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Suitability of Different LIDAR Data Sets for 3D Mapping of the Road Environment

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Summary: This paper presents a comparative study of LIDAR data sets and their suitability for 3D road environment mapping. For this purpose three data sets from different acquisition platforms are studied with consideration being given to not only the vectorization of elements on the road surface but also the detection of road furniture objects. While test digitizations are carried out manually, the potential of the data for automatic approaches is discussed using the methods found in recent literature as a basis. The focus of the study is to point out the strengths and weaknesses of the data sets for road mapping tasks. The results show that the decision for various data acquisition platforms is highly dependent on the final purpose for which the data is collected.

Zusammenfassung: *Eignung unterschiedlicher LIDAR Datensätze für die 3D Digitalisierung des Straßenraumes.* Dieser Beitrag beschreibt eine vergleichende Studie von LIDAR Datensätzen hinsichtlich ihrer Eignung für die 3D Erfassung des Straßenraumes. Dazu werden drei Datensätze aus unterschiedlichen Aufnahmeplattformen untersucht. Die Untersuchung umfasst neben Elementen auf der Straßenoberfläche auch die Erfassbarkeit von Objekten des Straßenmobiliars. Während im Rahmen dieser Arbeit manuelle Testdigitalisierungen durchgeführt wurden, wird das Potenzial der Daten für automatische Methoden anhand von Veröffentlichungen der vergangenen Jahre diskutiert. Die Studie zeigt Vor- und Nachteile der unterschiedlichen Datensätze für die Straßenraumerfassung auf. Die Untersuchung macht deutlich, dass die Entscheidung für die eine oder andere Aufnahmeplattform hauptsächlich davon abhängt, für welchen Zweck die Daten letztendlich verwendet werden sollen.

1 Introduction

The present paper compares three LIDAR (Light detection and ranging) data sets and their suitability for road environment mapping. The data sets are the results from different data acquisition platforms. Two are captured by airborne laser scanning systems while the third is from a mobile ground-based laser scanning system. They are characterized by significantly differing point densities. The two main questions discussed in this paper are: first, what objects can be detected from LIDAR point clouds resulting from different acquisition platforms; and second, how properties of LIDAR points like elevation values, point densities, or intensity information make such data sets suitable for 3D road mapping tasks. For this study, the test digitizations are supported by semi-automatic alignment methods based on the LIDAR data, but the vectorization process itself is done manually. Assumptions about the potential of the data for automatic detection methods are discussed using a review of different approaches in recent years as a basis. The test digitizations are only based on the data (data driven approach), which leads to some limitations if there are gaps in the LIDAR point cloud. Advantages of model driven approaches are mentioned at the relevant points in the text.

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Objects of the road environment considered in this study are elements that are parts of the road surface (road outlines, centerlines, lanelines, markings), linear objects along the roadsides (curbstones, crash barriers, noise protection walls) as well as road furniture objects such as traffic signs, traffic lights, pylons, and street lamps. In order to map those objects based on LIDAR data, it is assumed that a high-density point cloud is required to identify small objects, e. g., traffic signs, in detail, while a low-density point cloud is sufficient to extract the road surface or centerlines. Thus, consideration of the final purpose of the data regarding scale, level of detail, or required object types for a specific application are important in order to choose the appropriate data acquisition platform. Furthermore, in practice factors like the accuracy of the final product, costs, processing time and data processing efforts are essential for a decision about the method of data collection. Although these points are not included in this study, some are added in the concluding Section of the paper. There might also be existing geodata for roads from other sources, e. g., topographic data bases. Such data can be included as additional information in the road detection process. Furthermore, LIDAR data are used for adding the third dimension to 2D data or updating existing data bases. Examples of such approaches are mentioned in the literature review of this paper, but they are not given further consideration for the purpose of the study.

The following text points out the strengths and weaknesses of the data sets for road feature detection. On the one hand, it is directed at users in practice to support decisions about data capturing for road mapping tasks. On the other hand, because of the above-mentioned differences between the data sets related to capturing system parameters, missing reference data for accuracy evaluation, and the fact, that they do not cover the same area, this paper can only compare the data sets in a rather descriptive, general way. Therefore, this paper is also intended to give some ideas for future research work and further studies. Section 2 contains a review of LIDAR data acquisition methods and different approaches for road feature extraction from laser data as well as from images. Section 3 describes the materials used for this study. Next, Section 4 illustrates the scope for detecting and digitizing road features based on the different data sets. Finally, the results of the study are discussed and summarized in Section 5.

2 Literature Review

Two main laser data acquisition platforms are used for the purpose of road detection, airborne laser scanning and mobile ground-based laser scanning. The principles of airborne laser scanning as well as different application fields are described in several publications, e. g., (BRENNER 2006, HOFMANN et al. 2002, YU 2007). Examples for mobile ground-based laser scanning can be found in (KUKKO et al. 2007, BARBER et al. 2007). There are on-going research efforts at the Finnish Geodetic Institute (FGI) for modeling the road environment with data from the mobile scanning system "FGI Roamer" (JAAKKOLA 2008). Furthermore, on the software side special tools for handling large data sets from mobile laser scanners and for road environment mapping tasks are being developed (SOININEN, 2008).

There are different approaches to road extraction from airborne laser scanning data that have been published in recent years. One example is described in (CLODE et al. 2004, 2007). It utilizes the height and intensity information as well as the density of the laser points for the extraction of roads from the point cloud. From these extracted road points a binary image is created. The study is continued with an automatic road vectorization method based on the binary image. The result is a closed centerline network as well as parallel edges for each road. HATGER & BRENNER (2003) developed a method for road extraction from a point cloud by using a general planar region growing technique. The process shows its best results in urban areas with clear road margins. Another method in the study utilizes road centerlines from other data sources to extract the road extension. The study is continued by HATGER (2005). Further research is being carried out by OUDE ELBERINK & VOSSELMAN (2006a, 2006b, 2007) using the topographic database of The Netherlands as an additional data source. Their method utilizes the height information of the laser points in order to add the third dimension to the 2D road polygons from the topographic database. The extraction of pavement markings from laser data is described in (Toth et al. 2007). They use the intensity information of the laser points to separate markings from their surroundings. Based on these points, a curve-fitting algorithm creates lines which are used for quality assessment purposes in their study.

An extensive collection of automatic road extraction approaches based on aerial and high-resolution satellite images is given in (Mena 2003). A more recent overview is published by Mayer et al. (2006), who summarizes and compares the results of a EuroSDR project on methods for automatic road extraction from aerial and satellite images. Another study on this topic is being carried out by Hinz & Baumgartner (2003). Their road model considers geometric, radiometric and topologic characteristics of urban roads. Furthermore, information about global and local context is included in the extraction method. As a result, a network of polygons is shown representing the lanes of roads in an urban area. Tao (2006) gives an overview of several data-acquisition and object-reconstruction methods. The paper points out, that data acquisition from stereo images is a widely used process for 3D feature production. Its main disadvantage is the high manual digitization effort and the need for special equipment as well as high-level user skills. Single image-based data acquisition does not require those special components, but it also precludes the possibility of direct 3D feature extraction. According to the paper, the main research issue for all methods is the automation of digitization tasks. It also concludes that the use of multiple data sources seems to be more promising for automated feature extraction than any single method.

The detection of road furniture objects is discussed in publications that are related to the development of driving assistance systems. They focus on traffic sign detection from images or video sequences. Those approaches utilize the shape and color of traffic sign for detecting objects in real-time. An example is given in (Bahlmann et al. 2005). Another study is being carried out by Doubek et al. (2008). Their work introduces a method for the detection of street lamps from video sequences.

The above-mentioned approaches show the concentration of research on the automatic extraction of roads either from images or LIDAR data. They also point out the need for further development in this field. For practical use in particular, there is still a demand for reliable tools for automatic digitization tasks. At the moment, such tasks are done manually or semi-automatically. Another remaining issue is the detection and vectorization of 3D objects not only for the road surface but also for road furniture. For that purpose, LIDAR-based approaches seem to be an adequate option or addition to image-based methods.

3 Materials

In the present paper, three LIDAR data sets from different capturing platforms and with varied point densities are studied. Additionally, aerial images are available for two of the data sets. The data examples are described in Sections 3.1 to 3.3.

3.1 *Aircraft Laser Scan (ALS)*

The *ALS* data set is characterized by a comparatively low point density with approximately 4.4 points/m². The flights for the data acquisition were in spring 2006 and summer 2007. They were flown at an altitude of 1000 m. Furthermore, there are digital orthophotos for the area with a resolution of 20 cm. The flight campaign for the images was also in summer 2007. The data collection was carried out by the FGI in the Nuuksio test environment. The area covers the Nuuksio National Park in South-Finland, from which a highway and a major road were chosen for the present study.

3.2 *Helicopter Laser Scan (HLS)*

The *HLS* data set was produced from a corridor flight at an altitude of 120 m resulting in a point cloud with a density of approximately 35 points/m². The flight was done in fall 2006 by

Hansa Luftbild GIS GmbH. There are also orthophotos with a resolution of 5 cm available. The aerial images for the orthophoto production were recorded simultaneously with the LIDAR data. The corridor covers a segment of a motorway in the north-western part of Germany.

3.3 *Mobile Laser Scan (MLS)*

In contrast to the *ALS* and *HLS* data sets, the *MLS* example is captured by a ground-based mobile laser scanning system. Due to the scanning system mounted on the top of a car, the viewing field of the laser scanner is completely different compared with airborne-mounted systems. This leads to a very dense point cloud along the road (approximately 500–1000 points/m² in this data example) but prevents the detection of objects in the wider surroundings. On average, the point density is about 320 points/m² for this example. The big differences in point density on the road surface occur because of the changing speed of the car transporting the scanner system. The data was captured by Optech in winter 2008 along a suburban road in Coventry, England.

The following Sections refer to the data sets by using the abbreviations *ALS* for the aircraft laser scan, *HLS* for the helicopter laser scan, and *MLS* for the mobile laser scan.

4 Digitization of Road Features

This Section investigates the possibilities offered by each of the example data sets for the detection of road features and objects of the road environment. Those objects can be divided into three categories according to their visibility in LIDAR data: first, road features that can be detected in a digital elevation model (DEM) derived from LIDAR ground points, e. g., road outlines, provided that they are emphasized from the surrounding ground level (cf. Section 4.1); second, objects that can be detected in the intensity image of the laser points such as markings on the road (cf. Section 4.2); and third, objects that are visible because of their height from ground, e. g., traffic signs or crash barriers (cf. Section 4.3). The visibility of objects from the second and third category depends mainly on the point density. The third category also requires the existence of high-contrast intensity information.

All the available data sources are used for the manual test digitization carried out in this study. This includes the LIDAR data, a DEM derived from the ground points, and the orthophotos for the *ALS* and *HLS* data sets. The 3D digitization is further assisted by automatic alignment tools which adjust the elevation of the digitized elements according to the laser points. The potential of the data sets for the detection by automatic methods is discussed at the end of each Section.

4.1 *Road Outlines*

The manual detection of road outlines is first tested with the *ALS* data. In open areas the location of the outlines can be usually better identified in the images than in the laser data. If it is not possible to see the road boundaries in the orthophotos due to the smooth transitions between the road and the surrounding ground or shadows caused by trees or buildings, the DEM is helpful for placing the outlines correctly. Fig. 1 illustrates an example. However, it requires that the road surface differs in height from its surrounding or that the road outline is locally equal with terrain breaklines. There are different options for elevation model display to support the visual interpretation. A shaded surface with several light settings offers the most useful result for outline detection, possibly in connection with contour drawings. The optimal values for the light settings depend on the direction of the road and the slopes next to it. An angle approximately perpendicular to the slope direction and from the opposite side of the boundary that has to be digitized may offer the best choice. In addition to the settings for the display of the shaded surface, its contrast and structure can be tightened by a vertical exaggeration. The visualization methods for the DEM described above are also used for the *HLS* data examples to support the detection of road outlines or breaklines. In the *MLS* data set the road is bounded by curbstones which stand out clearly in the DEM. The dense point

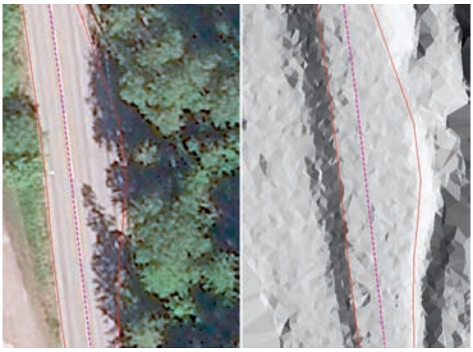

Fig. 1: A bus stop causes a change in road width that is hardly visible in the image, but can be seen in the DEM derived from the LIDAR data. Example from ALS data set.

cloud makes it possible to not only detect their correct location but also to determine the height of the curbstones as well.

For automatic road outline detection, methods mentioned in the literature review seem to be applicable to the three test data sets. Approaches like region growing algorithms as proposed in (Hatger & Brenner 2003) might produce better results for the *MLS* data set than for the other examples because roads are clearly bounded by curbstones. On the other hand, extraction techniques that utilize the point density among other factors as described in (Clode et al. 2004) are better suited to the *ALS* and *HLS* data sets because of their consistent point density than to the *MLS* data set with its differing point density on the road surface. For road outlines equal to terrain breaklines, methods for automatic breakline extraction can also be applied. One example is published by Briese (2004), who presents a 3D breakline detection method based on surface estimations along the breakline. For the *ALS* and *HLS* data sets in particular, these methods seem to be promising due to roads bounded by breaklines. For the *MLS* data set, where the road is bounded by curbstones, the breakline detection method of Briese (2004) is not an option. The availability of image data for the *ALS* and *HLS* data sets makes it possible to attach the RGB values to the LIDAR points as is shown in Fig. 2. This could offer opportunities to combine automatic approaches for road detection from images which use this color information with those for laser data.

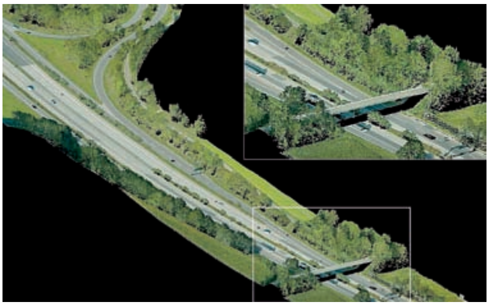

Fig. 2: Laser points from HLS data set, colored by RGB value. © Hansa Luftbild.

4.2 *Road Markings*

Markings on the road surface can be detected from LIDAR data, if the intensity information for the laser points is rich in contrast to distinguish between the markings and the surrounding surface. It requires clear and sharp markings in a bright color on a dark background in reality as well as a comparatively high point density in the laser point cloud. In order to study the intensity values of the three test data sets, a small sample from each of them is analyzed by counting the points within intensity ranges. For this purpose only points from the ground including road surface and markings are chosen. The *MLS* data set consists of an significantly larger intensity range than the other two data sets. Therefore, the *MLS* intensity range has been fitted to make the ranges comparable. It turned out that there are two or three local maxima for the number of points within the intensity values, one or two for points on the ground and one for markings. Due to the small number of points for markings compared with the number of other ground points, the maximum for markings can only be found in its local context while it is insignificant regarding the overall number of points. The results from the intensity study are summarized in Tab. 1.

The values in Tab. 1 show a clear difference between the *ALS* data set and the other two data sets. While for *HLS* and *MLS* data 81% and 88% of the points fall inside the decisive intensity ranges for ground points, the respective percentage for the *ALS* data is only 42%.

Tab. 1: Comparison of intensity values and the number of points for ground and markings for the three test data samples.

Comparison	ALS	HLS	MLS
Intensity range of all points	1–60	0–353	0–138
Intensity range with maximum number of points on the ground (> 1000 points)	15, 24–31	7–13, 19–39	5–18
Percentage of all points	42%	81%	88%
Intensity range with maximum number of points on markings (> than 20 points)	50	50–60	55–97
Percentage of all points	0.09%	7%	4%

A similar distribution exists for the percentage of points for markings with 7% (*HLS*), 4% (*MLS*) and an insignificant value of 0.09% for *ALS*. It can be concluded that the intensity values together with the point density for the *HLS* and *MLS* data sets provide a basis for identifying markings on the road surface. For both, the intensity ranges for ground and for markings, a significant number of points exists which leads to an intensity image that is clear and rich in contrast. This is not the case for the *ALS* data set. These conclusions are also supported visually by intensity images, which are illustrated in Fig. 3.

For an automatic extraction and vectorization of road markings it is essential to separate marking points from the laser data as a basis for line construction methods. As mentioned in the literature review of this paper, Toth et al. (2007) developed a method to create curves from laser points which represent linear pavement markings on roads. It can be supposed that such an approach is applicable to the *HLS* and *MLS* data sets. Additionally, the intensity images of the *HLS* and *MLS* data indicate the possibility of applying image based methods which distinguish between dark and bright pixel values for marking detection.

4.3 *Road Furniture*

For road furniture objects, the point density is again the most important factor for detection, determining the level of detail for vectorization. The visibility of objects is studied by separating the points in the LIDAR data sets into intervals according to the height above ground. Based on the height of road furniture objects within the example data sets, the boundaries are set as follows:

[1] 0.10–0.20 m [2] 0.20–2.00 m
[3] 2.00–4.50 m [4] 4.50–8.00 m
[5] 8.00–14.0 m [6] > 14.0 m

This differentiation does not only achieve an improvement in the visual interpretation of the point cloud but may also support automatic detection, because it makes it possible to specify the range of interest for the detection of certain objects.

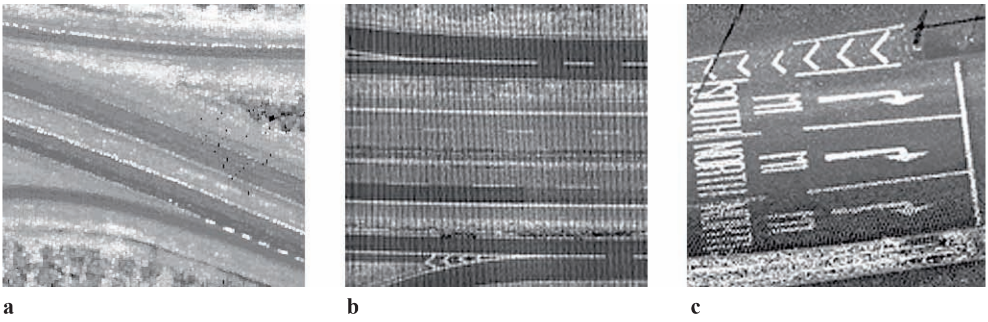
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Fig. 3: Comparison of intensity images, a) ALS data set, b) HLS data set, c) MLS data set.

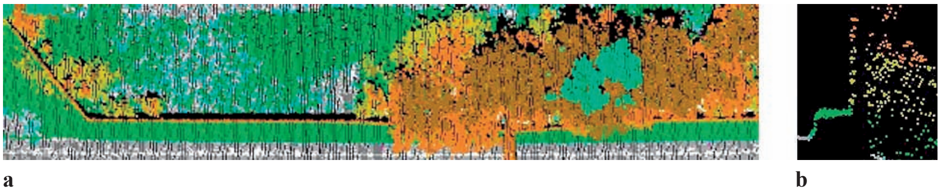

Fig. 4: Noise protection wall, top view (a) and side view (b) in the HLS data set. Colors: ground = gray, markings = white, height intervals [1] = light blue, [2] = green, [3] = yellow-green, [4] = orange, [5] = brown, [6] = mint.

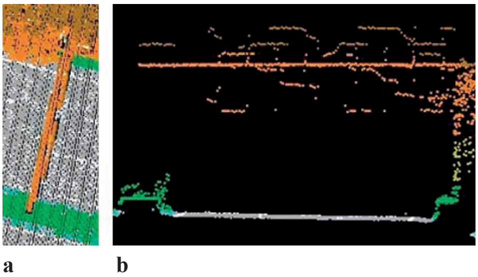

Fig. 5: Overhead gantry sign, top view (a) and front view (b) in the *HLS* data set. Colors as described in Fig. 4.

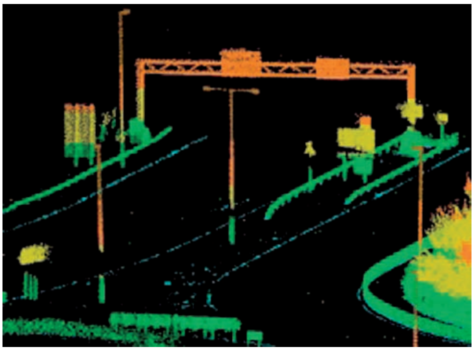

Fig. 6: Perspective view of the *MLS* data set. Colors as described in Fig. 4.

High objects such as street lamps and overhead gantry signs are located in intervals [4] to [6] in all three data sets. Large traffic signs in the *MLS* data set result in points in intervals [3] to [5]. Smaller signs and traffic lights are visible in intervals [3] and [4]. The *HLS* and *MLS* data sets include crash barriers along the roadsides, which are located in interval [2]. An easily detectable object in the *HLS* data set is a noise protection wall along the motorway (cf. Fig. 4). Due to its changing height the top of the wall is located in intervals [4] or [5]. Although the wall is overgrown with vegetation, its structure and location are visible in views from the top as well as in perspective views. The *MLS* data set also consists of curbstones, which are located in interval [1]. Examples for the *HLS* and *MLS* data sets are given in Fig. 4 to 6.

In the *ALS* example with its low point density the location of street lamps and other constructions is indicated only by a few points. The conclusion that points represent street lamps can be drawn from the regular distances between the point groups and their location along the road. Due to the small number of hits it is uncertain whether the points show the real height of the object. It is also possible that lamps are not represented in the point cloud at all. For the test digitization, 34 out of 41 street lamps could be identified visually, seven are not detectable. Two locations are uncertain because there are also no street lamps visible in the orthophotos used as reference data. Similar problems occur for other constructions. Only some points on the top of the object indicate the existence, but there is no shape or structure identifiable. This makes it impossible to identify the type of the object from the laser data. Therefore, the *ALS* data set is not suited to a data-driven modeling approach or detailed object vectorization. However, the integration of additional information about road furniture objects and their relations can support the placement of symbolic representations in a model-driven approach. But regarding the uncertainty of object detection within the *ALS* data set, those methods are also limited.

In contrast, the *HLS* and *MLS* data sets offer more scope for the detection of road furniture objects. Large constructions for traffic signs and linear objects are visible in detail in both data sets. While in the *HLS* data set smaller traffic signs and objects are not identifiable, the *MLS* data set gives a nearly complete representation of the road environment. Due to the possibility of viewing the point clouds from different perspectives, the data sets provide a basis for manual 3D digitization. However, both data sets show gaps in the point cloud. In the *HLS* data set, parts of large objects are missing (see example in Fig. 5). In the *MLS* data set gaps are caused by shadows behind other objects or cars. There are also objects that are not completely detected because of their position relative to the drive path (see Fig. 6 for an example). The problems of non-detected objects or object parts might be solved by capturing data from more than one flight or drive line in opposite directions along the road. This not only increases the point density, which would enable the detection of smaller objects in the *HLS* data set, but also captures objects from different directions. The lack of data can also be resolved in model-driven approaches as long as the type of the object can be identified. Regarding automatic methods, it can be supposed that model-driven approaches that utilize the object heights from the LIDAR data as well as object shape recognition methods are applicable to the *MLS* data set in particular and with limitations also to the *HLS* data set.

4.4 *Further Use of the Digitization Results*

The results of the digitization process are 3D vector elements for the road itself and several objects on and along the road. First, there are line or polygon features representing the road surface. According to the required level of detail, these elements include the whole road or, on a more detailed level, separate lanes for different driving directions (cf. Fig. 7). Those elements can be used for further processing of the LIDAR data, the DEM, or for GIS and cartographic mapping tasks. For example, the classification of LIDAR points on the road surface into a separate point class with the help of line or polygon elements may be useful for specific applications where a classification of the laser points into topographic classes is required. It is also essential for the creation of particular DEMs, as it is for the production of cartographic contours. There, polygons or line strings are applied as breaklines (cf. Fig. 8). Second, linear and point-like objects are represented by simple symbols or by detailed 3D models (cf. Fig. 7a), dependent on the aim and the desired level of detail of the final application. Once the objects are integrated in a GIS, they can be utilized for processing, visualizations, and analysis tasks.

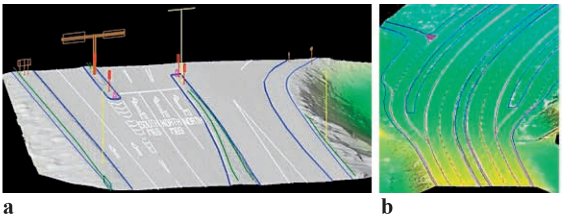

Fig. 7: Vectorization of road features based on LIDAR data. a) *MLS* data set, element colors: red = traffic lights, brown = traffic signs, yellow = street lamps, magenta = pylons, green = crash barriers, blue = outlines or curb stones, white = markings. b) *HLS* data set, line colors: blue = outlines, violet = markings, dashed red line = centerlines. DEM as shaded surface in the background.

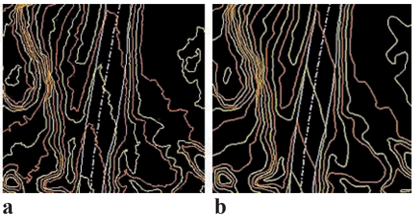

Fig. 8: Contour production based on LIDAR data. a) contours without breaklines, b) road outlines are included as breaklines to the contour creation. Note, that another method was used in addition to the breakline inclusion to create the contours as smooth, cartographic contour lines. Data from *ALS* data set.

5 Conclusions

This Section summarizes the results of the study. It leads back to considerations mentioned in the introduction about application-dependent data acquisition. While the two main questions (what objects can be detected in laser point clouds resulting from different acquisition platforms, and what properties determine the suitability of the data sets for 3D road digitization) have been discussed in detail in Section 4, the next paragraphs also compare the example data sets regarding factors such as the time and the effort for data processing.

The study of the LIDAR data sets and the manual digitization tests show that a comparatively low point density as in the *ALS* data set is sufficient to detect road outlines from a LIDAR based DEM. This is also approved by publications on automatic road extraction approaches, which use a lower or similar point density as in the *ALS* data set with 4.4 points/m^2 (e. g., 1 point/1.3 m^2 – Clode et al. 2004, 4 points/m^2 – Hatger & Brenner, 2003). With airborne laser scanning, large areas can be captured in a comparatively short time compared with other acquisition platforms. Due to the low point density it is also possible to process larger areas at the same time in processing demanding tasks than for data sets with a higher point density. This makes the *ALS* data set easier to handle for automatic approaches. It can be concluded that the *ALS* data set is suited to tasks such as simple road detection from LIDAR data and digitization of road outlines and centerlines for small-scale applications in manual or automatic approaches. The data set is not useful for marking extraction and the detection of road furniture as shown in Sections 4.2 and 4.3.

The intensity investigation in Section 4.2 reveals that the *HLS* and *MLS* data sets enable the complete detection of pavement markings. For both data sets, more than 80% of points on the ground and 7% (*HLS*) or 4% (*MLS*) of marking points fall into a decisive intensity range which makes it possible to separate markings from the surrounding road surface. The number of points for markings is also high enough to represent them as clear, sharp elements. The digitization of marking lines and figures can be done manually but it is assumed that automatic methods are applicable as well. The *HLS* example shows advantages for the digitization of elements on the road surface compared with the *MLS* data set. It provides a dense and uniform point distribution and is therefore convenient for automatic approaches that utilize these characteristics. Furthermore, a helicopter corridor flight is concentrated on the area of interest, in this case the road, but it also captures data from the surroundings. With its point density of 35 points/m^2 the data can still be handled more easily than data sets from ground-based collections. The *HLS* data example is well suited to road detection and digitization of road outlines, markings and, with restrictions, to road furniture as well. It is not possible to detect small point-like objects such as traffic signs from the point cloud. As discussed earlier, this lack of point density might be overcome by data collection from more than one flight line along the road in opposite directions with an appropriate overlapping area in flight direction.

The strength of the *MLS* data lies in the detailed representation of objects along the road that are captured from a near-ground position. For complicated areas like motorway crossovers or on extensive crossings, where airborne-based laser scanning would produce poor results, ground-based scanning can be used to capture the data for detailed 3D road feature digitization. However, the position of the scanning system on the top of a car leads to the shadow effects that have been mentioned in Section 4.3. These effects can only be partly reduced by a sophisticated drive pattern because the accessibility is limited to areas which the scanner can detect from its position on a car driving along the road. In addition, for the detection of long road segments, it seems to be more efficient to use airborne-based methods rather than ground-based scanning because over a long distance data collection by car is much slower than, for example, by helicopter. Furthermore, the resulting amount of data is much larger, which can lead to problems with data handling, processing and storing. Therefore, it can be assumed that automatic methods for feature detection are not applicable to such large data sets at the moment.

In future studies, data sets from different systems and covering the same area have to be studied for further conclusions towards the suitability of laser data for road environment mapping. Using data from the same area increases the comparability between the data sets and enables accuracy studies. A study of the applicability of automatic methods for roads as well as road furniture mapping directed at specific data sets is another topic for future work. This also includes a more detailed study of dependencies between detection results and the characteristics of laser data such as intensity values and point densities. Furthermore, the utilization of color information, either from true-color images or from color-infrared images, attached to the laser points should be considered in further research.

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References

Bahlmann, C., Zhu, Y., Ramesh, V., Pellkofer, M. & Koehler, T., 2005: A System for Traffic Sign Detection, Tracking, and Recognition Using Color, Shape, and Motion Information. – Intelligent Vehicles Symposium: 255–260.

Barber, D., Mills, J. & Smith-Voysey, S., 2007: Geometric validation of a ground-based mobile laser scanning system. – ISPRS Journal of Photogrammetry & Remote Sensing **63** (1): 128–141.

Brenner, C., 2006: Aerial Laser Scanning. – Systems, Processing, Applications. International Summer School Digital Recording and 3D Modelling, Aghios Nikolaos, Crete, Greece.

Briese, C., 2004: Three-dimensional modelling of breaklines from airborne laser scanner data. – International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences **35** (B3): 1097–1102.

Clode, S., Kootsookos, P. & Rottensteiner, F., 2004: The automatic extraction of roads from lidar data. – International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences **35** (B3): 231–236.

Clode, S., Kootsookos, P., Rottensteiner, F. & Zelniker, E., 2007: Detection and vectorization of roads from lidar data. – Photogrammetric Engineering & Remote Sensing **73** (5): 517–536.

Doubek, P., Perdoch, M., Matas, J. & Šochman, J., 2008: Mobile Mapping of Vertical Traffic Infrastructure. – Computer Vision Winter Workshop (CVWW) cmp.felk.cvut.cz/~perdom1/papers/cvww08.pdf (accessed: 15.12.2008).

Hatger, C. & Brenner, C., 2003: Extraction of road geometry parameters from laser scanning and existing databases. – International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences **34** (3/W13).

Hatger, C., 2005: On the use of airborne laser scanning data to verify and enrich road network features. – International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences **36** (3/W19): 138–143.

Hinz, S. & Baumgartner, A., 2003: Automatic extraction of urban road networks from multi-view aerial imagery. – ISPRS Journal of Photogrammetry & Remote Sensing **58** (1): 83–98.

Hofmann, A. D., Maas, H.-G. & Streilein, A., 2002: Knowledge-based building detection based on laser scanner data and topographic map information. – International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences **34** (3A): 169–174.

Jaakkola, A., 2008: Modeling of Road Environment with a Mobile Laser Scanner. – Finnish Geodetic Institute, internal presentation.

Kukko, A., Andrei, C.-O., Salminen, V.-M., Kaartinen, H., Chen, Y., Rönnholm, P., Hyyppä, H., Hyyppä, J., Chen, R., Haggrén, H., Kosonen, I. & Čapek, K., 2007: Road environment mapping system of the Finnish Geodetic Institute – FGI Roamer. – International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences **36** (3/W52): 241–247.

Mayer, H., Hinz, S., Bacher, U & Baltsavias, E., 2006: A test of automatic road detection approaches. – International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences **36** (3), 209–214.

Mena, J. B., 2003: State of the art on automatic road extraction for GIS update: a novel classification.

– Pattern Recognizion Letters **24** (16): 3037–3058.

Oude Elberink, S. & Vosselman, G., 2006a: 3D modeling of topographic objects fusing 2D maps and lidar data. – International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences **36** (4), on CD.

Oude Elberink, S. & Vosselman, G., 2006b: Adding the third dimension to a topographic database using Airborne Laser Scanner Data. – International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences **36** (3): 92–97.

Oude Elberink, S. & Vosselman, G., 2007: Quality analysis of 3D road reconstruction. – International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences **36** (3/W52): 305–310.

Soininen, A., 2008: Presentations on software development and vehicle based laser scanning. – Terrasolid European User's Event 2008, www.terrasolid.fi/en/presentations (accessed: 20.03.2008).

Tao, C.V., 2006: 3D Data Acquisition and Object Reconstruction for AED/CAD. – Large-scale 3D Data Integration: Challenges and Opportunities, 2006, CRC Press Taylor & Francis Group: 39–56.

Toth, C., Paska, E. & Brzezinska, D., 2007: Using pavement markings to support the QA/QC of LiDAR data. – International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences **36** (3/W49B), on CD.

Yu, X., 2007: Methods and techniques for forest change detection and growth estimation using airborne laser scanning data. – Academic dissertation in remote sensing, Publication of the Finnish Geodetic Institute **137**.

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Mobile Laser Scan (*MLS*): © Optech Incorporated, Toronto, Canada

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