



## TERRESTRIAL LASER SCANNING IN INVENTORY CONTROL OF WILDLIFE IN A MUNICIPAL PARK IN WROCŁAW

Eryk Klemiński, Damian Kasza

### Summary

The article presents the results of an experiment related to wildlife inventory control with the use of data from terrestrial laser scanning. The measurements were performed with the terrestrial laser scanning system – Riegl VZ-400i. The study area was the Obrońców Westerplatte square in Wrocław. The collected measurement data were pre-processed in a commercial – dedicated RiSCAN Pro environment. Operations related to point cloud georeferencing and its filtering were performed. The tree parameters were measured on the basis of a cloud point obtained in field surveys. This operation was performed with the use of the 3D Forest software. The investigations covered the main parameters of the tree (height and diameter) along with additional parameters, such as the distance between two points of the tree located furthest apart, the surface area of the orthogonal projection of the tree on the reference surface (terrain surface) and the height of the tree crown above the terrain surface. As a result of the performed analyses, an inventory of 70 trees was made within the Obrońców Westerplatte square in Wrocław. Part of the experiment was also to prepare a 3D model of a tree by using some available modeling algorithms. This part was performed in Sequoia software - dedicated to such operations. The software offers three modeling algorithms: Zhu/Bridson, metaballs and union of spheres.

### Keywords

tree inventory • laser scanning • 3D modeling

### 1. Introduction

Tree measurements performed as part of wildlife inventory control are frequently problematic. This is true particularly in the case of measuring tree heights, which – if done with the use of classic methods – may not only prove physically difficult but also provide significantly inaccurate results. As a result, measuring a large number of trees over a large area is a very time- and labor-intensive task. For example, measurements of tree positions require the use of a GNSS receiver or a total station [Szostak and Wężyk 2013]. Tree thickness is typically measured with the use of specialist tools such as relascopes or diameter calipers. Tree thickness can be also measured with the use of

a diameter tape [Wężyk et al. 2015]. The most difficult task, however, is to measure the tree height. The diameter tape can be also used for this purpose, but extending it from the top of the tree to its base (ground level) is often dangerous or impossible. Although laser rangefinders are frequently used, it is difficult to point the beam precisely to the top of the tree. A total station can be used, but dense vegetation will necessitate frequent changes of the measurement stations, while the trigonometry-based methods are nearly never sufficiently precise [Dudkiewicz et al. 2015].

Laser scanning seems to be a solution to the majority of the above-mentioned problems related to tree parameter calculations. It also provides a number of other advantages, such as the possibility to construct 3D models of the measured trees. This study presents a methodology, survey results and an evaluation of the potential for using terrestrial laser scanning (TLS) in inventory control of municipal green spaces. The study area was the Obrońców Westerplatte square in Wrocław.

## 2. Materials and methods

The main assumption behind the described experiment was to develop an approach for an automatic measurement of tree parameters. The input data were obtained in the form of a TLS point cloud. The tree parameters were measured with the use of algorithms available in the 3D Forest open source application. An additional objective was to test selected available modeling algorithms in the development of a numerical 3D tree model.

### 2.1. Description of the study area

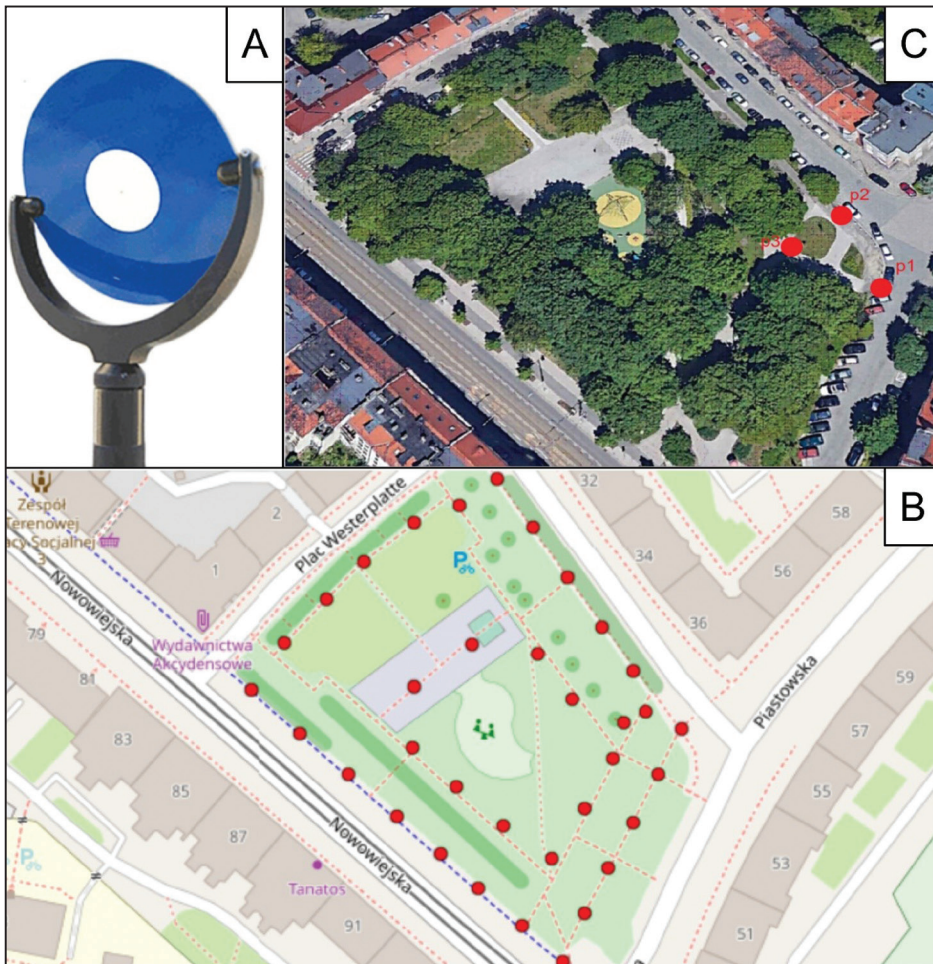
The wildlife inventory control was performed for an area covering the Obrońców Westerplatte Square in the central part of Wrocław. The square is located at the crossing of 4 streets: Nowowiejska, Piastowska, Waleczna and Westerplatte. The plot number is 38, and its area is 6882.00 m<sup>2</sup>. The earliest records and photographs documenting the square date back to the interwar period. At that time it was named Westerplatte Square. In the years 2015–2016 the square was extensively reconstructed, with newly built or rebuilt walking paths, lawns, benches and a new playground. The main reason for choosing this study area was the relatively moderate tree density in the square which was expected to facilitate the identification of individual trees.

### 2.2. Field measurements

The measurements were performed with the Riegl VZ-400i scanner. It is a pulse scanner and, along with the phase scanner, it is the most commonly used instrument in any types of measurements.

Prior to the field works, the measurement session was planned and the arrangement of the reference points was designed. The reference points served as locations for reflective survey targets (Fig. 1A), which allowed global referencing of the entire acquired data set (in the Polish PL 2000 system).

The arrangement of the scanner measuring stations was designed in such a manner that the scans allowed a possibly accurate coverage of the square area, and most importantly of the high plants in the square. For this reason, the optimal scanning procedure was decided to first follow a walking path around the square and subsequently a walking path located in the central part of the square (Fig. 1B). The locations for three reference survey targets were selected to ensure that all of the targets were visible from at least two measurement stations. The survey target locations (Fig. 1C) were first fixed with geodetic pins and subsequently measured with the use of a GNSS receiver in order to determine their coordinates (Table 1).



Source: Authors' own study

**Fig. 1.** View of one of the reference targets on the set survey control point (A); schematic view of the laser scanner locations (B); locations of the survey control points (C)

**Table 1.** Coordinates of the reference points in the PL2000 system

Point ID	X	Y	H
p1	5665160.117	6434321.266	116.140
p2	5665175.290	6434315.841	116.021
p3	5665169.822	6434304.644	116.532

### 3. Data processing

Raw data from the laser scanner were pre-processed in the dedicated RiSCAN Pro environment. This application allowed the scans obtained from all measurement stations to be combined into a single large point cloud (the so-called process of point cloud data registration). The scans were combined by following the so-called voxel approach. In effect, each point cloud was divided into voxels of a certain volume. A voxel is a cube of a finite volume, which contains the measured points. The edge length for a single voxel was set as in a typical urban area, i.e. 25 cm. The combining algorithm recorded the scans by comparing voxels from the adjacent stations. If for two subsequent stations an appropriate number of voxels covered the identical fragment of the surveyed space (and more specifically – the planes calculated from the points included in the voxels), the two scans were combined into one.

In the next processing stage, the data were adjusted and transformed into the external coordinate system. This was done with the use of the reference survey targets located in points having known coordinates. They served as a basis to fit the entire set of measured points into the external PL2000/18 coordinate system.

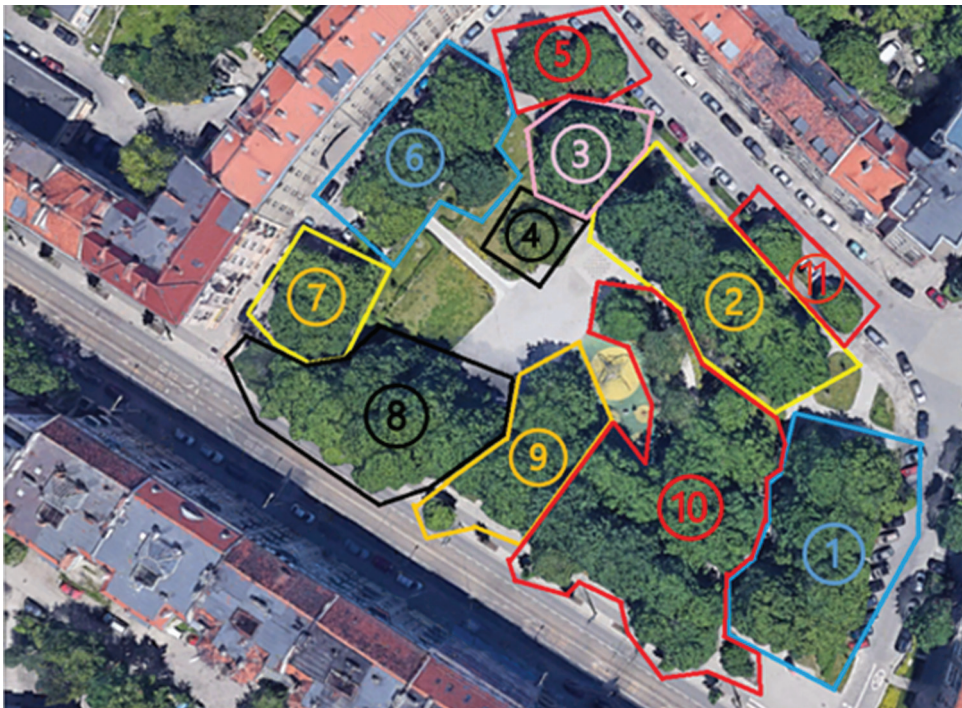
The tree parameters were calculated with the use of the 3D Forest software. The application is developed jointly at the Department of Forest Ecology of the Silva Tarouca Research Institute and the Department of Geoinformation Technologies, Mendel University in Brno, and serves to analyze TLS data.

In the first step, the point cloud needed to be imported into the 3D Forest application. However, the \*.las file exported from RiSCAN Pro (the data set comprising ~500 million points was around 9 GB in size) was too large to be fully imported into 3D Forest. Therefore, the study area was divided into 10 smaller zones. The zones were outlined in such a manner that as many trees as possible fitted completely in one zone. Subsequently, all the thus cropped point clouds were exported. Each of the exported zones was imported separately (into separate projects) into 3D Forest as a base point cloud.

In the next step, the points representing the ground surface were separated. This step was performed with the use of the *Terrain from octree* function. It divides the base point cloud into cubes. The cubes with the lowest values of the Z coordinate are identified as the 'terrain cubes'. The calculations required a certain distribution of cubes (the selected value was 5 cm). As a result, two data sets were obtained: a point cloud of the

terrain (comprising points classified as the ground) and a point cloud of the vegetation (comprising all the remaining points not classified as the ground). In the subsequent step, the improperly classified points were removed from the terrain cloud point. Most typically, above ten or a few tens of such misclassified points needed to be removed manually. The last step before the calculations was to manually identify individual trees in the vegetation point cloud. This was the most time-consuming step, as the cutting of individual points belonging to different trees required considerable precision. The tree parameters were calculated separately for each zone. The following attributes were calculated for each tree:

- tree position,
- height,
- length,
- diameter at the height of 1.3 m,
- surface area of the convex hull of the orthogonal projection of the tree,
- crown height,
- height of the lowest crown point.

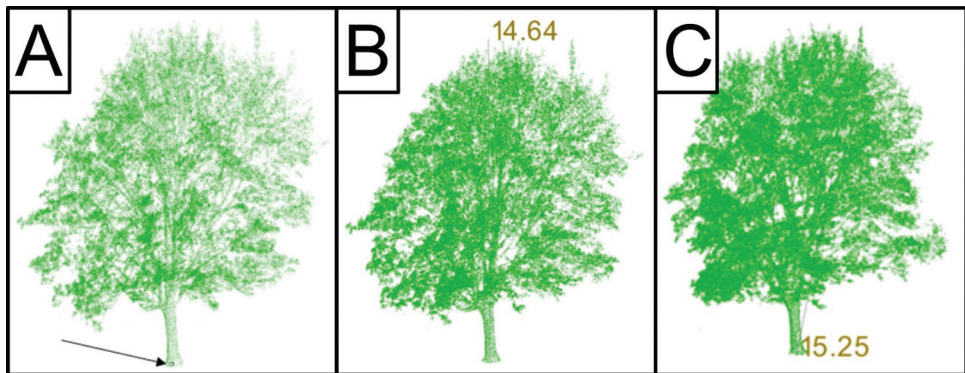


Source: Authors' own study

Fig. 2. Study area divided into zones

### 3.1. Tree position

The position of the tree is represented by the coordinates ( $X, Y, Z$ ) of the tree position at the ground. This is the key parameter required in the calculations of other parameters. Without it, calculating any of the above-mentioned parameters would be impossible. The  $X$  and  $Y$  coordinates are identified as the middle values of the coordinates from the set comprising the coordinates of all the points located between the lowest point of the tree and the height defined by the user. The points selected in the calculations were located 60 cm from the lowest point of the tree. The  $Z$  coordinate is calculated as a median of the  $Z$  coordinate from five closest terrain points. The tree position is represented in the application as a sphere with the center located in the calculated position and with a radius of 5 cm (Fig. 3A).



Source: Authors' own study

Fig. 3. Effect of calculating the position (A), height (B) and length (C) of the tree

### 3.2. Tree height

The tree height is calculated as the difference between the coordinate  $Z$  of the highest point from the cloud representing the tree and the coordinate  $Z$  of the tree position. The height is displayed in meters on the top of the tree, at the line drawn perpendicularly from the sphere (representing the tree position) towards the top of the tree, to its highest point (Fig. 3B).

### 3.3. Tree length

The length of the tree is calculated as an Euclidean distance between the points located furthest from each other. This distance is displayed at the terrain and represented by a line connecting the two points.

### 3.4. Tree diameter at 1.3 m

The diameter of the tree is calculated with the use of the Randomized Hough Transform (RHT). First, the heights of a set of points from 1.25 m to 1.35 m are transformed into the height of 1.30 m. In the next step, the method consists in searching for the center of each possible circle comprising at least two transformed points. The center of the circle that is most frequently repeated, i.e. comprises the greatest number of points is identified as the correct final result (Fig. 4A). The diameter is calculated from the following equation:

$$r^2 = (x - a)^2 + (y - b)^2 \quad (1)$$

where:

- $x, y$  – coordinates of the point on the circle,
- $a, b$  – coordinates of the center of the circle.

When calculating the diameter, the number of calculation iterations should be specified in the dialog box. The greater the number of iterations, the more precise the result, but the calculations will be more time-consuming and will require more computational power. The minimum number of iterations in calculating the diameter is 200. After several tests with different numbers of iterations, it was decided that the optimal number of iterations for calculating the tree diameter is 1000. The diameter is represented as a 10 cm high cylinder on the tree trunk (Fig. 4B).

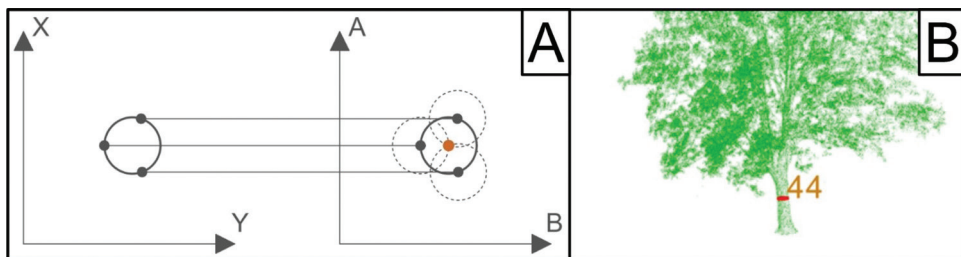
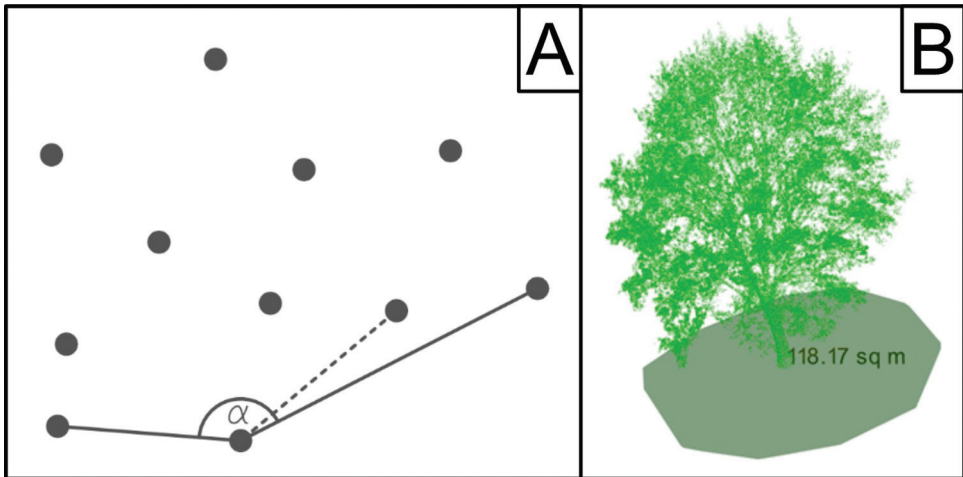


Fig. 4. Schematic diagram of the algorithm for identifying the center of the circle in calculations of the tree trunk diameter (A – Kral et al. 2018) and a representative result (B – Authors' own study)

### 3.5. Surface area of the convex hull of the orthogonal projection of the tree

The surface area of the orthogonal projection of the tree is calculated with the convex hull algorithm. In the first step, a point with the lowest value of the  $Y$  coordinate is found. This point is both the starting and the final point of the polygon. Subsequently, an angle  $\alpha$  between the vector  $(-1, -1)$  and the vector from the starting point towards each point from the cloud is calculated for each point in the point cloud of the tree. The point with the greatest angle  $\alpha$  is selected as the next point in the polygon. Subsequent

points are added to the polygon analogically, and only the  $(-1, -1)$  vector is substituted with the vector of the two last points of the polygon (Fig. 5A). The algorithm is repeated until the point with the greatest angle  $\alpha$  is again the starting point. A polygon constructed in such a manner has the largest possible surface area. The polygon is displayed at the height of the tree position together with the surface area expressed in  $\text{m}^2$  (Fig. 5B).



Source: Authors' own study

**Fig. 5.** Schematic diagram of the algorithm for calculating the convex hull (A) and a representative result (B)

### 3.6. Height of the tree crown and of the lowest crown point

The calculations related to the tree crown necessitated isolating a point cloud representing only the crown from the cloud point of the tree. Although the 3D Forest application allows an automatic detection of tree crowns, the function worked only in a limited number of cases. Therefore, it was decided to manually identify the tree crowns. The lowest point of the tree crown was set at the point in which branches and thick limbs with leaves start to grow from the trunk. The height of the crown is calculated analogically to the calculation of the total tree height, i.e. on the basis of the difference between the coordinate  $Z$  of the highest point of the crown and the coordinate  $Z$  of the lowest point of the crown (Fig. 6). The height of the lowest crown point is simply the height of the lowest point in the isolated crown cloud.





Source: Authors' own study

Fig. 6. Results of crown height calculations

#### 4. Results

A total number of 70 trees were laser scanned in the study area (Fig. 7). The following parameters were calculated for each of the trees: the position, the length, the diameter at 1.3 m, the surface area of the convex hull, the height of the tree crown and the height of its lowest point (Table 2). The results of the inventory control are presented separately for each zone (Fig. 2 Appendix A).



Source: Authors' own study

Fig. 7. Inventoried trees located in zone 1 (cf. Fig. 2)

Table 2. Tree parameters calculated for objects in zone 1

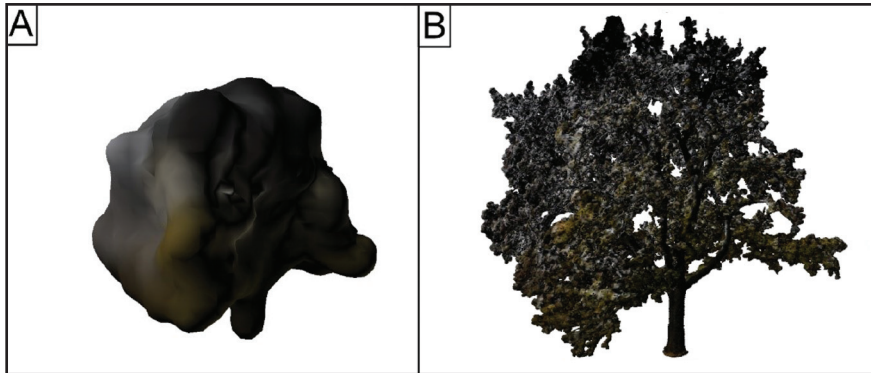
Tree	X	Y	Z	Number of points	Height [m]	Length [m]	Diameter [cm]	Surface area of the convex hull [m <sup>2</sup> ]	Height of the lowest crown point above ground [m]
1.1	362968.094	364371.563	114.556	478028	13.99	14.13	31.2	54.65	2.60
1.2	362971.656	364365.375	114.626	2608634	17.02	17.14	50.2	151.06	2.05
1.3	362974.219	364374.906	114.586	1333018	15.43	15.65	44.0	148.29	2.06
1.4	362982.750	364379.281	114.432	518661	13.91	13.96	31.2	67.84	2.69
1.5	362990.063	364383.281	114.430	1770234	14.28	15.27	31.8	142.32	2.37
1.6	362992.813	364377.375	114.565	4359925	15.68	15.80	50.2	150.46	1.50
1.7	362985.594	364373.344	114.667	1080853	13.96	14.06	39.4	71.07	2.07
1.8	362977.125	364368.531	114.727	113368	7.73	7.93	15.4	15.70	2.05

The last step of the experiment was to model a selected tree. The tree selected for this purpose was tree 2.5 (Appendix A) growing in the area in which the last scan was performed. More than 6 million points were surveyed on the surface of the tree. The modeling was performed in Sequoia, which is an application dedicated to such operations. The software offers three modeling algorithms: Zhu/Bridson, metaballs and union of spheres.

The default method set in Sequoia is the Zhu/Bridson method [Häger 2022]. The dialog window allows defining the radius value, which will be isolated from each point within the modeled cloud. The user can define this radius manually, depending on the particular needs, or can use an optimal radius generated by the application for the particular point cloud. The modeling process was performed with the default radius of 1 m and with a radius of 4.4 cm suggested by the application. The remaining general modeling parameters, such as the resolution and the resolution mode, were not modified. Other not modified default parameters dedicated to this modeling method included: the radius connection scale (responsible for connecting the spaces between the nearest points), the threshold value (defines the value below which the cloud will be cut) and the strength value (defining the strength of the cutting effect). Figure 8A shows the model with the default radius, and Fig. 8B shows the model with the radius suggested by the application.

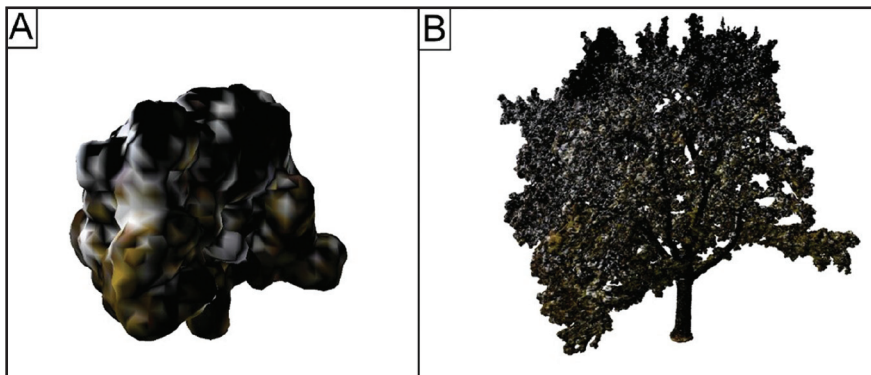
The metaballs method employs the classic blobmesh algorithm. The model constructed with the use of this algorithm consists of a set of balls which can connect to each other forming very smooth blended spherical objects [Kommareddy et al. 2014]. When using this modeling algorithm, it was necessary to define the geometrical radius as well as the scale of the radius value and the value of the surface level. The scale of the radius value is defined by the influence of the radiuses on each point, and the value of the surface level

affects the distance between the grid and the points – the greater the value the closer the grid. As in the case of the previous algorithm, two values of the geometric radius were used: the default value of 1 m and the suggested value of 4.4 cm. The default scale of the radius value and the default value of the surface level were not modified. Figure 9 shows the model constructed with the use of the metaballs algorithm.



Source: Authors' own study

**Fig. 8.** Tree model constructed with the use of the Zhu/Bridson algorithm with the radius of 1 m (A) and with the radius of 4.4 cm (B)

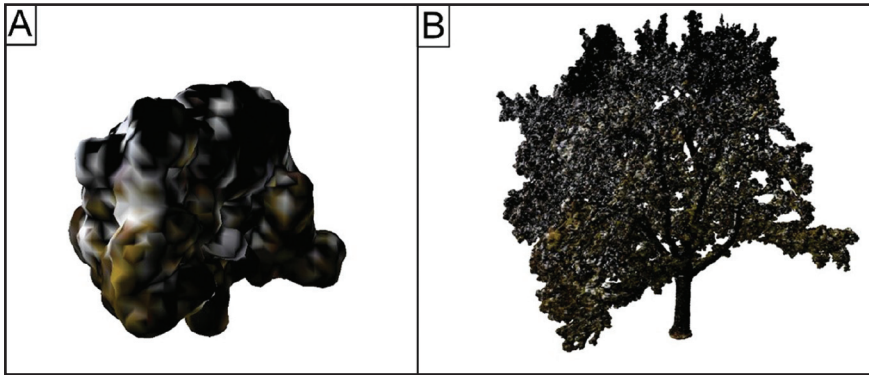


Source: Authors' own study

**Fig. 9.** Tree model constructed with the use of the metaballs algorithm with the radius of 1 m (A) and with the radius of 4.4 cm (B)

In the union of spheres method [Ranjan and Fournier 1996], each point is treated as a small sphere with a defined radius, and the model is a combination of all spheres without any control through the isosurface and without blending the spheres. Except

for the geometric radius, the algorithm does not offer an option to modify any modeling parameters. As in the previous cases, the geometric radius was set to the default value of 1 m and to the suggested value of 4.4 cm. Figure 10 shows the model constructed with the union of spheres method.



Source: Authors' own study

Fig. 10. Tree model constructed with the use of the union of spheres algorithm with the radius of 1 m (A) and with the radius of 4.4 cm (B)

Visual evaluation of the 3D modeling results using the three algorithms described above provided almost identical impressions. Elements of the trunk and branches, as well as foliage, have been recreated clearly and unambiguously. Also, the analysis of the number of triangles did not bring a clear conclusion (in all cases it was ~350,000 triangles). The only noticeable difference between the algorithms was in the execution of the modeling process itself. For the Zhu/Bridson algorithm, it was about 6 minutes, and for the metaballs and the union of spheres, about 7.5 minutes and 10 minutes, respectively.

## 5. Conclusions

A point cloud resulting from terrestrial scanning is a very good base for performing tasks related to numerical inventory control and tree modeling. The in-situ measurement performed with the Riegl Vz-400i was uncomplicated and relatively short (the transfer, the setting and the operation of the scanner in a new position required approximately 3 minutes). The most time- and labor-consuming operation was to process the results. In order to determine all of the required tree parameters in the 3D Forest application, the point cloud needed to be precisely filtered or even, in the case of large areas, divided into zones which were calculated separately.

Based on the described experience, it can be concluded that the presented methodology allows for undoubtedly faster and more precise determination of the tree

parameters in question compared to the traditional dendrological inventory. It is also worth noting that scanning the surveyed area allows us to literally archive the inventory area at a given moment (on the day of field measurements). Thus, it allows for carrying out any measurements/analyses at any time. Unfortunately, in addition to the undoubted advantages, this methodology has its weaknesses. Three-dimensional representation of reality in the form of a point cloud is unfortunately of little or no use in the situation when it comes to examining the health status of inventoried trees/plants. It is true that it is possible to identify e.g. dead trees, but the recognition of other diseases or the presence of pests is actually impossible [Dusza-Zwolinska and Dembowska 2018].

After each of the trees had been isolated, their parameters could be calculated. The position of the tree was the first parameter, without which no other parameters could be calculated. The calculation of the tree position, as well as of the tree height and diameter, is performed automatically, and the calculation speed depends on the available computing power. However, the application was unable to calculate the diameter of a coniferous tree located in the square, because a tree limb at the 1.3 m height was hidden in a low crown. The diameter could be neither calculated in the case of a tree whose main limb divided into two limbs at the height below 1.3 m. In this case, the calculations needed to be performed for the two limbs growing from the main limb.

The experiment allowed the identification of 70 trees located within the square. The positions of all of the trees were defined in the PL2000 coordinate system.

The experiment demonstrated that the algorithms available in the application may not always automatically handle data sets resulting from terrestrial laser scanning. In such cases, manual intervention of the operator was necessary. Coniferous trees seem to be the main problem, as the algorithms proved least effective in their case.

## Appendix A

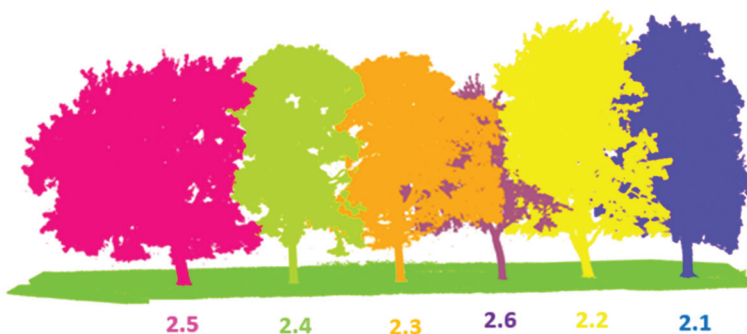


Fig. 1. Inventoried trees located in zone 2 (cf. Fig. 2)

Table 1. Tree parameters calculated for objects in zone 2

Tree	X	Y	Z	Number of points	Height [m]	Length [m]	Diameter [cm]	Surface area of the convex hull [m <sup>2</sup> ]	Height of the lowest crown point above ground [m]
2.1	363041.906	364354.625	114.479	3394915	17.47	17.77	53.6	175.52	1.47
2.2	363036.000	364358.500	114.450	2608207	17.82	17.91	53.6	141.34	2.16
2.6	363031.281	364361.875	114.412	1100642	13.58	14.8	40.0	110.99	2.39
2.3	363025.563	364365.969	114.412	2369554	15.03	15.64	44.0	161.77	1.62
2.4	363019.906	364370.000	114.397	2126076	15.40	15.48	40.0	133.61	1.45
2.5	363014.375	364373.875	114.448	6003049	15.05	18.95	62.4	217.40	0.69



Fig. 2. Inventoried trees located in zone 3 and 4 (cf. Fig. 2)

Table 2. Tree parameters calculated for objects in zones 3 and 4

Tree	X	Y	Z	Number of points	Height [m]	Length [m]	Diameter [cm]	Surface area of the convex hull [m <sup>2</sup> ]	Height of the lowest crown point above ground [m]
3	363051.938	364347.469	114.576	4337034	18.64	21.28	75.4	239.95	1.24
4	363043.031	364336.844	114.465	3167376	13.45	15.00	50.2	176.71	0.99



Fig. 3. Inventoried trees located in zone 5 (cf. Fig. 2)

Table 3. Tree parameters calculated for objects in zone 5

Tree	X	Y	Z	Number of points	Height [m]	Length [m]	Diameter [cm]	Surface area of the convex hull [m <sup>2</sup> ]	Height of the lowest crown point above ground [m]
5.1	363069.719	364342.031	114.248	1622754	14.64	15.25	40.0	118.17	1.50
5.2	363069.469	364351.313	113.825	3024597	9.05	10.94	31.2	96.07	1.54

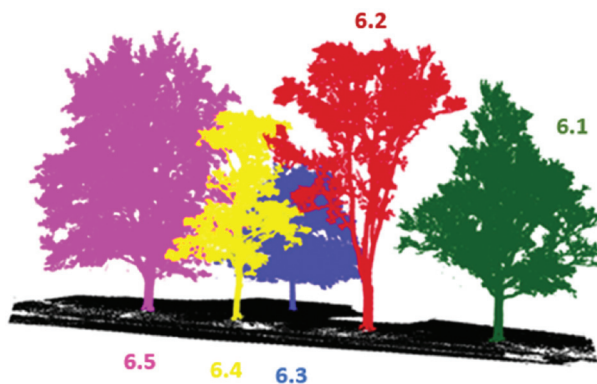


Fig. 4. Inventoried trees located in zone 6 (cf. Fig. 2)

Table 4. Tree parameters calculated for objects in zone 6

Tree	X	Y	Z	Number of points	Height [m]	Length [m]	Diameter [cm]	Surface area of the convex hull [m <sup>2</sup> ]	Height of the lowest crown point above ground [m]
6.1	363051.188	364310.688	114.453	1000984	15.55	16.61	50.0	134.86	2.16
6.2	363056.344	364316.406	114.447	541156	17.46	17.89	50.0	100.54	3.12
6.3	363053.844	364326.531	114.455	1450490	10.87	11.17	31.2	96.62	1.43
6.4	363061.750	364322.469	114.364	420317	12.89	13.24	25.6	64.58	2.57
6.5	363065.094	364327.188	114.447	1703958	17.22	17.37	45.0	158.45	1.47



Fig. 5. Inventoried trees located in zone 7 (cf. Fig. 2)

Table 5. Tree parameters calculated for objects in zone 7

Tree	X	Y	Z	Number of points	Height [m]	Length [m]	Diameter [cm]	Surface area of the convex hull [m <sup>2</sup> ]	Height of the lowest crown point above ground [m]
7.1	363036.000	364294.688	114.606	1660341	14.85	17.65	44.0	166.53	2.88
7.2	363040.844	364299.438	114.600	1173805	15.27	15.58	50.0	124.13	2.47



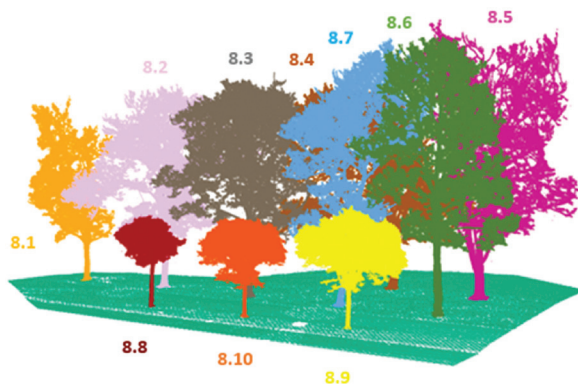


Fig. 6. Inventoried trees located in zone 8 (cf. Fig. 2)

Table 6. Tree parameters calculated for objects in zone 8

Tree	X	Y	Z	Number of points	Height [m]	Length [m]	Diameter [cm]	Surface area of the convex hull [m <sup>2</sup> ]	Height of the lowest crown point above ground [m]
8.1	363026.719	364285.906	114.562	387840	13.58	13.77	31.8	49.94	2.36
8.2	363022.156	364291.031	114.604	922903	14.51	15.51	39.4	112.51	2.46
8.3	363017.250	364296.406	114.589	832903	15.34	15.69	40.0	100.69	2.31
8.4	363017.438	364306.750	114.860	1375481	14.56	16.73	50.2	163.23	1.37
8.5	363012.969	364311.531	114.775	1233511	18.77	19.09	53.6	146.66	2.38
8.6	363007.563	364306.719	114.698	875597	17.49	19.09	31.2	65.06	3.51
8.7	363012.438	364301.500	114.541	525396	17.58	17.89	31.8	70.15	4.19
8.8	363015.813	364289.563	114.324	257780	6.11	6.19	19.6	17.64	2.59
8.9	363006.031	364300.375	114.354	525103	7.38	7.61	20.4	32.60	2.12
8.10	363010.969	364294.938	114.352	437558	6.24	6.3	20.0	26.65	1.83

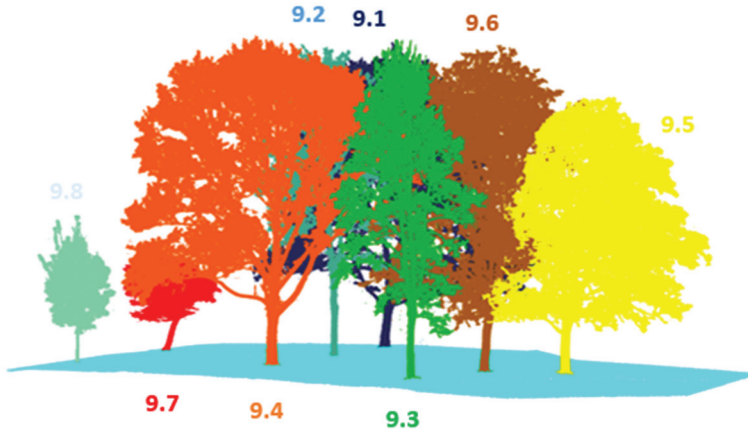


Fig. 7. Inventoried trees located in zone 9 (cf. Fig. 2)

Table 7. Tree parameters calculated for objects in zone 9

Tree	X	Y	Z	Number of points	Height [m]	Length [m]	Diameter [cm]	Surface area of the convex hull [m <sup>2</sup> ]	Height of the lowest crown point above ground [m]
9.1	363008.438	364316.594	114.756	1805644	18.44	18.59	40.0	149.32	4.00
9.2	363004.219	364321.250	114.693	681688	17.76	17.93	31.2	64.25	1.01
9.3	363004.625	364334.781	114.720	533476	16.64	16.68	25.6	52.87	1.70
9.4	362999.656	364325.844	114.761	2070453	17.69	17.84	50.2	173.04	2.55
9.5	363012.813	364334.563	114.793	1521803	13.75	14.00	31.2	116.23	1.72
9.6	363009.094	364332.844	114.778	1297252	16.38	16.52	31.8	128.20	1.81
9.7	362996.250	364311.125	114.369	566975	5.98	6.47	25.6	27.58	1.71
9.8	362990.156	364317.469	114.304	490171	8.46	8.49	22.2	22.64	1.58

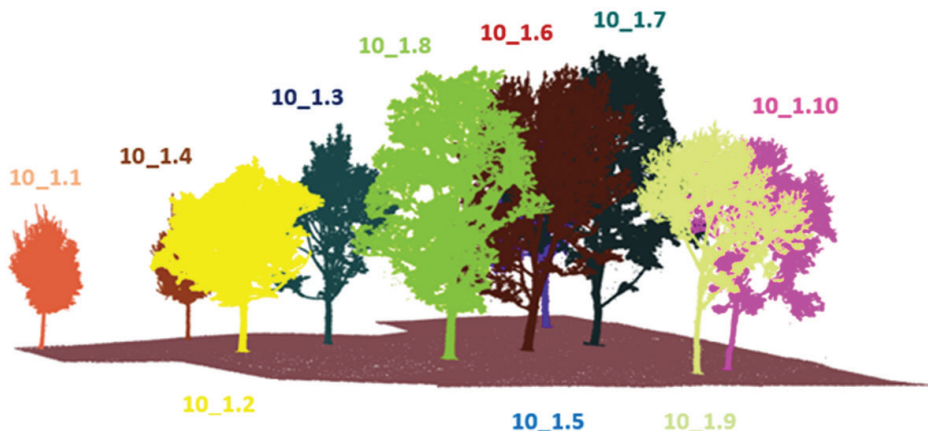


Fig. 8. Inventoried trees located in zone 10, part 1 (cf. Fig. 2)

Table 8. Tree parameters calculated for objects in zone 10, part 1

Tree	X	Y	Z	Number of points	Height [m]	Length [m]	Diameter [cm]	Surface area of the convex hull [m <sup>2</sup> ]	Height of the lowest crown point above ground [m]
10_1.1	362957.563	364352.813	114.394	355365	7.82	7.88	21.0	12.66	1.86
10_1.2	362968.031	364349.906	114.620	1243864	10.90	11.05	31.2	81.34	2.31
10_1.3	362972.500	364344.938	114.607	432923	12.94	13.01	25.6	44.26	2.39
10_1.4	362964.375	364345.500	114.334	295428	8.42	8.58	21.6	15.25	1.99
10_1.5	362986.281	364330.063	114.594	559095	13.43	13.6	31.2	49.59	3.29
10_1.6	362984.406	364342.594	114.752	1264510	17.40	17.49	45.4	104.90	2.24
10_1.7	362988.906	364337.375	114.595	2058782	18.69	18.81	39.4	124.32	2.40
10_1.8	362979.656	364347.688	114.673	1529464	16.85	16.87	44.0	114.05	2.61
10_1.9	362994.031	364346.625	114.751	516494	14.78	14.84	25.6	62.02	3.66
10_1.10	362996.281	364344.188	114.751	618676	13.96	14.08	25.6	59.68	2.86

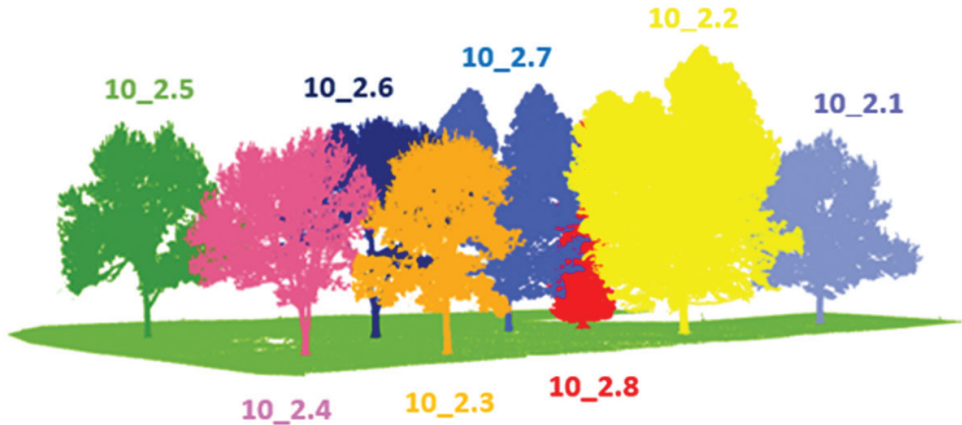


Fig. 9. Inventoried trees located in zone 10, part 2 (cf. Fig. 2)

Table 9. Tree parameters calculated for objects in zone 10, part 2

Tree	X	Y	Z	Number of points	Height [m]	Length [m]	Diameter [cm]	Surface area of the convex hull [m <sup>2</sup> ]	Height of the lowest crown point above ground [m]
10_2.1	363024.813	364348.344	114.652	1133057	11.40	11.46	31.2	81.87	1.33
10_2.2	363017.781	364354.656	114.725	2661495	16.19	16.29	31.8	136.32	0.97
10_2.3	363006.625	364364.031	114.665	978506	12.02	12.06	25.6	52.60	1.93
10_2.4	362999.000	364365.125	114.576	807565	12.18	12.24	31.2	79.24	2.41
10_2.5	362987.688	364360.938	114.708	1278760	12.44	12.61	25.6	66.82	1.66
10_2.6	363000.844	364358.875	114.742	1070152	12.51	12.66	31.2	79.13	1.62
10_2.7	363007.719	364355.344	114.796	1137806	14.09	14.29	25.6	67.88	1.59
10_2.8	363011.344	364351.625	114.657	579947	12.08	12.10		16.86	0.14

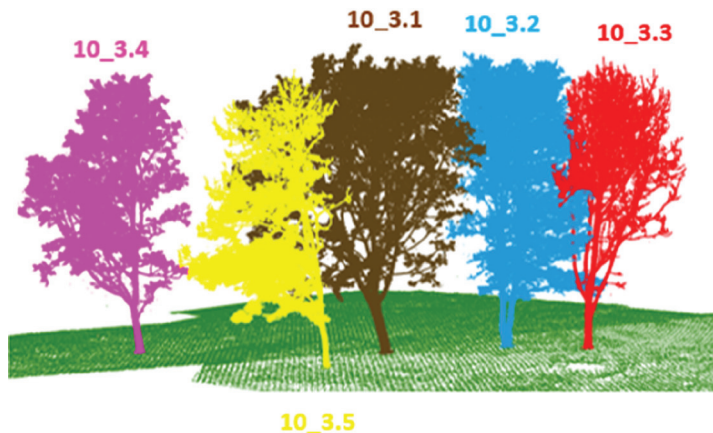


Fig. 10. Inventoried trees located in zone 10, part 3 (cf. Fig. 2)

Table 10. Tree parameters calculated for objects in zone 10, part 3

Tree	X	Y	Z	Number of points	Height [m]	Length [m]	Diameter [cm]	Surface area of the convex hull [m <sup>2</sup> ]	Height of the lowest crown point above ground [m]
10_3.1	362987.219	364355.375	114.782	1841782	14.71	14.86	40.0	125.52	1.77
10_3.2	362993.188	364354.344	114.721	1327203	14.29	14.50	25.6/25.6	75.40	0.98
10_3.3	362997.031	364355.531	114.759	393385	13.88	14.11	31.2	57.77	1.39
10_3.4	362975.625	364352.063	114.696	785983	13.47	13.54	25.6	53.38	1.68
10_3.5	362984.406	364358.625	114.725	818606	13.02	13.26	25.6	59.95	1.74

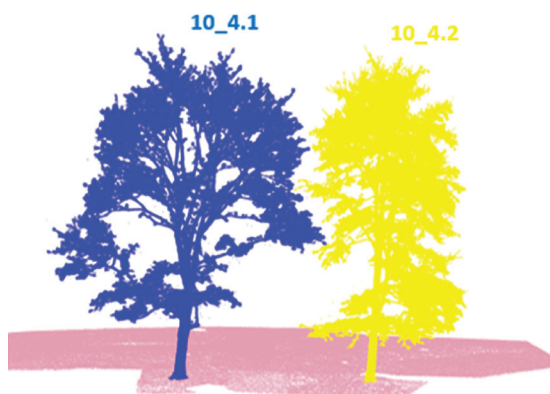


Fig. 11. Inventoried trees located on the boundary of zones 9 and 10 (cf. Fig. 2)

Table 11. Tree parameters calculated for objects on the boundary of zones 9 and 10

Tree	X	Y	Z	Number of points	Height [m]	Length [m]	Diameter [cm]	Surface area of the convex hull [m <sup>2</sup> ]	Height of the lowest crown point above ground [m]
10_4.1	362987.219	364355.375	114.782	1374123	18.68	18.82	40.0	125.52	1.77
10_4.2	362993.188	364354.344	114.721	1170091	18.25	18.31	44.0	75.40	0.98

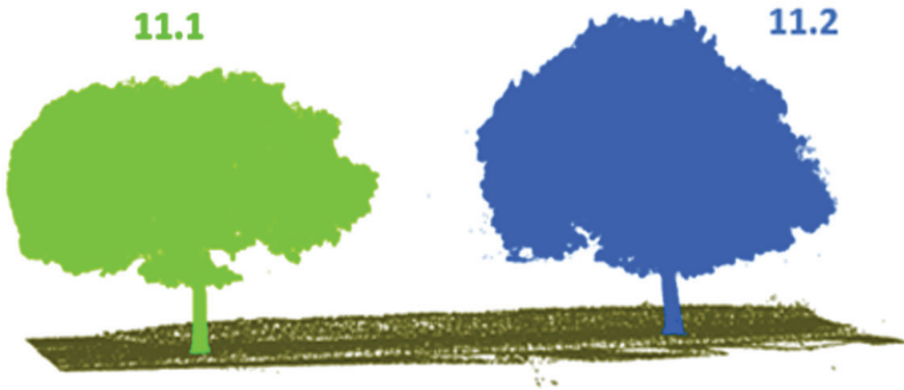


Fig. 12. Inventoried trees located in zone 11 (cf. Fig. 2)

Table 12. Tree parameters calculated for objects in zone 11

Tree	X	Y	Z	Number of points	Height [m]	Length [m]	Diameter [cm]	Surface area of the convex hull [m <sup>2</sup> ]	Height of the lowest crown point above ground [m]
11.1	363020.000	364385.031	113.962	1707150	6.62	9.19	25.6	68.25	1.42
11.2	363032.594	364376.281	113.864	2767317	8.69	11.65	31.2	126.45	1.40

In the case of tree 10\_2.8, the diameter at the height of 1.3 m was not calculated because it is a coniferous tree and its low crown did not allow the parameter to be calculated. In the case of tree 10\_3.2, two diameter values were calculated because the main limb divided into two limbs at the height of 0.98 m. The parameters of the two trees located at the border of zones 9 and 10 were calculated after calculating all parameters for the trees in the two zones.

## References

- Dudkiewicz M., Dąbski M., Durlak W. 2015. Dendroflora zabytkowego parku w Kijanach. *Acta Sci. Pol., ser. Formatio Circumiectus*, 14, 1, 15–25.
- Dusza-Zwolinska E., Dembowska M. 2018. Do czego potrzebne są inwentaryzacje dendrologiczne? *Aura*, 3.
- Häger A. 2022. Adapting the PIC/FLIP fluid simulation method to produce a LEGO water animation & evaluating its performance.
- Kommareddy S., Siripun J., Sum J. 2014. 3D Object Morphing with Metaballs. <http://www.evl.uic.edu/creativecoding/cs488/finalprojects/metaball/metaball.pdf> [access date: November 2018].
- Král K., Krůček M., Trochta J. 2018. 3D Forest. [3dforest.eu](http://3dforest.eu) [access date: November 2018].
- Ranjan V., Fournier A. 1996. Creating union of spheres models from multiple views. *Journal of Graphics Tools*, 1(4), 21–39.
- Szostak M., Wężyk P. 2013. Pomiary GNSS w przestrzeni leśnej przy wykorzystaniu różnej klasy odbiorników oraz wybranych trybów pomiaru. *Archiwum Fotogrametrii, Kartografii i Teledetekcji*, 25, 217–231.
- Wężyk P., Szostak M., Rysiak P., Zięba K., Hawryło P. 2015. Dąb Bartek 3D – naziemne skanowanie laserowe 3D pomników przyrody – nowy wymiar edukacji przyrodniczej. *Stud. i Mater. CEPL w Rogowie*, 17, 43/2, 7–15.

---

Mgr Eryk Klemiński (graduated student)  
Wrocław University of Science and Technology  
ul. S. Wyspiańskiego 27  
50-370 Wrocław  
e-mail: [erykwww@wp.pl](mailto:erykwww@wp.pl)

Dr. inż. Damian Kasza  
Wrocław University of Science and Technology  
ul. S. Wyspiańskiego 27  
50-370 Wrocław  
e-mail: [damian.kasza@pwr.edu.pl](mailto:damian.kasza@pwr.edu.pl)  
ORCID: 0000-0002-8973-155X