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Estimations of Forest Stand Parameters in Open Forest Stand Using Point Cloud Data from Terrestrial Laser Scanning, Unmanned Aerial Vehicle and Aerial LiDAR Data

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Abstract

Two of the very basic forestry parameters, the Breast Height Diameter (DBH) and Tree Height (TH) are very effective when characterizing forest stands and individual trees. The traditional measurement process of these parameters takes a lot of time and consumes human power. On the other hand, 3D Point Cloud (PC) quickly provides a very detailed view of forestry parameters, because of the development of computer processing power and digital storage in recent years. PC data sources for forestry applications include Airborne LiDAR Systems (ALS), Terrestrial Laser Scanning (TLS) and most recently the Unmanned Air Vehicle (UAV). In this study, the PC datasets from these sources were used to study the feasibility of the DBH and TH values of a d development stage (i.e. DBH > 52 cm in mature stage) oak stand. The DBH and TH estimates are compared with the onsite measurements, which are considered to be fundamental truths, to their performance due to overall error statistics, as well as the cost of calculation and the difficulties in data collection. The results show that the computer data obtained by TLS has the best average square error (0.22 cm for DBH and 0,051 m for TH) compared to other computer data. The size of Pearson correlation between TLS-based and on-site-based measurements has reached 0.97 and 0.99 for DBH, respectively.

Keywords: 3D remote sensing, TLS, ALS, UAV, diameter at breast height, forest tree height

1. Introduction

Precision forestry is a management system that aims to provide optimum efficiency from forest resources and minimize environmental damage by using modern techniques and technological tools (Gülci et al., 2015). The use of different sensor technologies for this purpose complies with the scope of Precision Forestry (PF) (Kovácsová and Antalová, 2010). PF offers a solution for monitoring and controlling the activities in forest management, specifically for exploring the forestry parameters such as Diameter at Breast Height (DBH), tree height (TH), crown diameter (CD), bark thickness, growing stock volume, etc. Conventionally, DBH and TH parameters are directly measured in on-site surveys at a tree-by-tree basis and are predominantly used in forest inventory studies for calculating carbon sequestration capacity (Paris and Bruzzone, 2019; Serengil, 2020). Although on-site measurements of DBH and TH are easy to conduct, they seem to be time and cost consuming and inadequate for a large scale forest. On the other hand, the high relationship of these parameters and other tree parameters such as diameter, trunk volume has made them indispensable. Using these allometric relationships, a parameter that is difficult to measure in practice can be estimated through other easily measurable parameters (Inan et al., 2017). As a matter of fact, heights can be estimated through DBHs by utilizing the high correlation between TH and DBH. In addition, the volume of a tree can be defined as a function of DBH, TH and form factor (Spurr, 1952; Philip, 1994). Another important relationship is between CD and DBH. In various studies (Ige et al., 2013; Arslan, 2016), it has been clarified that there is a strong relationship between CD and DBH and this relationship is generally explained by linear models. The existence of this relationship enables the estimation of forest stand volume and structure by using the CD data, which can be determined from LiDAR data obtained from different sources. Because of these relationships, all growth, volume, and yield tables in forestry studies have been prepared on the basis of DBH.

The first forestry biophysical parameters, dating back to the early 90's, were monitored by multi-spectral and radar remote sensing imaging technologies, providing the first global image of forestry. These 2D imaging technologies provide incomparable information about biomass levels. However, the need for 3D structures requiring high levels of detail and accuracy, especially

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for dendrometry of forestry, makes 3D Point Cloud data (PCD) indispensable in forestry applications (Cabo et al., 2018; Mielcarek et al., 2018; Arslan et al., 2021; Shimizu et al., 2022). Over the last 20 years, Light Detection and Ranging (LiDAR) data systems have become one of the keyways to learn about the structure, change and distribution of forest resources, thanks to their rapid, accurate and non-destructive results (Popescu, 2007). PCD from LiDAR systems has changed the way of monitoring forestry parameters (White et al., 2016).

The most popular technology for studying the structure of forests is the Airborne Laser Scanner (ALS) while the Terrestrial Laser Scanners (TLS) and handheld mobile laser scanners are also used in some extent. (Lou et al., 2018). The popularity of ALS is not only because it provides height information, but because the laser signal can penetrate gaps in the vegetation and thus provide a measurement of the ground and interior structure of trees. Although there are lots of successful examples of usage of ALS-based PCD on species diversity, wood volume etc., their usage is generally limited for stand-level forest management and monitoring due to their cost (Mielcarek et al., 2018; Hauglin et al., 2021). Indeed, the ground-based LiDAR systems, namely TLS, provide information that cannot be extracted using airborne LiDAR data, and with dense PCD. Thus, it is easy to obtain plot-level information in a short time (Koren et al., 2017; Cabo et al., 2018; Arslan et al., 2021; Tan et al., 2021; Lizuka et al., 2022) The popularity of TLS is due to its capacity to display 3D forest models with millimeter-level precision enables to estimate forest stand parameters like DBH. Recently, image-based PCD from Unmanned Aerial Vehicles (UAV) has been widely recognized in forestry because it is low-cost and provides canopy-related information in larger areas (Koc-San et al., 2018; Demir, 2018; Liang et al., 2019; Guerra-Hernandez et al., 2021; Shimizu et al., 2022). UAV imagery provides a 3D PCD and a textural and structural view of the area and is, therefore, an alternative to traditional measurement techniques in forestry operations. With height information and tree types, the DBH estimate is essential to understand the annual growth of trees, stress levels and surface biomass. Precise estimation of these parameters is a long-standing requirement in forestry and is required regularly. In this study, DBH and TH, considered one of the most important forest parameters, were estimated using PCD from UAV, TLS and ALS measurements for the d development stage (DBH > 52 cm in mature stage) open Oak stand and the results were evaluated on the basis of the corresponding values established on the based on their common traditional counterparts.

2. Materials and Methods

2.1. Description of the Test Site and Data

The study area is in the development stage d pure Oak (*Quercus* sp.) stand and is a part of the Istanbul Forest Regional Directorate. The region is also being monitored by the Istanbul University-Cerrahpasa Forestry Faculty for several silvicultural applications. Its coordinates are 41°14' 0.43"N and 28° 53' 35.57" E with an average altitude of 145 m (Figure 1). The reason for selecting a deciduous stand is to examine the performance of PCD data from different sources on an organic shape, unlike the cylindrical structure of the needle-leaf forest stand. Additionally, Oak stand's relatively slow growth rate enables us to use data sets from different dates and temporal resolutions.

2.1.1. On-Site Data: DBH and TH Measurements

DBH and TH are the most prominent stand parameters in forestry research. DBH is the measurement of tree diameter at 1.3 m above the ground line and is the most measured parameter of planted trees for many forestry studies (Spurr 1952; Philip 1994; Su et al., 2020; Patricio et al., 2022). During the field data collection, DBH measurements were conducted with conventional methods and on-site tree heights on the marked trees were measured using a Haglof Vertex Laser Range Finder.

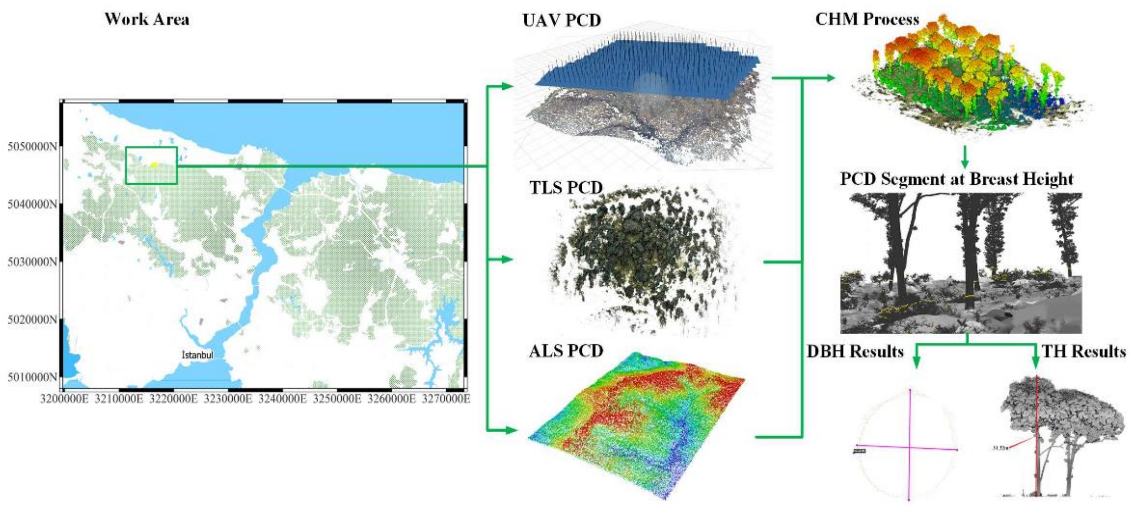


Figure 1. The geographic location of the study area with the perspective view sample PC raw data obtained from UAV, TLS and ALS, along with their preview products after post-processing

This specific range finder is specially designed for forestry applications and conventionally used to obtain tree metrics. It is also able to measure angles alongside distances and derive tree heights depending on this information. According to manufacturer specifications, it can achieve a 4 cm distance and 0.1° angle accuracy. The device also incorporates a GNSS unit that can reach down to 2.5 m positional accuracy in open terrain.

2.1.2. ALS-based PCD

ALS data has been obtained in leaf on summer season as a pre-processed point cloud as 1:1000 plots (Istanbul-F21-c-03-b-3-a and Istanbul-F21-c-03-b-3-b) from Bosporus Landscape Build Consultancy Technical Services (BIMTAS). The data obtained was then divided into sections to focus on our work area at the intersection of the parcels. The segmented data is used in the Canopy Height Modeling (CHM) process to estimate their DBH and TH, which will be further explained in detail in the Methodology Section.

2.1.3. TLS-based PCD

To extract the 3D structure of the entire area, 20 setups were conducted in front of the marked reference trees. In addition, four complimentary scan sessions were carried out to provide sufficient overlap between scan areas and to ensure almost no occlusion effect (Figure 2). The first two of the scans were carried out over geo-referenced stations to enable an accurate registration of TLS scans to the other dense PC data sets, i.e., UAV and PCD.

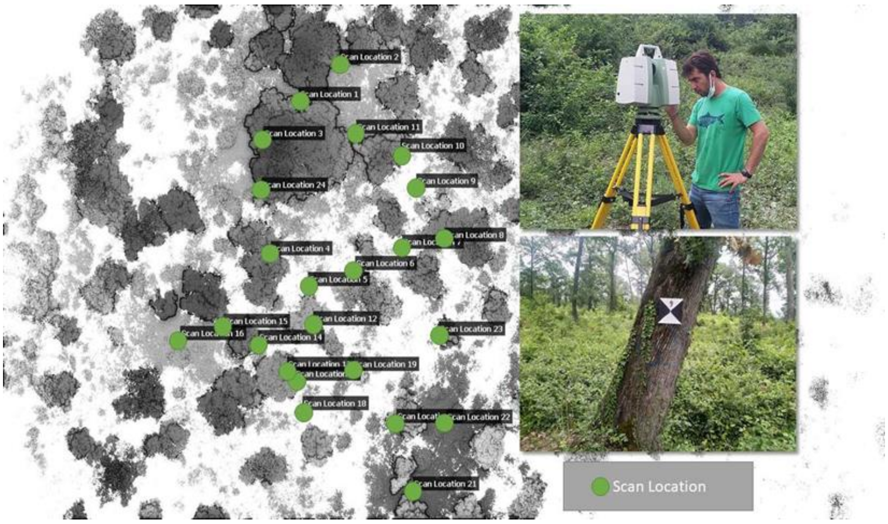


Figure 2. Distribution of TLS acquisition locations over the registered TLS-based PC data. Photos show the TLS collecting data and a marked Oak Trees in the study area

2.1.4. UAV-based PCD

The RGB images were acquired by DJI Phantom 4 with FC6310 camera at an altitude of 91.3 m with 2.34 cm/pix resolution. The flight mission covered a 178000 m2 area in 352 images. Once the images were collected, Agisoft Metashape was used to extract PCD from the image set. This software uses the Structure from Motion (SfM) technique to create the PCD. The number of points on the resulting point cloud was kept at 34545393, for homogeneity with other data sets level of detail and computational costs' sake.

2.2. Methodology

Figure 3 shows the PCD processing pipelines for each PCD data acquired by UAV, TLS, and ALS. In order to evaluate the performances of different PCD sources, each PCD was evaluated separately against in-situ-based data but with the same method. The method of evaluation in its essence is a binary classification of the ground points and canopy, followed by a filtering process of the canopy class according to height. This method is referred to as Canopy Height Modelling (CHM) and can be employed for all kinds of PCD regardless of its origin (Jensen and Mathews, 2016; Firoz et al., 2017; Mielcarek et al., 2018; Dobrowolska et al., 2022).

For the CHM process, each raw PCD was first geo-registered to the same coordinate system. This enabled us to maintain a consistent area of focus among each PCD from different sources. Each PCD was then subjected to noise filtering to remove solar glare and similar artifacts. Following this process, they were segmented according to the focus area in this study. This stage was followed using the Cloth Simulation Algorithm (CSF), which enabled us to classify the PCD as ground and off-ground. The resulting ground class was used to create a high-resolution Digital Terrain Model (DTM) of the area. DTM of the area has been created by using the Poisson surface Reconstruction algorithm with Dirichlet constraints to prevent the creation of extraneous areas (Figure 4).

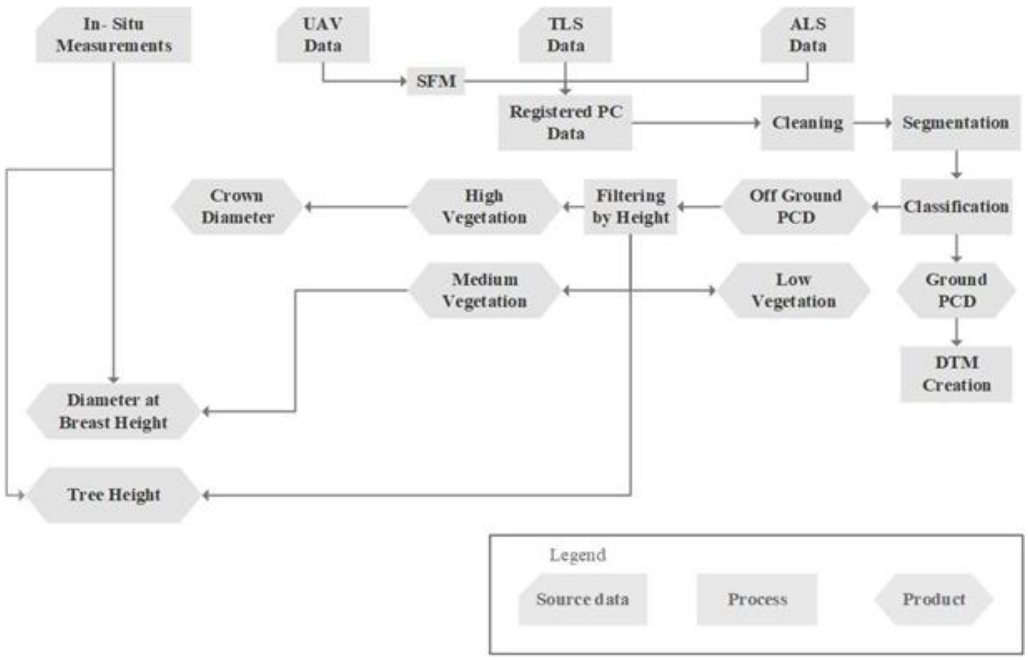


Figure 3. Process workflow

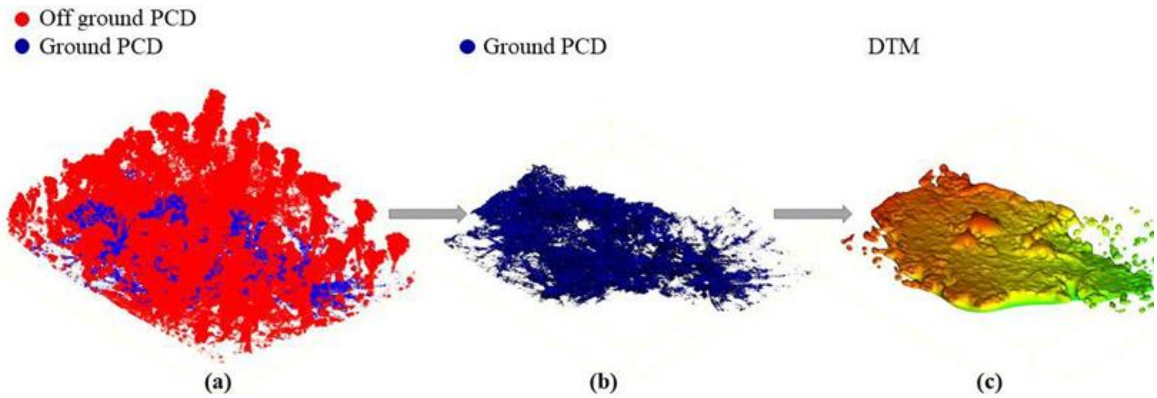


Figure 4. (a) Representation of binary ground (blue) and off-ground (red) classes obtained from PCD, (b) ground PCD (Blue), (c) DTM (colored by height) obtained from ground PCD

DTM is a crucial element in CHM. It enables users to ilter PCD points by their respective heights to a reference surface, therefore eliminating the effect of topographic undulation, when examining points at a certain level above ground. Thus, the importance of a high-resolution DTM became prominent during the evaluation of all PCD regardless of the data source.

2.2.1. Estimation of tree height and DBH from PCD

All marked trees were segmented into individual PCD to lessen the computational cost and to have an accurate reading for TH estimation. THs were then obtained using a local maxima algorithm (Tan et al., 2021) that uses point numbers and Z values of the PCD points as input (Figure 5).

As a result of the CHM process, each PCD became segmented according to the height above DTM. Segmenting PCD at breast height (1.35m) enabled us to obtain a uniform segment, which is 1.35 meters above the ground in every part of the working area, regardless of the topographic changes. The elimination of the topographic effect has provided the necessary PCD that represents tree segments at breast height throughout all PCD sources (Figure 6 a). Examining the segment of PCD at breast height allowed mathematical operations, such as fitting circles and ellipses, to obtain DBH values (Figure 6 b).

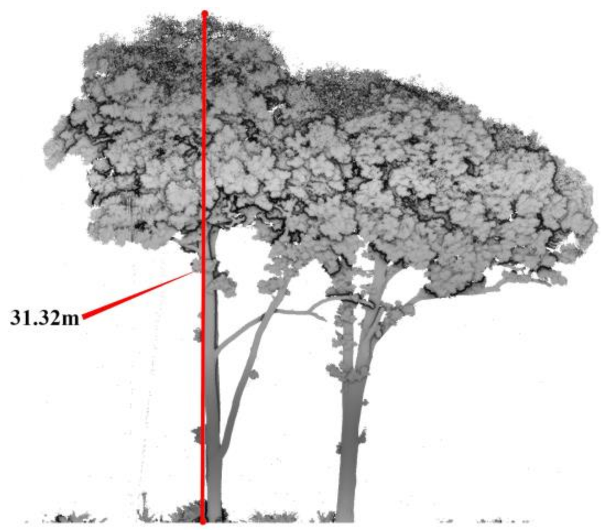
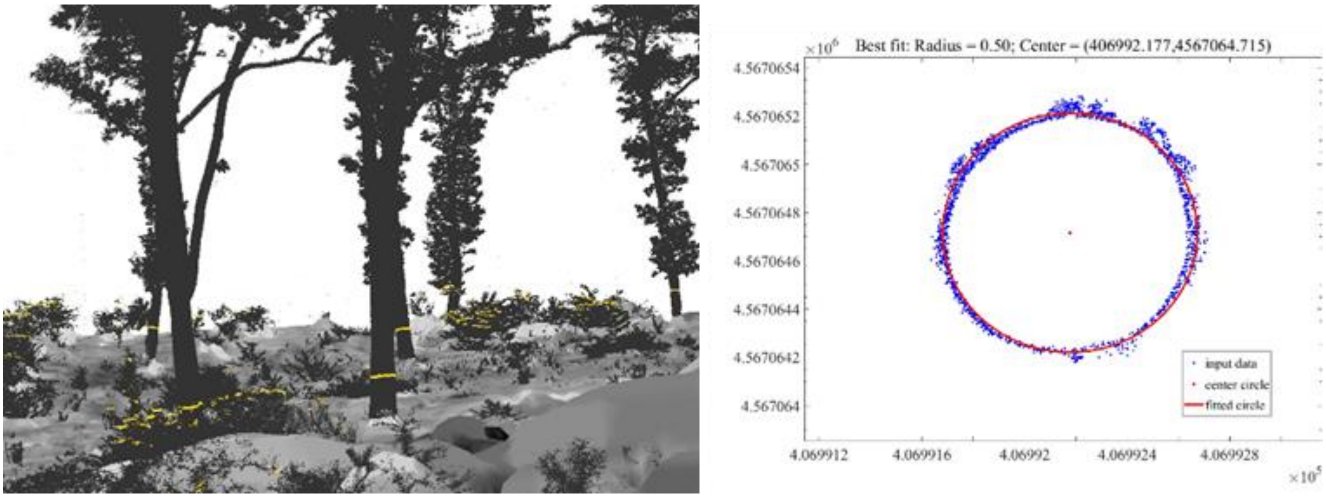


Figure 5. Representation of tree height obtained from PCD



(a) PCD Segment (b) Circle Fit

Figure 6. (a) Point Cloud Segment (thin yellow section) at breast height, obtained after CHM process. (b) Circle Fitted to the PCD segment at sample tree no: l, using Least Squares based algorithm

3. Results and Discussion

The on-site DBH and TH measurements in the Oak stand were used as the reference to present the performance of each PCD. DBH and TH values obtained from each PCD source can be seen as summarized in Table 1.

The correlation of results from different PCD sources with the reference data has been graphically represented in Figure 7. Figure 7(a) states that the DBH values obtained from TLS data show a 97.5% correlation with in-situ measurements. The highest and the lowest RMSE resulted in 1.8 cm and 0.22 cm, respectively. Furthermore, the correlation between in-situ and UAV-based DBH has shown minimally differing results of 92.7%. This high correlation is due to the advantage of the leaf-off season flight because DBH measurements from UAV data are heavily dependent on stand density and occlusion created by the canopy top. As the density increase, the upper canopy and nearby trees occlude the amount of data received from tree trunks, therefore, impacting the quality of DBH measurements from UAV data.

Table 1. DBH and height of each tree taken from on-site measurements and PCD from TLS, UAV and ALS

Sample	DBH (cm)				Tree Height (m)			
Trees	On-site	TLS	UAV	ALS	On-site	TLS	UAV	ALS
1	100.0	97.20	100.70	*N/A*	26.65	27.47	11.22	29.19
2	84.0	82.20	83.70	*N/A*	27.34	28.06	16.15	29.71
3	76.0	75.40	72.50	*N/A*	27.54	28.23	17.30	28.24
4	69.0	64.95	61.50	*N/A*	24.52	25.62	15.34	29.03
5	75.0	67.35	82.30	*N/A*	29.20	29.62	15.64	29.41
6	62.0	60.60	71.60	*N/A*	25.95	26.87	8.23	26.93
7	63.0	64.50	59.20	*N/A*	25.85	26.77	13.27	28.06
8	68.0	68.50	66.40	*N/A*	24.15	25.30	18.62	27.38
9	66.0	64.90	66.50	*N/A*	14.85	16.33	14.62	23.09
10	49.0	49.60	44.10	*N/A*	27.40	28.13	8.98	25.57
11	86.0	75.70	79.20	*N/A*	25.25	26.26	11.80	28.97
12	53.0	52.30	52.90	*N/A*	26.30	26.94	17.73	26.42
13	65.0	63.15	71.60	*N/A*	19.95	21.43	12.39	26.96
14	61.0	61.24	61.50	*N/A*	29.24	29.65	11.12	29.13
15	69.0	69.40	69.70	*N/A*	26.16	28.23	20.65	28.35
16	60.0	60.10	63.50	*N/A*	27.55	27.05	19.99	28.15
17	83.0	80.60	78.30	*N/A*	24.40	25.50	18.88	27.55
18	83.0	81.20	76.70	*N/A*	27.00	27.74	24.90	29.99
19	65.0	63.40	64.90	*N/A*	26.90	27.62	25.69	29.04
20	66.0	62.40	65.50	*N/A*	26.65	27.48	21.67	29.26

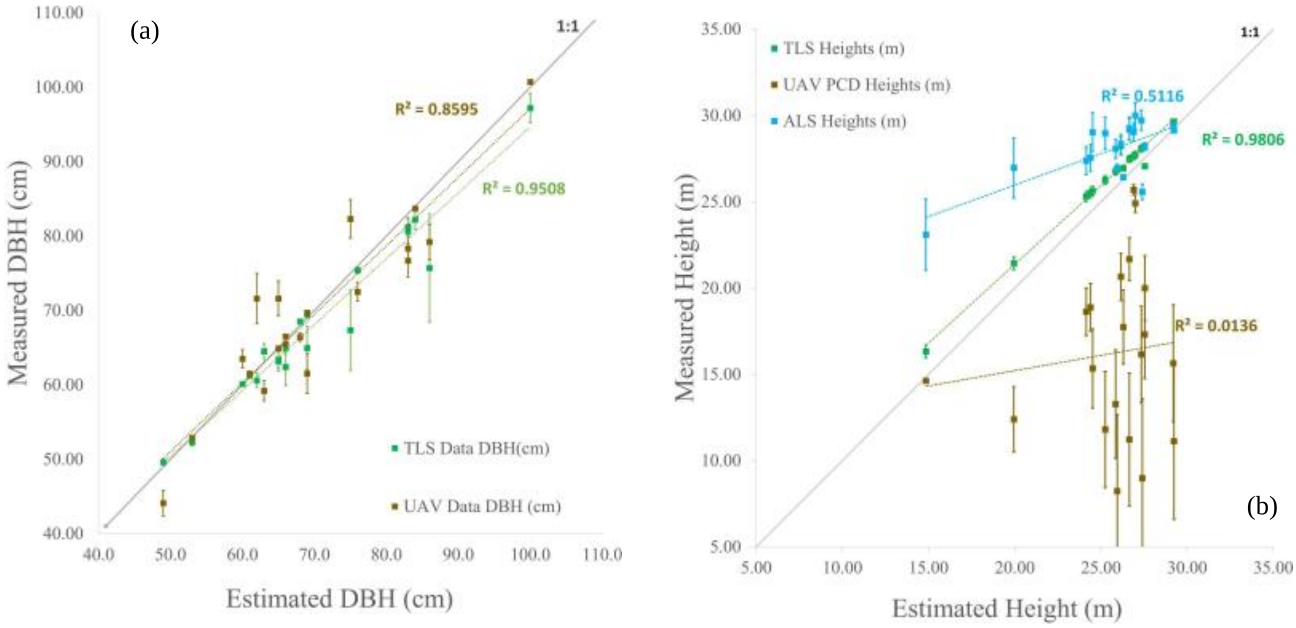


Figure 7. Comparison between the estimated DBH (a) and tree height (b) by each PCD and their corresponding in-situ measurements with model prediction standard deviation as error bars

As can be observed from Figure 7(b), the RMSE of estimated tree height by UAV, ALS, and TLS against in-situ measurements are 5.101 m, 1.300 m, and 0.051 m, respectively. ALS data has not provided any tangible information below the canopy, at least not on breast height level, for DBH measurements. However, tree heights are highly correlated with TLS results (with a correlation coefficient of 0.73). To obtain more information from ALS data, the tree trunks can be modeled using other, more complex, methods from the under canopy data such as those implemented and explained in another article (Arslan et al., 2021) and DBH can be estimated from it.

Since it was not within the scope of this work, implementation of the aforementioned complex processing methods has been postponed to be included in future work to save computer resources and time. Albeit ALS data exhibits some inconsistencies, possibly occurring from OEM's relatively low resolution to its counterparts in this work, in resolution and height accuracy, it shows promising potential for forestry applications; especially if supported with TLS data when and where needed. There is a low (12%) correlation between TH estimation from UAV and in-situ, mainly because the flights were performed during leaf-off season and the model height was generated from GPS data of the drone. Therefore, it can be suggested that a two-stage campaign on leaf-on and leaf-off seasons, for the same region, can prove more fruitful. Indeed, TH results from TLS PCD and in-situ measurements show a very high correlation at 99%. This result proves that at this stand type and canopy density, TLS is a very viable alternative for tree height detection. Meanwhile, ALS measurements show a 72% height correlation with in-situ measurements, and therefore, for specific applications, it can be considered a viable alternative.

All the PCD evaluations were performed on a computer with dual Intel(R) Xeon(R) CPU E5-2630 v3 at 2.40GHz, 2401 MHz, 8 cores, 16 logical processors, and 80 GB of ram. PCD raw data set consisted of 231362110 points for TLS, 34545393 points for UAV, and 33794335 million points for ALS. It should be taken into account that TLS data has been decimated to an average of 30 million points, before the analysis. The run times of the three PCD sources are 165, 158, and 150 minutes for TLS, UAV and ALS data, respectively. These computational times can be associated with the data amount of each source. Given this information, when evaluated with emerging results, in a computation time to the provided level of detail and accuracy, TLS data becomes highly prominent.

In light of these results and as outlined in Table 2, even at varying accuracy ratings, UAV, ALS and TLS offer faster, more economical and more accurate solutions for forest metrics than traditional methods. However, it is necessary to analyze the type and crown closure of the stand to obtain the optimal results that suit the need of the individual project and its requirements.

For predicting forest stand parameters, the literature contains several methods for processing ALS data (Reitberger et al., 2008; Lefsky et al., 1999; Drake et al.; 2002). Certain models can be applied to small or large-scale studies, and some methods are affected by leaf on-leaf off conditions like in this study. It is very important to determine the scope of suitability as each application changes the specific conditions, while predicting the key features such as TH, DBH etc.

Table 2. Summary of the characteristics, pros and cons of the PCD related tree height and DBH estimation methods

PCD Source	DBH	Tree Height	Advantages	Disadvantages
TLS	Available	Available	level of detail (very high-resolution data) millimeter accuracy point positioning	big files to process, small area coverage
UAV	Partially (leaf-off)	Available	quick, low-cost operations, integrity to thermal cameras, large area coverage, highest level of detail among airborne sensors	big files to process, heavily dependent on weather (winds and gusts), accuracy relies on GCP, occlusion prevents obtaining data below canopy above certain levels of opening
ALS	*N/A*	Available	large area coverage	high-cost operations, data is relatively inaccessible and/or canopy data is virtually nonexistent for forestry applications (few points per square meter)

The forest parameters derived from ALS data do not always show a high correlation. However, for some forest types, correlation is too high (Anderson et al., 2006), so equations are only valid when applied to specific forest types and environments (Hyde et al., 2005). UAV systems, while they have their shortcomings such as weather and acquisition time, can be proved to be very useful, especially at low crown closure stands, where occlusion is less and data below the canopy can be obtained by the UAV platform. On the other hand, TLS is unprecedented for obtaining below canopy information. However, above certain canopy closing levels, the TH estimate may be damaged by occlusion. There are also currently developing UAV techniques, such as by Hyyppa et al., 2020, to increase the domain of UAV in below canopy forestry applications.

4. Conclusions

PC datasets from three sources (i.e. ALS, TLS and UAV) were used to study the feasibility of the DBH and TH values of a sample oak stand. It was revealed that ALS systems can cover very large areas in days or hours and provide enough data to give a sense of a wide crown distribution of tree height and DTM of the area where a study area can be used as an additional and/or validator TLS or UAV. Still, ALS systems retain their capacity to deliver a certain amount of information below the canopy level. This information, if carefully handled in a more complex manner as previously stated, may allow users to derive some of the following canopy forest metrics, such as DBH. As a result, compared to conventional methods, whole PCD collection methods can cover larger areas, if not more, more accurately in a shorter time. Among the PCD sources involved in DBH and TH estimation, TLS (supplemented with ALS data when needed) stands out due to its measurement accuracy and fast data capturing process in a complex environment. The oldest of the data sources, ALS continues to operate quickly, but remains a higher-cost data source than the others. Although UAV-based PCD is gaining prominence, more research is needed to confirm its applicability in off-season foliar applications as a promising, easy and versatile tool.

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