EXTRACTION OF ROAD GEOMETRY PARAMETERS FROM LASER SCANNING AND EXISTING DATABASES

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ABSTRACT

Today's car navigation systems have reached a high level of maturity, using huge map databases with a high coverage and up-to-dateness. However, as additional applications gain importance, such as advanced driver information and warning systems, more detailed and accurate information on the true road geometry has to be incorporated into those databases. Properties like height, longitudinal and transversal slope, curvature, and width which are currently not present, have to be acquired and integrated. This article shows how existing databases either from public authorities or from private map providers can be used in combination with aerial laser scan data to derive such properties. Apart from a general discussion of the problem and our approach, first results are presented and discussed.

1 INTRODUCTION

Spatial information is crucial to many tasks, one important of them being car navigation. Introduced in 1995, car navigation systems nowadays are mature systems, offering route calculations, map display, map icons, and speech guidance. So far, however, driving hints derived from spatial data are limited to propositions about two dimensional geometric and topological issues, as the data set contains no information on height. As additional applications gain importance, such as advanced driver information and warning systems, more detailed and accurate information on the true road geometry has to be incorporated into those databases, such as width, height, and longitudinal and transversal slope.

With respect to height, few information is already available today. In Germany, three dimensional information is available through federal and national mapping agencies by means of digital terrain models (DTM's). The third dimension typically is stored separately, describing landscape's surface by regular, irregular or hybrid grids. A nationwide available regular gridded DTM provides a rather course planimetric resolution of 25 meters. The accuracy is assumed to be 26 meters (horizontally) and 20 meters (vertically), respectively. Besides that, several national mapping agencies provide additional products with slightly higher resolution and accuracy. Nevertheless, many planning firms already make intensive use of such data sets, but their resolution usually is not sufficient for precise design and description of road networks. In contrast, much more detailed three dimensional data can be provided by means of laser scanning techniques. Some national mapping agencies haven chosen laser scanning as default measurement technique for the production of DTM's (Knabenschuh and Petzold, 1999).

Applications of high resolution DTM's can be manifold. Design, planning, construction, operation and maintenance facilities can benefit directly from precise description of road networks. Car navigation systems can use three dimensional data for the optimized computation of routes. Driver assistance and warning systems can use it for automatic speed warnings ahead of sharp curves and hills, computation of visibility ranges and automatic adjustment of the car's headlights. Functions increasing drivers comfort include applications like drive train management or 3D navigation systems. Finally, safety functions could actively decelerate the car in front of anticipated dangers, especially vehicles carrying heavy or dangerous load. All of those applications are currently actively researched in the automotive industry. Additional possibilities lie in the more precise prediction of emissions rates of harmful substances and noise depending on varying road gradients.

2 RELATED WORK

The extraction of roads from spatial data sources like aerial or satellite images has been in scope of research for more than twenty years now. Many approaches are based upon techniques like edge detection or texture analysis (Dial et al., 2001). Other methods make use of dynamic programming or LSB-Snakes to further improve the results of the road extraction process (Gruen, 1997). Recently, the use of knowledge based approaches seems to gain more importance by means of rules and models (Hinz et al., 2001). Predefined information is acquired at a generic global level (eg. connectivity) and at a local level (e.g. context), respectively (Hinz and Baumgartner, 2002, Vosselmann, 1997). In addition, valuable properties can be taken from other existing spatial data sources like vector data (Zhang et al., 2001). However, little work has been done on the extraction of continuous surfaces like roads from laser scanning data so far. (Pattnaik et al., 2003) suggests laser scan data to gather information on road inventory. Information from a street database is acquired to set up predefined regions along roads. Subsequently, least squares regression is applied to those regions in order to compute appropriate values for longitudinal and transversal slopes. Apart from that, few approaches investigate discontinuities like breaklines. (Wild and Krzystek, 1996) and (Vosselmann, 2000) introduce constraints like curvature or slope for the extraction of linear features. (Brügelmann, 2000) uses breakline detection to identify dikes within laser scanner data.

3 DATA SOURCES

3.1 ATKIS

Spatial information which is provided through the Authoritative Topographic Cartographic Information System (ATKIS) describe topographic features of the landscape in vector format (AdV(Arbeitsgemeinschaft der Vermessungsverwaltungen der Länder der Bundesrepublik Deutschland) , 1998). Products which provide primarily two dimensional information are called Digital Landscape Models (DLM). ATKIS-DLM data is nationwide available.

Transportation related objects like roads either are modelled as simple or complex features. Features attributes provide information about lane or road width, number of driving lanes and functional road class. However, depending on the features type (road, way) not all of the attributes are present with every feature. Overall planimetric accuracy is aimed to be better than three meters. Depending on the underlying data source, however, errors of up to 10 meters can be observed.

3.2 GDF

GDF (Geographic Data File) is the European standard for digital road map databases (CEN TC 287, 1995). Aside from the road network, many more linear features are described, such as ferries, railways, waterways, and public transport. Additionally, area features and point features are contained in GDF.

GDF represents the road network using 2D nodes and edges. Thus, all geometry is approximated using a piecewise linear representation. GDF allows the specification of a z (height) value for each coordinate point, which is, however, not in use today. Other attributes already defined in GDF 3.0 include road gradient, height of pass and transverse gradient. The accuracy in position depends on map supplier and specification and typically ranges from 15 meters in open terrain down to about 3 meters in urban areas.

3.3 Laser Scan Data

The data sets used in this paper were acquired by airborne laser scanners, which will not be described here, see e.g. (Baltsavias, 1999b). From the scan data, a digital surface model (DSM), which contains both points from the ground surface and points from objects on top of the surface, like buildings and trees, as well as a digital terrain model (DTM) which contains the ground surface, is derived. Both DSM and DTM data sets are available by commercial companies. The planimetric accuracy of the laser points is approximately 0.5 m (Baltsavias, 1999a, Lohr, 1999) where the point density is up to 4 points per square meter. The accuracy in height is 0.01 up to 0.15 m (Briese et al., 2001, Wever, 1999).

The test regions used in this paper are a part of the city of Stuttgart, Germany, regularized to a 1 m grid, and a small part of Castrop-Rauxel in the western part of North Rhine-Westphalia, Germany, consisting of last-pulse ground points, regularized to a 0.5 m grid.

Figure 1 gives an overview of the second test region with map data from ATKIS overlaid. This particular region has been selected because it contains a multitude of different road classes. Grey lines denote local access streets, field tracks and county roads, yellow lines mark up superhighways and interstates.

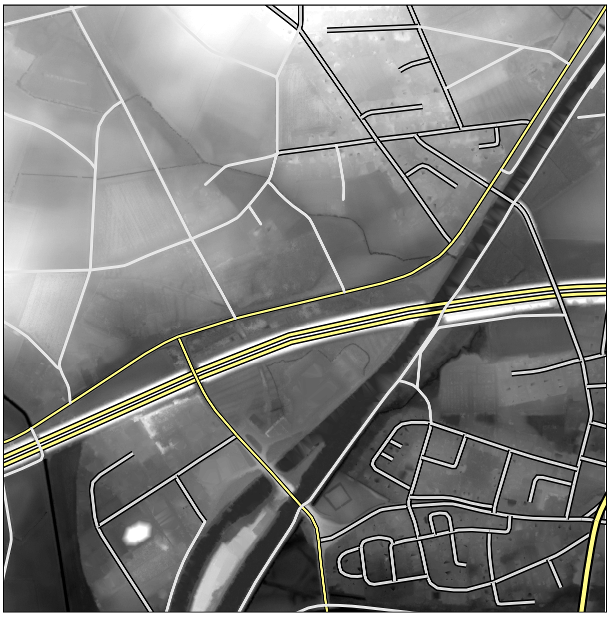


Figure 1: Test Area

4 ROAD PROFILES

Design and construction of roads and road networks in Germany usually is done by use of standardized methods and techniques. Some of them that are of interest within this context are described in detail in publications like eg. (Arbeitsgruppe Straßenentwurf, 1996). These guidelines both define rules for the longitudinal and transversal shape of roads.

Concerning longitudinal shape, three different geometric entities can be used to design the longitudinal shape of a road: lines, circular arcs and clothoids. They have to be combined in such a manner that there occur no or only small C^0 (position), C^1 (direction) or C^2 (curvature) discontinuities between different geometric entities. Curvature and inclination depend on the average travelling speed, approximately. These parameters are limited to certain ranges to ensure high levels of safety and driving comfort. For example, the inclination of highways is limited to a maximum of 9 percent, depending on the expected average travelling speed.

Additional constraints are given by means of standardized cross sections. Civil engineers can choose among nine different prototypes of cross sections to be used during the planning process of a road. Functional road class and estimated live load are essential delimiting parameters for the appropriate cross section prototype. Main characteristics of a cross section are prescribed by the number of lanes per driving direction. Additional properties are given by lane, edging strip and embankment width. Besides from that, inclination is limited to lie within the range of 2.5 up to 8 percent. Along segments of strong curvatures, cross sections usually show high values of inclination, in this case the carriageway is to be rotated around its longitudinal axis. Fig. 2 shows an example.

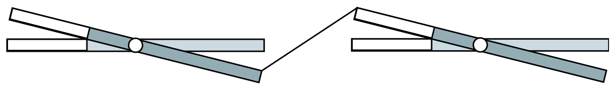


Figure 2: Inclined cross section prototype of dual highway along curved geometric entities.

Figure 3 shows a prototype cross section that is applicable for the construction of a dual carriage way, eg. a highway. In this case the cross section prototype prescribes divided carriage ways, two lanes, one side strip and an embankment per driving direction.

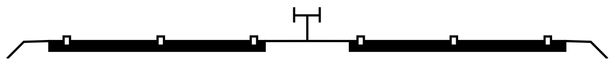


Figure 3: Typical cross section prototype for a divided carriageway.

5 SEGMENTATION OF LASER SCAN DATA

When segmenting laser scan data, one has typically the choice between methods which try to detect discontinuity, such as prominent points or edges, and methods which try to find continuity in the data, such as areas fulfilling certain criteria. Classical approaches for finding discontinuity are point operators which try to find isolated points, corners, or points being part of a one-dimensional curve (Haralick and Shapiro, 1992, Canny, 1986). Often, the extraction of linear structures is done in a second step by building contour chains from individual points. Alternatively, the discontinuity perpendicular to a linear structure can be defined in terms of the continuous areas to the left and right of the structure (Brügelmann, 2000, Wild and Krzystek, 1996), which in turn can be found using methods such as region growing. Noting that lines are bounded by points, and areas are bounded in turn by lines, more stable segmentation approaches can be obtained when zero, one and two-dimensional primitives are extracted simultaneously, a process sometimes called polymorphous segmentation (Fuchs, 1998).

It is always desirable to integrate as much prior knowledge as possible into the segmentation process. This can be knowledge as discussed in section 4 about the objects to be extracted, as well as the sensors used. In our case, roads do have certain minimum extends, continuous surfaces which can be approximated locally quite well by planes, and are more or less horizontal. Additionally, since existing information from GIS databases is used, the approximate location is known. Regarding the sensor, there is an estimate on the measurement noise being in the 10 to 20 cm range.

In the following, we will show two approaches, the first one being a general planar segmentation, and the second one being specially targeted at the segmentation of roads.

5.1 Using a General Planar Region Growing Segmentation

In general, region growing works by iterating the following three steps. (1) find the best seed region which fulfils the desired predicate, (2) add elements to the seed region (i.e., grow it) as long as they are connected to it and they too fulfil the predicate, and (3) if the region cannot be grown anymore, accept it and goto (1), using the remaining elements. In our case, finding the best seed region involves the estimation of local planes and looking for the smallest residuals. The predicate is a certain maximum distance ε of the points $(x, y, z)^T$ to the plane given by its Hesse normal form a, b, c, d associated with the region, i.e.

$$P(p_j) = \text{TRUE} \Leftrightarrow |ax + by + cz + d| < \varepsilon .$$

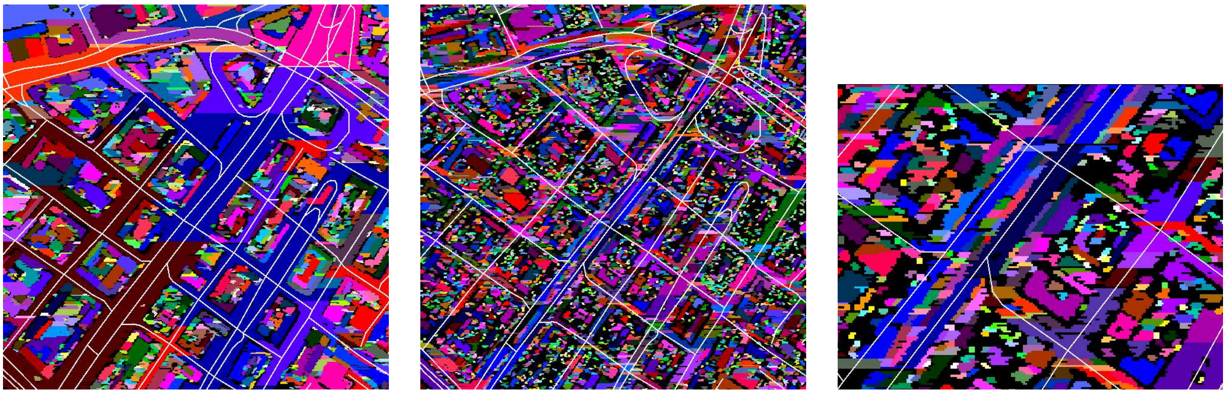
5.1.1 The scan line grouping approach A general problem of region growing approaches is that they are computationally expensive. This is due to the fact that elements are added one by one, and usually, a re-estimation of the predicate (the plane equation) has to take place after each addition. A fast region growing approach based on scan line grouping has been presented by (Jiang and Bunke, 1992). It works on regularized raster data and uses the fact that for a plane $z = ax + by + d$, all points along the line $y = y_0$ fulfil the equation $z = ax + by_0 + d$, i.e. the line equation $z = ax + d'$. Vice versa, in most cases, points fulfilling the line equation belong to only one plane. This is exploited to grow the regions not element-by-element but rather by adding entire scan lines. Thus, the algorithm uses the following four steps:

1. partitioning of each scan line $y = y_0$ into linear segments fulfilling corresponding line equations $z = ax + d'$. This actually can be done by successively subdividing the scanline (Douglas and Peucker, 1973, Duda and Hart, 1973)
2. search for a seed region by investigating overlapping linear segments of three successive lines y_{i-1}, y_i, y_{i+1}
3. growing the best seed region by adding neighboring line segments, as long as they still are part of the same plane
4. postprocessing: after all segments are grouped, points on the borders of the regions are possibly regrouped in order to reduce "jagged" borders.

This algorithm works quite fast and has performed very well in a segmentation comparison (Hoover et al., 1996). One drawback is that the algorithm works differently in x and y direction, performing a split approach along a scanline and a region growing across scanlines. This typically yields, despite postprocessing, "jagged" borders in one direction.

5.1.2 Application to the segmentation of roads Figure 4 shows some results of applying the general planar segmentation to range images. Figures 4(a),(b),(c) show a part of Stuttgart, regularized to a 1 m grid. The road centerlines from GDF are overlaid, but do not take part in any computation.

Figure 4(b) shows a segmentation with the parameters for scanline split and scanline merge set "coarse", meaning in the range of one meter. As one can see, large planar regions can be identified, most of them belonging to street



(a) (b) (c)

Figure 4: Different planar segmentations using the algorithm of Jiang and Bunke. (a) Segmentation with parameters set “coarse”. (b) Segmentation with parameters set “fine”. (c) Detail of (b).

surfaces. Buildings, on the other hand, are characterized by small and fragmented regions. As noted above, due to the principle of scanline grouping, left and right region borders tend to be jagged, while top and bottom borders are straight. Since the road network is not involved in the computation, of course the segmented regions split somewhere in the middle of the road segments. However, one could imagine that collecting segmented regions along street segments would be a reasonable approach to verify the position of the street, which would of course not allow a precise determination of the left and right borders.

If tolerances are set tighter, regions get consequently smaller, as shown in figure 4(b), parameters now being in the 0.1 m range. Although the segmentation now results in a huge amount of small regions, street surfaces can still be recognized quite well. Interestingly, the segmentation now is sometimes capable of finding different lanes of dual carriageways (figure 4(c)).

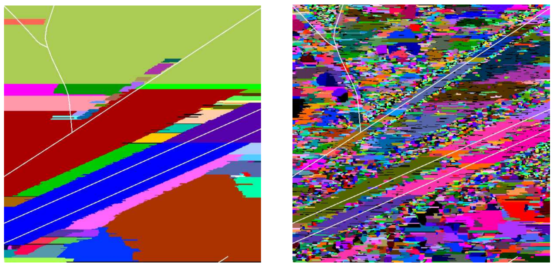
As one could expect, the situation is not as clear in open and mostly flat terrain, since then, the roads are not flanked as nicely by buildings.

Figure 5(a) shows such an example, where an embankment with motorway and some other roads are present in otherwise quite flat terrain. In this case, the “coarse” segmentation easily identifies the embankment and the motorway but misses the other roads. The “fine” segmentation, on the other hand, produces a large amount of small and large regions, making the identification of road regions not obvious (figure 5(b)).

To conclude, the general planar segmentation approach has the advantage that no additional information sources have to be introduced. Nevertheless, regions belonging to roads or even individual lanes are sometimes segmented quite well. Segmented regions could be “collected” later on using road centerlines. However, another approach would be to introduce centerline information earlier in the segmentation process. This is presented in the next section.

5.2 A Segmentation Along Road Segments

5.2.1 A RANSAC segmentation approach As pointed out above, prior knowledge should be used where available. In this section, we will assume that the centerline is somewhere between the true road boundaries.



(a) (b)

Figure 5: Examples for a planar segmentation on 0.5 m raster in open terrain. (a) Segmentation with parameters set “coarse”. (b) Segmentation with parameters set “fine”

The idea now is to use this information in a more sensitive segmentation, trying to extract the true road extents.

Of course, when there is no C^0 (height) or C^1 (inclination) discontinuity at the road boundaries, there is no way detecting it using laser scan data, and other data sources such as aerial images have to be used. However, the question is how reliable even small discontinuities can be detected. For example, a road may be bounded by an embankment, which usually is a relatively large structure. It may on the other hand be separated from the pavement or a traffic island by a kerb of only 15 cm in height. This seems to be hopeless, since it is close to the expected noise of the laser measurement. However, if one considers profiles perpendicular to the road, the point is that a 10 m wide road, scanned with 1 m density, will yield 10 measurements to estimate the road surface (assumed to be planar), leading to a standard deviation of about 15 cm / $\sqrt{10} \approx 5$ cm.

In order to be as sensitive as possible, we do not use the “split method” employed by the algorithm of Jiang and Bunke but instead the random consensus principle (RANSAC), intoduced by (Fischler and Bolles, 1981). For each profile sampled perpendicular to the road, a number of samples is drawn, each consisting of two points from the profile. Each such sample defines uniquely the parameters a, b, c of a line, and the consensus set from the profile is given by the set of points $(x, z)^T$ for which

$$|ax + bz + c| < \varepsilon \, . \quad (1)$$

Samples which lead to non-horizontal lines can be removed easily, noting that b is in fact the cosine of the inclination if the normal vector $(a, b)^T$ is normalized. From the remaining samples, the "best" is selected, which currently is the one leading to the largest connected consensus set which overlaps the road centerline from the GIS database.

There are currently no assumptions about the road width introduced. We obtain a simple estimate for the left and right border using a median filter. For each position along the road, the left and right ends of the consensus sets in a certain neighborhood (from $-n$ to $+n$ meters along the road) are used as input.

5.2.2 Results and discussion Figure 6 shows the approach for a single road segment. Starting from the original segment and the DSM (figure 6(a)), profiles are sampled orthogonal to the segment using a given sampling density of 0.5m (figure 6(b)). Note that in the shown images, the difference between 'black' and 'white' corresponds to only 2 meters in height. Working on the resampled image, the RANSAC segmentation described above is applied to each image line individually, yielding a stack of segments (shown grey in figure 6(c)). The left and right bounds are then determined using the median filter (shown black in figure 6(c)). Finally, the determined bounds can be mapped back to the original DSM for visual assessment (figure 6(d)). For this example, the consensus parameter (ε of equation 1) was set to 0.05 m.

Figure 7 shows the results for the scene shown in figure 1. As before, the consensus parameter was set to 0.05 m. Note that even though no "minimum width" or "maximum width" constraint is enforced, there are only a few cases where the road width seems to be entirely wrong. Please note also that the segmentation is able to extract the two lanes of the dual carriageway quite nicely, shown in detail in figure 8. Of course, these findings are qualitative in nature and have to be supported by a comparison with ground truth.

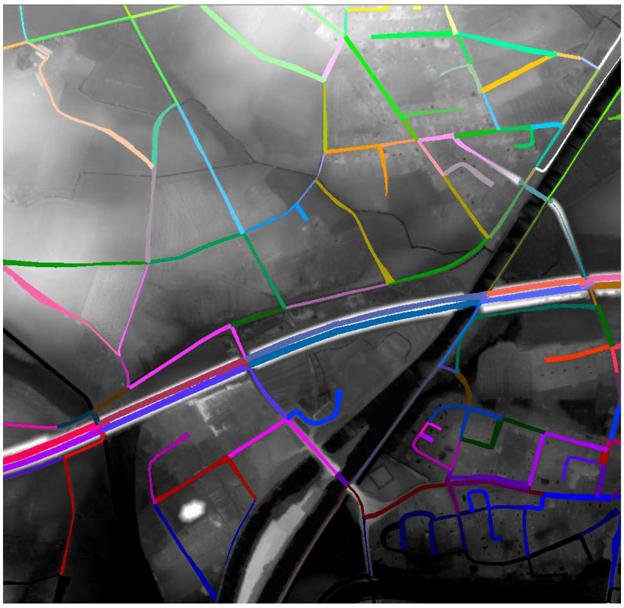


Figure 7: Road segmentation result for the scene shown in figure 1.

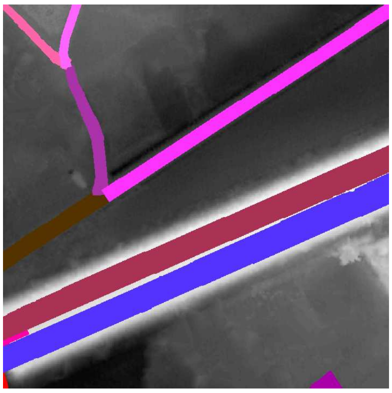


Figure 8: Close-up view of the segmentation result for the part shown in figure 5.

6 CONCLUSION AND OUTLOOK

In this paper, we investigated methods to combine existing information and laser scanner data to derive properties for future road map databases. The first method uses a general segmentation into planar surfaces, implemented as scan line grouping, in order to obtain regions belonging to roads. The second is more targeted towards finding the true extents of roads and uses road centerlines and a RANSAC based segmentation of profiles.

From our results, we conclude that road surfaces can be extracted surprisingly well from laser scan data. The general planar segmenter might be used to find the coarse position of roads if the centerline information from the GIS is far off. The profile approach, on the other hand, can be made more sensitive to detect road boundaries even in quite flat terrain, however the geometry from the GIS must correspond quite well to the laser scanner data.

There is much room for improvement in the future. The profile algorithm could be extended to base its estimation on a small surface along the road instead of on individual profiles. Additional information on streets could be integrated, such as information on standard lane widths or road classes. Of course, the road network connectivity must be exploited, which is currently not the case since road segments are considered individually. Finally, after this first tests on feasibility, quantitative results in terms of segmentation / ground truth comparisons have to be made.

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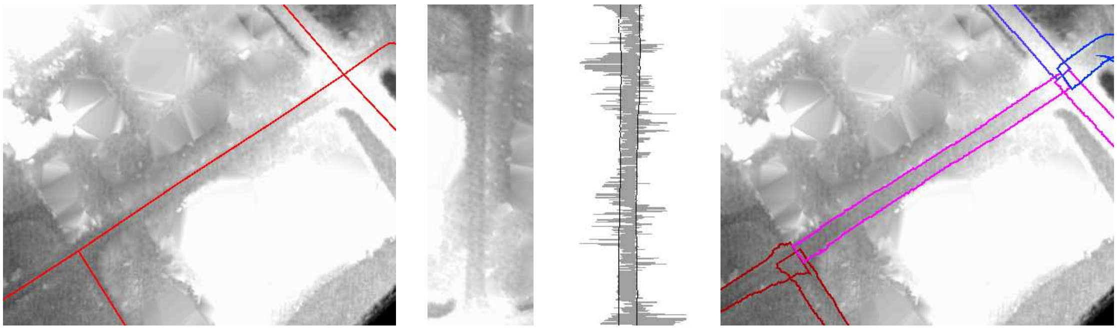
REFERENCES

AdV(Arbeitsgemeinschaft der Vermessungsverwaltungen der Länder der Bundesrepublik Deutschland) , 1998. Authoritative Topographic Cartographic Information System (ATKIS). Technical report, AdV.

Arbeitsgruppe Straßenentwurf (ed.), 1996. Richtlinien für die Anlage von Straßen (RAS), Teil Querschnitte (RAS-Q 96). Forschungsgesellschaft für Straßen und Verkehrswesen, Bonn.



(a) (b) (c) (d)

Figure 6: Segmentation along road segment. (a) Original DSM with road segment overlaid. (b) Resampled road segment. (c) Result of linewise segmentation (grey) and median filter determining left and right street bounds (black). (d) Backprojection of the result into the original DSM.

Baltsavias, E., Grün, A., and VanGool, L. (eds), 2001. Automatic Extraction of Man-Made Objects from Aerial and Space Images. Balkema Publishers, Netherlands.

Baltsavias, E. P., 1999a. Airborne laser scanning: basic relations and formulas. ISPRS Journal of Photogrammetry and Remote Sensing 54(2-3), pp. 199–214.

Baltsavias, E. P., 1999b. A comparison between photogrammetry and laser scanning. ISPRS Journal of Photogrammetry and Remote Sensing 54(2-3), pp. 83–94.

Briese, C., Kraus, K., Mandlburger, G. and Pfeifer, N., 2001. Einsatzmöglichkeiten der flugzeuggetragenen laser scanner. In: Tagungsband der 11. Internationalen Geodätischen Woche, Obergurgl, Innsbruck, Austria, pp. 17–26.

Brügelmann, R., 2000. Automatic breakline detection from airborne laser range data. International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences XXXIII(B3), pp. 109–116.

Canny, J., 1986. A computational approach to edge detection. IEEE Transactions on Pattern Analysis and Machine Intelligence 8(6), pp. 679–698.

CEN TC 287, 1995. Geographic data files version 3.0, GDF for road traffic and transport telematics. Technical report, CEN.

Dial, G., Gisbon, L. and Poulsen, R., 2001. Ikonos satellite imagery and its use in automated road extraction. In: (Baltsavias et al., 2001), pp. 357–367.

Douglas, D. and Peucker, T., 1973. Algorithms for the reduction of the number of points required to represent a digitized line or its caricature. The Canadian Cartographer 10(2), pp. 112–122.

Duda, R. O. and Hart, P. E., 1973. Pattern Classification and Scene Analysis. John Wiley and Sons, New York.

Fischler, M. A. and Bolles, R. C., 1981. Random sample consensus: A paradigm for model fitting with applications to image analysis and automated cartography. Communications of the ACM 24(6), pp. 381–395.

Fuchs, C., 1998. Extraktion polymorpher Bildstrukturen und ihre topologische und geometrische Gruppierung. PhD thesis, Rheinische Friedrich-Wilhelms-Universität zu Bonn, Institut für Photogrammetrie, DGK Reihe C, Nr. 502.

Gruen, A., Baltsavias, E. P. and Henricsson, O. (eds), 1997. Automatic Extraction of Man-Made Objects from Aerial and Space Images. Birkhäuser Verlag, Basel, Suisse.

Gruen, Armin; Li, H., 1997. Linear feature extraction with 3-d LSB-snakes. In: (Gruen et al., 1997), pp. 287–298.

Haralick, R. M. and Shapiro, L. G., 1992. Computer and Robot Vision, Vol. I. Addison-Wesley.

Hinz, S. and Baumgartner, A., 2002. Urban road net extraction integrating internal evaluation models. International Society for Photogrammetry and Remote Sensing, Graz, Austria, pp. 255–265.

Hinz, S., Baumgartner, A., Mayer, H., Wiedemann, C. and Ebner, H., 2001. Road extraction focussing on urban areas. In: (Baltsavias et al., 2001), pp. 255–265.

Hoover, A., Jean-Baptiste, G., Jiang, X. Y., Flynn, P. J., Bunke, H., Goldgof, D. B., Bowyer, K., Eggert, D. W., Fitzgibbon, A. and Fisher, R. B., 1996. An experimental comparison of range image segmentation algorithms. IEEE Transactions on Pattern Analysis and Machine Intelligence 18(7), pp. 673–689.

Jiang, X. Y. and Bunke, H., 1992. Fast segmentation of range images into planar regions by scan line grouping. Technical Report IAM-92-006, Institute of Informatics and Applied Mathematics, University of Berne, Switzerland.

Knabenschuh, M. and Petzold, B., 1999. Data post-processing of laser scan data for countrywide DTM production. In: D. Fritsch and R. H. Spiller (eds), Photogrammetrische Woche, Universität Stuttgart, Institut für Photogrammetrie, Stuttgart, pp. 233–240.

Lohr, U., 1999. High resolution laserscanning, not only for 3d-city models. In: Fritsch/Spiller (ed.), Photogrammetric Week 99, Wichmann, Stuttgart, Germany, pp. 133–138.

Pattnaik, S. B., Hallmark, S. and Souleyrette, R., 2003. Collecting road inventory using LIDAR surface models. In: Proceedings Map India 2003.

Vosselmann, G., 2000. Slope based filtering of laser altimetry data. International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences XXXIII, pp. 935–942.

Vosselmann, George; de Gunst, M., 1997. Updating road maps by contextual reasoning. In: (Gruen et al., 1997), pp. 267–276.

Wever, Ch.; Lindenberger, J., 1999. Experiences of 10 years laser scanning. In: F. Spiller (ed.), Photogrammetric Week 99, Wichmann, Stuttgart, Germany, pp. 125–132.

Wild, D. and Krzystek, P., 1996. Automatic breakline detection using an edge preserving filter. International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences XXXI(B3), pp. 946–952.

Zhang, C., Baltsavias, E. and Gruen, A., 2001. Updating of cartographic road databases by image analysis. In: (Baltsavias et al., 2001), pp. 243–253.