Testing the Performance of Hand-held Personal Laser Scanning Systems for Precision Forest Inventory

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Abstract: This research tested the performance of hand-held personal laser scanning (PLS) technology for estimating the diameter at breast height (dbh) in a lowland pedunculate oak (*Quercus robur* L.) forest. More precisely, this study assessed: (i) the accuracy of two, high-end hand-held PLS systems (ZEB Horizon and Faro Orbis); and (ii) various scanning schemes with different complexities. Three scanning schemes of different complexity were used by both instruments, and Faro Orbis provided more accurate dbh estimates than ZEB Horizon for each scheme. The results revealed an increase in the PLS data estimation accuracy that corresponds to the increase in complexity of the scanning scheme Additionally, the new ability of Faro Orbis to perform 'flash' (static) scans that mimic TLS was also tested, and obtained results revealed that flash scans produce slightly less accurate dbh estimates compared to the most complex walking (mobile) scheme.

Keywords: LiDAR; hand-held personal laser scanning; scanning schemes; diameter at breast height; forest inventory.

1 Introduction

The potential of 'classical' remote sensing (e.g., satellite and aerial images, airborne laser scanning) in forest inventory has long been recognized by both forestry science and practice (White et al. 2016). During the last two decades, constant and rapid technological progress regarding sensor miniaturization and algorithm development led to the emergence of various close-range remote sensing technologies (Jurjević et al. 2020, Liang et al. 2022). Compared to classical remote sensing, close-range remote sensing provides the acquisition of highly detailed data, that enables it to be used in individual-tree-based forest inventory. Currently, the static terrestrial laser scanning (TLS) system has the highest geometric quality enabling accurate extraction and estimation of the main tree attributes (Liang et al. 2022). However, the main limitation of TLS that hinders its operational use in forest inventory is the speed of data acquisition (Gollob et al. 2020, Balenović et al. 2021). Namely, to obtain high-quality data and reduce the occlusion effect caused by surrounding trees, for each forestry plot a multi-scan approach has to be applied, which is labour-intensive and time-consuming. On the other hand, mobile laser scanning systems can reduce occlusion problems and acquisition time, and therefore present a time-efficient alternative to TLS (Balenović et al. 2021). This is especially true for lightweight and highly mobile hand-held personal laser scanning (PLS) systems.

The emergence and availability of progressively advanced PLS systems in recent years have resulted in increased research into the possibility of their application in forest inventory, primarily for the assessment of key tree attributes (e.g. tree position, dbh, tree height, tree volume, etc.) (Gollob et al. 2020, Jurjević et al. 2020, Sofia et al. 2021, Tupinambá-Simões et al. 2023). Since PLS systems are constantly and rapidly advancing in terms of technical characteristics, continuous research on their application in forest inventory is inevitable. The main goal of this research is to test the performance of hand-held personal laser scanning technology in forest measurement, more precisely for estimating the diameter at breast height (dbh) in a lowland pedunculate oak (*Quercus robur* L.) forest. Therefore, this study aims: (i) to assess the accuracy of two, high-end hand-held PLS systems; and (ii) to compare different acquisition scenarios, i.e., various scanning schemes with different complexities.

2 Materials and methods

The research was conducted in a 100-year-old, mixed, lowland, even-aged pedunculate oak forest stand located in the management unit "Bolčanski-Žabljački lug" in Central Croatia, 70 km east of Zagreb. For this preliminary research, one circular sample plot (Figure 1) with a radius of 12.62 m (45°51'43"N, 16°40'06"E; 117 m a.s.l.) was chosen from a larger set of permanent plots.

Both field and PLS data were collected during the leaf-off conditions in February 2024. The coordinates of the plot centre were measured using the GNSS receiver Trimble R12i (Trimble, Inc., Westminster, Colorado, USA) connected to the Croatian network of GNSS reference stations (CROPOS). The position of each tree in the plot with dbh ≥ 5 cm was recorded by measuring the distance and azimuth from the plot centre. For each tree with dbh ≥ 5 cm, tree species was determined and dbh was measured using the diameter tape with a 0.1 cm precision (Table 1).

Figure 1. Panoramic view of the sample plot.

Table 1. Descriptive statistics of the sample plot for field measurement.

Tree species	N of trees	Mean ± SD of dbh (cm)	dbh range (cm)
Quercus robur L.	6	42.8 ± 6.7	32.1 – 49.9
Carpinus betulus L.	6	22.3 ± 6.5	12.0 – 31.8
Pyrus pyraster (L.) Burgsd.	2	16.0 ± 1.3	15.1 – 16.9
Ulmus laevis Pall.	1	6.6 ± n.a.	n.a.
Total	15	28.6 ± 13.8	6.6 – 49.9

PLS data were collected using the GeoSLAM ZEB Horizon (Geoslam Ltd., Nottinghamshire, UK) and Faro Orbis (FARO Technologies Inc., Lake Mary, Florida, USA). Faro Orbis is a successor to Zeb Horizon with improved technical characteristics (Table 2) and the addition of 'flash' (static) scans that mimic TLS. For sample plot scanning, three pre-planned scanning schemes of different complexity (Figure 2a-c) were used for both ZEB Horizon and Faro Orbis, while for Faro Orbis an additional two schemes were applied that incorporated flash scans (Figure 2d). One of these schemes included only flash scans (FS), while the second one included both flash scans and a scan obtained by walking between flash scans (FS*). To enable PLS point cloud georeferencing, four reference points were placed on the scan area and measured with a Trimble R12i receiver.

The pre-processing of the collected data was carried out in the Faro Connect (FARO Technologies Inc., Lake Mary, Florida, USA) software, which generated a point cloud. Georeferencing of the point cloud from the local to the HTRS96/TM coordinate system was carried out using the four reference points. Afterward, the point clouds were exported in las (LASer) format and further processed in LiDAR360 v7 (GreenValley Intl, California, USA) throughout several steps (outliers removing, ground points classification, normalization, dbh estimation). Dbh of each tree in the plot was manually fitted by the circle method using the TLS Seed Point Editor option. In total, eight different point clouds were processed and from each point cloud dbh was estimated for all trees on the plot.

Table 2. Technical specifications of Zeb Horizon and Faro Orbis.

Feature	Zeb Horizon	Faro Orbis
Range (m)	100	120
Acquisition rate (points/sec)	300,000	640,000
Field of view; horizontal/vertical (°)	360/270	360x290
Precision (mm)	up to 6	5 (mobile) / 2 (static)
Raw data file size (MB/min)	25-50	350

The accuracy of dbh estimates from PLS was evaluated with field reference data, i.e., dbh measured using a diameter tape. The evaluation was performed using a mean error (ME), a relative mean error (ME%), a standard deviation (SD), a root mean square error (RMSE), and a relative root mean square error (RMSE%).

3 Results and Discussion

The evaluation results for both PLS instruments and each scanning scheme are presented in Table 3.

Observed by PLS instrument type, it can be noticed that Faro Orbis provides more accurate dbh estimates than ZEB

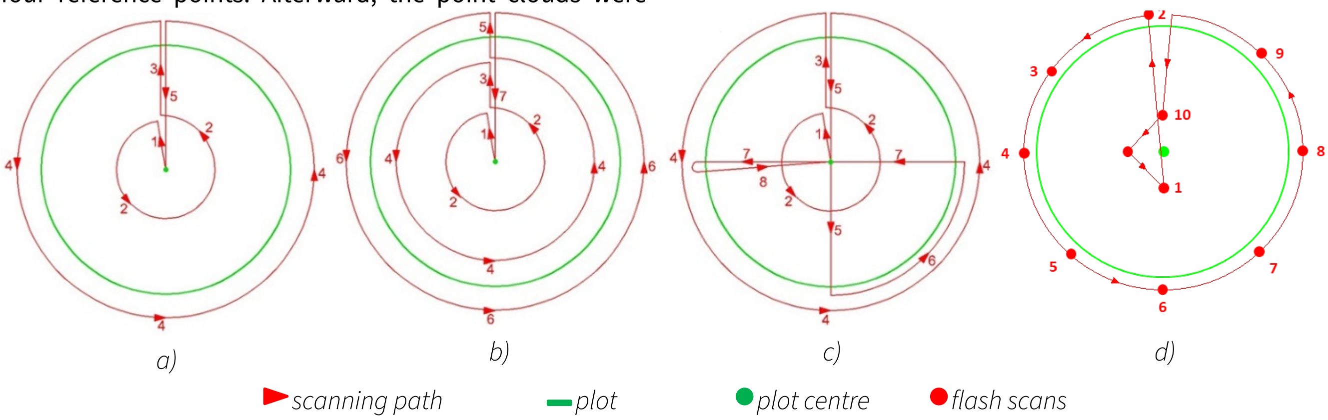

Figure 2. Pre-planned scanning schemes: a) scheme 1; b) scheme 2; c) scheme 3; d) scheme 4 with flash scans.

Table 3. Estimation accuracy of dbh for two PLS instruments (ZEB Horizon, Faro Orbis), and different scanning schemes in comparison to field reference data.

	ZEB Horizon			**Faro Orbis**				
Scheme	1	2	3	1	2	3	FS	FS*
ME (cm)	0.21	0.05	0.23	0.22	0.24	0.17	0.36	0.03
ME (%)	0.75	0.19	0.82	0.77	0.84	0.58	1.26	0.09
SD (cm)	0.95	0.81	0.76	0.49	0.52	0.37	0.32	0.42
RMSE (cm)	0.98	0.82	0.79	0.53	0.57	0.41	0.48	0.42
RMSE (%)	3.42	2.85	2.77	1.87	2.00	1.42	1.69	1.48

FS – individual flash scans, FS* - flash scans combined with walking scanning scheme.

Horizon. For Faro Orbis RMSE% values range from 1.42% to 2.00%, while for ZEB Horizon range from 2.77% to 3.42%. To the best of the authors' knowledge, this research is the first that tested the newest PLS instrument Faro Orbis in forest inventory. Comparison with other previous studies that utilized ZEB Horizon for dbh estimation (Gollob et al. 2020, Hyyppa et al. 2020, Sofia et al. 2021, Tupinambá-Simões et al. 2023), suggests that this study provides more accurate estimates. Namely, previous studies reported RMSE% values in the range from 3.50% to 12,01%. However, it should be considered that previous studies were conducted in different forest types with different forest structural and terrain characteristics. Also, they differ very much by plot size, scanning schemes, reference data (TLS or field reference data), software and algorithms for data processing and dbh estimation, etc.

Furthermore, the obtained results revealed an increase in the PLS data estimation accuracy that corresponds to the increase in complexity of the scanning scheme (from schemes 1 to 3) for ZEB Horizon. A similar situation is observed for Faro Orbis as well except for scanning scheme 2 which produced a slightly higher RMSE than scanning scheme 1. After detailed analysis, it can be confirmed that the main reason for slightly higher RMSE% values for scheme 2 is caused by a somewhat higher dbh estimation error (–1.0 cm) for one pedunculate oak tree (dbh = 49.0 cm). Similarly, ZEB Horizon scheme 2 also provides higher a dbh estimation error (–0.7 cm) for the same tree.

It is also revealed that Faro Orbis flash scans (FS) provide slightly less accurate dbh estimates (RMSE% = 1.69%) compared to scheme 3 (RMSE% = 1.42%). Merging point clouds from flash scans and a scan obtained by walking between flash scans (FS*) improve the accuracy (RMSE% = 1.48%) very close to the accuracy obtained by scheme 3. Despite the better resolution of flash scans compared to classical mobile scanning, it is obvious that the spatial distribution of ten flash scans does not provide sufficient point cloud coverage of the sampling plot area. The addition of several flash scans within the plot area might improve accuracy but will also increase scanning and processing time.

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Figure 3 shows RMSE% by tree species, i.e., for *Q. robur* and 'others' (*C. betulus*, *P. pyraster*, *U. laevis*). Results show that the dbh of *Q. robur* is estimated with considerably higher accuracy than the dbh of other tree species, which is somewhat expected. Namely, *Q. robur* trees in the plot have greater dbh and a more regular stem shape, unlike the other tree species (Table 1). This is in line with previous findings that reported greater errors in dbh estimation for smaller trees with dbh<10 cm (Ryding et al. 2015, Gollob et al. 2020). According to Gollob et al. (2020) due to the high noise of PLS, dbh of smaller trees is constantly overestimated regardless of various fitting methods applied. Dbh overestimations were also obtained within this research for all schemes and both PLS instruments. Furthermore, Figure 3 shows that both instruments and all scanning schemes estimate dbh of *Q. robur* with similar accuracy, i.e., with RMSE% ranging from 0.67% to 1.45%. On the other hand, it can be noticed that the accuracy of

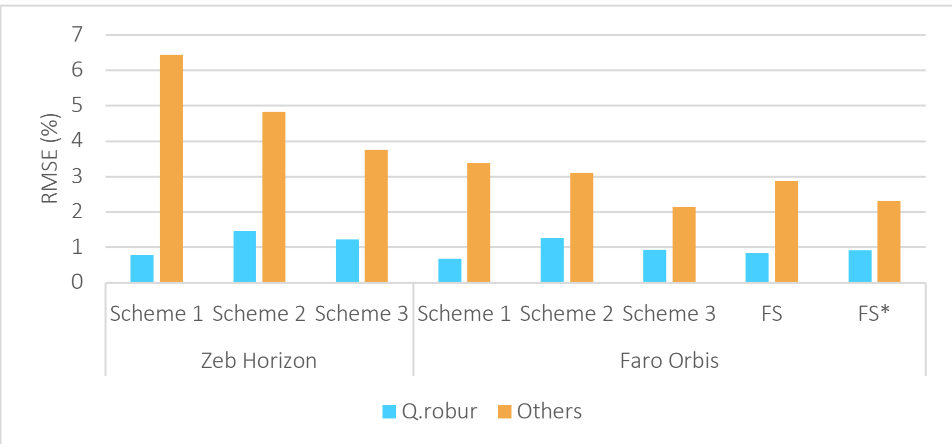

Figure 3. RMSE% values by Quercus robur and other tree species (Carpinus betulus, Pyrus pyraster, Ulmus laevis).

dbh estimates for other tree species is greatly dependable on the type of instrument used and the applied scanning scheme. The accuracy of dbh estimates significantly increases by increasing the complexity of scanning schemes. ZEB Horizon produces RMSE% of dbh estimates of 6.44%, 4.83%, and 3.76% for schemes 1, 2, and 3, respectively. Faro Orbis produces greater accuracy than ZEB Horizon, i.e., RMSE% of 3.38%, 3.10%, and 2.15% for schemes 1, 2, and 3, respectively.

4 Conclusions

For the first time, the performance of the newest commercial PLS instrument (Faro Orbis) was tested and compared with its predecessor (ZEB Horizon) and field reference data. Three scanning schemes of different complexity were used by both instruments, and Faro Orbis provided more accurate dbh estimates than ZEB Horizon for each scheme. Additionally, the new ability of Faro Orbis to perform 'flash' (static) scans that mimic TLS was also tested, and obtained results revealed that flash scans produce slightly less accurate dbh estimates compared to the most complex walking (mobile) scheme. Although flash scans generate point clouds of greater precision, the spatial distribution of ten flash scans did not provide sufficient point cloud coverage of the sampling plot area. However, this research confirmed the great potential of PLS technology in precision forest inventory, as well as provided preliminary results on the potential of the newest PLS instrument.

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