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Accuracy of forest road Digital Terrain Models captured using Airborne and Mobile Light Detection and Ranging Technology and Photogrammetry

Miroslav Kardoš[1]*, Łukasz Borowski[2], Ivan Sačkov[3], Julián Tomaštík[1], Daniel Čurila[1], Kamil Maciuk[4], Michal Ferenčík[1], Izabela Basista[4]

[1]Technical University Zvolen, Zvolen, Slovakia
e-mail: kardos@is.tuzvo.sk; ORCID: http://orcid.org/0000-0002-9458-5040
e-mail: tomastik@is.tuzvo.sk; ORCID: http://orcid.org/0000-0001-6691-8357
e-mail: curila@is.tuzvo.sk; ORCID: http://orcid.org/0009-0005-9275-7418
e-mail: ferencik@is.tuzvo.sk; ORCID: http://orcid.org/0000-0002-2676-1292

[2]University of the National Education Commission, Krakow, Poland
e-mail: lukasz.borowski@uken.krakow.pl; ORCID: http://orcid.org/0000-0001-7356-5377

[3]National Forest Centre, Zvolen, Slovakia
e-mail: ivan.sackov@nlcsk.org; ORCID: http://orcid.org/0000-0001-8379-5635

[4]AGH University of Krakow, Krakow, Poland
e-mail: maciuk@agh.edu.pl; ORCID: http://orcid.org/0000-0001-5514-8510
e-mail: basista@agh.edu.pl; ORCID: http://orcid.org/0000-0002-0820-5380

*Corresponding author: Miroslav Kardoš, e-mail: kardos@is.tuzvo.sk

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Abstract: The evaluation of the accuracy of generated DEMs using three remote sensing techniques on three types of forest road surfaces was performed. As a sample data, we used the forest road constructed from asphalt, concrete road slabs, and paving stones located in Vígľaš, Central Slovakia. We evaluated the vertical accuracy of the DEMs produced by mobile laser scanning (MLS, Leica Pegasus, 840 pts/m^2), airborne laser scanning (ALS, Leica ALS 70, 9 pts/m^2), and aerial photogrammetry (AP, Leica RCD 30, 5 pts/m^2). DEMs were generated in ArcGIS with a final resolution of 0.5m using the IDW method. The accuracy of DEMs was evaluated with the reference dataset on 700 check points. Regarding road surface capture quality, terrain generation, and point density, the MLS method dominates. It provides the RMSE values in range of ± 0.01 m to ± 0.03 m. The ALS method provided balanced RMSE results irrespective of surface type (RMSE ± 0.04 m to ± 0.05 m). The AP has the highest variability on all surface types (RMSE ± 0.12 m to ± 0.22 m). For AP, the decimeter-level accuracy is not sufficient for construction and maintenance purposes. This method provided the largest blunders at the road parts closest to the trees. ALS, with its ability to partially penetrate the forest canopy, can provide complex information about forest roads for inventory purposes. MLS provided the best spatial accuracy, enabling both construction and maintenance works. In any case, the advantage is that these data types can be combined.

Keywords: Mobile Laser Scanning, Digital Elevation Model, photogrammetry, forest road, Airborne Laser Scanning

1. Introduction

Forest roads are essential for efficient forest management, and for decision support. Detailed planning is required for their construction since the building and maintenance of forest roads are the most significant investments the forest owner makes (Hunt and Hosegood, 2008). The existing network of forest roads is also used by others, such as the public, hunters, farmers, anglers, tourists, and bikers (Fidelus-Orzechowska et al., 2018; Apollo and Andreychouk, 2020; Dudáková et al., 2022).

The hauling process can cause considerable damage to roads, even those of the best quality. Therefore, road maintenance is an integral part of forest management, and an effective damage detection system can prevent costly repairs of heavily damaged roads. Roads in good condition are essential: rugged road surfaces with ruts and holes reduce the efficiency of timber transportation. In the extreme conditions, damaged roads become unpassable. A rapid response to damage, determined by efficient damage detection, is thus a vital part of forestry, which can prevent costly, large-scale repairs (Juško et al., 2022).

Several methods can record the road surface for various applications, including noise modelling, road maintenance, safety, navigation and many others (e.g. Lehtomäki et al., 2010; Morley et al., 2023). Digital elevation models (DEMs) can be made using multiple methods with differing levels of accuracy (Apollo et al., 2023). Generally, photogrammetry and laser scanning (LiDAR), both mobile and airborne versions, are two basic ways to create point clouds. A very important factor for further DEM analyses is its accuracy, which can be affected by several factors. They include the characteristics of point clouds, such as density, the distribution of points in space, classification strategy, and the interpolation method used (Skaloud and Schaer, 2012).

Photogrammetric methods are based on digital photogrammetry workflows, including image matching and bundle block adjustment. Image matching used within the digital aerial photogrammetry workflow is suitable for larger areas when the ground is not invisible due to dense vegetation (Gil et al., 2013). In this case, the created DEM equals the DSM (digital surface model).

Unlike passive optical sensors, airborne laser scanning (ALS) enables the acquisition of multiple returns, which provide information about the vertical structure of a forest, individual trees, and the understory under a dense canopy. In densely forested areas, road structure can be revealed by a DTM produced from classified LiDAR point clouds. Various characteristics of forest roads, including their condition, length, positional accuracy, and road grade, can be derived from the LiDAR data (White et al., 2010). Airborne (ALS) and Terrestrial Laser Scanning (TLS) technologies provide high-resolution 3D spatial information, which can be efficiently applied for characterizing forest resources and topography (Kweon et al., 2020; Maciuk et al., 2021).

Mobile laser scanning (MLS) uses real-time GNSS/ INS observations to georeference the LIDAR data. MLS systems, as a combination of multiple disciplines, sensors, and data fusion systems (Xu et al., 2015), can provide accurate and dense point clouds. The application of MLS systems based on various vehicles is well-documented in urban areas (Ferenčík et al., 2019). Even in forests, they provide rapid scanning, very dense point clouds due to the proximity of the terrain (Hrůza et al., 2018), and can, therefore represent an efficient technology to monitor the state of forest roads. In particular, vehicle-based MLS systems can efficiently obtain accurate data, thus facilitating rational decision-making in systematic forest road management, using the best spatial information for given spatiotemporal conditions (Kweon et al., 2020). The data from mobile mapping is widely used in various applications, where the users obtain a statistically verified quality statement on the geometric accuracy of the acquired point clouds or derived products (Hofmann and Brenner, 2016). A strip survey is a typical application for the MLS system where a road profile in terms of long sections, cross-sections, etc., is needed. Traditionally, this was done with total stations, levels and, more recently with Global Navigation Satellite Systems (GNSS). Total station is currently taking a secondary role in places with insufficient GNSS coverage. ALS and photogrammetry can be used if the topography is the primary concern, less ground-specific detail is required, and large areas/lengths of road need to be surveyed. The MLS is a strong competitor under such conditions. In specific cases, the dependence of MLS on GNSS position referencing can be considered a drawback, as its repeatable accuracy will be in the same range as that of GNSS (Botes, 2013).

Most existing research on forest transportation focuses on identifying and mapping forest roads, e.g. David et al. (2009), Azizi et al. (2014), Buján et al. (2021), Ferraz et al. (2016), Hrůza et al. (2018), Lehtomäki et al. (2010), White et al. (2010). The research conducted on the evaluation of DEMs under forest stand conditions includes assessment of the vertical accuracy of the extracted understory DEM in dense forest vegetation and complex terrain (Cateanu and Arcadie, 2021), identification of the factors affecting the final accuracy of the DEM under forest conditions (Hyyppä et al., 2004), utilization of the first pulse ALS data in boreal forest conditions (Yu et al., 2005), evaluation of DEMs accuracy in dense forests (Balenović et al., 2018) and an evaluation of ALS, MLS and photogrammetric structure from motion (SfM) techniques with various DEM interpolation methods (Kardoš et al., 2024).

However, forest roads represent the intermediate step between the standard forest environment and open areas. Apart from the lowest category of temporary roads for timber skidding, forest roads are open areas affected by the proximity of forest stands on their edges. These can negatively affect the technologies used for terrain acquisition, together with the surface characteristics. In addition, depending on the forest road category, these are made with different parameters and different types of surfaces. Moreover, new innovative remote sensing technologies (like MLS), besides well-established airborne photogrammetry and laser scanning, require detailed research, especially in forestry.

In this study, we assessed and evaluated the accuracy of the generated DEMs using three different remote sensing techniques (aerial photogrammetry – AP, airborne laser scanning – ALS, and mobile laser scanning – MLS) on three types of forest road surfaces (asphalt, concrete road slabs, and paving stones). The land surveying method was used as a reference, combining GNSS observation with total station measurements.

2. Materials and methods

The area of interest is represented by a forest road located in Central Slovakia (Fig. 1), with an overall length of 6238 m and an elevation range of 359 to 411 m in the Baltic height system.

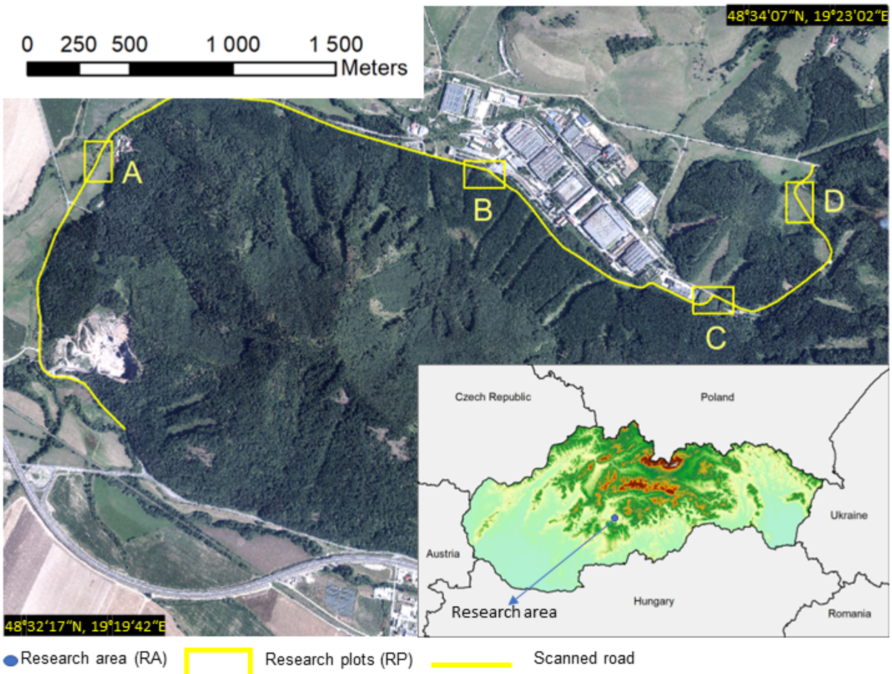

Fig. 1. Localization of test fields

Seven test fields were selected: three for asphalt (A, B section, 150 m each), two concrete road slabs (B, C section, 100 m), and two stone pavement (C, D section, 100 m). The macrostructure of these road surfaces derived from high-density ALS data is shown in Figure 2.

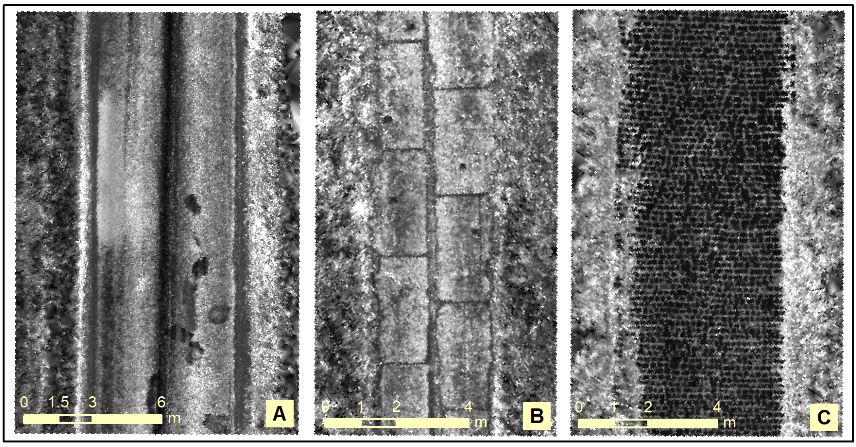

Fig. 2. Example visualization of road surfaces based on intensity values from airborne laser scanning data: (a) asphalt road, (b) concrete road slabs, (c) paving stones

As a reference, we used data gathered in 2018 by the land surveying method, consisting of combined GNSS observations and total station measurements. GNSS observations were conducted using a Topcon Hiper GGD receiver with RTK corrections from the SKPOS national positioning service. For each test field, at least three points were observed, which were used for tachymetry. One point was used as a set for a total station (Topcon GPT9003M) and at least two of angle orientation. Each surveying data was collected using a single-station method of directions aimed at a prism. Overall, 700 points were measured, and each test field (road section) consists of 20 five-point profiles. Their accuracy does not exceed 0.05 m for positioning, and the internal (between points) – 0.015 m. Visualization of checkpoints is shown in Figure 3.

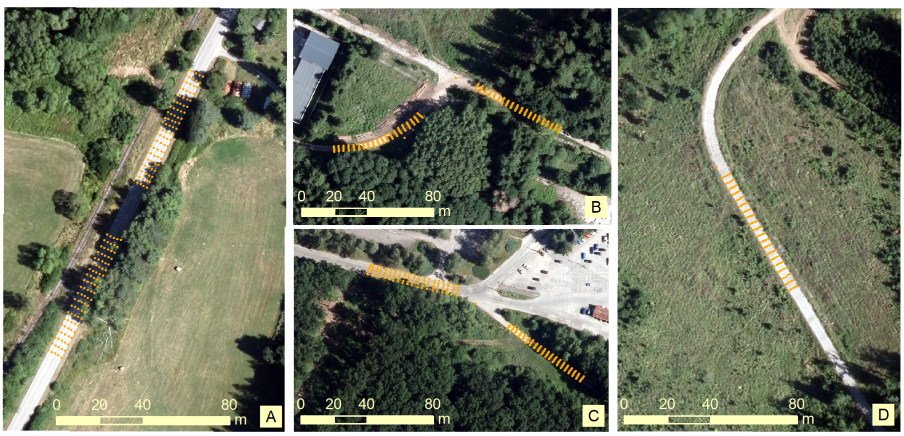

Fig. 3. Detailed view of the research plots with measurements of the reference data

2.1. Aerial imaging and airborne laser scanning

Aerial photogrammetry and Lidar datasets were acquired in 2018 using the RCD 30 camera and ALS 70 CM scanner (Leica Geosystems AG) mounted on a Cessna 206 aircraft. An average flying height was 1526 m with 60% end lap and 30% side lap of the photos. ALS sensor was set up for a 43° field of view and 282 kHz laser pulse repetition rate. The average overlap of the scanned strips was 39%. The width of the scanned strip was 700 m and the transverse overlap between strips was 20–58%.

AP's points-cloud was calculated using the Match-T DSM software using a cost-based matching technique. Refining image orientation was based on ground control points in the Trimble INPHO software. ALS point clouds were processed in the software HxMap (Leica Geosystems AG). The absolute orientation of Lidar strips was performed using ground control points (surfaces with different orientation and slope). The georeferenced and oriented point cloud was classified using SCOP++ strong strategy. The resulting characteristics of such generated point clouds are shown in Table 1.

Table 1. Point cloud and resulting DTM characteristics

	Average point spacing (m)	DTM resolution (m)	Number of points/m^2
AP	0.46	0.5	4.7
ALS	0.33	0.5	9
MLS	0.03	0.5	840

2.2. Mobile laser scanning

Mobile laser scanning (MLS) was carried out in the summer season 2017, using a Leica Pegasus (Leica Geosystems AG) system mounted on pickup. Scanning was realized at 2 m above ground, with a sensor field of view of 360° × 270° and a 1016 kHz scanning rate. Approximately 10.4 km of forest roads were scanned, primarily the road body and the immediate surroundings. MLS point clouds were processed in Leica Pegasus Manager software. The point cloud density was approximately 840 points per m^2. The resulting point cloud and trajectory were determined with GNSS and IMU in the ETRS89 coordinate system with heights above the GRS80 ellipsoid (EPSG: 3046). The point clouds were classified using SCOP++ strong strategy to obtain ground points.

2.3. Digital Terrain Models generation

The digital terrain models of forest roads were generated from achieved point clouds in the ESRI ArcGIS Desktop 10.8 software. We have used the inverse distance weighting (IDW) interpolation technique for DTM generation. For each road surface, all datasets were processed in the same coordinate system (ETRS89, ETRS89-h) and DTM resolution (0.5 m).

2.4. Assessment of the Digital Terrain Models accuracy

Statistical evaluation of the DTMs was realized in two steps, according to the methodology presented in Sačkov and Kardoš (2014). The first step was to determine the absolute differences (ei) between the values of the generated DTMs (Z_{dtm}) and reference datasets (Z_{ref}) (Eq. 1). For each reference check point, the z coordinates from the individual DTMs were extracted using map algebra using the ArcGis software (Esri). Then, the achieved differences could be evaluated:

$$e_i = Z_{\text{dtm}_i} - Z_{\text{ref}_i} \tag{1}$$

In the next step of statistical evaluation, the mean difference ($\overline{e}$ – Eq. 2), standard deviation (s_e – Eq. 3) and the root mean square error (RMSE – Eq. 4) at a given confidence level were computed:

$$\overline{e} = \frac{\sum_{i=1}^{n} e_i}{n}, \tag{2}$$

$$s_e = \sqrt{\frac{\sum_{i=1}^{n} (e_i - \overline{e})^2}{n-1}}, \tag{3}$$

$$\text{RMSE} = \sqrt{s_e^2 + \overline{e}^2}. \tag{4}$$

Further, we tested achieved values for statistical significance. At first, we tested the shape and probability distribution of the differences using the Shapiro–Wilks W-test to select appropriate statistical test. Based on these results and the fact that data sets are equal ($n_1 = n_2$), the Student's parametric pair test (normal distribution of differences) and the Wilcoxon non-parametric pair test (differences have not normal distribution) were selected.

3. Results

A summary of the results of the normality tests of the differences between the heights extrapolated from DTMs and reference values is presented in Table 2. Then, in Table 3, we present the results of parametric or nonparametric testing for the whole set of values grouped by data source and road surface, in the form of the p-value as a test criterion. We tested the "z" attribute values from the generated DTMs and the field measurements against each other.

Based on the statistical test results, we can conclude that with the 95% confidence interval, the ground elevation values observed from all three types of terrain detection techniques for all three types of surfaces, are significantly different ($p < 0.05$) from the reference ground elevation values. The mean differences, standard deviations and RMSE values for all three types of terrain detection techniques and three types of surfaces are reported in Table 4.

Table 2. Test of normality of the differences between the heights from the DTM and the reference measurements

	MLS	ALS	AP
Asphalt	$p < 0.05000^*$	0.1025	$p < 0.05000^*$
Concrete	0.1320	$p < 0.05000^*$	0.6233
Paving stones	$p < 0.05000^*$	$p < 0.05000^*$	0.2580

*The analysed data doesn't meet the normality condition according to the Shapiro–Wilks W-test

Table 3. Results of the statistical test of significance of the differences between the values of the heights from the DMT and the reference measurements

	MLS	ALS	AP
Asphalt	$p < 0.05000^*$	$p < 0.05000^*$	$p < 0.05000^*$
Concrete	$p < 0.05000^*$	$p < 0.05000^*$	$p < 0.05000^*$
Paving stones	$p < 0.05000^*$	$p < 0.05000^*$	$p < 0.05000^*$

*Statistically significant differences according to the Student's parametric or Wilcoxon non-parametric pair test

Mean differences, standard deviations and RMSE values for all three types of terrain detection techniques and three types of surfaces are reported in Table 4 and Figure 4.

Table 4. Mean differences, standard deviations and RMSE values

	MLS			ALS			AP		
	$\bar{e}$	s_e	RMSE	$\bar{e}$	s_e	RMSE	$\bar{e}$	s_e	RMSE
Asphalt	–0.01	0.01	0.01	0.03	0.02	0.04	0.26	0.09	0.25
Concrete	–0.01	0.02	0.02	–0.01	0.05	0.04	0.13	0.18	0.21
P. stones	–0.02	0.02	0.03	0.01	0.05	0.04	–0.03	0.10	0.10

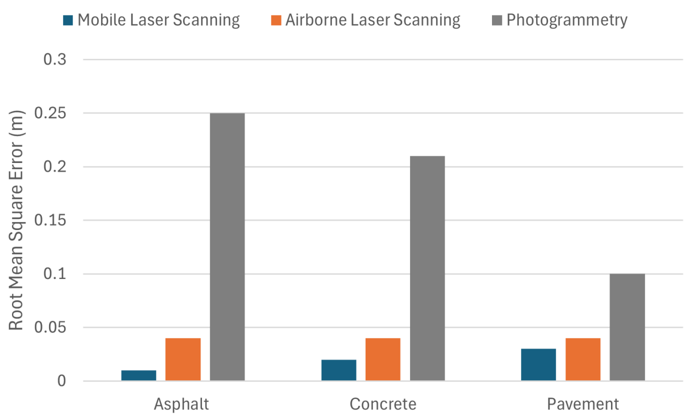

Fig. 4. RMSE values for all remote sensing techniques and road surfaces

3.1. Mobile laser scanning

Table 4 and Figure 5 provide the resulting values of the MLS technology. The best results were achieved on the asphalt surface (–0.01 m ± 0.01 m), following the surface created from concrete slabs (–0.01 m ± 0.02 m), and stone pavement (–0.02 m ± 0.02 m). Statistically significant differences from reference data (underestimation in all three cases) were observed at the $\alpha = 0.05$ significance level on all three surfaces. The minimum deviations were observed for the asphalt surface type and ranged within the interval of ± 0.025 m. In contrast, maximum deviations were observed for the pavement surface type and fluctuated from –0.06 m to +0.052 m. This method achieved the lowest differences between the estimated terrain elevation and the measured reference values, the RMSE values with a 68% confidence interval were in the range of ±0.01 m (asphalt), ±0.02 m (concrete), and ±0.03 m (stone pavement).

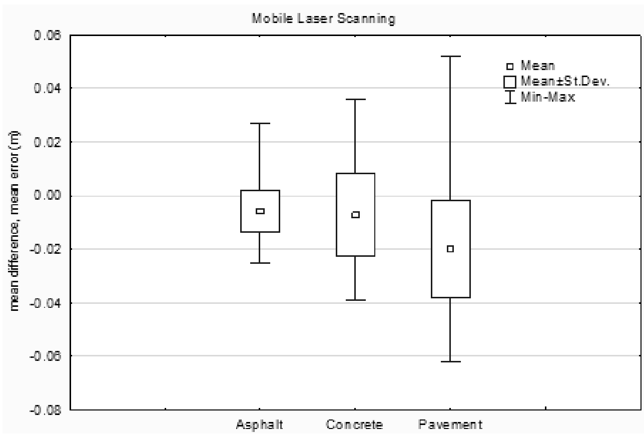

Fig. 5. Statistical characteristics of data acquired using MLS according to road surface

3.2. Airborne laser scanning

The ALS observed a significant mean difference of –0.01 m ± 0.05 m on the concrete surface (underestimation to the reference data) (Table 4 and Fig. 6). For the stone pavement surface type, we observed a mean difference value of 0.01 m ± 0.05 m, and for the asphalt, a value of 0.03 m ± 0.02 m; in both cases, a statistically significant overestimation (at the $\alpha = 0.05$ significance level) was proved compared to the reference data. The smallest range of deviations was observed for the asphalt surface (–0.44 m to 0.086 m), with a more significant range for the concrete slabs (–0.12 m to 0.20 m) and stone pavement surface (–0.08 m to 0.24 m). We observed the same RMSE values of ±0.04 m on all three surface types, indicating that the estimated terrain detected by the ALS method will be within the range of ±0.04 m with 68% confidence compared to the reference values.

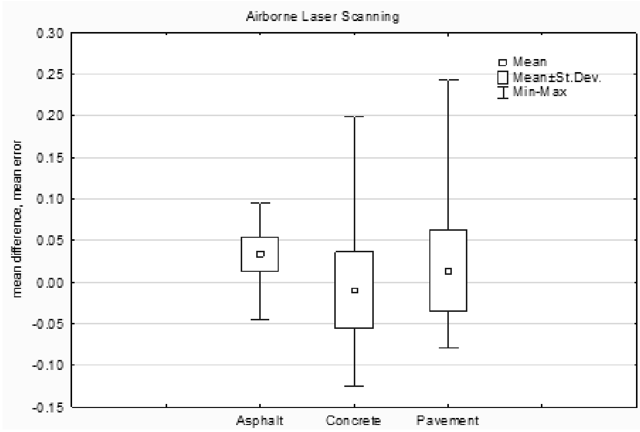

Fig. 6. Statistical characteristics of data acquired using ALS according to road surface

3.3. Aerial photogrammetry

The AP datasets provided the lowest mean difference (–0.03 m ± 0.10 m) on the stone pavement surface, while the highest mean difference was recorded for the asphalt surface (0.26 m ± 0.09 m). The mean difference of 0.13 m ± 0.18 m was achieved on the concrete surface (Table 4 and Fig. 7). The asphalt and concrete surfaces produced significantly overestimated results compared to the reference data at the $\alpha = 0.05$ significance level. Positive deviations were observed for the asphalt surface type and ranged from +0.02 m to +0.48 m. In contrast, the largest variability was observed for the concrete and fluctuated from –0.29 m to +0.48 m. Deviations from –0.29 m to +0.19 m were observed on the stone pavement surface. This method produced the highest difference in the estimated terrain height from the reference values, with the observed RMSE values in the range of ±0.10 m on the stone pavement to ±0.25 m on the asphalt surface.

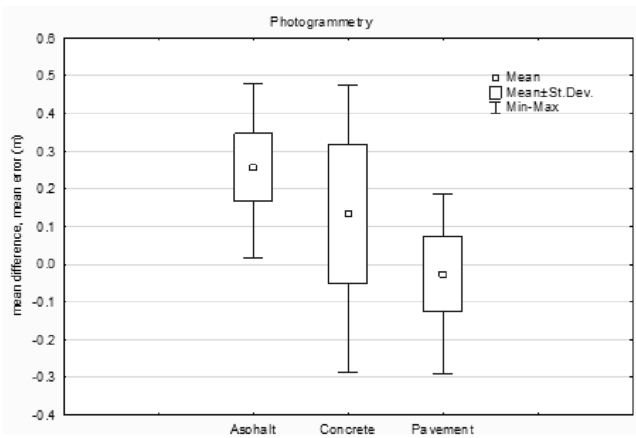

Fig. 7. Statistical characteristics of data acquired using aerial photogrammetry according to road surface

4. Discussion

We compared two airborne and one mobile terrestrial remote sensing technology to capture the forest road surface. For this purpose, we conducted the experiment on three different forest road surface structures.

In terms of road surface capture quality, subsequent terrain generation, and number of points per m^2, the MLS method provided the best performance. Compared with terrestrially measured data through a combination of GNSS and total station, it provided the smallest mean differences and RMSE values (from 1 cm to 3 cm, depending on the road surface type). At the same time, the method provides balanced results regardless of surface type with the lowest variability. The results achieved by the MLS technology are within the theoretical accuracy of the measurement method that was used to get the coordinates of the reference points (2–3 cm horizontal and vertical accuracy). Regarding data post-processing, filtering and DTM generation, it is the most time-consuming method, requiring high computational capacity. On the other hand, it allows the generation of a detailed terrain model that can capture the finest details, enabling applications such as road surface damage detection, damage calculation and derivation of accurate repair costs.

Hofmann and Brenner (2016) provided an evaluation of the RIEGL VMX-250 MLS point clouds with reference datasets for several campaigns and reference datasets, measured on the test field, based on a geodetic network and included data of planar façade elements for analysing the accuracy of the horizontal location and street profiles for height accuracy analyses. The accuracy analysis was based on the least squares strip adjustment using the deviation between reference data and point clouds in the direction of their normal vectors. The results after the adjustment varied from 1.1 mm for scanner 1 and –5.3 mm for scanner 2 with a standard deviation of 7.2 mm and 11.1 mm. (Poreba and Goulette, 2013) achieved the accuracy of the MLS point clouds using the LARA 3D prototype in urban area by comparison with other more accurate reference points (checkpoints measured by a total station, similarly to our study) resulting in an accuracy better than 0.3 m. They also found that the uncertainty in the identification of common points, this method is affected by man-made error and limited by point cloud resolutions. Hrůza et al. (2018) used mobile laser scans, close-range photogrammetry, terrestrial laser scanning and ALS to compare height differences of forest roads. The differences calculated between particular models and geodetic measurements show that close-range photogrammetry achieved an RMSE of 0.0110 m, and the RMSE of terrestrial laser scanning was 0.0243 m. They concluded that these two methods are sufficient for monitoring the asphalt wearing course of forest roads. By contrast, MLS with an RMSE of 0.3167 m does not reach the required precision for the damage detection of forest roads due to the vegetation affecting the measurements' precision. Similar results are achieved by ALS, with an RMSE of 0.1392 m. Compared to our results, the performance of the MLS and ALS was much better in both cases in our study. Our results are also in cope with Kukko et al. (2012), whose performance of evaluated systems (ROAMER MLS and Akha backpack MLS) shows absolute accuracy of the object reconstruction from point clouds of several centimeters (RMSE 20 mm (Akha) and 23 mm (ROAMER)), both regarding plane and elevation. The error figures for the elevation precision were found to be slightly less than double the horizontal errors, 14 mm and 29 mm, for the ROAMER and Akha, respectively.

Regarding achieved height accuracy, the ALS method was ranked slightly worse than the MLS but still much better than aerial photogrammetry. It provides balanced RMSE results irrespective of surface type (4 cm for all three surfaces), which are almost within the accuracy interval of the terrestrial reference data. We observed minor differences, e.g. a higher mean difference for the asphalt surface, but with a lower variability of values. For less homogeneous surfaces, we noted higher variability, but the mean difference value is close to zero. Nevertheless, the observed differences were statistically significant (slight underestimation in the concrete surface and slight overestimation in the case of the stone pavement). We have evaluated the ALS technology as providing balanced results, resulting from the technological procedure of point cloud processing, which means block alignment of the individual scanned strips, and due to classification strategy, where the points with gross errors are eliminated. In our previous study (Sačkov and Kardoš, 2014), the important fact that we identified was that at the $\alpha = 0.05$ significance level, all the terrain height values in the models differed significantly from their measured values. This difference was usually positive, meaning the terrain height generated from the ALS data was overestimated to the actual height. Although our research shows slightly worse results in the ALS dataset than the MLS results, we have to conclude that the input point cloud densities are different. For the MLS, there is almost 100 times higher density than for ALS. The greater robustness of the data resulted in a more accurate DTM interpolation. The effect of LiDAR point density on the DTM accuracy was examined, for example, in the study of (Cateanu and Arcadie, 2021), where they analysed the impact of the density of the filtered data on the quality of ground surface modelling (from 0.89 to 0.09 points/m^2) by randomly removing point observations in 10% increments. The reduction of point density led to a less accurate DTM in all cases. However, the ALS's ability to obtain information about the terrain under the forest cover represents a significant advantage over photogrammetric mapping methods, even in worse weather conditions. Especially in forested areas, recording the first but also last and intermediate echoes, in the case of laser scanning, provides a better opportunity to collect measurements of the ground (Höhle and Potuckova, 2011). In the study of (Suleymanoglu et al., 2023), both UAV LiDAR and MLS data were investigated to obtain geometric parameters of roads. That means cross-sectional/longitudinal profiles of the road sections were extracted and compared with reference data. A comparison of the longitudinal profiles obtained from DTMs derived from the MLS and UAV-LiDAR revealed RMSE values of 1.8 cm and 2.3 cm, with the average deviation of cross-slopes for both surfaces being 0.19% and 0.18%, respectively. These findings coincide with our results when we take into account the differences between the technology used (e.g. UAV vs airborne LiDAR).

Compared to other methods, aerial photogrammetry provided the highest RMSE variability (±0.10 m stone pavement, ±0.21 m concrete and ±0.25 m asphalt). The method provided the least accurate results among the three methods tested on all three surface types. Rahmayudi and Rizaldy, (2016) concluded that there are many factors influencing DTM production using a semiautomatic image-matching method. Homogeneous areas were the leading cause of error points in mountainous terrain and flat terrain. DSM image matching in such an area tends to be lower than the actual value and becomes depression points. Of course, several other factors influenced the result of the photogrammetric methods, such as the type of lens used with a 53 mm focal length, the flying height, the GSD resolution, and the overlap of the images. The high differences between the RMSE results depending on the surface type correspond to the image correlation capabilities. Better achieved results on the pavement stone surface could be associated with its heterogeneous texture, whereas traditional image correlation techniques observe better results of the homologous point identification. Another factor that could influence the variability and determination of the real terrain model of forest roads under or near forest stands is relief displacement; as the distance from the principal point increases, relief displacements occur radially, meaning that the objects on the terrain tend to tilt and cover other objects (Wolf et al., 2014). The theoretical expected achievable accuracy of z coordinates of automatic triangulation with simultaneous bundle block adjustment may range within 1/1000 of flying height (Wolf et al., 2014), which means the theoretical value of 15 cm in our study. Photogrammetry provides sufficiently accurate data for mapping forest roads and automated identification of their surface and area of damage; however, these must not be overlain by other objects, e.g. vegetation and trees along the road. The laser scanning methods presented in this work eliminate this disadvantage of photogrammetry. If photogrammetry should be used to produce highly accurate terrain models of forest roads, it is essential to use data with a lower flight height, optimally in the non-vegetation period. Photogrammetric photos taken by unmanned aerial vehicles from a few meters height could help to overcome this issue.

Hobi and Ginzler (2012) evaluated the vertical precision of two generated DSM from WorldView satellite images and ADS80 sensor of a forested area. The extracted heights from the models were compared with the terrestrially measured data. The authors evaluated the height precision of the data using the root mean square error. For WorldView, the authors state an RMS of 0.32 m and a DSM of ADS80 of 0.08 m. The accuracy of a DSM varied with land cover type, and forested areas were the most challenging areas for surface height modelling among the land cover types. Similar research using MLS, ALS and photogrammetry done by Botes and Geomatics (2013) that has not been realized in a forest environment is consistent with our conclusions. MLS (Streetmapper 360) did the best in the strip survey test with an accuracy of 0.010 m RMS. Accompanied by the advantage of the point spacing of 700 points/m^2 against the ALS of 1.1 points/m^2, it ensured a high-density survey of high accuracy. ALS did exceptionally well in their test by more than double the general performance with 17 mm RMS. Photogrammetry had the worst results in their study, with a RMS of 0.141 m. For the DTM generation, we used the inverse distances (IDW) method. For example (Su and Bork, 2006) provided information in their study that the IDW is a simpler and more accurate interpolation method than kriging for DTM generation when high-density point clouds are processed (> 0.75 points/m^2). In previous research under the canopy of forest stands (Sačkov and Kardoš, 2014), we found that the differences between the terrain models created by various interpolation or conversion methods were only random. Thus, an interpolation technique which is simpler or more effective from the point of view of the end-user could be selected. The complex difference between the estimated terrain height and the measured value was located with 68% confidence at intervals of ± 18 cm (DTM Leaf-on) and $\pm 13 - 14$ cm (DTM Leaf-off) on the ALS datasets.

5. Conclusions

We analysed, evaluated and compared two aerial methods routinely applied in forestry mapping (photogrammetry and laser scanning) and mobile laser scanning for the measurement of forest road surfaces.

Aerial, large-scale photogrammetry can be used only for forest road inventory, moreover, it can only be used when trees' canopy does not occlude the roads. The decimeter-level height accuracy is not sufficient for construction and maintenance purposes. In our research, we took advantage of the data obtained during a periodical aerial photogrammetric survey, which was relatively easy to obtain. These surveys are planned for different purposes (the basic forest inventory and road identification). However, the photogrammetric methods using unmanned aerial vehicles (UAVs), close-range photogrammetry, or airborne photogrammetric data taken in a leaf-off season with higher ground sampling distance (GSD) and photo overlap produce DSMs, which are more suitable for precise terrain measurements.

The airborne laser scanning, with its ability to partially penetrate the forest canopy, can provide complex information about forest roads for inventory purposes and broader area surveys. Still, the better accuracy enables it to be used in more detailed applications.

The only terrestrial method in our study – mobile laser scanning – provided the best spatial accuracy, enabling construction and maintenance works related to forest roads. Compared with airborne methods, it provides limited information about the surrounding environment. Most detailed information is referenced to the subject of the measurement, in our case, the forest road.

To choose the appropriate method, the knowledge of the environment in which these methods are intended to be applied is essential. It is necessary to subordinate the choice of methods to this and know what we can expect from which method within specific settings. In any case, the advantage is that these data types can be combined to detect the road surface correctly while they have similar or slightly worse accuracy (ALS vs MLS). The combination of ALS and photogrammetry provides the possibility to identify and classify roads over larger areas using DTM and image data, while the MLS has an advantage in terms of damage calculation and identification.

Therefore, the users must select the appropriate method according to their requirements (either less accurate complex information – AP, ALS or detailed information with limited wider context – MLS).

Author contributions

Conceptualization: M.K., I.S., D.C.; methodology: M.K., I.S., D.C.; resources, M.K., I.S.m D.C.; validation and formal analysis: J.T., Ł.B., K.M., I.B.; writing – original draft preparation: M.K., I.S., Ł.B., D.C.; writing – review and editing, M.K., I.S., M.F.; funding acquisition: M.F., J.T., Ł.B.

Data availability statement

The data presented in this study are available on request from the corresponding author.

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