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DETECTION OF TECHNICAL PARAMETERS FOR FOREST ROAD NETWORK ASSESSMENT USING MOBILE LIDAR DATA

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ABSTRACT

Forest road networks constitute critical infrastructure mandated to comply with established technical standards. Traditional, survey-based methods used in determining road network adherence to standards are time-consuming and costly, with shortcomings accentuated in the presence of steep terrain and dense vegetation. This study introduces a novel method that relies on mobile ZEB1 LiDAR data to assess forest road technical parameters. The technical parameters evaluated in the Plattenhardt Baden-Württemberg, Germany study area include roadway width, road slope, profile curvature, road surface flatness and ditch network. The method delineates forest roads via point cloud classification and subsequent Digital Terrain Model (DTM) derivation to assess their parameters and adherence to class-specific standards. An accuracy assessment performed against total station data (using LEICA TS 15) revealed no significant statistical differences in the measured road parameters. The proposed methodology is reliable, precise and well-suited to short road networks.

KEYWORDS : ZEB1 mobile laser scanner, Leica TS 15

1 INTRODUCTION

Forest road network assessment and maintenance is an aspect of forest management with vital importance. Many classical survey methods have been followed for technical assessment of forest roads (Karagiannis et al. 2001, Drosos et al. 2006, Giannoulas et al. 2014, Plisovikos et al. 2014, Giannoulas et al. 2015). Classical survey methods require the use of different instruments (e.g. theodolite, compass, clinometer, measuring tape) and are also time-consuming because the foresters have to establish several sample sites that cover the road network without bias. Usually large groups of foresters are needed to do field work. Forest vegetation introduces challenges, because dense canopy blocks satellite signal which is required for GPS measurements and thus position errors are present during road assessment (Jianyang et al. 2005, Karagiannis 2008). The primary scope of this research is to develop a methodology which allows the precise and reliable technical assessment of forest roads concerning the parameters of roadway width, road slope, profile curvature, road flatness and ditch network using LiDAR data collected with a mobile, hand-held laser scanner (i.e. ZEB1, GeoSLAM Ltd. 2015). This laser scanner has not been used before for this purpose. The main scientific questions of the study refer to the extent that ZEB1 can be used under forest conditions and the way that ZEB1 LiDAR are used for technical assessment of forest roads.

2 THEORETICAL BACKGROUND

2.1 ZEB1 Laser Scanner

The ZEB1 device is a hand-held mobile laser scanner that emits one-return pulses and includes no intensity values. ZEB1 contains two main parts (Figure 1) i.e. a laser scanner and an inertial measurement unit (Bosse et al. 2012). It uses Simultaneous Localization and Mapping (SLAM) technology to georeference the resulting point cloud. A SLAM-capable robot can navigate and map surroundings without using GPS, a property rather useful in forested landscapes (Ryding et al., 2015). This is accomplished by multi-angle detection and identification of scene objects. The ZEB1 inherent accuracy is between 2-3 cm, and the pulse repetition frequency is 43.2 kHz (GeoSLAM Ltd. 2015). It is important to mention that from a mobile platform laser pulses sufficiently penetrate gaps in vegetation and we can derive terrain information under canopy. The penetration is affected by the laser beam divergence (Aldred and Bonnor, 1985). ZEB1 must be used in closed loops (GeoSLAM Ltd. 2015) because the error growth is prevented in the data collection. Therefore data collection should start and finish at the same place. Any offset between the first and the last pass is the error included in the data and it is spread through the loop. Point cloud registration errors are lower when the scene includes many unique static features (Bailey and Durrant- Whyte, 2006). However, if there are some few moving objects that do not move in the same direction then a good solution is possible. The field work of this study showed that the scanner must not move too fast otherwise it is not able to detect objects that were visible in previous spots especially when the scanning direction changes. Furthermore, limitations in continuous data acquisition duration limit its applicability to short road networks (i.e. maximum 30-35 minutes duration of continuous data capture is recommended).

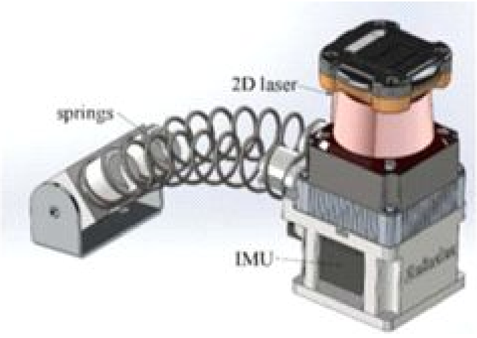


Figure 1: ZEB1 technical parts (Bosse et al. 2012)

2.2 Forest Roads

Four forest road classes have been identified in Germany, each with different technical characteristics (cf. Dietz et al. 1984, Karagiannis 2008, Eskioglou 2010):

- Class A Roads, connecting state and rural networks with forests. The roadway width must be 8m in non-rocky soils. The road slope ranges between 3% and 8% and the profile curvature ranges between 1 and 4 %.
- Class B Roads, connecting class A roads to managed forested areas. Width must be 4-6 m in non-rocky soils. The road slope ranges between 3% and 8% and the profile curvature between 1 and 4 %.
- Class C Roads, connecting class roads A and B to forest stands where forest products are collected. The roadway width must be 5 m in non-rocky soils. The road slope ranges between 3% and 12% and the profile curvature ranges between 1 and 4 %.
- Tractor Roads used by tractors and fraught animals that transfer wood from the harvest site to forest roads. The roadway width must be 3 m in non-rocky soils. The road slope ranges between 3% and 25% and the profile curvature can vary.

Roadway width refers to the distance between the two profile edges of the road-body. The traverse grade between these two road edges is defined as profile curvature. Road slope is the lengthwise grade of the road-body (Eskioglou 2010). These road technical characteristics depend on soil type. Here non-rocky soils are considered because they are mostly found in the study area.

2.3 Related Literature

Forest road detection has been previously attempted by using airborne LiDAR data and segmentation and classification techniques. White et al. (2010) have studied the mapping of forest roads using airborne LiDAR in steep terrain in the Santa Cruz Mountains, California, and compared accuracy against classical field survey measurements. They found out that "in comparison to the field-surveyed road center line, the LiDAR derived road exhibited positional accuracy of 1.5 m, and total road length within 0.2% of the field surveyed length" (ibid., p. 1120). Azizi and Nazafi (2014) have used the support vector machine method to classify airborne LiDAR-derived terrain into road and off-road classes. They found that more than 95% of the LiDAR derived road was delineated within 1.3 m of the field survey methods. Moreover, Sherba et al. (2014) achieved 86% road classification accuracy by following an object-based classification of abandoned logging roads under dense canopy in Marin County, California. David et al. (2009) detected forest pathways using airborne LiDAR. They developed a region growing methodology based on previously detected seed segments and reported a 3 m horizontal shift in the position of the detected pathways.

Kiss et al. (2015) studied parameters pertinent to road quality (i.e. surface wear, flatness, seasonal damages, and drainage network) using airborne LiDAR. They applied the topographic position and the standardized elevation index, on digital terrain models of different resolutions and achieved the most accurate results when resolution ranged between 0.20 and 0.50 m.

The use of ZEB1 laser scanner in forest conditions is an emerging topic of study. Ryding et al. (2015) have evaluated the use of the ZEB1 in calculating tree diameter at breast height (DBH) and stem position. They found that with stems exceeding 10cm in DBH the relative root mean square error for DBH and stem position was 1.5 cm and 2.1 cm respectively.

3 METHODOLOGY

Mobile Laser Scanning (MLS) data were collected in October 2015 in the forest of Plattenhardt in Baden-Württemberg, Germany (Figure 2), by using the hand-held mobile laser scanner ZEB1 (GeoSLAM Ltd 2015). The data comprised point clouds from two closed loops with 0.3 m post spacing and represented five forest roads; one in each of the A, C, and tractor classes, and two in class B for a total length of 1.75 km. Field data were also captured in January 2016 using the total station Leica TS 15. The study area contains mostly non-rocky moderate arid clay soils and is dominated by European Beech *(Fagus sylvatica),* Sessile Oak *(Querqus petraea),* and English Oak *(Querqus robur).*

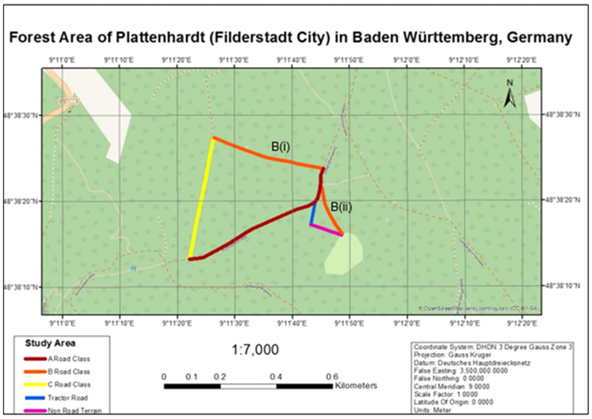


Figure 2: Map of study area

The data analysis methodology is shown in Figure 3. The two MLS point clouds were registered using the Iterative Closest Point (ICP) algorithm. ICP registers point clouds based on proper point associations. Given these point associations a transformation is done between the two point clouds following the Singular Value Decomposition theorem (Burgrad et al., 2014). Point cloud registration was done with the software Cloud Compare Version 2.6.1. The points in the merged cloud were then classified as terrain and off-terrain using the parsimoniously parameterized Multiscale Curvature Classification (MCC) algorithm (Evans and Hudak 2007). The MCC algorithm is well-suited to forest conditions because it minimizes commission errors while retaining a substantial proportion of ground points necessary for detailed and accurate digital terrain models (Evans and Hudak 2007). Utilizing the points classified as ground, a 25 cm DTM was generated using inverse distance weighted interpolation. The resolution selected approximated the nominal point cloud spacing, as suggested by Chow and Hodgson (2009). A DTM-based extraction of forest roads is often inhibited by a, usually smooth, transition zone between the road surface and neighboring terrain. Standard pixel-based and object -oriented classification methods require the spectral response of the pixels (Walter 2004). However, the ZEB1 LiDAR based DTM includes no spectral information. To quantify uncertainty in the transition zone and delineate road edges I employed a fuzzy number Gaussian membership (Pappis and Siettos 2000). This was accomplished by dividing the MLS trajectory line, which is known to lie on the road surface, to 2m segments, and selecting the points classified as ground and located within 1m from each segment end. The mean and standard deviation of point elevation present in each 1 m-radius circle were calculated and used in the fuzzy number Gaussian membership function for each segment. The classified DTM presented a speckled appearance because of the salt-and-pepper effect (i.e. isolated pixels that do not belong to the same class with their neighbors). To suppress this problem DTM cells with calculated membership probability equal to or exceeding 0.95 were selected and labeled road. This threshold was empirically applied because it minimized the salt-and-pepper effect. Following the road detection, road borders were digitized and subsequently "collapsed" (a GIS procedure) to delineate center lines. To assess road parameters, transects were derived vertically to the road center line every 10 m. The length of each transect was equal to the roadway width. Road profile curvature was calculated along each transect and then the mean profile curvature was calculated for each road. Road slope was calculated along the center line of each road every 10 m and then the mean slope was obtained for each road. Derived parameter values were compared to established standards for each road class.

To evaluate road surface flatness and detect ditches, the Standardized Elevation Index (SEI) was employed. SEI is defined as the difference between the elevation value of each cell (on the road raster) and the average elevation value of its neighbor cells, divided by the standard deviation of the neighborhood (Kiss et al. 2015). The neighborhood was defined as a 5x5 cell centered on the processed cell, because it allows detecting large road surface abnormalities. Negative SEI values indicate depressions, positive values local elevation maxima (bumps), and values around zero indicate flat areas. The SEI units are given in standard deviations. Linear depressions alongside the roads are assumed to represent ditches.

Field data used for accuracy assessment were obtained by using a Leica Total Station offering nominal distance and angular measurement precision of 2 mm and 0.004 mrad respectively. The Leica instrument measured 3 points on the road surface every 15 m; two on the opposite edges and a third on the center line. These measurements were then converted to roadway widths, profile curvatures and road slopes. The two sample T-Test and the Aspin-

Welch Unequal Variance T-Test, were used to evaluate statistical significant difference between the means of ZEB1- and Leica TS 15-based measurements (i.e. comparing the means of two datasets).

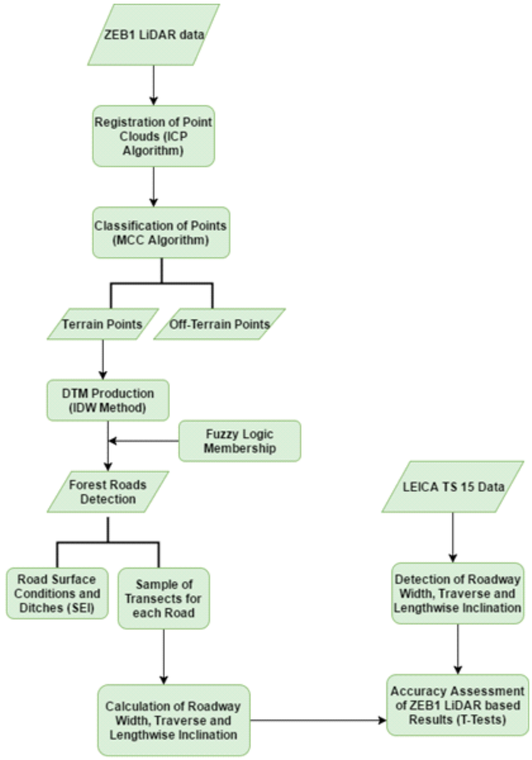


Figure 3: Workflow Chart

4 RESULTS

4.1 Detected Forest Roads

The detected forest roads (following the fuzzy number Gaussian membership) are presented with blue color on the digital terrain model in Figure 4. The length of each road is maintained because the road lengths measured using the total station and the road lengths following the tested method differ slightly (Table 1).

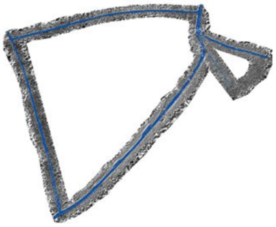


Figure 4: Detected forest roads (with blue color) on the digital terrain model of the study area

Table 1: Length of forest roads

Road	Road Length-Total Station (m)	Detected Road Length (m)	Difference (m)
A	629.4	629.2	0.2
B (i)	405.9	405.66	0.24
B (ii)	157.2	157.07	0.13
C	450.4	450.13	0.27
Tractor	105.4	105.3	0.1

4.2 Roadway Width, Profile Curvature and Road Slope based on ZEB1 Data

The tables 2, 3 and 4 present which roads were found to follow the roadway width, profile curvature and road slope standards according to each road class. Only the second road of Class B (i.e. B ii) follows (on average) the roadway width standard. All roads deviate, on average, from the standard profile curvature except from the tractor road, because its profile curvature can vary. Finally, the class C road and the tractor road comply (on average) with the road slope standard while the rest of the roads do not follow this standard. It is essential that repair works are conducted on the roads that do not follow the aforementioned technical standards. Otherwise, the transportation of forest products by vehicles will be problematic.

Table 2: Mean roadway width results for each road compared to the standards

Road	Mean Roadway Width (m)	Standard Roadway Width (m)
A	5.04	8
B (i)	3.45	4-6
B (ii)	4.35	4-6
C	3.87	5
Tractor	4.05	3

Table 3: Mean profile curvature results for each road compared to the standards

Road	Mean Profile Curvature (%)	Standard Profile Curvature (%)
A	0.51	1-4
B (i)	0.88	1-4
B (ii)	0.85	1-4
C	0.88	1-4
Tractor	1.08	Can vary

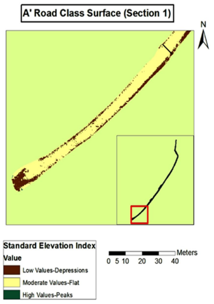
Table 4: Mean road slope results for each road compared to the standards

Road	Mean Road Slope (%)	Standard Road Slope (%)
A	10.12	3-8
B (i)	9.52	3-8
B (ii)	9.71	3-8
C	7.51	3-12
Tractor	11.40	3-25

4.3 Road Flatness and Ditches Network based on ZEB1 Data

The SEI values within the range -0.04 – 0.05 (moderate values) were considered here as flat areas. Lower values indicated depressions and larger values indicated bumps. Depressions of linear shape alongside the road body were recognized as ditches. Figure 5, presents a section of class A road where SEI was applied and provides a profile from this road segment. SEI was applied to all road rasters (i.e. roads are parts of the DTM) and it was found that the largest portion of pixels of each road raster belonged to flat surface. The class B road (i) had the most bumps, the class B road (ii) had mainly flat surface, and the tractor road had the most depressions (Table 5).

Figure 5: (a) Section 1 of class A road- road surface conditions. The thick black line on the road surface refers to the profile of the figure 5b. (b) Road profile from section 1 of class A road. The road surface is flat and alongside the road body there are two ditches.



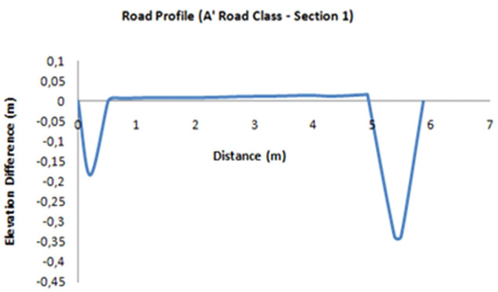


Table 5: The percentage of cells of each road surface that belongs to depressions, flat areas and bumps

Road Surface (percentage of cells- %)	Road A (%)	Road B(i) (%)	Road B(ii) (%)	Road C (%)	Tractor Road (%)
Depressions	20.5	19.9	17.2	18.6	32.04
Flat areas	79.2	44.7	79.8	62.6	57.6
Bumps	0.16	35.3	2.8	18.7	10.3

4.4 Accuracy Assessment

The calculated mean roadway width, profile curvature and road slope of each road based on LEICA TS 15 data (Table 6) revealed same technical problems that were detected when same technical parameters were calculated using ZEB1 data. In both cases the same roads were found to follow the technical standards or deviate from them.

According to two sample t-tests and Aspin- Welch unequal variance t-tests, there was found no statistically significant difference between the results based on LEICA TS 15 data and ZEB1 data. The tables 7, 8 and 9 refer to the implemented t-tests. In all cases the null hypothesis is that there is no statistically significant difference between the means of road technical parameters derived from ZEB1 and total station data sets (i.e. H_0: m_1=m_2).

Table 6: Mean roadway width, profile curvature and road slope (based on LEICA TS 15 data)

	Road A	Road B(i)	Road B(ii)	Road C	Tractor Road
Mean Roadway Width (m)	4.59	2.99	4.07	4.17	3.49
Mean Profile Curvature (%)	0.86	0.92	0.76	0.67	3.86
Mean Road Slope (%)	9.13	8.88	9.33	7.19	12.05

Table 7: T-Test regarding roadway width parameter

Roadway Width (H_0: m_1=m_2, a=5%)		
Roads	**P value**	**Reject H_0**
Road A	0.375	No
Road B(i)	0.61	No
Road b(ii)	0.218	No
Road C	0.165	No
Tractor Road	0.162	No

Table 8: T-Test regarding profile curvature parameter

Profile Curvature (H_0: m_1=m_2, a= 5%)		
Roads	**P value**	**Reject H_0**
Road A	0.252	No
Road B(i)	0.862	No
Road b(ii)	0.423	No
Road C	0.153	No
Tractor Road	0.117	No

Table 9: T-Test regarding road slope parameter

Road Slope (H_0: m_1=m_2, a=5%)		
Roads	**P value**	**Reject H_0**
Road A	0.281	No
Road B(i)	0.397	No
Road b(ii)	0.237	No
Road C	0.352	No
Tractor Road	0.405	No

5 DISCUSSION

The proposed methodology has been proven reliable, delivering precise estimates of forest road attributes. The fuzzy number Gaussian membership function has been successfully applied in the extraction of roads with borders blending into their surroundings. The 0.95 probability threshold provided the best results because it minimized the speckled appearance of the classified DTM. I determined that only one (class B ii) of the road segments examined complied with established width standards, and only the class C and the tractor road with the slope specification. No statistically significant differences between the results obtained by using the LEICA TS 15 and ZEB1 data were found, suggesting that MLS is a reliable alternative for expeditious, economical, and trustworthy identification and assessment of forest roads. The SEI index was useful for evaluating road surface flatness and identifying ditches.

The main advantage of using the ZEB1 laser scanner under forest conditions, is its independence from GPS signal reception, which is often problematic under canopy, thanks to the SLAM technology. The ZEB1 offers accurate measurements, simple operation, and low weight. The absence, however, of intensity information for each cloud point, complicates feature identification and classification. Furthermore, limitations in continuous data acquisition duration limit its applicability to short road networks.

Unlike traditional survey techniques that use compass, clinometer, measuring tape and optical theodolite (Doukas, 2004), the MLS-based acquisition of field data is expeditious, uncomplicated, and can be performed by a single person.

Compared to other studies that employ synergies of airborne LiDAR and airborne or satellite imagery for forest roads detection and assessment, the application of MLS technology is practically independent of canopy cover and pulse penetration issues. MLS enables detailed mapping of short forest road networks, unattainable by other photogrammetric or remote sensing means.

Suggested improvements include the use of reference height data or reference DTM of the study area (currently not available) so that the overall geospatial positional accuracy is evaluated. Densification of the total station data would enable the accuracy assessment extended to road surface conditions and the ditches network. Additional road technical parameters (e.g. serpentine conditions) can be examined in the future. The collection of paired road transects (same intervals) in the field and also on the DTM will improve the results because we will be able to detect when the estimates based on LiDAR data deviate from the estimates based on total station data at transect level. An acceptable error for a given cross section can be defined and then we can determine how often the estimates based on LiDAR data exceed this error. Scan-to-scan accuracy can be assessed, and the ability to detect changes in road conditions (ditch erosion, signs of side-slope failures, etc.) must be considered. Furthermore, repeated monitoring of road conditions with subsequent mobile LiDAR scans is recommended. These suggestions shape the framework for future research directions and improvements.

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