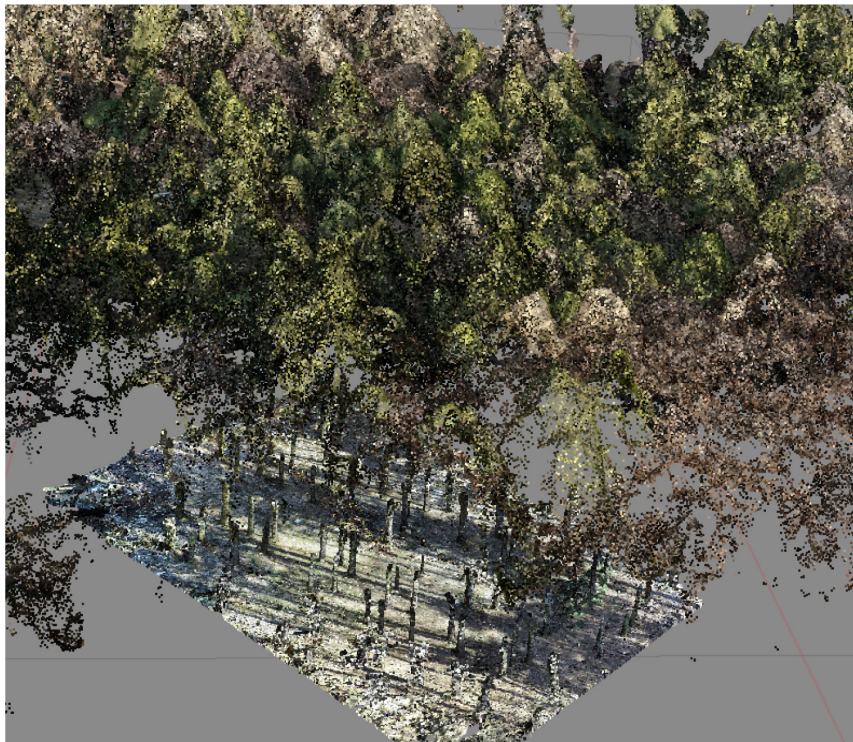




Modeling and characterization of forest stands using aerial and terrestrial photogrammetry



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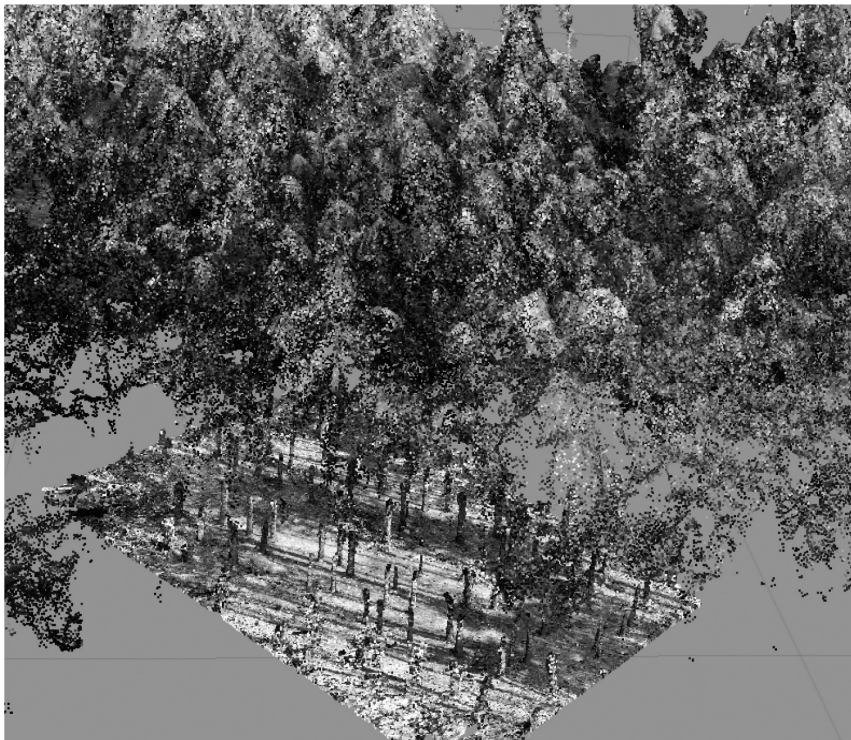
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Abstract

The master 's thesis focused on forest inventory process based on the photogrammetric point cloud. The study deals with forest stand data collecting using terrestrial and aerial photogrammetry. The raw data – digital images were taken by walking through the forest stand with the imaging device carried on the measuring rod and by the drone with mounted camera.

This thesis describes data processing in the Agisoft PhotoScan, where are the raw images processed to the 3D point clouds. 3D point clouds were analysed in the ArcMap SW. From the modelled stems, the cuts at breast height were extracted, from which, the single stem diameter at breast height (DBH) was calculated. Based on ArcMap SW analysis, the tree height was calculated. For the tree height values calculation, the canopy height model (CHM) was created by so-called inversed watershed method. Volume of the individual stems was calculated from the values based on the photogrammetry data. Calculated stand characteristics were compared with ground true data, collected by the conventional methods. The calculation of the stand characteristics was achieved with RMSE 1,5 m error of the tree height, 2,9 cm error of the DBH and 0,14 m³ of the single stem volume. It was concluded that the presented technology can be used for forest inventory. Thanks to the possibility of its operative application, i.e. the possibility of updating the stand data at very short intervals is therefore possible to evaluate the actual thinning interventions in the premature stands, development of the regeneration of the stand, and also the potential threat of the stands by calamitous pests.

Keywords: UAV, UAS, drone, photogrammetry, forest inventory, structure from motion, remote sensing, tree height, diameter at breast height, stem volume, stand model

Table of content

Abstract	3
List of abbreviations	6
1. Introduction	7
1.1 Introduction to the topic	7
1.2 Structure from motion	8
1.3 Terrestrial photogrammetry.....	11
1.4 Aerial photogrammetry	17
1.5 Aim of the work	20
2. Materials and Methods	21
2.1 Experimental site.....	21
2.2 Forest stand reference data acquisition	22
2.3 Terrestrial imagery	23
2.4 Aerial imagery.....	26
2.5 Image acquisition evaluation.....	27
2.6 Data processing in Agisoft PhotoScan	28
2.7 Point cloud processing in ArcMap	31
2.8 Stem volume calculation based on aerial and terrestrial photogrammetry data.....	37
2.9 Statistical evaluation	37
3 Results	38
3.1 Tree detection on the plots	38
3.2 Estimation of the DBH.....	39
3.3 Estimation of tree height	42
3.3 Tree stem volume estimation	44
3.4 Assessing the time demand of forest inventory technology from photogrammetric point clouds	45

4. Discussion	47
4.1 Forest stand characteristics estimation workflow	47
4.2 Factors affecting data collection.....	47
4.3 Accuracy of results	49
4.3.1 Deviation of position of detected trees.....	49
4.3.2 Diameter at breast height.....	49
4.3.3 Tree height.....	50
4.3.4 Stem volume.....	51
4.4 Possibilities to apply in practice.....	52
4.5 SWOT analysis.....	53
5. Conclusions	54
References	56

List of abbreviations

2D	Two-dimensional
3D	Three-dimensional
CHM	Canopy height model
DBH	Diameter at breast height
DSM	Digital surface model
DTM	Digital terrain model
GCP	Ground control point
GPS	Global positioning system
LiDAR	Light detection and ranging
NFI	Nation forest inventory
PCT	Pre-commercial thinning
RGB	Red-Green-Blue
RMSE	Root mean square error
SfM	Structure from motion
SW	Software
UAV	Unmanned aerial vehicle

1. Introduction

1.1 Introduction to the topic

Forest stands are in constant evolution and their characteristics are constantly changing with age. Since forest stands are the main economy factor in the managed forest and it is expected to generate profit, their characteristics need to be monitored during development. The monitoring of changes in stand characteristics changes takes place at several levels. From local small stands for the needs of forest management, pre-stock inventory, or for the purpose of selling wood at site. Planting characteristics are also controlled in large areas of large economic entities, whether state-owned or private properties. The highest level of data collection on forest stands is at national level – National Forest Inventory (NFI), which evaluates changes in state of forest stands at national level. These comprehensive data on forests serve as a basis for international reporting on the state of forests in the Czech Republic.

Forest stands are a complex of diverse species, structures, types and phases where the stand characteristics are so specific that it is not easy to generalize and accurately present these characteristics. Therefore, it is necessary to perform a specific data collection for each forest stand. The evaluation of inventory areas, as well as areas of common stands, is both physically and time-consuming. Inventory of forest stands requires a great deal of staff and time, which may be a problem in the future. Ordinary inventory methods cannot guarantee up-to-date data acquisition or recurrent collection at shorter intervals.

Unmanned aerial vehicles (drones) have witnessed boom at the turn of the 20th and 21st centuries, but since 2010, their boom has risen dramatically. The prices of drones that can be used to carry the camera have dropped so low that they can be afforded by almost all forest management subjects. The use of unmanned technologies, along with relatively cheap cameras providing high-quality images, shifts these technologies forward.

Another important step for using unmanned technologies for forest inventory purposes are softwares capable of processing the acquired images using advanced algorithms into outputs usable in common geoinformation systems. The Structure from Motion method (SfM), a movement structure, allows continuous forest imaging and highly accurate data to be used to model and estimate its characteristics. This method can be used both in unmanned technologies and in the imaging of stands from the ground. By the combination of terrestrial

and aerial data collection technology, it is possible to gain many forest stand characteristics. For the purpose of inventorying the forests, they are mainly basic characteristics such as the diameter at breast height, tree height, basal area or standing volume of the forest.

For precision forestry – especially in countries where forest complexes are very extensive – aerial and terrestrial imaging technology can be a major shift in efficiency and precision. In terms of time consuming, this technology can provide opportunities for inventorying larger areas, not only for pre-commercial thinnings (PCT), thinnings or final felling planning, but also for road network planning, regeneration monitoring, biotic and abiotic disaster monitoring. A great benefit of the technology is also the possibility of periodic updating of data on stand characteristics, which can help in the evaluation of realized harvest, logging, or when deciding on future interventions.

1.2 Structure from motion

Structure from motion (SfM) is one of the techniques how to obtain earth surface and produce 3D forest structure modelling. The SfM uses an algorithm of computer vision for the images obtained by digital cameras (Wallace et al. 2016). By the SfM method is possible to get point clouds, which are made by techniques as computer vision and photogrammetry. SfM is based on basic principles of classical stereo photogrammetry, when 3D point clouds are generated by the clearly defined geometric characteristics. SfM works with the data similarly as multiple-image photogrammetry, where images capture one concrete point obtained from different angles. SfM is superstructure of the classical stereo photogrammetry, which could be built thanks to advanced algorithms, as for example invariant function scale transformation and thanks to possibilities of graphic chips parallel beam adjustments (Zarco-Tejada et al. 2014). Thanks, those progressions and software which are user-friendly, is possible to assign corresponding characteristics from many images. These images, which needs to overlap, to obtain information about concrete point are captured from many angles and as many of those images is available, the better result could be achieved. By the enormous development of the computer technology is possible to process a huge amount of data, thus thousands up to millions of images. Forest stand data – 3D point cloud, obtained by the SfM technology could be used for analysis and calculations of forest stand characteristics, as tree height, forest stand canopy or amount of biomass and that for single trees level or even whole forest stand.

According to Wallace et al. (2016) is 3D point cloud creation from data obtained by the SfM method 16 times more time demanding compare to LiDAR. With an experimental plot of 15 ha, 425 RGB images were captured. From those images, 89 million points was generated. Those points represented the experimental plot plus extra points from the surroundings of the plot. Whole process of the point cloud generation took 24 hours in total. Compare to laser scanning, the point cloud generation from the LiDAR data took only 1,5 hours in total. Significant difference in point clouds is also in the point density per square meter. The LiDAR point density per square meter was 174, which was compared to 5642 points per m² of the SfM point cloud significantly less, and therefore, the SfM point cloud provides more accurate data. Point cloud difference is show in the Figure 1. It is possible to see a high occurrence of empty areas at the SfM point cloud, where is almost impossible capture the brunching or the stem shape.

By the time-consuming creation point cloud from the SfM images and high computing power, it seems that usage of data from the LiDAR is more advantageous. One of biggest problem of LiDAR is the price of the data. Despite the costs for LiDAR dropped, for the research and for the operational purposes is still high. For the one-time data need is the LiDAR option well-founded, but for the annually refresh of the data, or even a several times per year, then is LiDAR data acquisition impossible. The price of laser scanning data of 1 ha can be even 0,2 USD, but provided that the scanned area is in the order of thousands of square kilometres (Asner, 2009). However, for small areas, the price per ha is much higher. In that case, the minimal prices for the scanning can vary in even 1000 USD. If the subject's schedule is to scan periodically, then is possible to buy complete set for the photogrammetric SfM method data acquisition with the same price as one-time LiDAR data acquisition.

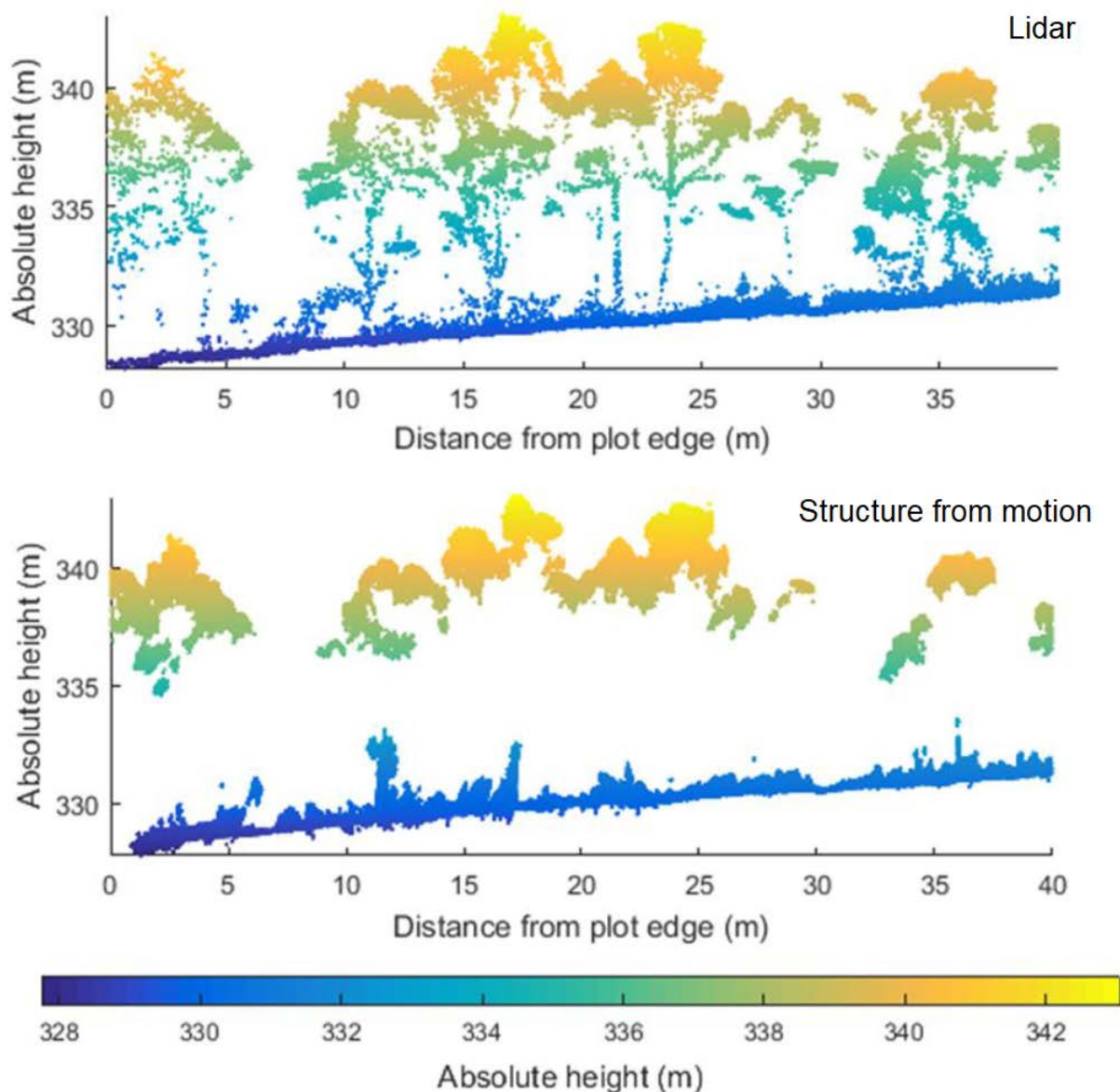


Figure 1 Illustration from Wallace et al. Comparison of point cloud from LiDAR and SfM data. It is obvious, that point cloud from SfM is not that precise, because the understory points cannot be captured. (Wallace et al., 2016).

The disadvantage of the aerial SfM is the problem of creating digital terrain model (DTM) in a full canopy cover. For example, in a very richly structured stand, canopy can be so overwhelmed that it will not be possible to get DTM from images taken by drone, using the SfM method. It is therefore appropriate to use the ground-based SfM method to obtain this model, which would otherwise have to be provided from external sources, which would not benefit the economy of projects. When the subject already has aerial imaging equipment, then these, mostly digital cameras, can simply be used to obtain accurate DTM.

SfM algorithms are able to generate 3D point clouds using computer vision and photogrammetry in fully automated mode. The creation of models from a large number of not sorted images is done by automatically finding of so-called key points in individual frames (Daudois and Ellis, 2010). These points are then automatically sorted, and the continuity of their properties or the direct match of the key points on the different frames are recorded. A very important step of the SfM method is the subsequent adjustment of the coordinates of the points in the 3D space, including the positions and orientation of the camera, as well as its parameters using the large data arrangement algorithm. Software using these algorithms, such as Bundler (Snavely, 2010), PhotoScan (Agisoft, 2006), Pix4D (Pix4D, 2011), VisualSFM (Changchang, 2013), 3DF Zephyr (3DFLOW, 2014) 1994), provide automated creation of 3D clouds of points. Outputs can be obtained from variously captured images, from different cameras, even with different internal parameters.

1.3 Terrestrial photogrammetry

Digital terrain model, and in particular the shape and size of the stems, cannot always be obtained by aerial photogrammetry. In dense spruce monocultures it is almost impossible. However, if SfM methods of aerial photography are transferred under dense canopy, it is possible to obtain accurate data of stand characteristics, such as spacing, density, and above all, the diameter at breast height (DBH) of individual trees. SfM method, along with the multi-angle stereophotogrammetry, allows to calculate the geographic coordinates of the measured objects – trees from the series of images, similar to aerial SfM imaging. (Miller et al., 2015). Similarly, 3D point clouds can be obtained using automated 3D methods. This is followed by the creation of a 3D model of the stand, from which the estimated characteristics, such as single stem volume can be derived.

Errors in data retrieval, and therefore errors in processing, may be due to several causes. Most often, however, errors arise in segments where the visibility of the tree is limited (Surový et al., 2016). This is primarily the stem base and the crown of the tree. The ability to reduce these errors is to increase the imaging capacity. With more than five cameras, the accuracy of the models is increasing dramatically, but the use of eight or more cameras is no longer improving the results. When using 5 or more cameras, a difference in the DBH of 0.59 cm was achieved with RMSE = 1.87 cm, which can be considered as sufficient accuracy for forest inventory purposes.

Estimation of tree stem parameters using the SfM method is described by Forsman et al. (2016). A prototype of a multi-camera device was used to capture data. A 5-camera imaging device is shown in Figure 2. An example of images from three cameras shows the assigned epipolar lines for a red-marked key point with which (and many other such points), it is possible to align and link all images in one 3D model. (Figure 3).



Figure 2 Device with five cameras carried on EasyRig 2.5 (Forsman et al., 2016).



Figure 3 Example of images from three cameras, with different direction, carried on EasyRig 2.5. (Forsman et al., 2016).

The imaging took place on each plot, approximately from its center. The image was taken in twelve directions, divided by 30 ° angles, and took less than two minutes for each area. The point cloud (Figure 4) count approximately 30.000 points for each plot area, in a circle of 12 m from the center of the plot. It was important to set the direction and slope of the cameras to capture the stem of the tree at a height of 0.9 m to 1.7 m.

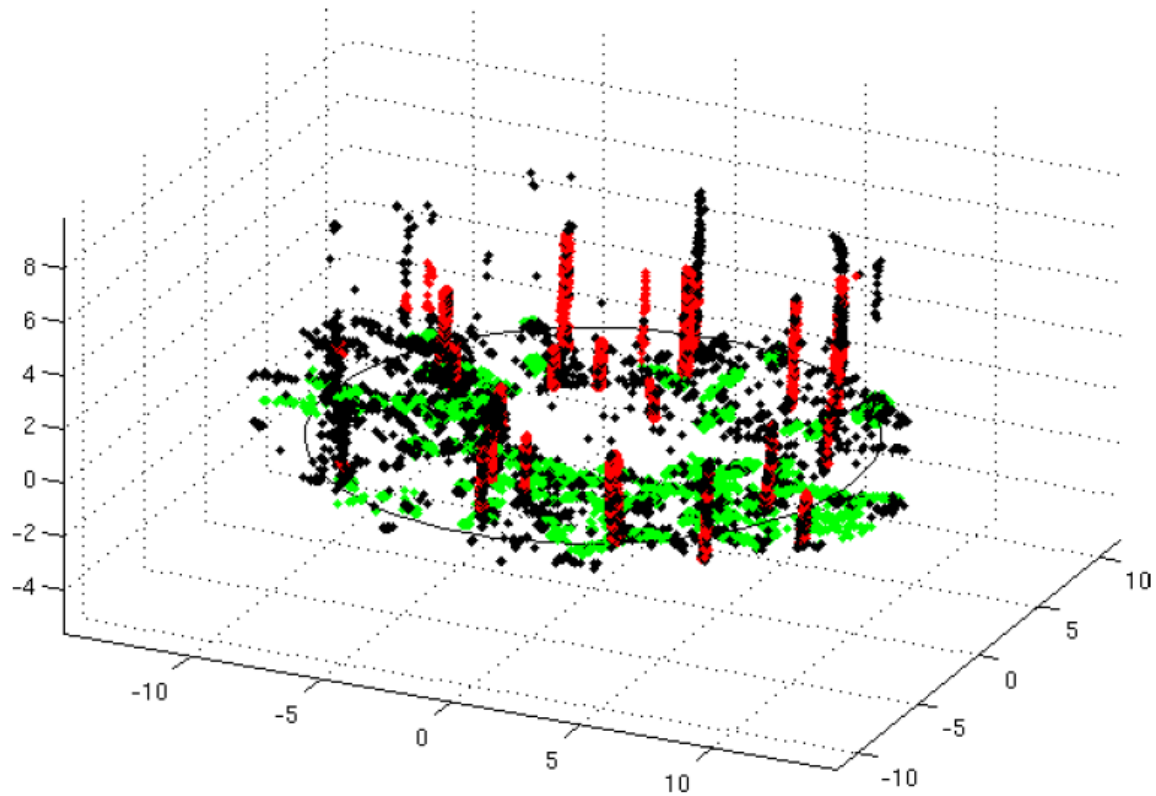


Figure 4 Point cloud of the plot, the circular segment has a diameter of 12 m, where the surface points are green, individual tree stem points are red and the black color is for other points (Forsman et al., 2016).

Out of 25 areas in the study by Forsman et al., only 6 areas could be evaluated, as the other areas had poor lighting conditions. It was too intense lighting and also many dark shadows that negatively affected the pictures. 76% of trees were detected on the areas where appropriate data could be obtained. The error in tree position ranged in average to 0.5 m. The DBH was obtained for 42% of the trees with a difference of 1 cm compared to the measured values and with a mean quadratic error $RMSE = 7.2$ cm. In conclusion, the conditions for good image quality in forests are very significantly influenced by light conditions, high tree density and dense undergrowth.

Mokroš et al. (2018) describes various approaches to collecting photogrammetric images. The study evaluated seven different methods of collecting photogrammetric data using the SfM method. All imaging was done as terrestrial imagery. This imaging was taken by walking with the camera carried on the camera carrier, held in hand and also on the telescopic rod. Other parameters were also the position of the camera in the vertical and horizontal direction. The emphasis of the study was on finding the optimal movement of the imaging device in the stand. The camera's trajectory during imaging is essential in post-processing of photos. Software for converting raw photos into point cloud are able to produce accurate point cloud similar to LiDAR outputs. The first step is to align images and find the camera positions from which the pictures were taken. Forest vegetation is a very diverse structure, but to compare hundreds of images, each of which contains several stems that are very similar in a uniform vegetation, it is not easy to distinguish and classify this similar tree stems. For the align of images, the camera's position plays a role when imaging, and aligning hundreds of pictures with different camera paths is difficult for the software. The study investigated how these trajectories affect image processing and ongoing alignment. Four different imaging trajectories were performed. Figure 5 shows the camera's trajectory in the terrestrial imaging of the stand when passing through the stand. The first "waves" trail (Figure 5a) was carried out with a smooth passage, without stops. The imaging was continuous, and the track was formed by six perpendicular lines. The second imaging trail was taken along the perimeter of the plot (Figure 5b). The photographer moved slowly around the circumference of the boundaries of the area and shot the area manually.

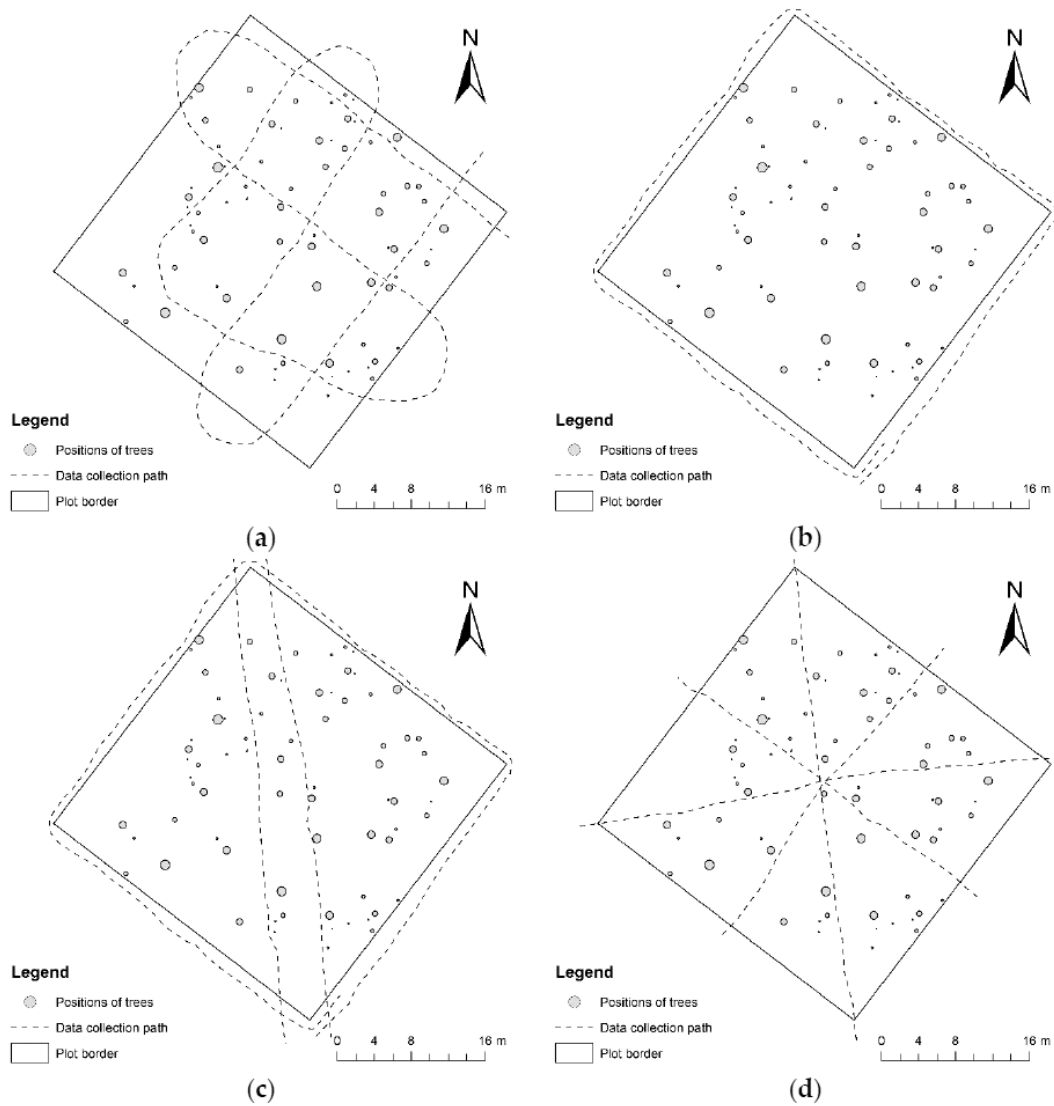


Figure 5 Terrestrial imagery trajectory (Mokros et al., 2018).

The third route (Figure 5c) was a combination of (a) and (b) when the area was imaged from the edge of the surface boundaries, and two lines were guided inside the surface. The last route (Figure 5d) was made by eight lines, which always began and ended outside the surface, and intersected in the center of the plot. The results showed that images could not be matched correctly when processing data from the “waves” path. In this method, three different methods of carrying the camera were examined. The device was carried on a 2.5-meter stick, the DJI Ronin-M camera holder, and the photographer’s hand directly. Even one of the cameras carrying methods did not work properly. For other routes, the camera was always carried by hand, and all of them were aligned.

The same study (Mokros et al., 2018) also dealt with the measurement of the DBH. Seven different data collection methods were evaluated for the calculation of the DBH. These methods combined the different camera holding options (2.5m stick, DJI Ronin-M camera holder and handheld support), camera orientation (horizontal and vertical), shooting mode (continuous, with stops) and various camera movements (4 different routes, see Figure 5). With three continuous imaging methods (4 continuous scanning methods at all), it was not possible to align the images, so even the DBH could not be calculated. For the continuous imaging method, where image alignment was possible, the accuracy of the results (RMSE = 20.93%) was the worst of all other methods. The best results (RMSE = 16.67%) were achieved by the hand-held camera method and the vertical orientation of the camera. The imaging took place manually with short stops, and the route of the walk led along the edge of the plot with two lines inside the plot area. The last two methods differed from the best method only by the different paths of the photographer's movement (Figure 5b and Figure 5d). Based on the accuracy of the results, both methods appear to be statistically indistinguishable by RMSE = 18.39% and 18.92%, respectively.

1.4 Aerial photogrammetry

Torresan et al. (2017) summed up several studies that presented the use of drone data collection techniques in forestry across Europe. The types of drone used, the types of sensors carried, and especially the aims of the works and the subjects of research were evaluated. Figure 6 shows the percentages of the above-mentioned criteria in selected European case studies.

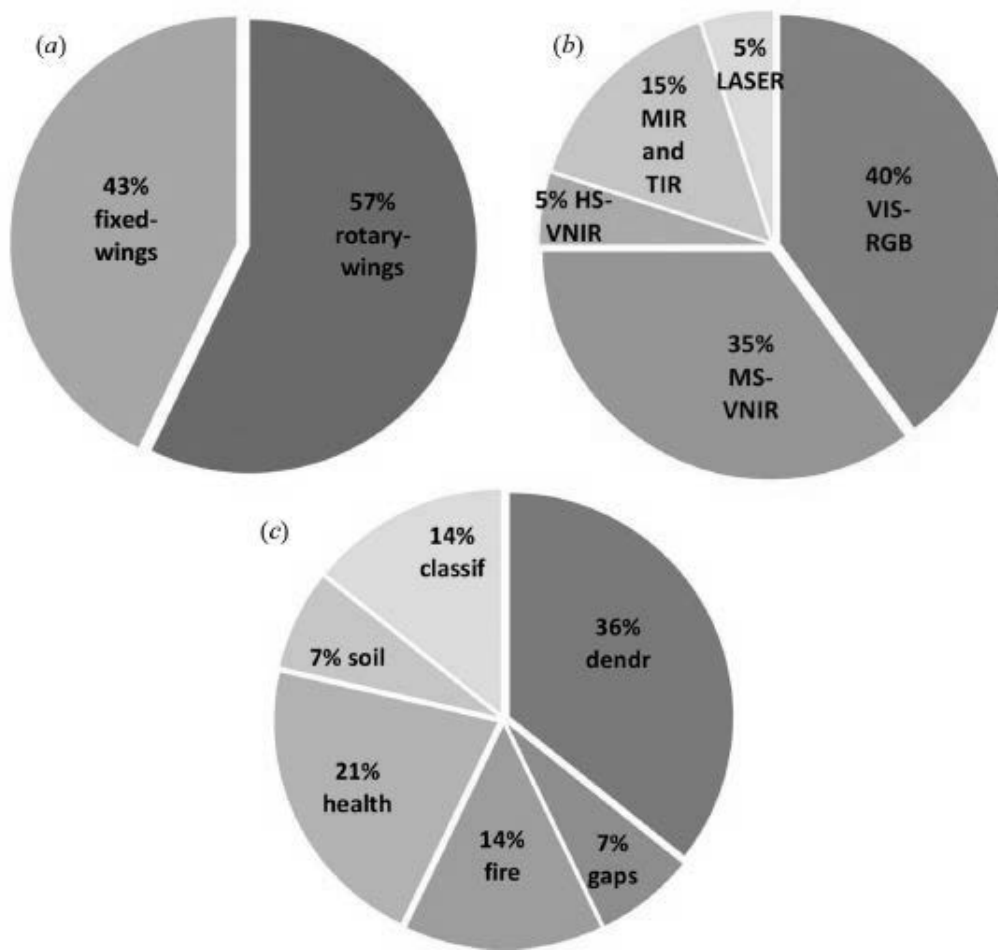


Figure 6 Percentage representation of drone utilization for forestry purposes. Drone type (a), sensor type (b) and purpose of use (c) (Torresan et al., 2017).

Drone with a fixed and rotary wing was used for forestry purposes, with the rotation wing predominance, figure 6. The most used sensor was the camera, unlike the laser, which was used only in 5% of cases. The purpose of UAV utilization was 36% to obtain dendrometric variables. In 14% of the cases, the state of health of the plant was surveyed. Drones has also been used for classification of species composition, control of fires and their consequences, assessment of soil condition and monitoring of gaps.

Dandois and Ellis (2013) mapped deciduous stands in America. A small drone, along with a commercially available camera, was used for taking pictures. Taking pictures of more than 1,800 hectares of forest has provided a highly accurate 3D canopy model. The authors demonstrated the suitability and economic benefits of technology for phenological research.

To determine the height, Lisein et al. (2013) introduced the technique of collecting data using a fixed-wing drone. The authors have pointed out the possibilities of using dendrometric data collection technology with cheap equipment compared to conventional laser scanning.

Hyypä et al. (2008) summarizes methods and results of UAV laser scanning for collecting data on forestry characteristics for forest inventory purposes. Several studies on the tree height estimate have concluded that the estimated heights are almost always underestimated. In the nine case studies investigated, tree heights were always underestimated, an average of 0.79 m. The most probable reason for these underestimations of heights is understory. Laser scanning provides a very accurate surface and terrain model, but it seems that sometimes understory can be identified as a terrain (affecting DTM), thereby influencing the height estimation.

The stand volume is one of the most important forest stand characteristics. Goodbody et al. (2017) estimated volume gain based on drone photogrammetry data. In 2013, data collection was performed by laser scanning and in 2015 the data was updated using drone photogrammetry. Volume growth was assessed only at individual tree level. Finally, it was confirmed that UAV photogrammetry technology can be used to update data acquired by laser scanning in the past. New data that can be acquired continuously can make a significant contribution to future planning.

The aim of using unmanned technology was to assess the extent of the wind calamity as quickly as possible. Based on the data from the aerial imaging, the direction of the windthrown trees was determined and the extraction plan could be created. The possibilities of accessibility of the stand, as well as the direction of the process of harvesting and harvesting of wood were evaluated. The area of the entire calamity area was 49 hectares, and four aerial events were required for the whole area (Figure 7).

The assessment of wind calamity with a such scale would take weeks, not only because of the size of the area, but also because of the very inaccessible and steep terrain. The visibility and clarity of the area was very low, and work safety was also taken into account here. Based on these factors, it was appropriately assumed that ground assessments would be both inefficient, impractical and dangerous. The result of the work was a quick and very accurate assessment of the extent of the calamity. Based on the data obtained, it was possible to

process a harvesting plan and therefore the logging operations were very effective and very safe (SmartPlanes, 2018).

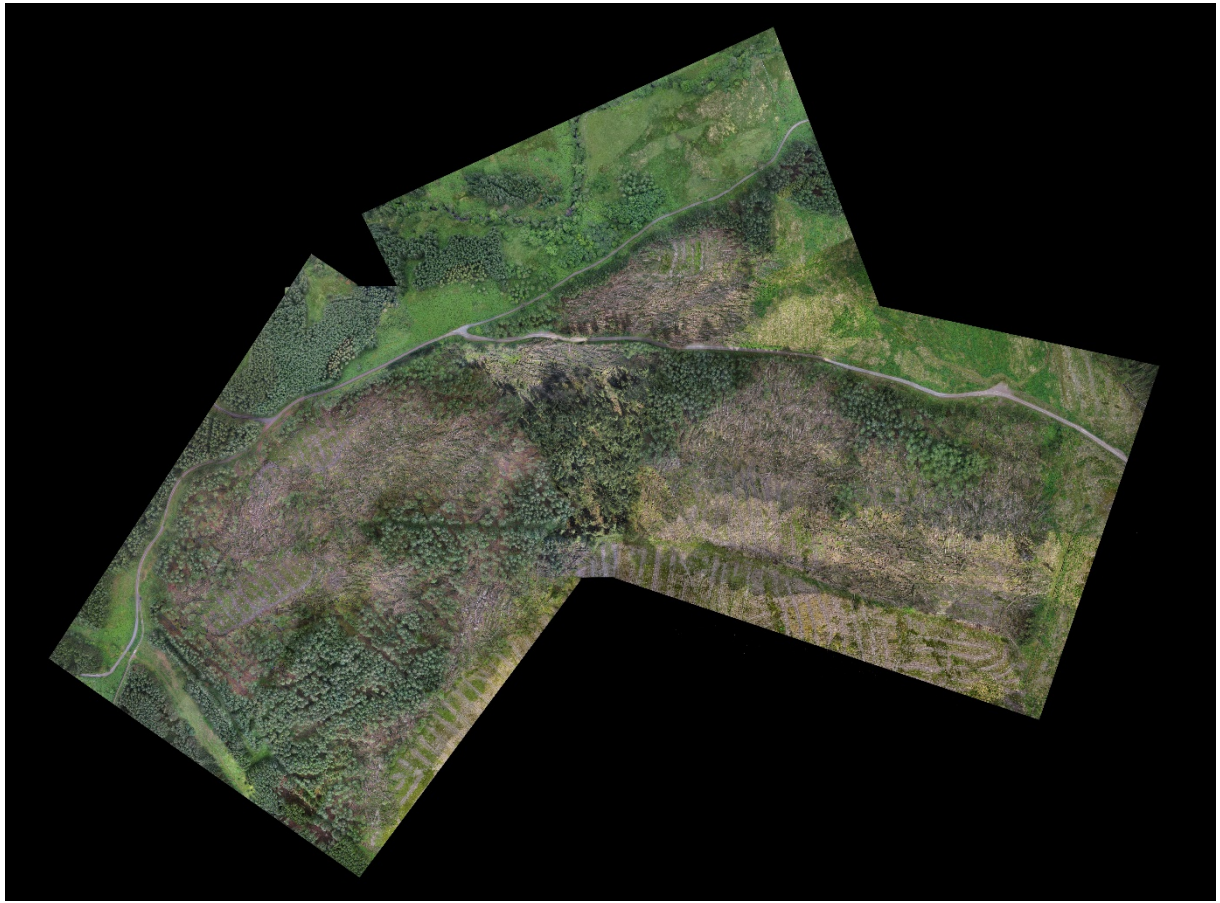


Figure 7 The resulting image created by overlaying images from four flight events (49ha) (SmartPlanes, 2018).

1.5 Aim of the work

The aim of this work is to evaluate forest inventory technology based on photogrammetric point clouds. The practical aim of the work was to show possibilities of the forest inventory technology based on terrestrial and aerial photogrammetry. Diameter at breast height (DBH), tree height and stem volume were calculated from the 3D model based on the photogrammetric point clouds. Time requirement, advantages and disadvantages of technology was evaluated to outline the future possibilities of practical application of technology in the forestry sector.

2. Materials and Methods

The work included several phases. These phases could be characterized by the type of action to data collection, following data processing and at least data interpretation with statistical evaluation.

2.1 Experimental site

The experimental site was chosen in Norway spruce stand, close to the Brno city. Centre of the plot is at coordinates 49°17'44.1" and it's 485 m above the sea level. The area of experimental stand is 3,34 ha with the age of 83 years and with 200 trees per ha.

The experimental plot is mixed stand, where is the Norway spruce (*Picea abies*) dominant with 74% representation. The forest stand is formed by other three admixed species – Scots pine (*Pinus sylvestris*) 14 %, European larch (*Larix decidua*) 5 % and European beech (*Fagus sylvatica*) 7 %. Species composition is shown in the Figure 8.

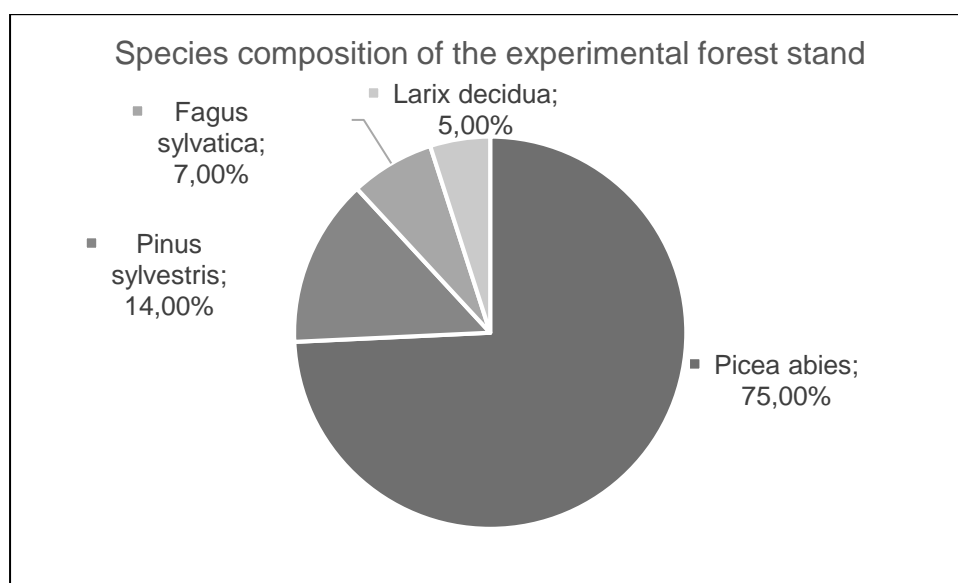


Figure 8 Species composition of the experimental forest stand.

The sample plot contained 55 trees on the area of 0,3 ha. After pre-commercial thinnings and thinnings is the spacing irregular, but it indicates, that it was established by even row spacing. Forest canopy was evaluated from the aerial imagery and the canopy cover occupied 80 % of the stand area. The average height is 28 m with one dominate crown layer with a weakly developed second layer of Beech with an average height of 22 m.

2.2 Forest stand reference data acquisition

In a first step, forest stand data was necessary, therefore stand characteristics as tree heights, diameter at breast height (DBH) and their positions were collected. These characteristics were important as the control values for the statistical comparison. Before all tree positions measures, three reference ground points were measured by GPS station Topcon Hiper Pro and added to total station Topcon GPT-9003M and all 55 tree positions were measured by the total station. Positions were measured as a middle of the stem at breast height. All the measured positions were put into cadastral net. These positions were used to compare with tree position obtained from the photogrammetric point clouds. Figure 9. show the point cloud of the sample plot with the reference ground points.

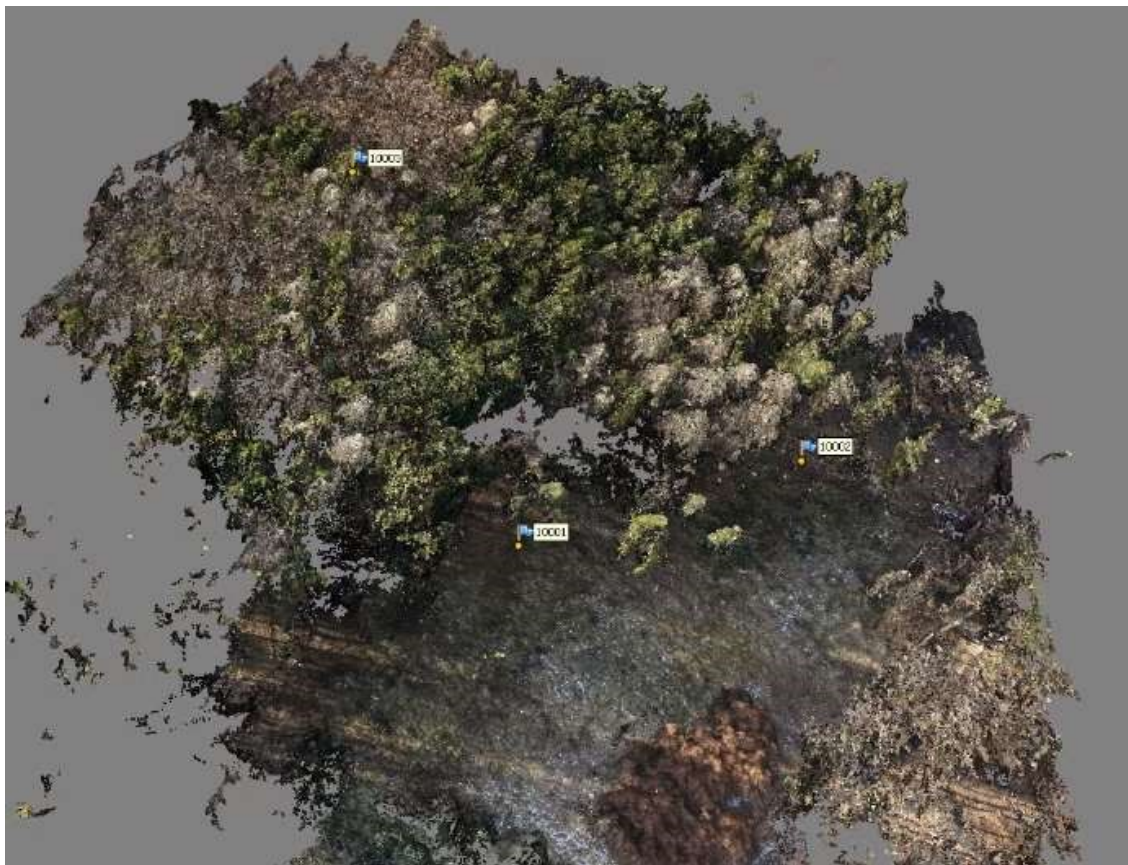


Figure 9 Point cloud of the sample plot with the reference ground points.

DBH was measured for all trees by calliper. Measurement was conducted in two perpendicular measurements. The final DBH was also the average from two measurements.

Tree heights were measured by laser hypsometer TruPulse 360B. The tree heights were measured twice, from different position and the final height was the average from two

measurements. These heights served for comparison with the heights estimated from the aerial imagery data.

Digital images collection was terrestrial and aerial and photogrammetric imagery was performed by the SfM method.

2.3 Terrestrial imagery

For the terrestrial imagery it was necessary to deploy the ground control points and measure their positions. Six ground control points (GCP) in total were deployed evenly in the forest stand. The positions of the GCP were measured by a total station, to avoid the inaccuracies by using the GPS under the forest canopy. GCPs were put on plain ground after removing the organic material to increase the contrast between the dark brown ground and white GCP. The higher contrast served to easier automatic detection of GCP or manual identification of GCP in the Agisoft PhotoScan.

In the Figure 10 is shown six GCP types used at terrestrial imagery.

Terrestrial imagery was done by two different cameras. First camera used was Sony Alpha NEX-5R and the second imaging equipment was made up of two cameras GoPro HERO 5 Black, which were mounted on the telescopic rod. Cameras were directed to the same direction, but with different angle of view, to capture wider area. Cameras were inclined at the 45° and 55° approximately, to capture tree stems from the ground to at least 2 m of height. Terrestrial imagery was carried out by the telescopic rod at the height of 4 m above the terrain surface. Imagery with the Sony camera was carried out, so the camera was carried by the one who performs the imagery by walking in lines through the forest stand. The spacing between lines was 5 m approximately and the imaging was done in two perpendicular directions. Imaging regime of the camera was automatic. It was sequential imagery, with the capturing period of 1 sec, that is continual capturing with a record in every second. In the case of two GoPro cameras, the imaging regime was a video in 4K format. In figure 11 the trajectory of the Sony camera is shown. Black points represent positions of the camera, when the image is captured. By the scale is obvious, that for the creation of the final stand model, images overlay was at least 9 images for each single point of the model.

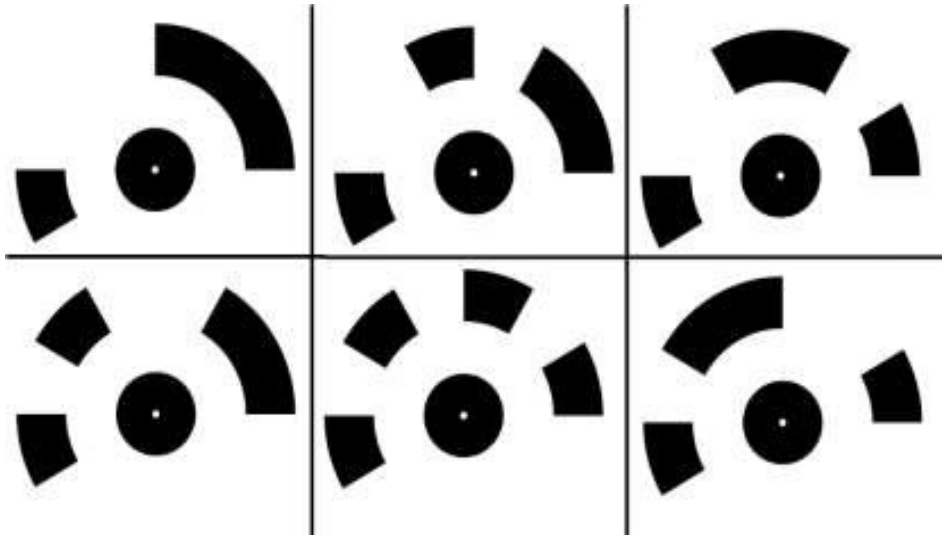


Figure 10 GCP used for the terrestrial imagery (above) and one real GCP used at the imagery (below).

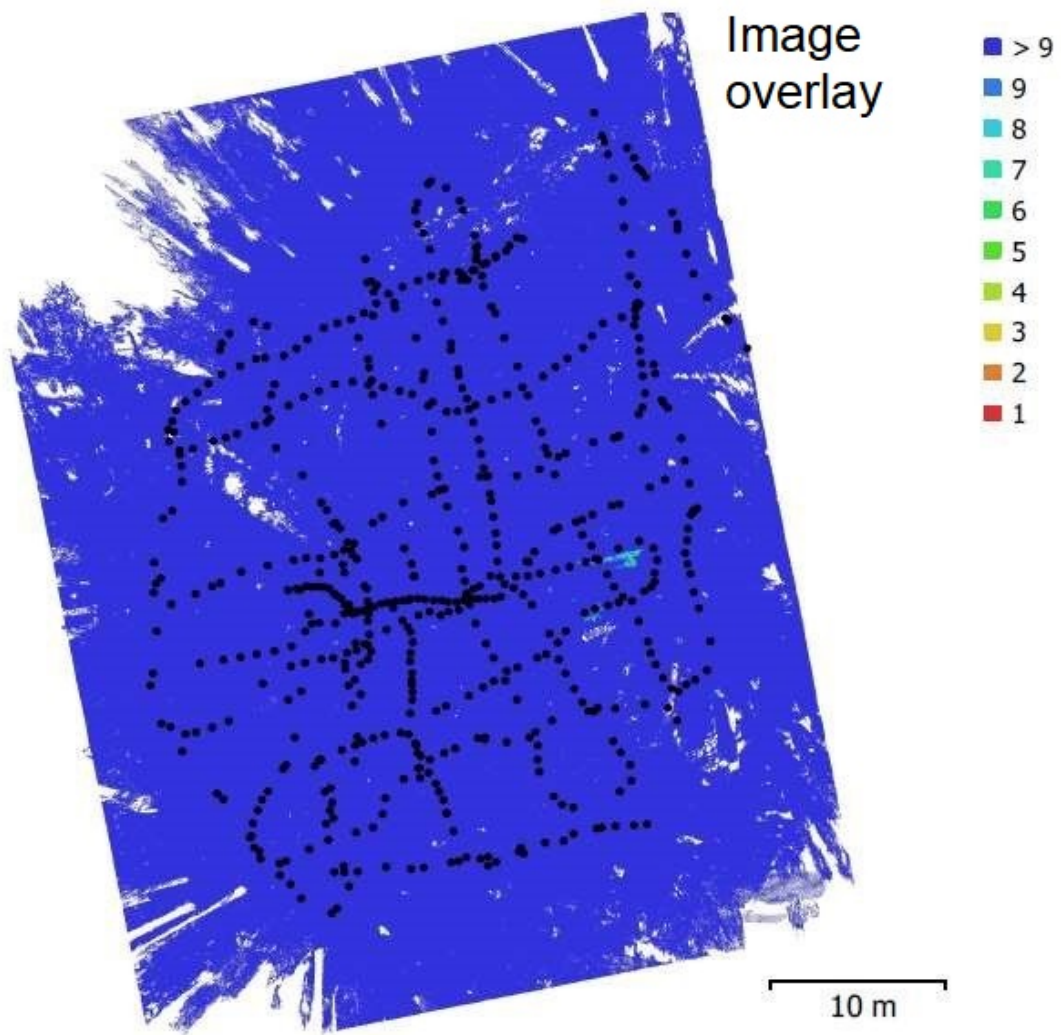


Figure 11 Trajectory of the Sony camera imaging. The blue colour interprets the overlay of more than 9 images. Black dots are position of camera, when the image was captured.

The trajectory of two GoPro cameras was chosen differently. Cameras moved in circles around each GCP. The reason for the different trajectory was to have easier image alignment.

In Figure 12 is shown the trajectory of imaging by two GoPro cameras.

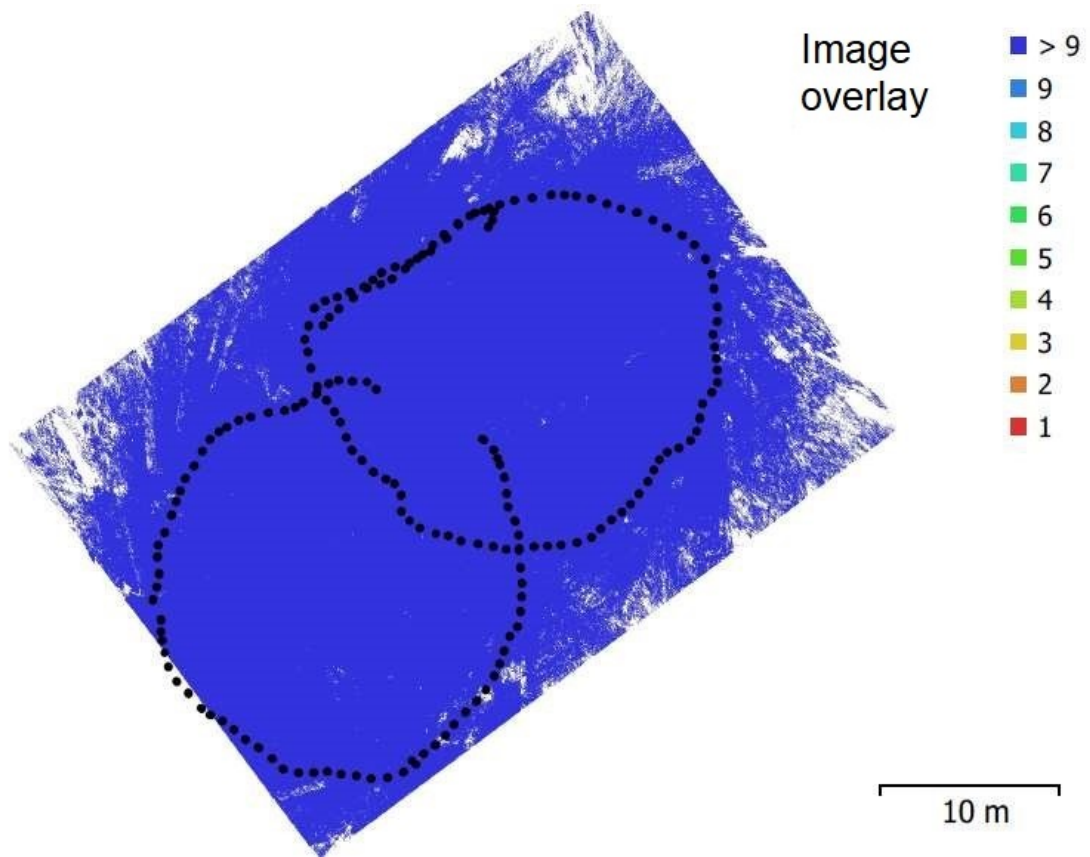


Figure 12 Trajectory of two GoPro cameras imaging. The blue colour interprets the overlay of more than 9 images. Black dots are position of camera, when the image was captured.

2.4 Aerial imagery

Aerial imagery took place in several dates. Data acquisition was conducted from the November 2017 till March 2018. For the aerial imaging of the forest stand, hexakopter DJI 800 (DJI, Shenzhen, China) was used. First step of aerial imaging was to deploy four GCPs. It was necessary to place them to such places, where is possible to see them from the height. After GCPs coordinates acquisition was conducted aerial imagery itself. Thanks to DJI software was possible to set up the flight route beforehand. Flight route with the camera positions is shown in Figure 13.

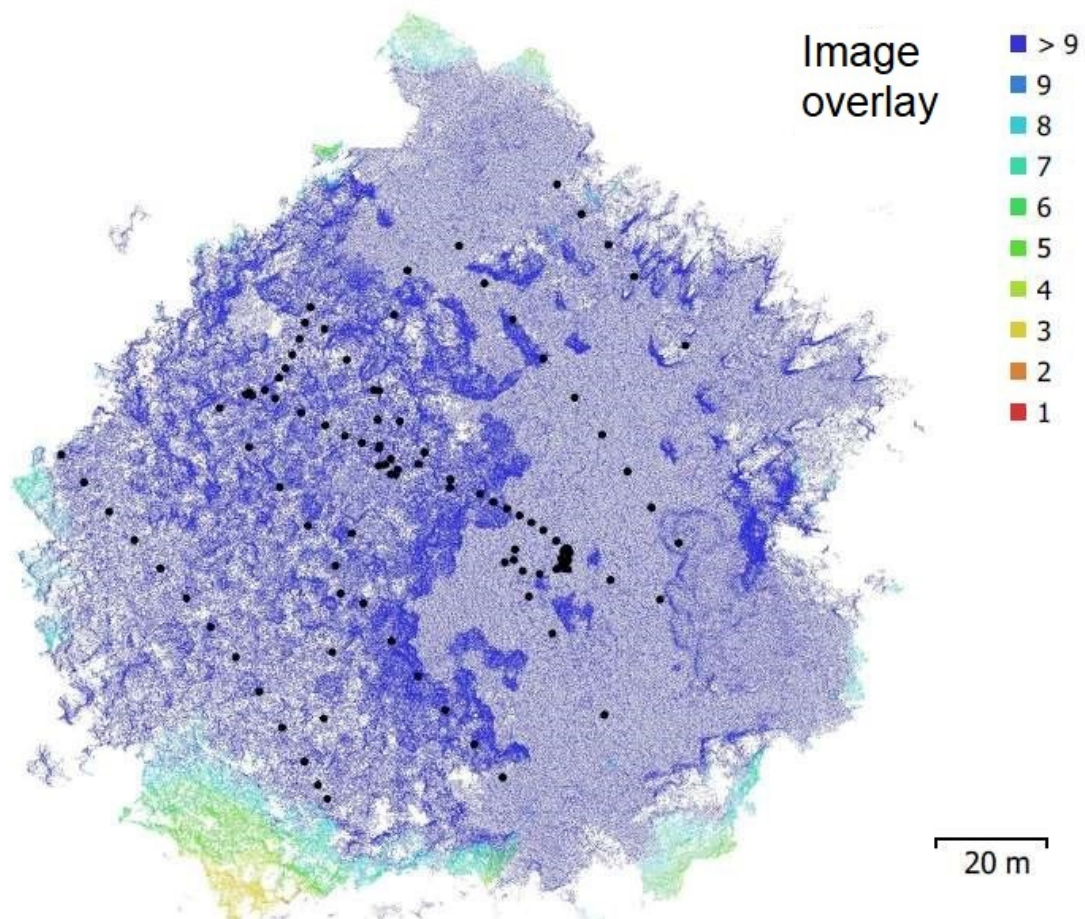


Figure 13 Flight route with the camera positions. The blue colour interprets the overlay of more than 9 images. Black dots are position of camera, when the image was captured.

Imaging was conducted at a height of 74 m and for the experimental plot (0,3 ha) took less than 30 minutes, including the preparation of the flight route. As imaging equipment was the Sony camera carried on the drone. The flight data were imported to the Agisoft PhotoScan software (Agisoft LLC, St. Petersburg, Russia), and were processed to 3D surface model.

2.5 Image acquisition evaluation

Aerial imagery went smoothly and the data from it had high quality, so their processing in the PhotoScan was smooth. Terrestrial imagery was done six times in total. The reason was the low quality of the acquired data, or data acquired inappropriately. At the first imagery, it was captured a proper number of images with sufficient overlap, but the camera settings were wrong. That mistake was done by the wrong used ISO sensitivity, which was chosen too high and hence multiple luminous noise caused blurred images. Such poor, blurred images was not possible to use for the DBH estimation, because the estimated values could be negatively influenced. Also, it would not be even possible to process the images to 3D

models. Other problems with terrestrial imaging were low image overlap, wrong angles of camera tilt, what caused for example inappropriate tree stem capturing. A few times was the quality of images decreased and influenced by light conditions and also by the climatic conditions, so the imaging had to be repeated.

After completing the field works, collected data were loaded to the Agisoft PhotoScan software and processed to a dense point cloud, which was processed in the ArcGIS ArcMap software.

2.6 Data processing in Agisoft PhotoScan

Data from the aerial imagery contained 290 images in total. In terrestrial imagery was captured 1317 images in total. For GoPro cameras was 4K video regime used, later was the video cut to a single images. Possibility of video data collecting was used, to try a fast data collection, with quite fast movement in the forest. Images were extracted from the video as one image for each second of the video, so it was collected 384 images in total. Agisoft PhotoScan software (Agisoft LLC, St. Petersburg, Russia) is a software, that allows automatic data processing in digital photography form. Software uses SfM algorithms and provides 3D point cloud creation and 3D spatial data, digital models as well.

After many data processing unsuccessful tries, image editing was necessary. Zoner Photo Studio X (Zoner software, a.s., Brno, The Czech Republic) was used to edit images. Software provides a bulk filter to make sharpen images and also a simple vignetting, which highlight the stems in the middle of images. Those two steps were very useful and significantly improve the input data for Agisoft PhotoScan.

A first step in data processing in Agisoft PhotoScan was inserting coordinates, which served for connecting a point cloud to a cadastral network. Coordinates of GCPs were assigned to markers (symbols of single GCP), though which was possible to automatically find markers in all images. Automatic detection of the GCPs was done by the Detect Markers tool. At the aerial data processing there was no problem with automatic detection of markers, because all projections were perpendicular, so software could detect them. For images from the terrestrial imagery, only one marker was detected. Software could not detect markers, whose projections were not exactly perpendicular.

Because all the GCP were not detected, it was necessary to find 5 of them manually. With high quality of images there were no problems with manual detection. This manual detection procedure is time consuming, but it can greatly affect the quality and precision of the results.

When all markers were detected, images were aligned for the purpose to determine the inner and outer orientation elements. This was done using the Align Photos tool, with the high accuracy, because then the tool works directly with full image resolution.

Subsequently the Optimize Camera Alignment tool was used to fully automatic alignment of the inner and outer orientation elements. With these steps a so-called sparse cloud of points was created. This cloud of points counts tens of thousands of connecting points, which then generate a so-called dense point cloud. A very important step is to filter these connection points. In the first few attempts to create a dense point cloud, this filtration was not performed, which affected the computing time of the dense point cloud for up to several tens of hours. Filtration of the connection points was performed by the Gradual selection tool, which is used to filter out connection points unnecessary for dense cloud formation. Connecting points were filtered based on 4 criteria. The values given in Table 1 were considered as optimal values.

Table 1 Criteria used for filtration of connection points for all data.

Criteria	Value
Reprojection error	0,5
Reconstruction uncertainty	10
Image count	2
Projection accuracy	6

From the photos taken with the Sony camera, a sparse point cloud after filtration contained 66,000 connecting points, 42,000 points of GoPro cameras and 18,000 points of aerial photography.

After processing and editing the input data, Build Dense Cloud tool created a dense point cloud that allows filtering of distant points alongside the resulting quality. High point cloud

quality and slight filtering of outlying points were selected. Figure 14 shows a dense point cloud from the drone data and from the ground imaging.

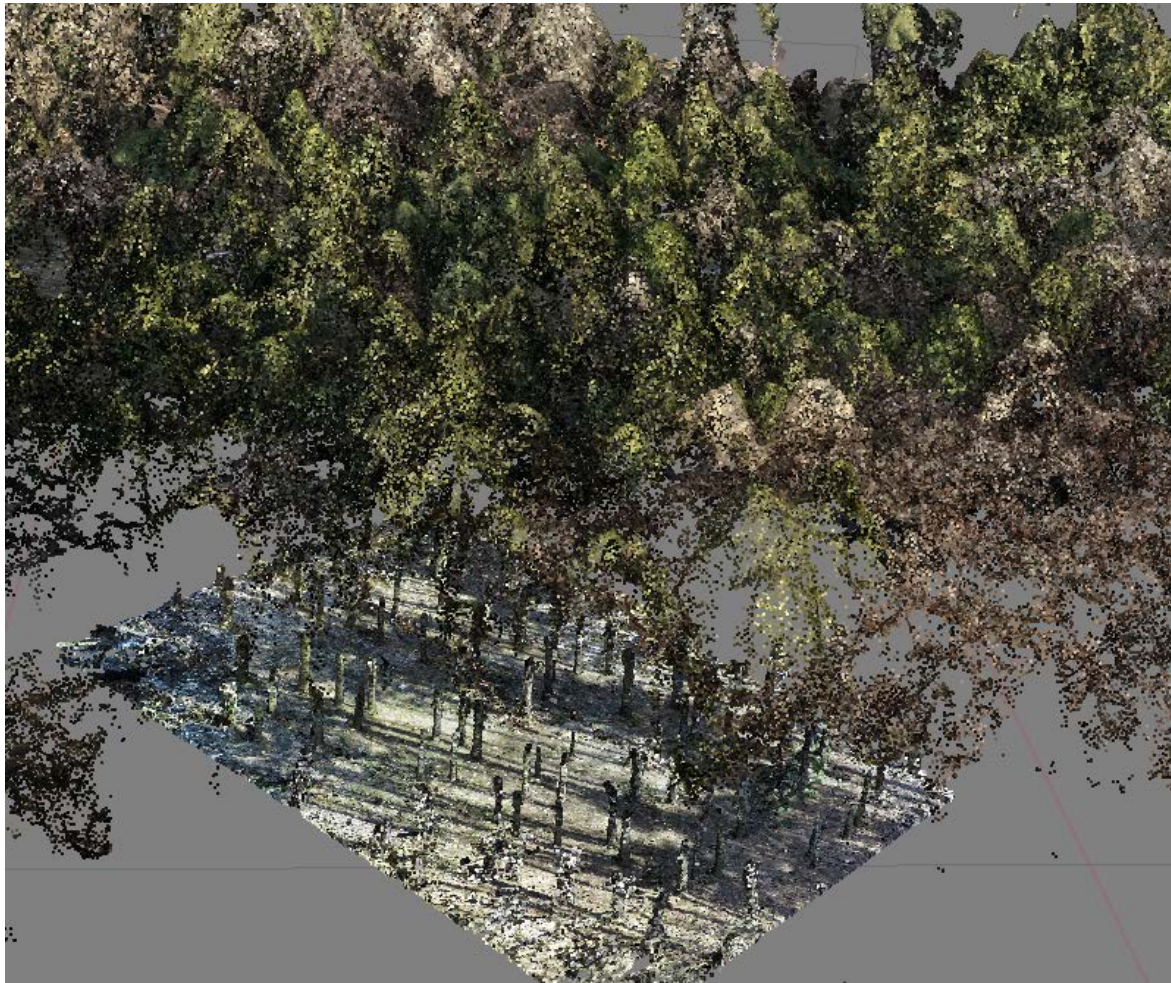


Figure 14 A dense point cloud made from aerial and terrestrial imaging data.

The resulting dense point cloud contained more than 56 million points from Sony images, 35 million from GoPro images and 1.5 million from aerial images. Figure 15 shows a 3D model of stems from the photogrammetric point cloud.

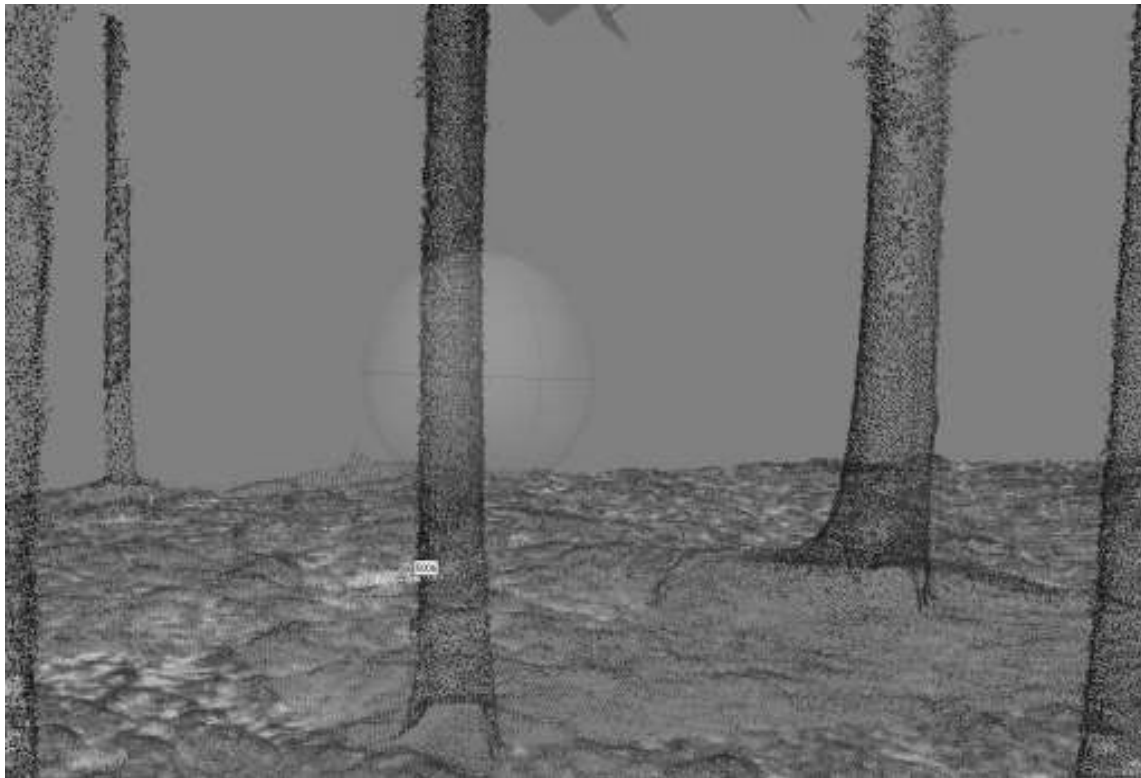


Figure 15 3D model of stems from the photogrammetric point cloud.

So far, the procedure for data processing from both aerial and terrestrial imagery has been almost identical, except for minor variations. To calculate the DBH, a dense point cloud has to be transferred to ArcGIS ArcMap software. This transfer was done by exporting points in * LAS 1.3 format. This points export was done using the Export Points tool. The dense cloud dataset was then processed using the LAStools extension for ArcGIS. That is all in Agisoft software to calculate the DBH from the terrestrial imagery. To calculate tree heights, the dense point cloud was exported as a terrain surface model. This model was the basis for creating a canopy height model (CHM) from which tree heights were calculated in SW ArcMap.

2.7 Point cloud processing in ArcMap

Determination of tree heights was done using the inverse river basin method. This method required a digital terrain model (DTM), which was used by aviation laser scanning (DTM 5G) and was acquired by the university for research purposes, and a digital surface model (DSM) made from UAV images. The entire ArcMap process was based on the automated method presented by Mikita et al. (2016), see Figure 16. The following describes a procedure for calculating the DBH and tree heights for calculating the volume of the individual tree stems.

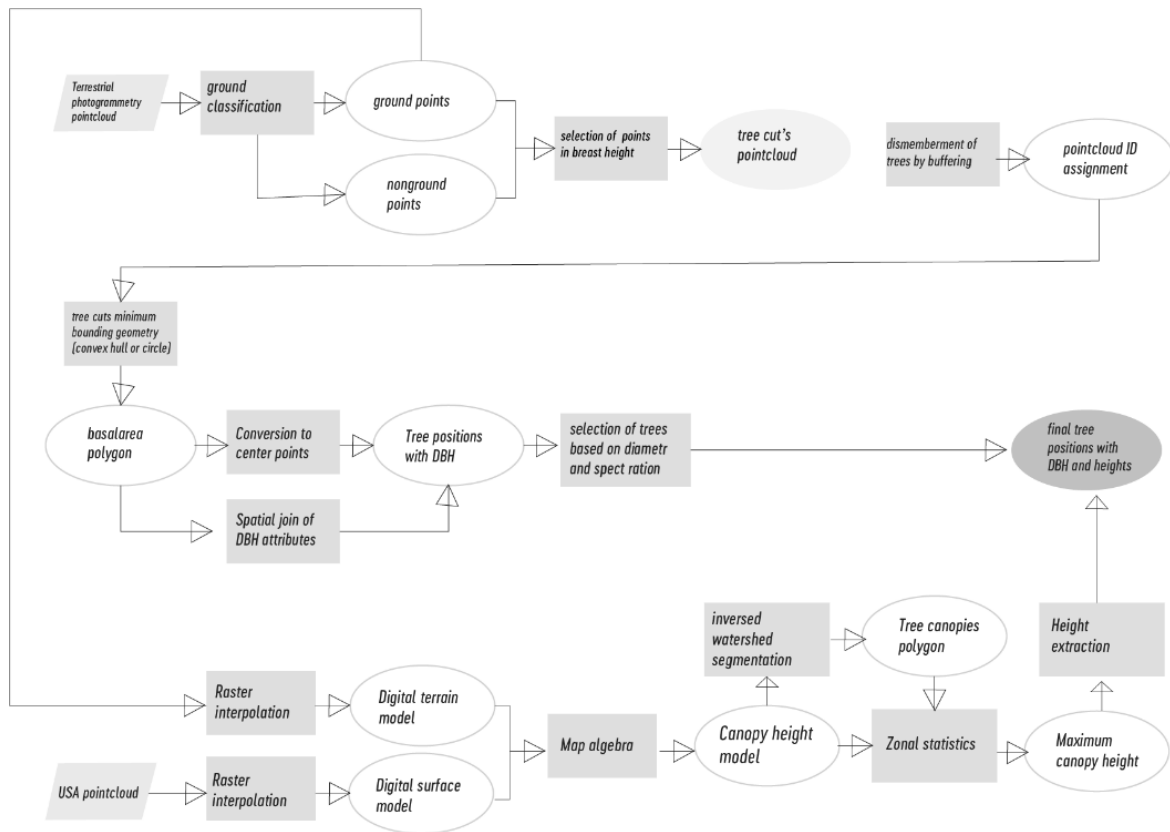


Figure 16 Automated Data Processing Model in ArcMap SW (Mikita et al., 2016).

ArcGIS ArcMap (Esri, 1999) is the cornerstone of the ArcGIS for Desktop toolkit. This software allows analysis of spatial data, its processing and subsequent interpretation in the form of databases or maps. For the Point Cloud Analysis, a superstructure for ArcGIS LAsTools (Rapidlasso GmbH, 2007) was necessary. This extension allows you to work with point clouds from both laser scanning and even photogrammetric point clouds.

First, a canopy height model (CHM) was created by deducting DTM from DSM. Using the Minus tool that subtracts DTM bitmap values from DSM, CHM was created. Because the CHM model was very detailed, it was necessary to generalize it using the Focal statistics tool. Highlighting the model was necessary to create unique crowns for each tree. Without this generalization, some or two peaks could be distinguished for some trees, which was undesirable.

Using the Negate tool, the CHM was multiplied by -1, in the overturned vertices of which a downward depression occurred. Subsequently, flow direction was calculated by plotting the flow direction and using the Flow length tool. In each of the depression, the microchannel

was calculated, at the lowest point of which was the position of the top of the tree. Figure 17 shows the micro basin generated by CHM overturning. At the lowest point of each micro basin is the position of the top of the tree.



Figure 17 Micro basins with detected tree tops. A sample of the plot.

The micro basin points with the smallest value, ie zero, were to be classified as the tree top. This classification was performed by the Reclassify tool when the original zero values were converted to 1 and all other original values were removed. The result was a raster layer of point character that contained exact positions of tree tops and elevation data. The rag layer was transferred through the polygons to the point layer with information about the location and height of the tree. Figure 18 is a 3D view of the CHM cross section with micro basins and detected tree tops.

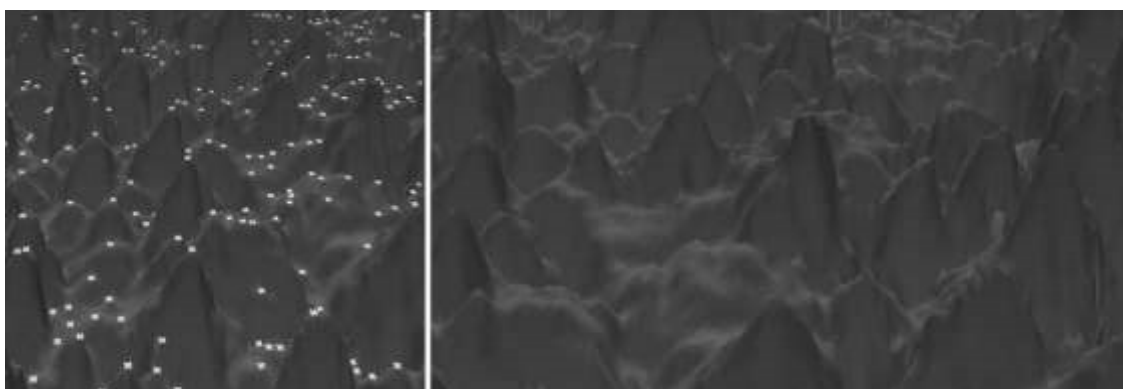


Figure 18 3D CHM cross section preview with visualization of detected tree tops. Yellow dots represent the tree tops (left) and to the right 3D CHM cross section.

The point layer of trees detected from drone data was assigned to the point layer of the terrestrial measured trees using the Spatial Join tool. Assignment was made on the basis of the spatial proximity of the peaks and treetops. In the attribute table of the resulting layer, it was already possible to subtract the height differences detected against the heights measured.

Data for estimates of DBH has to be exported from Agisoft PhotoScan software in *. LAS format i.e. point cloud. Using the LAStools tool kit extension, the point cloud was modified into single trunk sections. Since the point cloud was too large, by the Lasthin tool it was narrowed, and the cell size was 1m. To achieve the height value at different distances from the ground, it was necessary to classify the ground. The tool found the lowest point of each cell and thus classified the ground points.

The cut of the stems at the DBH was performed by the Lasheight tool, where all points of the point cloud from 1.30 m to 1.35 m above the ground were selected. The resulting point cloud was then converted to the shapefile format. Figure 19 shows an outline of the plot with cutouts of individual trees at height of 1.3 m.

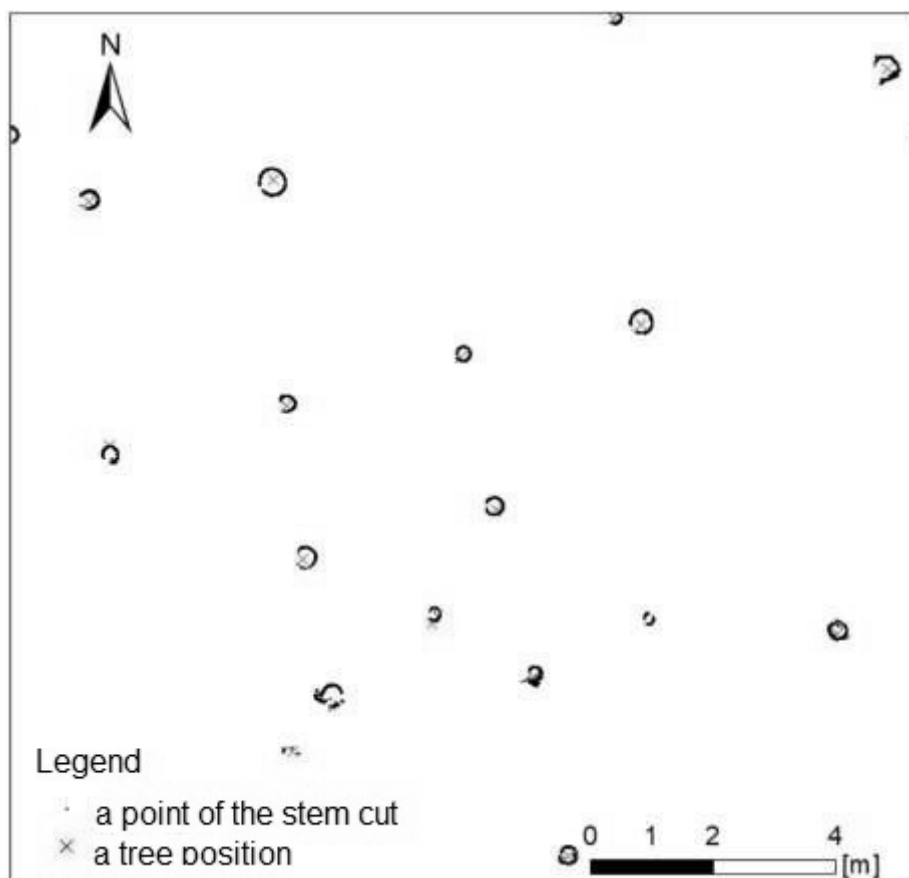


Figure 19 Stem sections at a height of 1.3 m, a part of the experimental plot.

It is evident from Figure 19 that not all sections are evaluated completely. Figure 20 shows the cut options, from perfect to average or bad. The red cross represents the center of the trees' location from the ground measurement.

At the top of the figure there are almost perfect cross sections of the trunks (Figure 20a), on the basis of which the estimated DBH was influenced by a small error. In the Figure 20b, the cross sections are average, and the errors were different in DBH estimation, according to the geometric shape used (circle fitting; convex hull) method. No accurate data could be obtained from the cross sections shown in the Figure 20c.

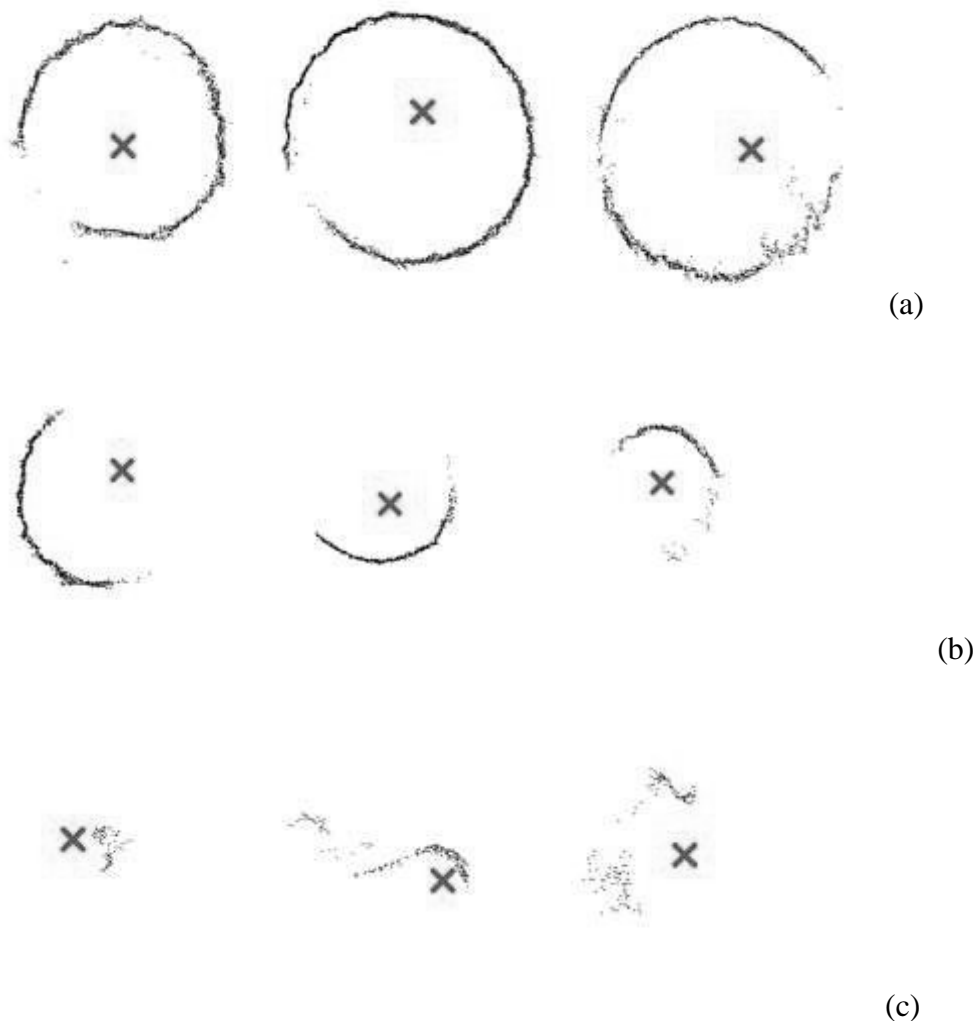


Figure 20 Examples of the stem cross sections. Perfect (a), average (b), bad (c).

The shapefile point cloud was wrapped using the Buffer layer with a continuous layer created by joining all of the points' buffers. Using Multipart to Singlepart tool, complex buffers were

divided into single points that were then linked to the points of the original cloud using the Spatial join tool.

To determine DBH, the Minimal bounding geometry tool was used to create a continuous border layer around the cross-section points. The tool allows to select a few methods, from which the circle fitting and the convex hull were chosen.

Figure 21 illustrates examples of the trunk section results using the circle fitting method. The blue circle represents the resulting matrix on which the DBH was calculated. The circle fitting method is better suited for incomplete cuts, where it calculates the missing section of the cut into a full circle.

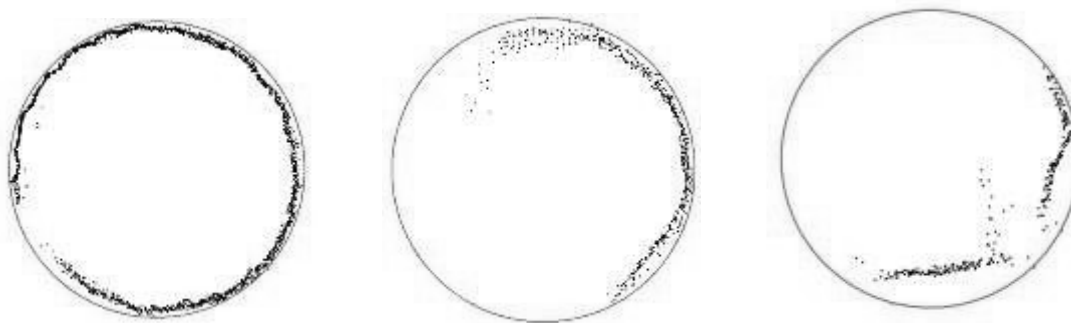


Figure 21 Example of delineation of stem cross sections, circle fitting method. On the left is a perfect cut, the middle average and the right cut is wrong.

Another method for obtaining DBH was the convex hull method. This method is best suited for perfectly formed stem cross sections where it accurately copies the trunk circumference and the accuracy of the estimated values is then very high. However, if the method is used for average or even wrong cuts, the resulting values are very inaccurate, see Figure 22.

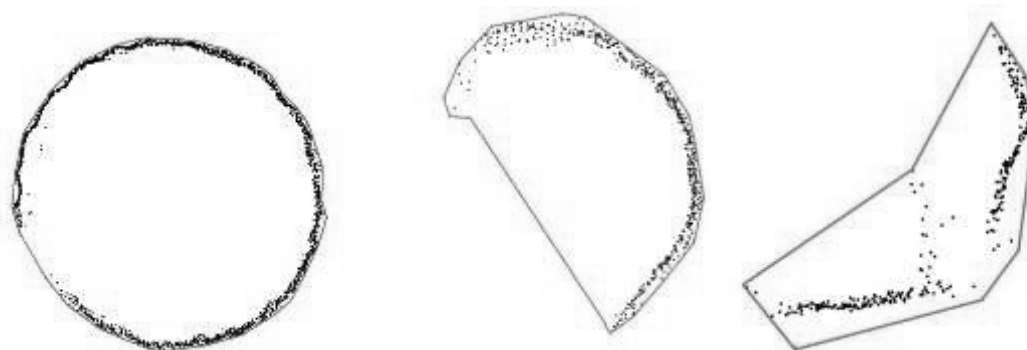


Figure 22 Convex hull wrapping method. On the left is a perfect cut, middle average and right cut is wrong.

Using the Feature to Point tool, stem cuts polygons were converted to points with the center of gravity of the stem, and then assigned to ground measurement points. In the attribute table, the DBH of each tree were then calculated.

2.8 Stem volume calculation based on aerial and terrestrial photogrammetry data

The volume of individual stems was calculated on the basis of the estimated DBH and tree heights, from which the stand volume was derived. The stem volume was calculated with a function for Norway Spruce (*Picea abies*) in Europe by Mikita et al (2016).

$$V = 0.000031989 \times (d + 1)^{1.8465} \times h^{1.1474} - 0.0082905 \times (d + 1)^{-1.0204} \times h^{0.8961}$$

Function 1 Function used for calculating stem volume for Norway spruce (*Picea abies*), (Mikita et al., 2016).

2.9 Statistical evaluation

After estimating the DBH and tree heights, a statistical evaluation of the precision of the estimated values compared to the measured values was performed. For the evaluation, the paired t-test with a significant level at 0,05 and the root-mean-square error were used.

3 Results

Based on the data captured by drone and the terrestrial imaging, the selected stand characteristics were calculated. The DBH, tree heights and stem volume were estimated and compared with the values measured by conventional methods in the stand.

Table 2 lists the basic parameters of the point clouds made from aerial and terrestrial photogrammetry data. The highest point cloud accuracy and subsequent model was achieved with the Sony Alpha NEX-5R camera. The resulting positional deviation was 3.25 mm, while the highest positional deviations were achieved using GoPro cameras, where the resulting deviation was 27.8 mm.

Table 2 Characteristics of point clouds created from aerial and terrestrial photogrammetry data.

Form of data collection	Model resolution [cm/pixel]	Number of GCPs	Deviation [mm]	Deviation [pixel]
Aerial photogrammetry	1,83	4	4,45	0,09
Terrestrial photogrammetry (Sony Alpha NEX-5R)	0,16	6	3,25	0,03
Terrestrial photogrammetry (GoPro HERO 5 Black)	3,57	4	27,8	0,28

3.1 Tree detection on the plots

All 55 trees of the plot were detected during aerial imaging. However, seven trees were mistakenly detected by a neighboring tree or a tree that overlaid this tree with its crown.

For terrestrial imaging, 54 trees were detected using the Sony camera. Only one tree was not detected, and it was a beech with 34,5 cm DBH. The tree was on the edge of the plot, and therefore this error was probably caused by a low overlay of images that captured this tree.

When using the GoPro cameras, one tree was also not identified, and it was a beech with 19,5 cm DBH.

Table 3 lists the differences of the positions detected from the ground imaging compared to the total station target locations. According to the mean square error of 0.27 m, it is clear that the positions of the detected trees are not the same in comparison to the measurements. This error is due to geodetic measurements that measure the position of the tree on the trunk circumference, while for trees detected, the location is determined in the top of the tree. However, this error does not have any effect on the resulting estimates of DBH and heights, because the tree spacing is not less than 1 m, so the attribute linking of the trees measured and detected with this relatively large deviation is possible and correct.

Table 3 Comparison of tree positions automatically detected and geodetically measured.

	Min	Max	Mean	Standard deviation	RMSE
Deviation [m]	0,01	1,78	0,11	0,24	0,27

3.2 Estimation of the DBH

The DBHs were calculated based on terrestrial photogrammetry data and compared with the DBH values measured in the stand. Table 4 lists the minimum, maximum, and mean values of the DBH measured and calculated based on terrestrial photogrammetry data using the Sony NEX-5R camera.

Table 4 DBH measured and calculated from Sony NEX-5R images.

	Min	Max	Mean
DBH measured [cm]	12,0	46,0	27,7
Sony NEX-5R DBH calculated circle fitting [cm]	8,3	51,0	31,1
Sony NEX-5R DBH calculated convex hull [cm]	7,8	44,5	27,1

Two methods - circle fitting and convex hull - were used to calculate DBH. Table 5 lists the differences between measured and calculated DBHs. The convex hull method has produced

more accurate results. According to RMSE, the method is 1.2 cm more accurate than the circle fitting method. The DBH was calculated with a RMSE of 2.9 cm.

Table 5 Comparison of differences with measured DBH (Sony NEX-5R).

Sony NEX-5R	Min	Max	Mean	Standard deviation	RMSE
DBH – circle fitting [cm]	-9,0	9,8	2,0	3,5	4,1
DBH – convex hull [cm]	-6,4	6,8	-0,5	2,9	2,9

Using the circle fitting method, RMSE = 4.1 cm, with the DBH values being overvalued on average. This method, by describing a circle around the point clouds, could cause overvaluation in imperfectly modeled stem cuts, or overestimation of stems with unevenly circular cross-sections.

Figure 23 on the right shows that the convex hull method slightly underestimates the DBH. This method accurately copies the point clouds and cannot overvalue the thickness. However, the method is only applicable to perfectly processed point clouds, because poorly generated stem cuts could significantly underestimate the DBH values.

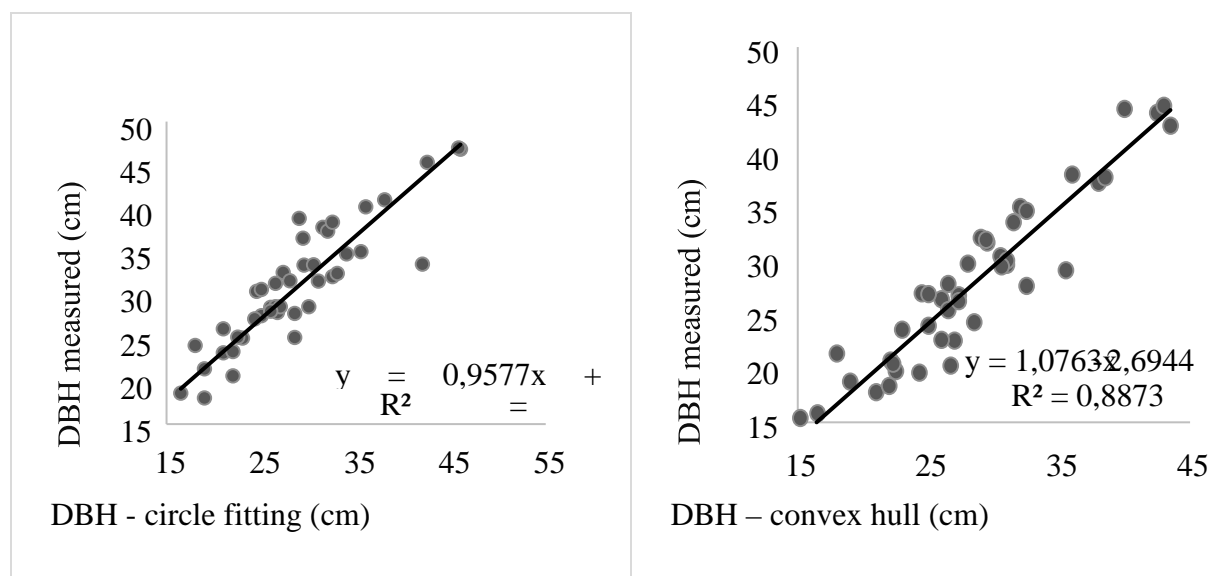


Figure 23 Comparison of measured DBH with DBH calculated by circle fitting (left) and convex hull (right).

Table 6 lists the DBH measured and calculated from terrestrial photogrammetry data using GoPro HERO 5 cameras.

Table 6 DBH measured and calculated from GoPro HERO 5 images.

	Min	Max	Mean
DBH measured [cm]	16,5	42,5	28,2
GoPro HERO 5 DBH circle fitting [cm]	28,3	42,5	29,1
GoPro HERO 5 DBH convex hull [cm]	11,7	42,0	26,8

Using cheap GoPro cameras brought comparable results. The capture was fast, but it depended on good weather conditions more than Sony camera. Compared to the results from the Sony NEX-5R, the RMSE was a few millimeters higher. Using the circle fitting method, the results of the two sensing devices almost did not differ (1 mm), but for the convex hull method, the error was greater by 8 mm. Also, the thickness overvaluation trend in the circle fitting and devaluation method of the convex hull method was comparable. According to GoPro results (Table 7), both methods could be evaluated and compared. For both sensors, better results were achieved with the convex hull method, with the difference between RMSE of 12 mm (Sony) and GoPro 5 mm, respectively.

Table 7 Comparison of differences with measured DBH (GoPro HERO 5).

GoPro HERO 5	Min	Max	Mean	Standard deviation	RMSE
DBH circle fitting [cm]	-4,2	8,4	0,3	4,2	4,2
DBH convex hull [cm]	-7,7	4,2	-1,4	3,4	3,7

3.3 Estimation of tree height

Heights of individual trees were calculated from aerial photogrammetry. Table 8 shows the values of the heights measured in the stand and the values of the heights calculated. Tree heights were evaluated from a basic set of data of 55 trees. The minimum height-calculated value - that is 0 meters - represents the value when the tree was not identified, and its height could not be estimated.

Table 8 Measured and calculated tree heights.

	Min	Max	Mean
Height measured [m]	12,4	34,3	27,5
Height calculated [m]	0	31,6	27,1

The results of the comparison of differences in measured and calculated heights are given in Table 9. Extreme values of height difference (-29 m and 16.6 m) were due to incorrect detection of a particular tree. This error occurred with seven trees, due to the detection of a tree next to it, or a tree that covered its tree in the sub-level with its crown. Because of these extreme values, there was no good results from the statistical comparison. Incorrectly detected trees were in lower canopy layer, deciduous trees, larch without assimilation apparatus or dead tree. After removal of the extreme values from the basic file, significantly better results were achieved. The mean value of the differences of the heights to be compared has dropped to 0.01 m and at the same time there was a significant decrease of the total mean quadratic error to 1.5 m, which means that the method of estimating tree heights is much more suitable for spruce monocultures or its application must be carried out during the vegetation period.

Table 9 Comparison of differences in measured and calculated tree heights.

	Min	Max	Mean	Standard deviation	RMSE
Height [m]	-29	16,6	-0,4	6,8	6,8
Height, without the extreme values [m]	-3,2	5,85	0,01	1,4	1,5

Figure 24 shows the relationship between heights measured by conventional methods and heights calculated from aerial photogrammetry data. Extreme values of poorly detected trees significantly affected the resulting accuracy of the estimate. It can be seen from the chart that values nearing the mean value are underestimated.

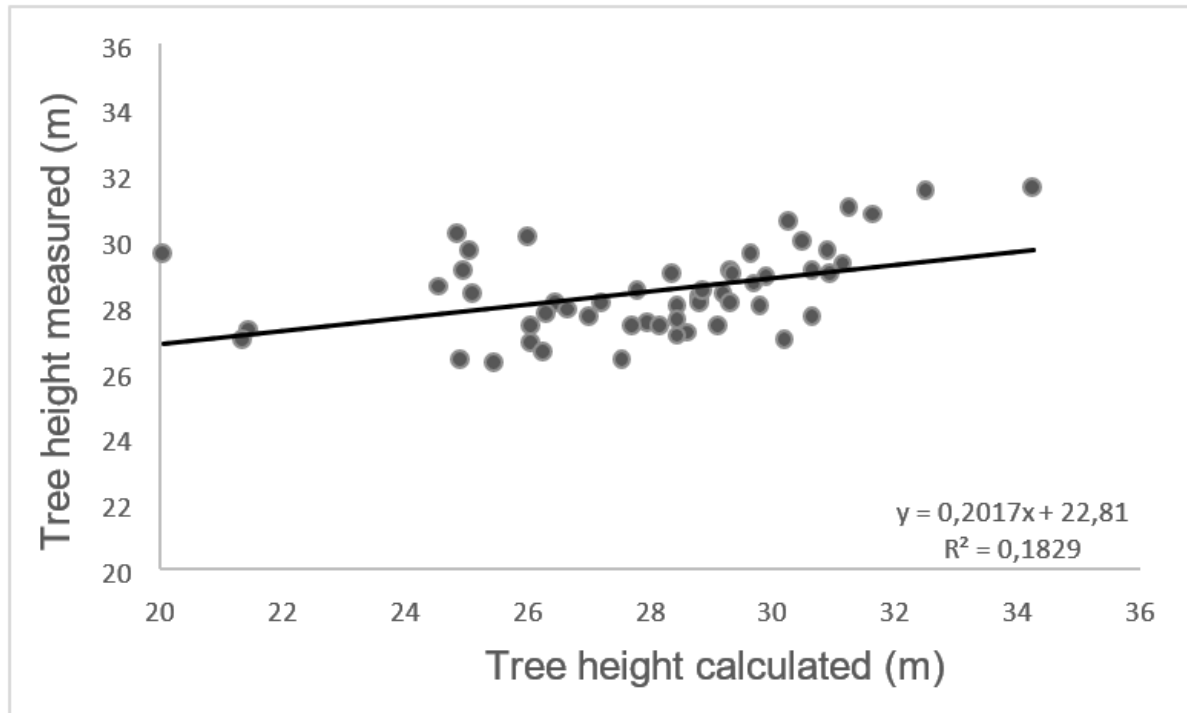


Figure 24 Comparison of heights measured with heights calculated.

The relationship between measured heights and heights calculated without extreme values is shown in Figure 25. It is clear from the figure that the heights are relatively evenly spaced around the mean value (mean height difference was 0.01 m). The root mean square error RMSE has dropped to 1.46 m, which is a difference of more than 5 m compared to a set of data including wrong, extreme values.

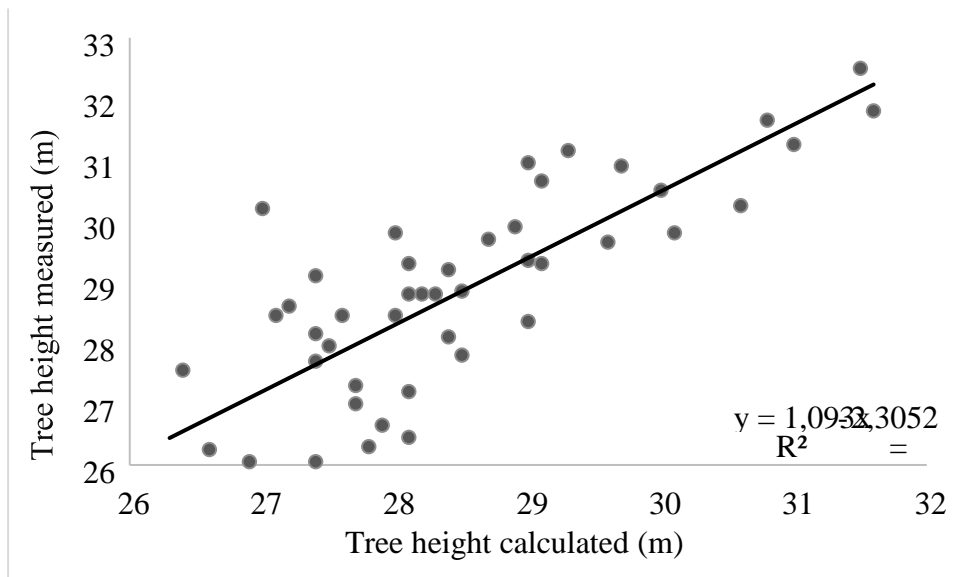


Figure 25 Comparison of heights measured with heights calculated without extreme values.

3.3 Tree stem volume estimation

Based on the calculated values of DBH and tree heights the volume of individual stems was calculated (Table 10). This volume was calculated from both methods (circle fitting, convex hull). The standard deviation of 0.17 m^3 and the RMSE 0.19 m^3 were obtained by comparing the values calculated with the real values measured in the stand. The resulting volumetric values correlated with the values of the DBH. Consequently, for the convex hull, a standard deviation of 0.16 m^3 was reached and the RMSE also dropped to 0.14 m^3 .

Table 10 Comparison of differences in measured and calculated volumes of individual stems (Sony NEX-5R).

Sony NEX-5R	Min	Max	Mean	Standard deviation	RMSE
Stem volume circle fitting [m^3]	-0,45	4,25	0,08	0,17	0,19
Stem volume convex hull [m^3]	-0,39	0,26	-0,04	0,13	0,14

As shown in Figure 26, it was possible to reaffirm the trend when the volume values for the circle fitting method were slightly overestimated, while the convex hull method was underestimated.

It was also found that the RMSE was again lower for stem volumes calculated from the convex hull method. The RMSE value was 0.14 m^3 , and therefore 0.05 m^3 lower than the circle fitting method.

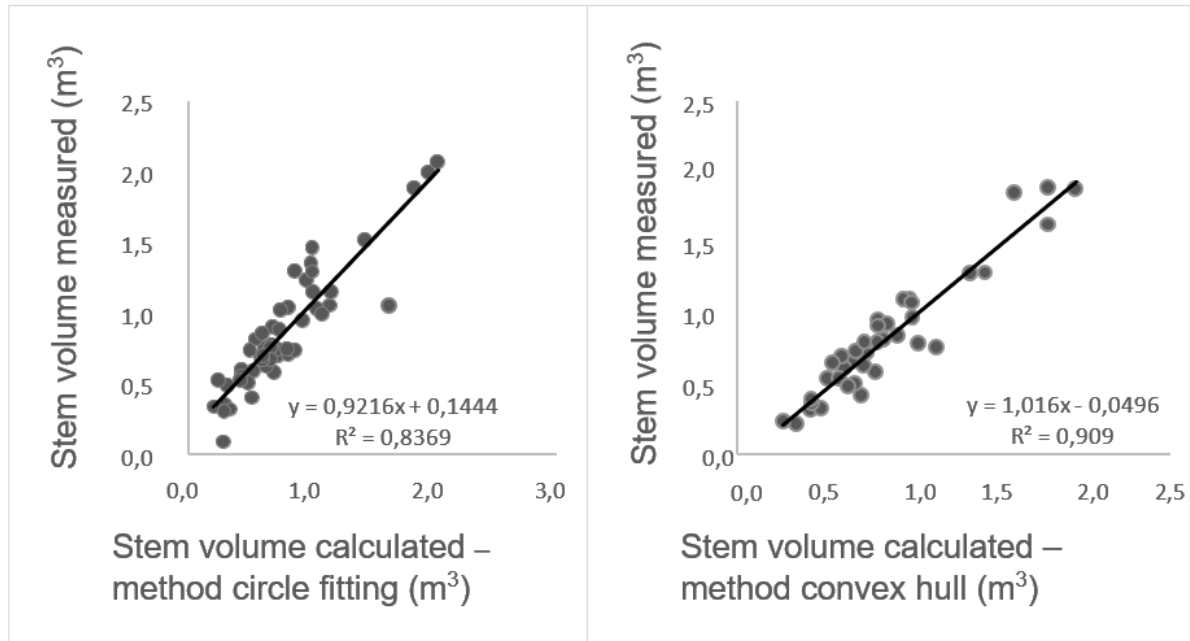


Figure 26 Comparison of measured volumes with stem volumes calculated by circle fitting (left) and convex hull (right).

3.4 Assessing the time demand of forest inventory technology from photogrammetric point clouds

Data collection for forest inventory from the photogrammetric point cloud was relatively fast. In a two-person team, GCPs were measured in approximately 30 minutes. Data collection of 55 trees on an area of 0.3 ha was divided into several steps. The geodetic measuring of the tree positions took approximately 20 minutes, with the simultaneous measurement of DBH. Subsequently, aerial photography (fully automatic data collection) was carried out simultaneously with the measurement of tree heights, which took about another 20 minutes. Terrestrial imaging by one device took about 10 minutes. Thus, the total time demand of the forest inventory technology from the photogrammetric point cloud was approximately 80 minutes for the area of 0.3 ha. For one hectare of forest cover, the time requirement could be 120 minutes. This time period is then extended by the computation time. By using top-of-the-line imaging techniques and thus direct data processing capabilities, it would be possible to achieve a 20-hour computing process with a minimum of time for the operator. The process of this work was time consuming and computer

technology took in the order of hundreds of hours. The reason was the effort to find optimal parameters for editing raw images, but above all to find parameters for creating point clouds.

Aerial imaging, provided the optimal weather and light conditions, is not affected by the stand character and the time requirement is so constant. Terrestrial imagery, however, is unlike the highly influenced by the stand character. Measurement of tree heights can be time-consuming, depending on tree species, canopy density, season, or visibility. Thickness measurements as well as ground imaging can be significantly affected by dense undergrowth or PCT residues. Due to the high variability of forest stands, the time intensity of forest inventory technology from the photogrammetric point cloud is very diverse.

4. Discussion

4.1 Forest stand characteristics estimation workflow

The technology of forest inventory from a photogrammetric cloud point is, in my view, a highly competitive method of forest inventory based on aerial or terrestrial laser scanning data. UAV technology as a carrier of aerial imaging and commercially available cameras is very progressive and affordable. Presented technology has a great advantage in a relatively easy methodical procedure that does not require complicated training. Professional drones are supplied with software that allows precise flight planning. Therefore, there is no need for special education in drone control, and the basic computer skill is sufficient. In terrestrial imaging, it is necessary to know at least the basics of photography and how to set camera parameters under different lighting conditions.

When processing raw data, it is necessary to know how to edit photos, especially the creation of bulk filters, because of large amounts of images. Depending on the area of the surveyed area, resp. the number of pictures can range from hundreds to tens of thousands of images at the desired data quality. When data processing in Agisoft PhotoScan, the biggest challenge is the extreme demands on computing. Photo copying and cloud creation can be handled by regular PCs, however, for faster calculations, extra performance is essential. When creating a dense point cloud on a high-performance computer, the calculation time for an area of 0.3 hectare ranged depending on the required quality in tens of hours. By combining 4 computers in order to reduce the computational time, the time requirement was greatly reduced.

Working with ArcMap is no longer so time-consuming, and the automated method of estimating tree DBH and tree heights is almost unnecessary for human intervention. The most important step is to find the appropriate parameters and the required quality of individual outputs. Then, after summarizing these steps to create an algorithm directly in ArcMap, it is enough just to upload input data, let the program run automatically, and finally pick up the finished results.

4.2 Factors affecting data collection

Although data collection is very fast and can be applied in any stand, the factors that affect technology are many. The most important factor that affects both ground and aerial imagery is weather. Strong winds and rainfall are factors that make data collection impossible.

Compared to laser scanning, where these factors play a much smaller role, the photogrammetric data capture approach is limiting. Light conditions are very variable, both during the year and during the day. Under clear weather, a high incidence of shadows occurs in the forest. These shadows have a significant effect on the formation of point clouds, since the imaging of one tree from multiple angles results in a change in the ratio of the luminous and shaded area of the trunk, which makes it difficult to find connecting points, and can increase the point cloud error. If there is an inaccurate point cloud, the accuracy of the estimated characteristics is reduced. In my opinion, the most suitable conditions for imaging is slightly cloudy to cloudy, provided the light intensity sufficient to capture high-quality images under the stand canopy.

Other factors are the number of trees, the undergrowth density and the average DBH. Terrestrial imaging is affected by the distribution of trees in the stand; if the spacing is dense, it is necessary to adjust the imaging trajectory. The lower the number of trees in the stand, the shorter the imaging trajectory can be. However, if the number of trees in the stand is high, it is necessary to extend the route, ie in the case of the line route - to reduce the spacing between the lines, in the case of a circular path to reduce its radius. For high-quality output, it is necessary for the imaging trees to be captured from all sides, so that a perfect cut of the stem can be created. For example, when using this technology for forest valuation, the accuracy of estimating DBH is very important. Density of the undergrowth can also negatively affect cloud formation and it can have a large impact on the ease of passage through the stand and at high density then significantly affect the time demand of the imaging. In order to obtain accurate DBH, the method appears to be suitable for stands at the felling age where the DBH exceeds 25 cm. In the work, trees with lower DBH were modeled with a higher error than trees with bigger diameter.

Different imaging techniques produce different quality data. Two types of imaging devices were used in this work, namely the Sony NEX-5R and two GoPro HERO 5 cameras. For all the rated features, better results have been achieved with the Sony camera. For example, when calculating tree diameter, the RMSE at the Sony camera gave 5 mm lower values. This difference is not great, but I think it makes it possible to judge the quality of the image. I also think that if a more powerful camera is used, much better results would be achieved.

4.3 Accuracy of results

This diploma thesis explores possibilities of estimation of stand characteristics based on photogrammetric cloud of points. In the work were evaluated the basic vegetation characteristics - the DBH, the height of the tree and the stem volume.

4.3.1 Deviation of position of detected trees

An important criterion for the derivation of the forest characteristics is the accuracy of the forest model and, above all, the accuracy of the positions of the trees detected. In this study, tree position deviations of 0.24 m were obtained from geodesy-oriented locations with 0.27 m RMSE. These deviations are due to a different approach in position acquisition. For geodetic positioning, the value is subtracted at the surface of the stem rather than at its center, while the tree's location is determined at the center of the stem top when the tree is detected from a 3D point cloud. The deviation of this work is comparable to other studies. Forsman et al. (2016) reports deviations of up to 0.5 m. Mikita et al. (2016) states that the positional accuracy of the detected trees was subject to an error of RMSE of 0.46 m. From the point of view of influencing the results of the calculated stand characteristics, this error is negligible, because the spacing of premature stand or mature stand is several times higher than 0.5 m, therefore, the next tree can not be detected.

4.3.2 Diameter at breast height

In the case of an estimate of the DBH, different results were obtained in this study. Two methods for assessing the thicknesses of the stem, namely circle fitting and convex hull, were used to derive the DBH. For both sensing devices, the results of the convex hull method were better. This is confirmed by the results of Mikita et al. (2016), where the convex hull method also provided better results than circle fitting.

The imaging was done with two types of instruments. Better results came from the Sony camera when the RMSE of 2.9 cm was achieved with the convex hull method compared to RMSE 3.4 cm for GoPro cameras. Compared with studies by other authors, the results are worse and better. Mokroš et al. indicates that the mean deviation of the DBH from the measured values was 5.2 cm. In the case of this study, the mean variation was at best only 2.9 cm. In another study (Forsman et al., 2016), the accuracy of an estimate DBH with RMSE of 7.2 cm was achieved, which is higher than 4 cm in comparison with the results of this work. Other studies of the DBH calculation have achieved significantly better results. In the

study, Surový et al. (2016) was a 5-cameras used, where is possible to see a significant difference from this study. The difference in the DBH estimated with RMSE of 1.87 cm was so low, because the use of five cameras allowed a good imaging of the stand and the subsequent creation of a very precise model of the stand. Highly accurate results were achieved by Mikita et al. (2016). The accuracy of the results of the estimated DBH was only 0.9 cm RMSE. I think that the achievement of such a high accuracy was also due to character of the studied stand. Studied stand was in felling age with an average DBH of 38 cm. In my opinion, the accuracy of the method of estimation of the DBH is directly proportional to the DBH of the trees of the assessed stand. The higher the values of the surveyed DBH, the more accurate the estimation based on the photogrammetric point cloud is. Important factor, in my opinion, is not only the DBH of the trees, but also the character of the stand, the smaller number of trees per unit area, the lesser the density of the undergrowth and the good lighting conditions.

4.3.3 Tree height

Tree height can be easily and quickly estimated using drone photogrammetry. Based on the results of this work it can be stated that the use of this technology in multi-level stand is not ideal. This is due to the fact that only the tree crowns at the top level of the stand are captured during aerial photography. Trees in lower layers cannot be captured in the image and therefore their height cannot be estimated. A similar trend is also described by Iizuka et al. (2017). Their research carried out in uneven stand reached the same conclusion - the suppressed trees in the sub-level cannot be detected and evaluated their height. In their case the accuracy of the tree height estimation with RMSE of 1.7 m was achieved, which is similar to the results of this diploma thesis with RMSE 1.5 m. However, if technology is used in a uniform, single-level forest, much better results can be achieved. Mikita et al. (2016) achieved a tree height estimation with 1.02-meter RMSE, which is absolutely sufficient for forest inventory purposes. High accuracy was then given by the high uniformity of the stand without many sub-level trees.

UAV/drone photogrammetry for the tree height estimation has several limitations. An important factor is the use of different input data for creating the canopy height model (CHM). This model is the basis for deriving tree heights. CHM is the difference between DSM (digital surface model) and DTM (digital terrain model), where the digital terrain model plays a big role. According to Hyyppä et al. (2008) when using data only from UAV

photogrammetry, the estimated tree heights are underestimated by an average of 0.79 m. This may be due to the slight inaccuracy of DTM created from UAV photogrammetry data, where understory is inaccurately detected as the terrain. For the purpose of this work, DTM 5G was used, a model created by aerial laser scanning, which provides much more precise DTM than UAV photogrammetry. Underestimation of tree heights was minimal in this work. The mean value of the deviations for all trees evaluated was -0.4 m, while in the set of trees without extreme values, the mean deviation was 0.01 m.

Another important factor is, in my opinion, the growing season. Several deciduous tree species (larch, beech) were found on the plot, the height of which was estimated to be very inaccurate. Some trees were not detected at all, and the others were detected, but with large error in position. Consequently, the vegetation period is indifferent to coniferous trees, whereas for leafy trees and larch it is necessary to take into account these problems during imaging, and the time of imaging should ideally be chosen in plots with a fully developed assimilation apparatus.

I assume that the overall accuracy of tree heights is slightly higher than the RMSE values says. I think that measurement of heights by conventional methods is not flawless, and for a very accurate measurement a great deal of effort is needed, and for example, in a dense spruce stand, it is not always easy to find the top of the tree or even correctly measure its height. Accurate measurement would take a lot of time. In my view, UAV photogrammetry is in this unrivaled.

4.3.4 Stem volume

The last evaluated characteristic was the stem volume. The results correlated with the input data error. Using the convex hull DBH and tree heights without extreme values, the RMSE was 0.14 m³, compared to the stem volumes calculated from the values measured in the stand. Mikita et al. (2016) were able to estimate both the DBH and height of the trees with higher precision, so for the estimation of the volume of the stems the RMSE reached only 0.08 m³. I think these results have been achieved thanks to the character of the spruce stand. Therefore, I would not hesitate to evaluate this method of forest inventory as very precise and I would recommend its practical use in mature stands or unmixed premature stand.

4.4 Possibilities to apply in practice

The use of drones in forestry is very well documented by Torresan et al. (2017), which presents 6 possible forest areas for the use of this technology (Figure 6). The interest in these technologies is also documented by Goodbody et al., 2017. Figure 21 shows the development of the number of publications dealing with the UAV. Since 2010, there has been an extreme increase in the number of scientific publications, which is a sign of great interest in technology.

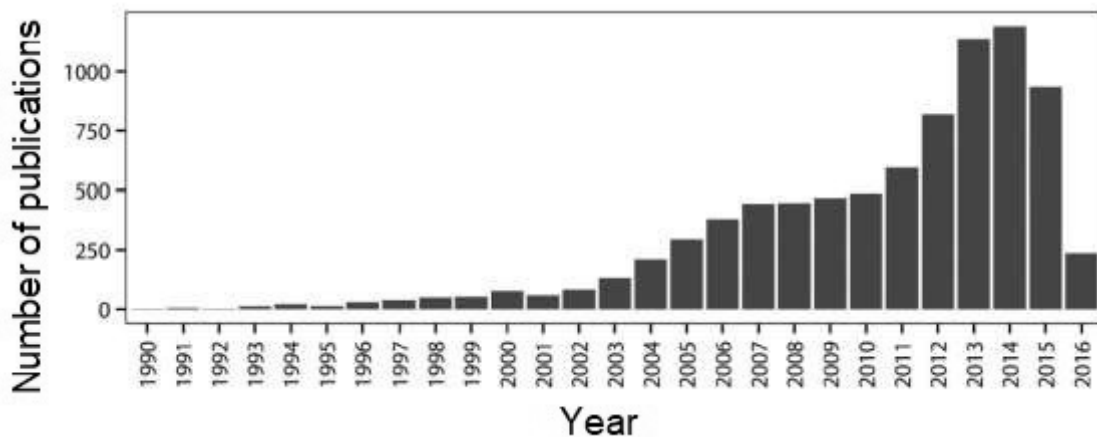


Figure 27 Number of publications about drone use from 1990 to August 2016 (Goodbody et al., 2017).

According to the global trend in UAV research, it is possible to conclude that the potential of this technology is enormous. In my opinion, technology is very variable, and not all of its benefits have been found yet. In the future, we can expect to accelerate and streamline the whole technology through real-time data processing. Thanks to the high-capacity data transfer from the imaging device directly to the remote server where they are processed, these data can be immediately used for subsequent analysis.

If UAV technology is connected to photogrammetry and land-based data collection, a very effective tool for forest inventory is found. Due to the price / performance ratio, the forest inventory technology from the photogrammetric point cloud is insurmountable in the forestry sector. Complete technology can be purchased in the order of tens of thousands of crowns. With a bigger investment (~ 100 000 SEK), it is possible to buy a very powerful device capable of capturing tens of hectares of forest with one flight event.

4.5 SWOT analysis

SWOT analysis in the Table 11 shows the summary of above information about technology and present its strengths and weaknesses, opportunities and threats.

Table 11 SWOT analysis of forest inventory technology from photogrammetric point clouds.

Strengths	Weaknesses
Speed of data collection	High dependence on weather
Simplicity of data collection	High technological demands
Low cost of technology	Limited computing capacity
Sufficient accuracy of outputs	Impossible to collect data in winter for broadleaves
Automated data processing	High time requirements for data processing
Opportunities	Threats
Legislative anchoring of data collection technology	Non-recognition of data collection technology by law
Technique development = increase accuracy of estimation	Develop new, better technology
Inventory of large forest complexes	Prohibition of UAV use
Increased demand for technology	
Development of high-quality Opensource software	
Reduction in technology prices	

5. Conclusions

The diploma thesis deals with possibilities of forest inventory from photogrammetric point clouds. The possibilities of using the technology were examined by estimating the DBH, tree heights and subsequent calculation of the volume of individual stems. These estimated values were then compared with the values measured in the stand.

The research was carried out on a plot of land of 0.3 ha, in a mixed forest dominated by Norway spruce. A total of 55 trees were measured on the area using conventional methods. Data collection took place both on land and in the air. Two imaging devices were used for terrestrial imaging, namely the Sony NEX-5R camera and two GoPro HERO 5 cameras. The image was taken through the passage through the stand with the imaging device carried on the measuring rod. For aerial photography, a drone with a rotating wing that carried the Sony camera was used.

The obtained images were processed into a point cloud in Agisoft PhotoScan SW, and this point cloud was then analyzed in ArcGIS SW. Out of the point clouds, the cuts of the modeled tree stems were extracted at a height of 1.3 m. Two methods were used for estimating the DBH: circle fitting and convex hull. Better results were obtained with the convex hull method, when the RMSE was 2.9 cm.

Tree heights were calculated from the canopy height model (CHM), using the so-called inverse river basin method. According to the results obtained, it was found that the method using the photogrammetric point cloud does not allow the evaluation of tree heights in the deep sub-level. For main level and top height trees, the method is very appropriate and gives accurate results. The deviation of the heights calculated in comparison with the values measured in the stand was subject to a RMSE of 1.46 m, which is sufficient for forest inventory purposes.

The calculation of the volume of the individual stems was affected by the error of the estimated heights and DBH of the trees. The results of the calculated stem volume values were loaded with RMSE 0.14 m³. Technology of remote collection of dendrometric quantities based on photogrammetry is very easy and unpretentious for workers. The time requirement of a complete collection of data on a plot of 0.3 hectare was approximately 80

minutes. Subsequent data processing is, however, much more time-consuming. To create a point clouds, a really powerful computing technology is necessary. Data processing after finding the appropriate procedure and required output quality for 0.3-hectare area took approximately 25 hours. However, computational time can be greatly reduced by the use of powerful computing technology.

The advantage of technology is undoubtedly its low price, which allows periodical inventory of forest stands at short intervals. These very detailed and up-to-date stand data provide valuable information for forest planning and decision making. The biggest drawbacks of technology include high dependence on appropriate weather. Technology cannot be used in strong winds and rain, and sufficient light intensity is also important.

Described technology combining the use of drone and photogrammetry provides a wide range for its use in forestry. Obtaining dendrometric data along with the great flexibility of technology provides increased efficiency in forestry and enables the application of precision forestry. Up-to-date data of stand also allows for the creation of accurate maps, for example, for planning harvesting interventions, including pests preventive harvesting or road network planning. With the help of this technology, it is possible to effectively evaluate the forest regeneration and the state of young forest stands. In terms of forest protection, technology can be used to assess the occurrence and condition of calamity pests, or as a preventive fire protection.

On the basis of the facts described, it is possible to point out the advantages of technology, whose development needs to be further explored and exploit the potential of technologies to 100 %.

Based on the results of this work, it has been demonstrated that the technology can be used for forest inventory, i.e. very accurate estimation of stand characteristics. Estimation of dendrometric quantities is not the only potential application of this technology.

The greatest advantage of the whole technology is the possibility of its operative application, i.e. the possibility of updating the stand data at very short intervals. It is therefore possible to evaluate the actual thinning interventions in the premature stands, for example the development of the regeneration of the stand, but also the potential threat of the stands by calamitous pests.

References

- Advanced Web Technologies. (2018). GoPro HERO5 Black. Available at: <http://obchod.gohd.cz/gopro-hero5-black> [2018-11-27].
- Agisoft LLC. (2006). Agisoft PhotoScan. Available at: <http://www.agisoft.com/> [2018-11-27].
- Asner, G. P. (2009). Tropical forest carbon assessment: integrating satellite and airborne mapping approaches. *Environ. Res.* 3. 1748–9326 p. Available at: <http://iopscience.iop.org/article/10.1088/1748-9326/4/3/034009/meta> [2018-11-27].
- Dandois, J. P., Ellis, E. C. (2013). High spatial resolution three-dimensional mapping of vegetation spectral dynamics using computer vision. *Remote Sensing of Environment* 136. 259-276 p.
- DJI Innovations. (2012). Spreading wings S800 User manual. DJI Innovations, 21 p.
- Esri. (1999). About ArcGIS. Available at: <http://www.esri.com/arcgis/about-arcgis> [2018-11-27].
- Forsman, M., Börlin, N., Holmgren, J. (2016). Estimation of tree stem attributes using terrestrial photogrammetry with a camera rig. *Forests* 7, 61. 20 p. Available at: <http://www.mdpi.com/1999-4907/7/3/61> [2018-11-27].
- Goodbody, T., Coops, N., L Marshall, P., Tompalski, P., Crawford, P. (2017). Unmanned aerial systems for precision forest inventory purposes: A review and case study. *Forestry Chronicle* 93. 71-81 p.
- Changchang, Wu. (2013). VisualSFM : A Visual Structure from Motion System. Available at: <http://ccwu.me/vsfm/> [2018-11-27].
- Iizuka, K., Yonehara, T., Itoh, M., Kosugi, Y. (2018). Estimating Tree Height and Diameter at Breast Height (DBH) from Digital Surface Models and Orthophotos Obtained with an Unmanned Aerial System for a Japanese Cypress (*Chamaecyparis obtusa*) Forest. *Remote Sens* 10, 13. 15 p.
- Lisein, J., Pierrot-Deseilligny, M., Bonnet, S., Lejeune, P. (2013). A photogrammetric Workflow for the Creation of a Forest Canopy Height Model from Small Unmanned Aerial System Imagery. *Forests* 4 (4). 922– 944. Available at: <http://www.mdpi.com/1999-4907/4/4/922> [2018-11-27].
- Mikita, T., Janata, P., Surový, P. (2016). Forest Stand Inventory on Combined Aerial and Terrestrial Close-Range and Photogrammetry. *Forests* 7, 8. 14 p. Available at: <http://www.mdpi.com/1999-4907/7/8/165/htm> [2018-11-27].
- Miller, J., Morgenroth, J., Gomez, C. (2015). 3D modelling of individual trees using a handheld camera: Accuracy of height, diameter and volume estimates. *Urban For. Urban Green.* 14. 932–940 p.
- Mokroš, M., Liang, X., Surový, P., Valent, P., Čerňava, J., Chudý, F., Tunák, D., Saloň, Š., Merganič, J. (2018). Evaluation of Close-Range Photogrammetry Image Collection

- Methods for Estimating Tree Diameters. *Geo-Inf.* 7, 93. 13 p. Available at: www.mdpi.com/2220-9964/7/3/93/pdf [2018-11-27].
- Pix4D. (2011). Meet Pix4D. Available at: <https://pix4d.com/about-us/> [2018-11-27].
- Rapidlasso GmbH. (2007). LAStools. Available at: <https://rapidlasso.com/lastools/> [2018-11-27].
- SmartPlanes. (2018). Rapid aerial assessment of forest windblow. Available at: <http://smartplanes.com/portfolio-posts/rapid-aerial-assessment-of-forest-windblow/> [2018-11-27].
- Snavely, N. (2010). Bundler: Structure from Motion (SfM) for Unordered Image Collections. Available at: <http://www.cs.cornell.edu/~snavely/bundler/> [2018-11-27].
- Sony corporation. (2013). Digitální fotoaparát s výměnnými objektivy. 259 p. Available at: <http://download.sony-europe.com/pub/manuals/consumer/4472075611.pdf> [2018-11-27].
- Surový, P., Yoshimoto, A., Panagiotidis, D. (2016). Accuracy of reconstruction of the tree stem surface using terrestrial close-range photogrammetry. *Remote Sens.* 8, 123. 13 p. Available at: <https://www.semanticscholar.org/paper/Accuracy-of-Reconstruction-of-the-Tree-Stem-Surface-Surov%C3%BDYoshimoto/d4cc5ac88a3cf5aa2f7883e7d3c597edf8ffac49> [2018-11-27].
- Topcon Positioning Systems. (2004). Hiper Pro Operator's Manual.
- Torresan, Ch., Berton, A., Carotenuto, F., Di Gennaro, S. F., Gioli, B., Matese, A., Miglietta, F., Vagnoli, C., Zaldei, A., Wallace, L. (2017). Forestry applications of UAVs in Europe: a review. *International Journal of Remote Sensing* 38. 8-10. 2427-2447 p. Available at: <https://www.tandfonline.com/doi/abs/10.1080/01431161.2016.1252477> [2018-11-27].
- Wallace, L., Lucieer, A., Watson, Ch., Turner, D. (2012). Development of a UAVLiDAR System with Application to Forest Inventory. *Remote Sensing* 4. 1519-1543.
- Wallace, L., Lucieer, A., Malenovský, Z., Darren, T., Vopěnka, P. (2016). Assessment of forest structure using two UAV techniques: A comparison of airborne laser scanning and structure from motion (SfM) point clouds. *Forests* 7, 62. 16 p. Available at: <http://www.mdpi.com/1999-4907/7/3/62> [2018-11-27].
- Zarco-Tejada, P.J., Diaz-Varela, R., Angileri, V., Loudjani, P. (2014). Tree height quantification using very high resolution imagery acquired from an unmanned aerial vehicle (UAV) and automatic 3D photo-reconstruction methods. *Eur. J. Agron* 55. 89– 99 p. Available at: <https://www.sciencedirect.com/science/article/pii/S1161030114000069> [2018-11-27].
- 3DFLOW. (2014). 3DF Zephyr Available at: <https://www.3dflow.net/3df-zephyr-pro-3d-models-from-photos/> [2018-11-27].