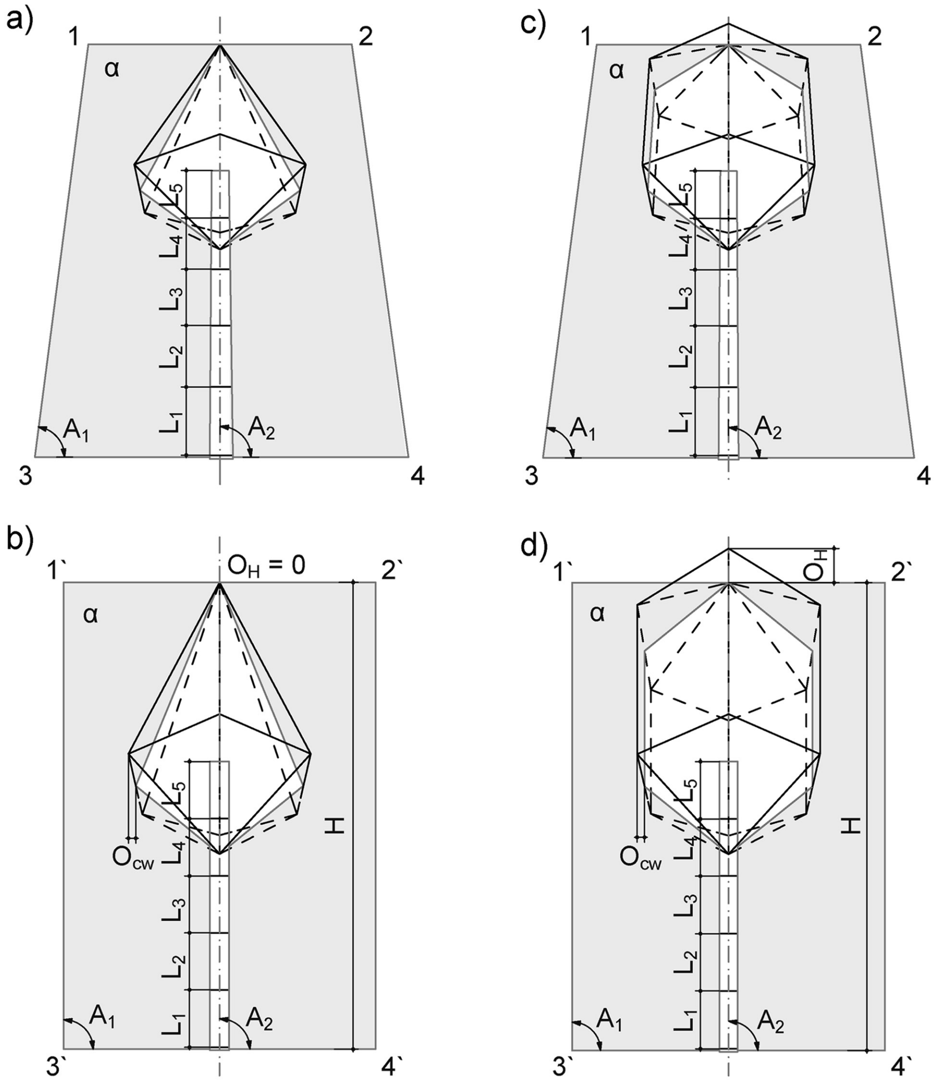

Fig. 2. Simple volumetric models of a coniferous (a, b) and deciduous tree (c, d). Perspective images (a, c) and images after perspective distortion reduction (b, d). H = height of the tree, O_H = difference between actual height of the tree and the measured height, L_1 – L_5 are segments of equal length, O_{CW} = difference between the actual crown width and the measured value in regards to the projection plane (α), A_1 and A_2 are angles of 90°, points 1–4 and 1`–4` are the four control points

it is necessary to use a reference object (a physical representation of the plane α); it can be a building facade, a billboard or any other object containing a large, flat surface that is relatively easy to measure. This idea provides a substitute for a camera model. The establishment of the parameters of transformation for a specified camera type and position (distance and angle) regarding the reference object images is performed only once; then, using the same parameters of projection, the reduction of perspective distortions and scaling can be applied to the images of trees (Fig. 2). We have used the following image settings: distances to the object (15–35 m, with 5-m intervals) and angles for the line of sight of the camera (10–35°, with 5° intervals). The preliminary study in a dense beech forest showed that this range of parameters was enough to capture all large, mature trees growing in different conditions. The most frequently used camera setting was: a 20-m distance and camera angle of 20°.

The relationship between the plane of the object and its image is defined by the equations:

$$X = (a_1x + a_2y + a_3) / (c_1x + c_2y + 1),$$

$$Y = (b_1x + b_2y + b_3) / (c_1x + c_2y + 1),$$

where X and Y are the coordinates of a point on the object's plane, x and y are the coordinates measured on the image, and a_i, b_i, c_i are eight parameters of projection. The measurement of the four control points results in the establishment of the eight unknowns

(a_1, a_2, a_3, ..., c_2). As a result, one can calculate the two-dimensional coordinates of any point on the image plane by using the above equations (Grussenmeyer et al., 2002). The available computer software uses a predetermined relationship for each pixel in the image, transforming it into an orthophotograph of the plane.

The transformation can be performed using QGIS (2016), an open source software which enables image transformation (with the Georeferencer tool), scaling, digitisation and measurement of distances and areas; all data including forest plots' characteristics were stored in a single QGIS project file. QGIS enables writing the control points to an output file, which greatly facilitates the image transformation procedure (see Appendix for details).

Digitisation (vectorization)

Vector graphics can be obtained using the resulting raster image by digitising the axes of the trunk and branches (Fig. 3). The digitising (vectorization) strategy regarding trees was described by Godin et al. (1999). The core concept of the procedure is sampling points (nodes) on the tree branching system's image to obtain segments representing axes of the trunk and branches. We have assumed that the human eye can trace the branching system axes starting from the tree base, even when it is partially occluded or self-occluded by branches. The software used (QGIS v. 2.8.1) provides great digitisation capabilities, available with the advanced digitising toolbar (see Appendix for details) redundant space. Digitised axes can be assigned to classes of thickness; we have developed nine classes, eight of which are 10 cm each and one that is 5 cm for the thinnest branches that underwent digitisation procedure (between 5 and 10 cm thick). Another option is to assign the axes according to branching order, the concept is well described in de Reffye et al. (1988). With a prepared vector graphic, the axis lengths can be measured automatically within a class of thickness or specified branching order. The exemplary geometric models are presented in Fig. 4.

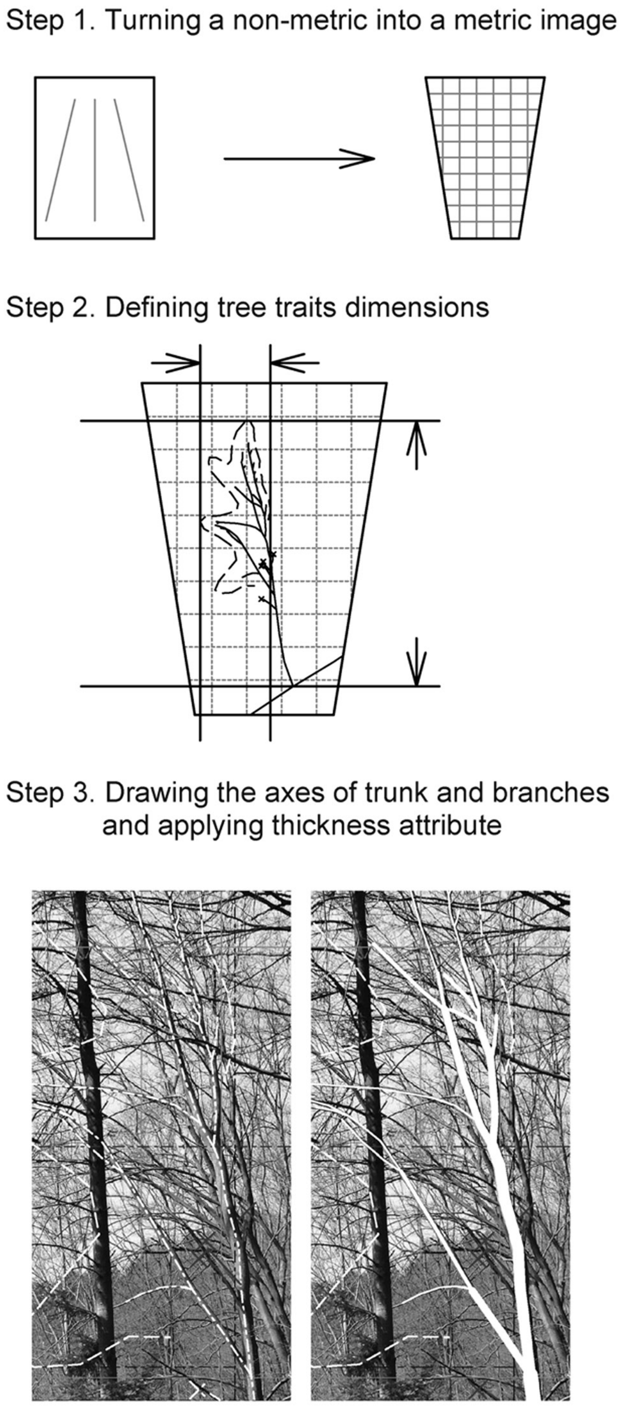

Fig. 3. Scheme of laboratory work. For each step, the timing is: 1: ca. 10 (15) min; 2: ca. 10 (15) min; 3: ca. 20 (30) min

Measurement of the following parameters was performed: inclination of the tree main axis from the vertical (IA), height of the tree (H), diameter at breast height (DBH), crown width (CW) and crown radii in the lower and upper slope direction (respectively: CR1 and CR2), height to the first fork (height of the trunk, HT), crown length on both sides of the trunk (CL1, CL2), slope inclination (S) and estimation of the number of trees competing for light (N) within a circle of specified radius, e.g., 10 m from the target tree (tree density within the plot) (Fig. 5). On the basis of the traits and parameters, the following values can be calculated: crown width asymmetry ($CWA = CR_{max} – CW/2$, where CR_{max} is CR1 or CR2, whichever is greater), crown length asymmetry ($CLA = CL1/CL2$), crown slenderness ($CS = H/CW$), redundant coma and space, the total length of the trunk and branches (as a sum of digitized segments' lengths) within an individual tree (L), the number of segments per class of thickness per tree and the average segment length per class of thickness. It is

Fig. 4. Ten exemplary geometric models out of 31 created for testing the single image method. Data obtained from individual mature beech trees (*Fagus sylvatica* L.) in Ojców National Park, S Poland

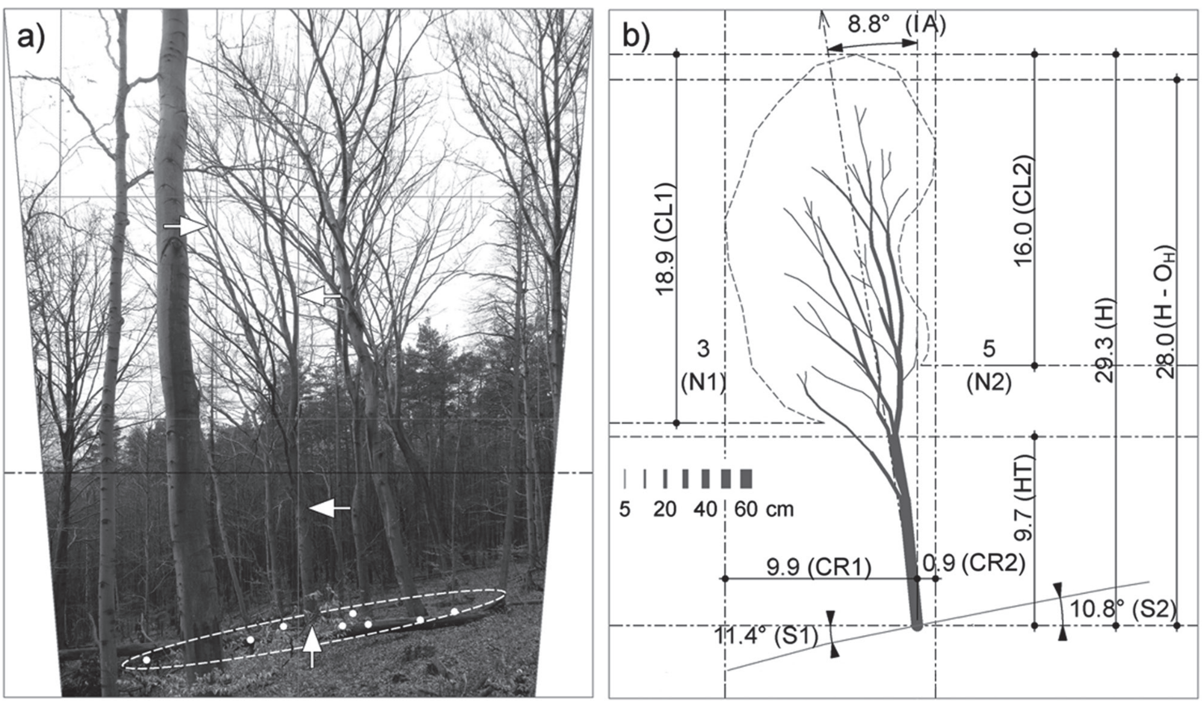

Fig. 5. The transformed image of a test tree, denoted by white arrows (a) and vector image with measurements (b). Measurement of the following parameters can be performed (lengths given in meters): deviation of the tree main axis from the vertical (IA), height of the tree (H), crown width (CW) and crown radius in the lower and upper slope direction (respectively: CW1 and CW2), height of the trunk (HT) and the length of the crown on the lower and upper sides of the slope (respectively: CL1, CL2), slope inclination (S) and the number of trees competing for light within a circle of specified radius (e.g., 10 m from the target tree; circle drawn by using a simplified terrain model, fitted in ArchiCAD) on the lower and upper side of the slope (respectively: N1, N2). Note that CL1 or CL2 + HT < H, that was the case for 22 out of 31 trees in our study, thus (H – (HT + CL)) could be seen as a separate trait

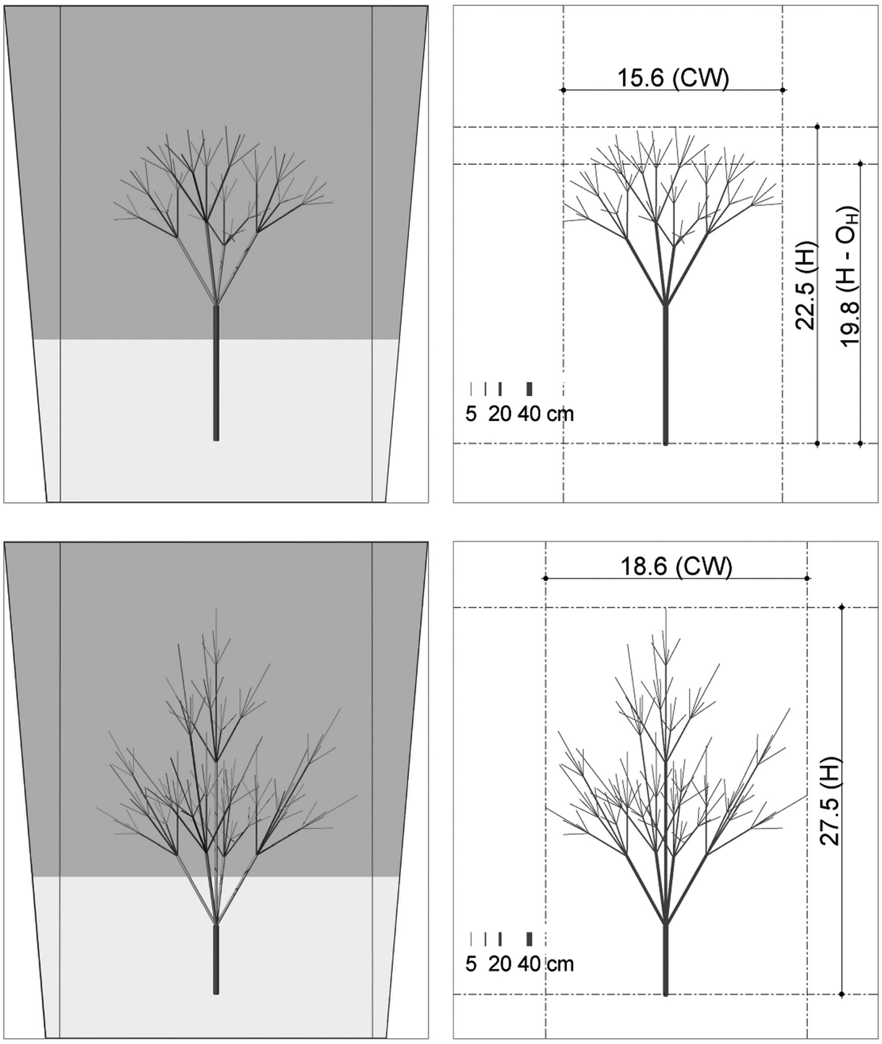

Fig. 6. Simple 3D tree-like models based on L-system rules: sympodial (top) and monopodial (bottom) models. Visualization (left) and vectorization with measurements (right)

also possible to determine the wood volume within a class of thickness (V) (as the product of the length of the segment and the area of a circle with a specified diameter). Additionally, we analysed the correlations between selected parameters and tree size denoted by its DBH; we used Spearman's rank correlation to determine the strength and direction of monotonic relationships (both linear and non-linear). To our knowledge branch length is rarely included in allometric analyses due to lack of such data; the computations were done with R v. 3.2.3 (2016).

Accuracy

The accuracy assessment aimed in defining the change in measurement error with growing distance between the measured part of the tree and the plane α. For that purpose, we used virtual tree-like 3D models, of contrasting forms (simple monopodial and sympodial models, Fig. 6), generated with L-system rules, with known dimensions. The software used was 'L-System 5', written by Timothy C. Perz; and ArchiCAD (https://myarchicad.com/), which enables 3-D modelling and image simulation. The measured values were established by using computer simulated images, taken with specified virtual camera parameters (distance to the object was 25 m, the camera angle was 10°, and the viewing angle was equal to the digital camera's we used. We also conducted an analysis of the sensitivity of the method to changes of camera distance (for the settings: 20 and 30 m) and angle (for the settings: 10, 20 and 30°), based on the measurements of selected traits (H, CW, and length of 10 cm thick branches: $L_{(0.10)}$) and the models (Fig. 6).

Results

Our method yielded an overall view of the whole tree structure (Fig. 4, 5), extracted from the background by the means of manual digitisation. The values of the traits described in previous section were derived automatically from the geometric model (Table 1). Among the size-dependent characteristics, total length of trunk and branches was the most DBH-correlated trait. The analysis showed that the strength of the correlation decreased gradually with decreasing branch thickness, and it became not significant at the level of 30 cm thick branches. Consequently, similar results were found for total wood volume (V), as a function of branch or trunk length and the class of thickness. Crown width was much more size-dependent than height of the tree or crown length. Smaller trees had more slender crowns than the bigger ones, as indicated by the negative and significant correlation with DBH. The results confirm that DBH have a large impact on the crown architecture and biomass (Bartelink, 1997; Skovsgaard & Nord-Larsen, 2012). The most interesting and closest relationship, between DBH and branch length, may be seen as a supporting observation for the high importance of water transport distance, in the context of hydraulic architecture of trees and the pipe model theory (Tyree & Ewers, 1991).

In terms of idealized (virtual) conditions, we estimated the relative error of the measurement of H, CW and the length of the trunk and branches (L) (Fig. 7, Tab. 2). In general, the accuracy decreased with the growing distance of the measured objects to the projection plane α. In the case of H measurement (monopodial model) and CW (monopodial and sympodial models), the relative error was less than 1%, which corresponds well with the results of Tommaselli & Reiss (2005) obtained for 2-dimentional objects. The measured distances were contained in

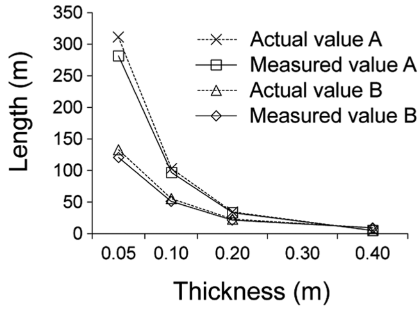

Fig. 7. Comparison of the measured and actual length for different thickness of trunk and branches. A: monopodial model, B: sympodial model

Table 2. Measured values (with the presented method), actual (known) values and the relative percent errors for selected traits of the tree-like virtual 3D models presented in Figure 7: length of trunk and branches with thickness of 0.40, 0.20, 0.10 and 0.05 m (L), overall height (H) and crown width (CW)

Trait	Measured value (m)	Actual value (m)	Relative error
A. Monopodial model			
$L_{(0.40)}$	4.78	4.80	–0.4%
$L_{(0.20)}$	33.29	34.56	–3.7%
$L_{(0.10)}$	97.05	103.68	–6.4%
$L_{(0.05)}$	281.00	311.10	–9.7%
H	27.46	27.38	0.3%
CW	18.57	18.49	0.4%
B. Sympodial model			
$L_{(0.40)}$	9.62	9.60	0.2%
$L_{(0.20)}$	21.83	23.04	–5.3%
$L_{(0.10)}$	50.82	55.30	–8.1%
$L_{(0.05)}$	120.75	132.74	–9.0%
H	22.47	19.80	13.5%
CW	15.58	15.50	0.5%

Table 1. Summary of the measured architectural traits: minimal, maximal and mean values, standard deviations and Spearman's rank correlations for diameter at breast height (DBH corr.); in case the correlations were significant at the level of 0.05 the p-values were shown. Data obtained from individual mature beech trees in Ojców National Park, S Poland

Abbreviation*	Unit	Min.	Max.	Mean	SD	DBH corr.	p-value
DBH	cm	30.0	96.0	54.1	17.1		
H	m	20.1	36.2	28.7	4.2	0.434	1.46E-02
CW	m	5.2	19.2	11.0	3.6	0.745	1.56E-06
CL	m	4.4	23.7	14.5	4.7	0.488	5.30E-03
HT	m	1.0	24.1	10.7	6.2	–	–
IA	°	–3.1	18.0	5.1	4.8	–	–
L	m	44.5	238.5	118.2	50.6	0.905	2.79E-12
L(0.05)	m	11.4	133.2	64.5	32.6	0.811	3.08E-08
L(0.10)	m	7.1	45.4	20.1	10.3	0.806	4.32E-08
L(0.20)	m	3.1	34.7	14.8	8.6	0.436	1.43E-02
L(0.30)	m	1.9	28.3	9.8	6.9	–	–
V	m^3	0.8	11.6	3.3	2.2	0.864	3.76E-10
CWA	m	0.1	9.1	2.8	2.1	–	–
CLA	–	0.7	2.5	1.3	0.4	–	–
CS	–	1.6	5.5	2.9	0.9	–0.568	8.68E-04

*DBH – diameter at breast height, H – height of the tree, CW – crown width, CL – crown length, HT – height of the trunk, IA – inclination angle, L – total length of the trunk and branches, L(0.05–0.30) length of trunk and branches in the classes of thickness: 5–10, 10–15, 15–20 and 20–30 (cm), V – wood volume (a function of L and the classes of thickness: 5–30 cm), CWA – crown width asymmetry, CLA – crown length asymmetry, CS – crown slenderness (= H/CW).

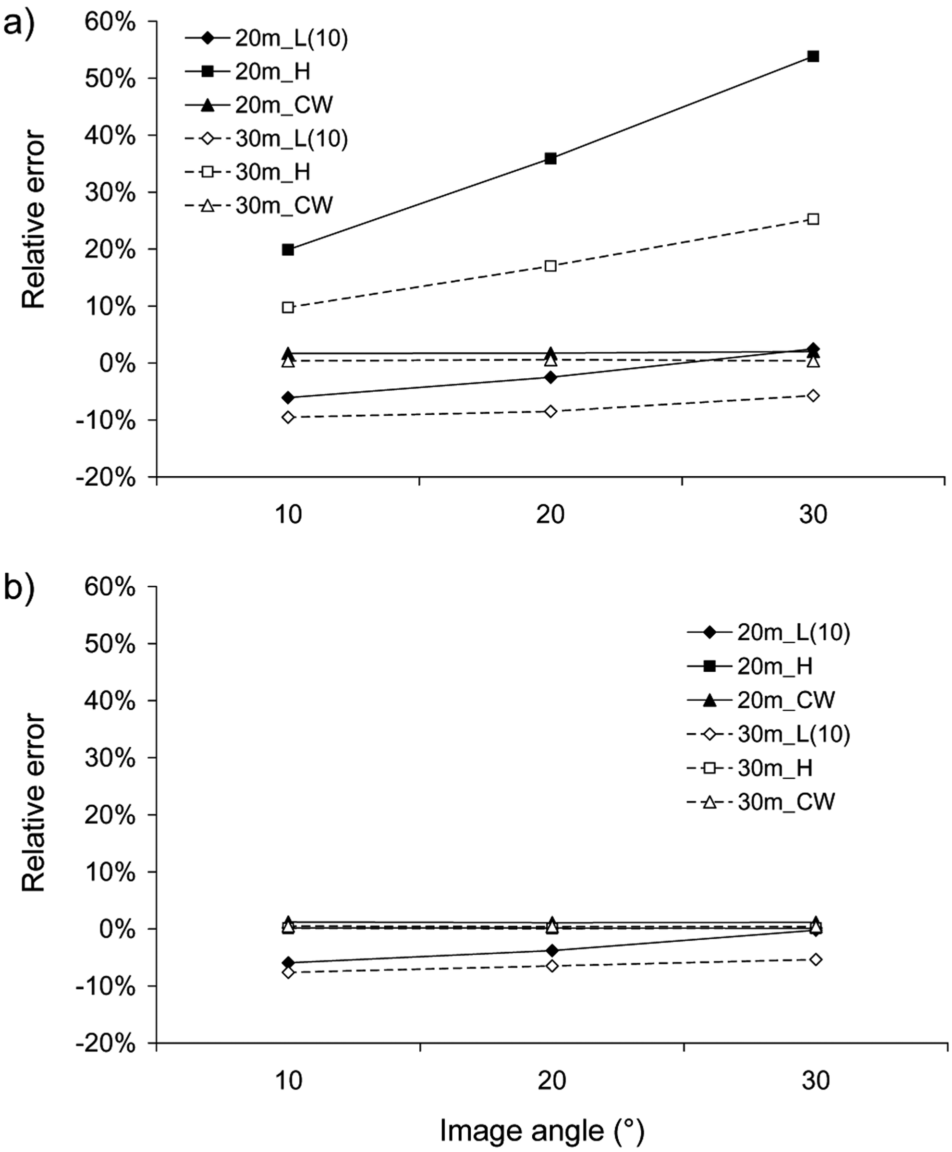

Fig. 8. A sensitivity analysis of the method to changes of camera distance and angle. The analysis is based on the measurements of selected traits (H, CW and $L_{(0.10)}$) and uses the sympodial (a) and monopodial (b) models presented in Fig. 6

or were very close to the plane α. This was different for the H of a sympodial model (error = +13.5%), as the top was occluded by the edge of the crown. The corresponding type of error may concern tree height measurement with a tangent method (Larjavaara & Muller-Landau, 2013).

For the L measurement, the smallest error obtained was for the vertical trunks, close to plane α (between –0.4% and +0.2%), and the largest was for the thinnest (and farthest from plane α) branches (between –9.7% and –9.0%). The error of the same type refers to all trees being measured with this method, and L can also be considered as a relevant comparative index.

The sensitivity analysis (Fig. 8) showed that the method was most stable in the case of CW measurement for both models. It was also stable for H measurement in the case of the monopodial model (while the top was well visible in the image and contained in the plane α). The highest and most changeable relative error was for the H measurement of the sympodial model (four highest points, not contained in the plane α). The measurement of $L_{(0.10)}$ was sensitive to both camera distance and angle, the measured value increased with decreasing image distance and increasing angle; in the studied range of parameters, this led to a decrease in the relative error (in case of the sympodial model: from –9.5% to +2.5%). However, setting the image angle to positions above 30° and image distance below 20 m may lead to large increase in the measurement error. The method's accuracy is also sensitive to the image resolution, we advise not to go under the resolution used in our study (i.e., 3672 × 4896 pixels), which gave the output pixel size ranging from 1 to 4 cm^2 for pictures taken from a distance of 20 and 35 m, respectively (in case of the former, we could not measure with better accuracy than 1 cm, and for the latter: 2 cm).

Discussion

The main advantage of the proposed photogrammetric method is the ability to measure the branching system of large, leafless individual trees growing in a dense forest without the necessity of using a background screen. The application of the method resulted in the correct representation of angles and distances between elements contained in the analysed plane α (Fig. 2) (error less than 1%), with gradually decreasing accuracy along the growing distance between the plane α and the measured part of the target tree (error up to ca. 10%, as shown by the tests with the virtual trees (Fig. 6)). The results seem promising, e.g., comparing to Tree Analyser tested by Delagrange and Rochon (2011), where the error of measurement for the crown diameter was between 17% and 10%, depending on the voxel size (7 cm or 3 cm, respectively). We predict that the error of our method can be larger or different in the case of real tree measurements (e.g., because of occlusion by neighbours and irregular tree shape); therefore, further calibration is needed; based on trees growing in managed forest, which were previously designated for harvesting; or using a remote-sensing method which was fully calibrated; this opens a new field for future research.

Limitations of the method are mainly related to the specific quality of images used and the desired accuracy of the measurements. Another limiting factor could be the level of occlusion or self-occlusion of the analysed branching systems. In the case of very dense stands, tracing the axes of the trunk and branches can be difficult and lead to omitting some (mainly thinner) branches when digitizing. The varying terrain slope (which considerably affected the visibility of the neighbouring trees' position) was a limitation for the estimation of N, therefore it was a concept that could not be fully implemented in our pilot study; it may be more useful in case of flat terrain, e.g., in the lowland forests. In such conditions, the circle that represents the plot could be easily fitted by using an analogous method (reference image).

Our results show that the sensitivity of the method to changes of camera distance and angle varies with particular traits: being lowest for the CW measurement and highest for the H of the sympodial model. Consequently, it is best to keep a specified camera distance and angle during a single study, and in the case of the need for a change of image parameters, some additional calibrations may be necessary to obtain uniform accuracy. Here, we proposed to choose wide viewing angle camera to capture large trees from relatively small distance, however, in case of narrow viewing angles the range of accuracy could be much smaller (e.g., applicable when only a part of the tree or a small tree would be analysed).

The method is estimated to take ca. 15 minutes of fieldwork and 1 hour of preparation work for one tree, without including the analysis of the obtained data. It is difficult to compare the timing with other methods because the architectural traits measured are different. However, the described method seems very quick compared to previous studies. For example, in the case of the photographical method for analysing the radiation interception by an individual tree (Van Elsacker et al., 1983), the fieldwork lasted for approximately half a day for one tree. In the case of the ground monitoring of light-shadow windows of a tree canopy for yielding canopy light interception and morphological traits (Giuliani et al., 2000), the images have to be taken several times a day.

Single image photogrammetry may have a broader use both in protected areas and managed forests by providing a wide range of information, useful in taking management decisions. Particularly, the method: (1) could be included in works related to forest inventory and determining the qualitative characteristics of trees in managed forests (like the quality of the trunk, vitality and the proportions of the crown); (2) may be useful in describing the architecture of coniferous trees (e.g., solitary trees or growing in low-density stands); (3) may be helpful in determining the mechanical stability of trees, especially important in such areas as roadsides and trails; (4) may serve as a planning tool, in the case of historic parks and alleys and city green areas; (5) may be used to analyse trees of varying size and even branches, as soon as the photos are taken in the appropriated conditions. The collected material, in the form of images, contains much more information than those mentioned here, and may be useful for further research purposes, as a record of the current state of an individual or a stand. Pictures with certain parameters could be repeated in the future, providing comparative data for determining the changes within and among stands, in the forest canopy and in the individual tree itself.

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Author contributions

AG and KK were involved in the conceptual work. KK conducted the fieldwork, developed the method for tree architecture description and performed analysis. AG and KK contributed to writing the final manuscript.

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