Fast determination of parametric house models from dense airborne laserscanner data

Hans-Gerd Maas
Faculty of Civil Engineering and Geosciences
Section of Photogrammetry and Remote Sensing
Delft University of Technology
Thijsseweg 11, 2629JA Delft, The Netherlands
phone +31-15-278 2556, fax +31-15-278 2745, e-mail h.-g.maas@geo.tudelft.nl

Abstract:

In addition to its primary application field in the determination of digital elevation models, airborne laserscanning data has a great potential for modeling man-made objects such as houses. This publication shows a fast procedure for detecting and modeling buildings from raw airborne laserscanner data without the need of additional GIS or image data. Segmentation of the data is based on the computation of height texture measures, morphological filtering and local histogram analysis. The actual building model generation is based on the analysis of invariant moments applied to the segmented datasets: The parameters of standard gable roof type buildings are determined as closed solutions from ratios of binary and height-weighted moments of segmented point clouds. Deviations from the chosen building model such as dorms on a roof can be detected and modeled in a subsequent model fit analysis step.

Applied to a dense laserscanner dataset with an average point density of approximately five points per square meter, the technique shows good results. Further analysis shows that the point density can be reduced to one point per square meter at a tolerable loss of accuracy. Being fast and parallelization-friendly, even an implementation of the techniques in near-realtime systems seems feasable.

Keywords:

Airborne laserscanning, building extraction, height texture, invariant moments

1. Introduction

Airborne laserscanning has become a viable technique for the provision of digital elevation data during the past few years. As an active technique, it delivers reliable height data without requirements to surface reflectance variations. The inherent 3-D nature of laserscanning data saves time consuming and potentially erroneous matching techniques and yields a high potential for realtime applications if laser range data can be fused with GPS/INS data onboard an aircraft. The accuracy potential of airborne laserscanning is in the order of 5 - 10 cm.

In most datasets acquired with the aim of digital terrain model generation, the spatial resolution of airborne laserscanning is in the order of one point per ten square meters. Modern systems, however, offer data acquisition rates of 10 to 80 kHz. Installed onboard an airplane flying at 100 knots per hour, a 10 kHz system allows to measure strips of 200 meter width with a density of one point per square meter. Using systems with higher data rates (e.g. TopoSys) or installing systems on slower moving helicopters, even much higher point densities can be achieved. As an alternative, data from multiple flyovers may be merged. Applying such techniques, point densities in the order of five points per square meter are absolutely realistic.

This opens a wide range of new application fields to airborne laserscanning, including the generation of 3-D building models (e.g. Haala/Brenner, 1997) and the monitoring of electrical powerlines (e.g. Takahashi/Chen, 1998). Especially the generation of 3-D building models as a substantial part of virtual city models has become a major field of photogrammetric research in the past few years. Besides a number of approaches based on the semi-

ISPRS Workshop on Mobile Mapping Technology
Bangkok, Thailand**,** April 21-23, 1999

automatic (e.g. Lang/Förstner, 1996) or automatic (e.g. Henricsson et al., 1996) interpretation of scanned aerial imagery, techniques based on merging high-density laserscanner height data with available 2-D ground plans have e.g. been shown by (Haala/Brenner, 1997) and (Brenner/Haala, 1998).

Figure 1 shows an example of a range image generated by airborne laserscanning. In the following, a technique for automatically detecting and modeling buildings based purely on dense airborne laserscanner data will be shown and analyzed. As a first processing step, buildings are detected and segmented by applying image classification techniques on height texture measures of laserscanner data binned to a regular grid image structure (see chapter 2). From the thus segmented clouds of points belonging to individual buildings, parametric building models are derived by techniques based on the analysis of invariant moments (see chapter 3). Practical results from applying the techniques to a dataset with a density of five points per square meter are shown in chapter 4.

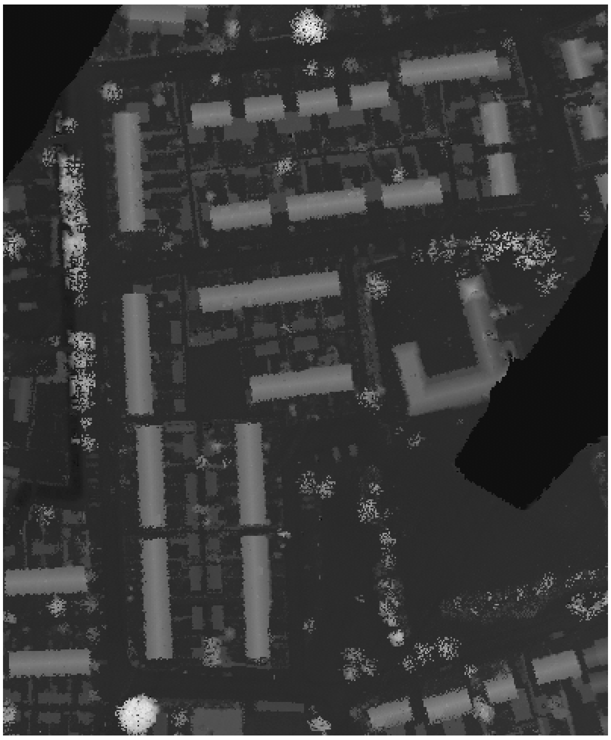

Figure 1: Grey-coded laserscanner height data binned to a 0.5 meter grid.

2. Segmentation

The first step in the processing of the laserscanner data is a segmentation of the range data. A meaningful cue in the segmentation of laserscanner range images is the analysis of height texture measures obtained from local variations of height. In the following, some height texture measures will be defined and used as bands in a classification-like approach to segment the range image. For reasons of compatibility with available software installations, the range data was binned to a regular grid structure, and the heights were linearly scaled to 8-bit grayscale data (Figure 1). As an alternative, the same texture measures might also be applied to neighbouring original data points organized in a triangulated irregular network structure. See (Maas/Vosselman, 1999) for a short review on further segmentation techniques used in airborne laserscanning.

The definition and analysis of texture measures has been used in many image processing and image understanding applications for a long time. While intensity patterns are being evaluated in 2-D imagery, the actual height of data points can be used instead when using $2^1/_2$-D laserscanner data. The dataset used for practical evaluation of the techniques discussed here (chapter 4) consists of first-pulse measurements. That means that the time of the rising edge of the returning laser pulse echo is recorded, which has consequences especially concerning the height patterns obtained over vegetation. An analysis of a number of texture measures applied to this height data resulted in the following measures suitable for the segmentation of airborne laserscanner data with the aim of extracting buildings:

- The original height data allow for a discrimination between high objects such buildings and trees on the one side and objects like streets or plain ground on the other. In data over hilly terrain, band- or highpass filtered height data might be used.
- The result of applying a Laplace filter to the range data will emphasize edges or noise and thus deliver large values in vegetation, while plane roof faces will obtain zero values.
- The maximum slope around each pixel is determined from the local slopes in X and Y. The use of a slope image is valuable for distinguishing tilted roofs from flat roofs or street as well as from trees, where the slope will reach very large random-like values.

As the objects to be detected in this data do not show predictable spatial patterns, co-occurrence measures showing relative frequencies with which heights occur in shifted processing windows were not further analyzed. The results of applying the above mentioned filters to the height image are temporarily stored as new bands. To reduce noise caused by small objects such as antennae or chimneys on roofs, the obtained bands were median-filtered.

The thus generated new bands are used as input to a maximum likelihood classification, which is initialized by sparse training regions containing the object classes 'tilted roof', 'flat roof', 'vegetation', 'flat terrain' and 'no data'. As an example, Figure 2 shows the class 'tilted roof' of a part of the dataset shown in Figure 1. Alternatively, the user may also edit the class signatures and covariances directly, if a-priori knowledge on building heights, roof slopes, tree heights etc. is available.

Without post-classification processing applied to the results of the classification this segmentation shows two major deficits:

- The result shows some noise in the way that single pixels within an object to be segmented are misclassi-fied.

- As a general tendency the edges of buildings will be misclassified, mostly as vegetation, as a consequence of large gradients.

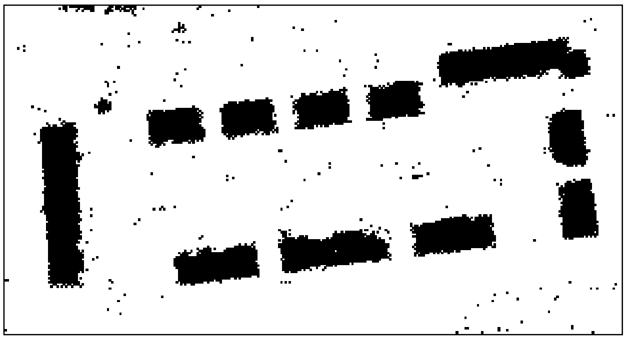

Figure 2: Class 'tilted roof' from multispectral classification

These deficits can be removed by splitting the result of the classification into individual bands for each class of objects and postprocessing those bands by morphological filtering. Concerning the houses, which are of primary interest here, a significant improvement can be achieved by a closing step followed by dilation. As a final processing step, connected components labeling will deliver the basis for filtering individual point clouds for each house.

The complete data processing chain as used in range data segmentation is outlined in Figure 3. Note that depending on the type of laserscanner data variations of the processing scheme concerning the chosen texture measures and the postprocessing steps may be required. This will especially apply when last-pulse data or simultaneous first- and last pulse data is being used.

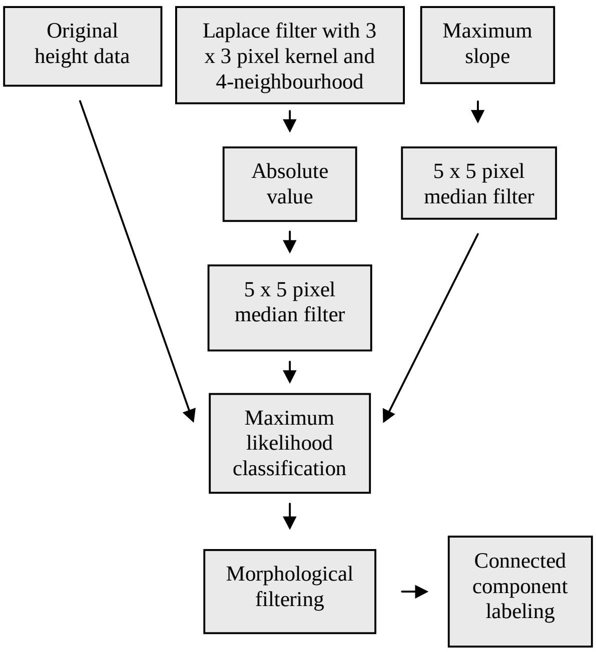

Figure 3: Data flow in segmentation of range data

3. Building modeling

The result of the segmentation procedure contains separated point clouds for every detected building. These point clouds are further used to generate parametric building models.

3.1 Analysis of invariant moments

For the reconstruction a model-driven approach based on the analysis of invariant moments is applied, which is described in more detail in (Maas/Vosselman 1999, Maas 1999) and will be only briefly outlined in the following:

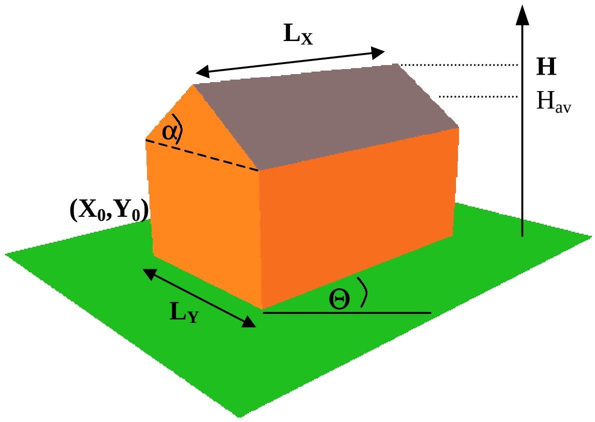

Figure 4: 7-parameter standard gable roof building

1. First and second order invariant moments for a synthetic building model are expressed in an equation system of moments as a function of the parameters of the assumed building model. In the case of a 7-parameter gable roof building with rectangular ground plan as shown in Figure 4, these parameters are position, length, width, orientation, height, roof orientation and steepness.
2. This equation system is solved for the building model parameters, i.e. the building model parameters are expressed as functions of 1st and 2nd order invariant moments.
3. The moments of all segmented point clouds are computed, and the building parameters are derived from these moments.

To avoid effects caused by an interpolation to a regular grid, the approach is applied to the original irregularly distributed laserscanner data points, while the segmentation was applied on gridded data. This fact in combination with effects of the post-processing of the classification result requires a refinement of the segmentation within the individual point clouds, which is performed by local histogram analysis and subsequent thresholding.

Based on the shift-, scale- and rotation-invariant forms of binary moments

$$m_{ij} = \sum_{P=P_1}^{P_n} X_P{}^i \cdot Y_P{}^j$$

and height-weighted moments

$$M_{ij} = \sum_{P=P_1}^{P_n} X_P{}^i \cdot Y_P{}^j \cdot H_P$$

of clouds of n points (X_P, Y_P, H_P), the parameters can be computed. This computation may be performed in an adjustment procedure. More interesting, however, a direct solution is possible if a system consisting of seven equations based on ratios of 0^{th}, 1^{st} and 2^{nd} binary and height-weighted moments is solved symbolically (Maas/Vosselman, 1999). The seven parameters of this closed solution are:

Position: $X_0 = \frac{m_{10}}{m_{00}}$, $Y_0 = \frac{m_{01}}{m_{00}}$

Shift invariance: $\overline{M}_{ij} = \sum_{P=P_1}^{P_n} (X_P - \overline{X})^i \cdot (Y_P - \overline{Y})^j \cdot H_P$

Orientation: $\Theta = \frac{1}{2} \cdot \arctan \frac{2\overline{m}_{11}}{\overline{m}_{20} - \overline{m}_{02}}$

Rotation invariance:

$$M'_{ij} = \sum_{r=0}^{p} \sum_{s=0}^{q} (-1)^{q-s} \cdot \binom{p}{r} \cdot \binom{q}{s} \cdot \Psi \cdot \tilde{M}_{(p+q-r-s)(r+s)}$$

with $\Psi = (\cos\Theta)^{p-r+s} \cdot (\sin\Theta)^{q+r-s}$

Length: $L_X = \sqrt{\frac{12 \cdot m'_{20}}{m'_{00}}}$

Width: $L_Y = \sqrt{\frac{12 \cdot m'_{02}}{m'_{00}}}$

Roof inclination: $\alpha = \arctan\left(8 \cdot \frac{M'_{00} \cdot \left(\frac{M'_{20}/M'_{02}}{m'_{20}/m'_{02}} - 1\right)}{\frac{M'_{20}/M'_{02}}{m'_{20}/m'_{02}} \cdot L_Y}\right)$

Height: $H = M'_{00} + \frac{L_Y}{2} \cdot \tan\alpha$

Scale-invariance is dispensable in this scheme as only ratios of moments are being employed, which is compelled by the fact that in the case of irregularly distributed discrete data points the absolute values of moments depend on the number of data points in the segmented region.

The non-orthogonal projection geometry of a laserscanner in the across-flight direction causes biases in some parameters as a consequence of an inhomogeneous distribution of data points on tilted planes of different orientation. This effect can be modeled and applied to the results (Maas, 1999): Based on the numbers of points n_1 and n_2 falling onto the two roof faces which are counted recursively, a weight factor $P = 2n_1/(n_1 + n_2)$ is defined and used in correction terms for the centroid of the building

$$\Delta\overline{X} = \frac{Y \cdot (P-1)}{4} \cdot \sin\Theta \ , \quad \Delta\overline{Y} = \frac{Y \cdot (P-1)}{4} \cdot \cos\Theta \ . \qquad \text{(eq. 1)}$$

Similar effects may be caused by inhomogeneous point densities as a consequence of partial 2-strip coverage of a building. In such cases the ground plan parameters of the building are better derived from an analysis of the bounding box of the point cloud obtained from the refined segmentation.

3.2 Model fit analysis

In a subsequent data-driven model analysis step, a goodness of fit can be determined by projecting the model into the point cloud and computing residuals for every data point. This allows for a rejection of the computed house model in case of bad fit and for the detection and elimination of outliers in the data points or points situated on objects like antennae or chimneys. Moreover, the analysis of the deviations between model and point cloud allows for the detection and modeling of certain systematic deviations from the chosen building model, which may for example be caused by dorms on a roof. Applying binning techniques to detected outliers, local point clouds describing dorms can be isolated. Applying the above shown moment analysis technique with constraints on the orientation, 4-parameter models of dorms can be derived from local point clouds containing a minimum of 8 - 10 data points.

The closed solutions shown above can easily be modified for other standard roof types such as hip, desk or graded roofs. Buildings with a complex ground plan will require a procedure of splitting non-rectangular ground plans into primitives (Weidner/Förstner 1995, Haala/Brenner 1997) and merging (possibly constrained) best solutions for the primitives. In principle, the applicability of the technique may also be widened by computing a set of higher order moments and comparing those with moments in a database containing a variety of building types. The multitude of possible building designs and the noise sensitivity of higher order moments will, however, pose limitations to this approach.

4. Practical test

The segmentation procedure and analysis of moments as outlined in chapter 2 and 3 were applied to laserscanning data acquired by the FLI-MAP system. FLI-MAP (Fugro N.V., see e.g. Pottle, 1998) is a helicopter-based laserscanning system with 8kHz sampling rate, which is mainly used for corridor mapping. It acquires 40 profiles per second with 200 points per profile. Range measurement is limited to first-pulse capture at 20-200 meter distance, thus providing a maximum strip width of 200m at a scan width of 60^o. Orientation parameters are determined by a set of four GPS receivers and a vertical reference unit. In addition to the laser range measurements, the FLI-MAP system is capable of delivering 6-bit intensity data.

As a consequence of the low flying height and the slow speed of the helicopter as well as the narrow strip width, the point density achieved by the FLI-MAP system is usually rather large (more than one point per square meter). A dataset of a part of a Dutch village (Figure 1) acquired in March 1997 was used for verification of the techniques discussed in chapter 2 and 3. In this dataset a point density of 5.3 points per square meter was achieved in regions with single-strip coverage; in the overlap regions of neighbouring strips the density was accordingly higher.

4.1 Building detection and segmentation

The post-processed result of the region shown in Figure 2 is shown in Figure 5. Note that this result of the low-level segmentation procedure is further refined by the step of model fit analysis during building generation.

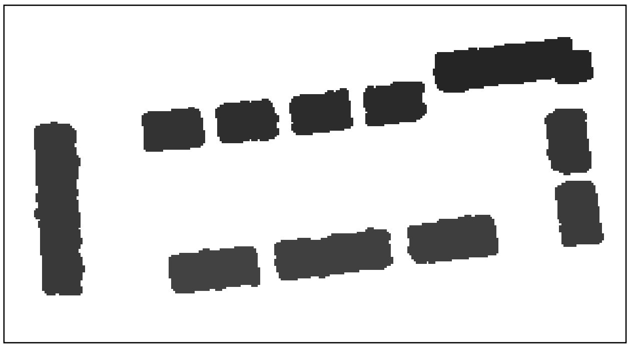

Figure 5: Result of postprocessing applied to Figure 2

For a visual comparison, Figure 6 shows an aerial image of the region shown in Figure 5. Note that this image was taken at a different data and not used in the segmentation and reconstruction process.

Figure 6: Aerial image of the region shown in Figure 5

Basically, the intensity of the laser pulse echo, which is recorded by the FLI-MAP system and inherently georeferenced with the height data, might be used as an extra cue in the segmentation process. In practical tests, however, this reflectance image turned out to be rather noisy and did not lead to a significant improvement of the classification results.

4.2 Building reconstruction

Figure 7 shows the building models generated from the laser data, using the segmentation as shown in Figure 5. All garages and sheds in the region are missing as not part of the chosen building model. An extension of the top right building in Figure 5 gets unintentionally generalized. Most dorms are detected and correctly modeled; two dorms are missing due to a lack of data points, possibly caused by mirror reflection on water present on the horizontal surfaces.

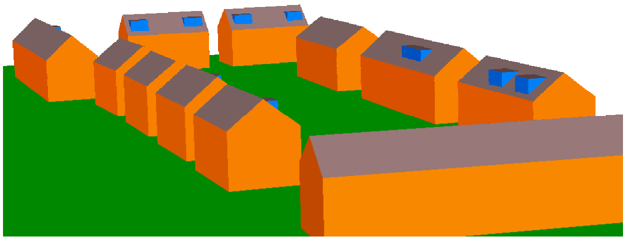

Figure 7: Reconstructed buildings with dorms (120° rotated, see http://www.geo.tudelft.nl/frs/laserscan/laser_mom.html for a VRML model)

The computation times for building reconstruction are in the order of 0.8 seconds per building in the current non-optimized implementation on a HP workstation. Applying some optimization and reducing the amount of internal checks and data output, the computation time per building can be reduced considerably. Moreover, the technique is rather parallelization-friendly, so that even near-realtime implementations seem feasible.

4.3 Accuracy considerations

No sufficient ground truth was available to verify the accuracy of all determined building parameters. Some precision figures can, however, be derived from the variation of the parameters and from available 2-D GIS data:

- The 11 houses shown in Figure 7 belong to a settlement of equally designed buildings with varying length. Assuming identical width, height, orientation and roof inclination for all houses, the following average parameters and RMS deviations were determined:

	width	height	orientation	inclination
average	8.09 m	11.33 m	6.9°	37.4°
RMS	0.16 m	0.11 m	0.8°	1.6°

Table 1: Average and RMS of identical model parameters of the buildings shown in Figure 7

- The model fit analysis delivered a RMS deviation of 10 cm between point clouds and models of buildings complying with the assumed models.
- 2-D GIS data generated by analytical photogrammetry from 1 : 3000 scale imagery was available for the 11 buildings shown in Figure 7. A comparison with this data suffers from overhanging roofs and the size of the laser spot. The roof reconstructed from first-pulse laserscanner data will always be larger than the ground plan of a building; therefore the mean deviation of 21 cm in width and 35 cm in length was subtracted. After subtacting this systematic effect, the RMS of the deviations of the building dimensions derived from the 2-D GIS data and those reconstructed from the laserscanner data was 19 cm in width and 21 cm in length. Note that these deviations are also influenced by the highly elliptical shape of the FLI-MAP spot and by planimetric shifts of strips in regions of two-strip coverage. These shifts are probably caused by the lack of

an INS in the FLI-MAP system and were found to be in the order of several decimeters at maximum.

4.4 Point density reduction

The point density of five points per square meter as available in the dataset forming the basis for the results shown above has to be considered an ideal case and may be unrealistic for general urban modeling applications at present. Therefore the building reconstruction was repeated with stepwise thinned datasets.

Using the parameters of the buildings derived from the dense dataset as reference, the RMS deviation of the parameters computed from the thinned datasets are listed in Table 2.

P/m^2	centroid		Θ	length	width	height	roof slope
2.6	0.03	0.01	0.2	0.09	0.03	0.03	0.3
1.3	0.10	0.06	0.4	0.19	0.08	0.04	0.5
0.65	0.23	0.14	1.0	0.28	0.16	0.07	1.5
0.33	0.40	0.20	1.9	0.57	0.20	0.19	3.2
0.17	0.95	0.39	2.9	0.85	0.50	0.41	6.9
0.08	1.32	0.61	6.0	1.13	0.68	0.73	12.1

Table 2: RMS deviations between parameters computed from dense and thinned datasets (units: [m],[°])

The computations with thinned datasets show that gable roof type buildings may be reconstructed from point densities in the order of one point per square meter at a loss of accuracy that may be tolerable for many applications. At point densities of significantly less than one point per square meter a reasonable reconstruction will not be possible. The most sensitive of the parameters is obviously the roof slope. But also building orientation errors turned out to be critical for visualization purposes: A RMS of 2° of orientations within a group of buildings does clearly disturb the visual impression. Most dorms get lost already in the first reduction step to 2.6 points per square meter; at a point density of one point per square meter no dorms can be reconstructed.

5. Discussion

Airborne laserscanning depicts a very powerful tool for the acquisition of data for the generation of virtual city models. Buildings can be automatically detected and modeled from dense laserscanner 3-D point clouds without the need of any further source of information such as digital imagery or 2-D GIS information. Laserscanner datasets may be segmented by the analysis of height texture measures in a classification-like approach. Closed solutions were formulated for gable roof type buildings with rectangular ground plan and can be extended to other standard types. Irregularities such as dorms on gable roofs can be detected and modeled in the same manner. more work has to be performed on the reconstruction of buildings with a non-rectangular ground plan.

The point density to be aspired for the reconstruction of buildings should be at least one point per square meter. If building details such as dorms on roofs are to be modeled, a point density in the order of five points per square meter should be provided. This data density allows an accuracy potential in the order of 10 - 20 cm.

Despite this stand-alone potential of laserscanning, a high-resolution digital camera integrated on a laserscanner platform remains desirable. Besides image information to be used for texture mapping, it may provide valuable information on edges, thus forming a perfect complement to laserscanning data. Moreover, data from an integrated multispectral sensor might also be used to strengthen the segmentation process and to widen the range of objects, which can be detected and modeled.

Acknowledgement

The author would like to thank the Survey Department of Rijkswaterstaat in Delft for providing the FLI-MAP laserscanner data used in this study.

References:

- Brenner, K., Haala, N., 1998: Rapid acquisition of virtual reality city models from multiple data sources. IAPRS, Vol. 32, Part 5, pp. 323-330
- Haala, N., Brenner, K., 1997: Generation of 3D city models from airborne laser scanning data. Proceedings EARSEL Workshop on LIDAR remote sensing on land and sea, Tallinn/Estonia
- Henricsson O., Bignone F., Willuhn W., Ade F., Kübler O., Baltsavias, E., Mason, S. Grün A., 1996: Project Amobe: Strategies, current status, and future work. IAPRS, Vol. 31, Part B3, pp. 321-330
- Lang, F., Förstner, W., 1996: 3D-City modeling with a digital one-eye stereo system. IAPRS, Vol. 31, Part B4
- Maas, H.-G., 1999: Closed solutions for the determination of parametric building models from invariant moments of airborne laserscanner data. Submitted to ISPRS Conference 'Automatic Extraction of GIS Objects from Digital Imagery, München/Germany, 6-10. 9. 1999
- Maas, H.-G., Vosselman, G., 1999: Two algorithms for extracting building models from raw laser altimetry data. ISPRS Journal of Photogrammetry and Remote Sensing 52 (2)
- Pottle, D., 1998: Helicopter-based observations replace traditional surveying. Geodetic Info Magazine 2/98, pp. 62-65
- Takahashi, Y., Chen, X., 1998: Monitoring powerline systems by using airborne laser range data. IAPRS, Vol. 32, Part 5, pp. 382-385
- Weidner, U., Förstner, W., 1995: Towards automatic building reconstruction from high resolution digital elevation models. ISPRS Journal, 50(4), pp. 38-49