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Two algorithms for extracting building models from raw laser altimetry data

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Abstract

Two new techniques for the determination of building models from laser altimetry data are presented. Both techniques work on the original laser scanner data points without the requirement of an interpolation to a regular grid. Available ground plan information may be used, but is not required. Closed solutions for the determination of the parameters of a standard gable roof type building model based on invariant moments of 2 1/2-D point clouds are shown. In addition, the analysis of deviations between point cloud and model does allow for modelling asymmetries such as dorms on a gable roof. By intersecting planar faces nonparametric buildings with more complex roof types can also be modelled. The techniques were applied to a FLI-MAP laser scanner dataset covering an area of 500×250 m^2 with a density of more than 5 points/m^2. Within this region, all but one building could be modelled. An analysis of the variance of the parameters within a group of buildings indicates a precision in the range of 0.1–0.2 m. © 1999 Elsevier Science B.V. All rights reserved.

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1. Introduction

The automation of the generation of 3-D city models as required by many users of geographic information systems has become a major focus of photogrammetric research in the past few years. Starting with 2-D image processing techniques, researchers did soon turn towards 3-D approaches like grouping features matched in multiple images. Both semi-automatic (e.g., Lang and Förstner, 1996) and fully automatic photogrammetric approaches (e.g., Henricsson et al., 1996) have been developed. The automatic extraction of parametric and prismatic building models from dense digital elevation models generated by photogrammetric techniques or airborne laser scanning has been shown by Weidner and Förstner (1995).

Due to its advantages as an active technique for reliable 3-D point determination without requirements towards surface reflectance variations and time consuming error-prone matching techniques, airborne laser scanning has meanwhile become a rather important source of information for the generation of 3-D city models. Although the point densities delivered by most systems in standard operation mode are still too small (often in the order of 1 point/10 m^2), sufficiently dense datasets can be acquired with several systems today.

A number of authors has shown approaches for the generation of 3-D building models mainly or solely based on laser altimetry data: Haala and Brenner (1997) extract planar roof primitives from dense

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laser altimetry data (TopoSys sensor, 4 points/m^2) by a planar segmentation algorithm, using additional ground plan information for gaining knowledge on topological relations between roof planes. Lemmens et al. (1997) show the fusion of laser-altimeter data with a topographical database to derive heights for roof-less cube type building primitives. Hug and Wehr (1997) show the detection and segmentation of houses from ScaLARS height and reflectivity data based on morphological filtering with successive progressive local histogram analysis; in addition, they use the laser reflectivity measure for separating buildings from vegetation. Haala et al. (1998) derive parameters for 3-D CAD models of basic building primitives by least-squares adjustment minimising the distance between a laser scanning digital surface model and corresponding points on a building primitive; the boundaries of buildings are derived from ground plans. The implementation is limited to four standard building primitives and combinations of those. Further refinement has to be performed interactively.

In the following, we show two new approaches for the automatic derivation of building models from laser altimetry data. The first approach is based on the analysis of invariant moments of point clouds: closed solutions for the parameters of standard gable roof house types are derived from 0th, 1st and 2nd order moments, and asymmetries such as dorms on the roof are detected and modelled. The second approach is a data driven technique based on the intersection of planar faces in triangulated point. Common to both approaches is the fact that they use the original 3-D data points rather than data interpolated to a regular grid, thus avoiding unwanted effects caused by interpolation. Moreover, they can be applied to laser altimetry data without the need of any further source of data, such as 2-D GIS data. As an option, such data may be used to strengthen the technique or to warrant consistency with available information.

2. Segmentation

With either interpolated or original data, the laser altimetry data has to be segmented as a first processing step. In our approach, segmentation means only the extraction of a point cloud describing a building from the laser altimetry data. Such a segmentation of laser altimetry data may be obtained in several ways.

- In many cases, available 2-D GIS information can be used as reliable and usually sufficiently accurate source of information—with the advantage of data integrity but the restriction that roofs are often larger than the ground dimensions of a building.
- In sufficiently dense datasets of regions with limited terrain roughness, the detection of local maxima and the analysis of histograms of regions around these maxima will often clearly indicate a reasonable threshold value and the boundaries of buildings.
- Filtering techniques applied to laser scanning data to derive digital terrain models (e.g., Kraus and Pfeifer, 1997) can basically be considered inverse to the task discussed here and may thus also be used to support segmentation.
- The reflectance value delivered by some airborne laser scanner sensors may be used as an additional source of information in the segmentation process, making use of the high reflectivity of healthy vegetation in the near infrared (Hug and Wehr, 1997). The monochromatic nature of this reflectance in the wavelength of the laser will, however, pose limits to the use of this cue. Moreover, most laser scanner systems today operate in the time-of-flight mode and do therefore deliver rather poor reflectance data quality; an exception is the ScaLARS system (Hug, 1994) which is based on phase measurement principles.
- A future option will be the analysis of spectral signatures captured by a multispectral or hyperspectral scanner integrated on an airborne laser scanner platform.

The dataset used in the work described in the following was segmented by the application of thresholding, binning, morphological filtering and connected component labelling techniques. A further segmentation into individual roof planes is either not required or part of the modelling scheme.

3. Derivation of house model parameters from invariant moments

The analysis of invariant moments has been used in image processing for a long time. Early publications go back to the 1960s (e.g., Hu, 1962).

In the continuous domain, moments are defined as:

$$M_{ij} = \int_{x_1}^{x_2}\int_{y_1}^{y_2} x^i y^j f(x,y)\,\mathrm{d}x\,\mathrm{d}y \tag{1}$$

with i,j the order of the moment and $f(x,y)$ the continuous image function.

Airborne laser scanning delivers discrete, irregularly distributed 2 1/2-D point data with the height H as a function of planimetric coordinates X and Y. Height-weighted moments can be computed by summation over a segmented group of data points $(P_1,\dots,P_n)$:

$$M_{ij} = \sum_{P=P_1}^{P_n} X_P^i Y_P^j H_P \tag{2}$$

In most image processing applications the invariance of moments towards shift, scale and rotation is required:

- Shift invariance can be obtained by relating coordinates to the centre of gravity:

$$\overline{X} = \frac{M_{10}}{M_{00}}, \quad \overline{Y} = \frac{M_{01}}{M_{00}},$$

$$\overline{M}_{ij} = \sum_{P=P_1}^{P_n} \left(X_P - \overline{X}\right)^i \left(Y_P - \overline{Y}\right)^j H_P \tag{3}$$

- Scale invariance, in addition to shift invariance, is obtained by setting $\overline{M}_{00}$ to 1:

$$\tilde{M}_{ij} = \left(\frac{1}{\sqrt{\overline{M}_{00}}}\right)^{i+j+2} \overline{M}_{ij} \tag{4}$$

- Rotation invariance, in addition to shift invariance, can be obtained by principal axis transformation:

$$\Theta = \frac{1}{2}\arctan\frac{2\overline{M}_{11}}{\overline{M}_{20} - \overline{M}_{02}} \tag{5}$$

$$M'_{pq} = \sum_{r=0}^{p}\sum_{s=0}^{q} (-1)^{q-s}\binom{p}{r}\binom{q}{s}(\cos\Theta)^{p-r+s} \times (\sin\Theta)^{q+r-s}\,\overline{M}_{(p+q-r-s)(r+s)}$$

In these investigations, scale invariance was not used, only shift and rotation invariance. By using at the right side of Eq. (5) a scale invariant moment instead of a shift invariant one, all three types of invariance can be achieved.

For a further discussion on invariant moments, see, e.g., Teh and Chin (1988).

3.1. Closed solutions for standard gable roof type houses

In the following, we will concentrate on a standard gable roof type house model containing the coordinates, length, width and height of a building as well as its orientation, roof type and roof slope (Fig. 1). Based on binarised data with $H_P = 1$ in Eq. (2) for computing binary moments m_{ij}

$$m_{ij} = \sum_{P=P_1}^{P_n} X_P^i Y_P^j \tag{6}$$

and their shift and rotation invariant form (Eq. (5)), ground shape, dimensions and orientation of a building can be determined. Using the height as a weight for computing shift and rotation invariant moments M'_{ij}, the roof type as well as height and slope of the roof can be determined. All parameters can be derived as closed solutions from 1st and 2nd order moments. Note that building parameters can only be derived from ratios of moments (e.g., moments normalised by division with m'_{00}), as 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. Assuming an unbiased distribution of laser scanning data points, the coordinates of the centroid of a building are

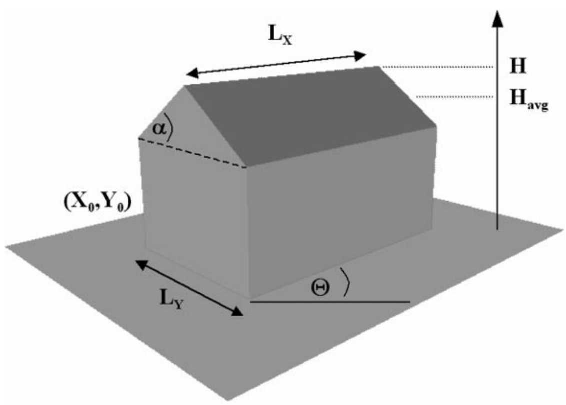

Fig. 1. Standard gable roof house type.

obtained via normalised 1st order moments m'_{10}/m'_{00}, m'_{01}/m'_{00} of binarised data (Eq. (3)). The principal axis direction Θ, which describes the orientation of the building, is obtained from Eq. (5). If the ratio of the rotation invariant moments $q_2 = m'_{20}/m'_{02}$ is smaller than 1, 90° has to be added to Θ in order to describe the orientation of the longer axis.

Assuming a rectangular ground shape of a building, its ground dimensions L_X and L_Y can be obtained directly from the formulation of 2nd order rotation invariant moments of binarised data in the continuous domain (Eq. (1)):

$$m'_{20} = \int_{-L_X/2}^{L_X/2}\int_{-L_Y/2}^{L_Y/2} x^2 \mathrm{d}x\mathrm{d}y = \frac{1}{12}L_X^3 L_Y,$$

$$m'_{02} = \int_{-L_X/2}^{L_X/2}\int_{-L_Y/2}^{L_Y/2} y^2 \mathrm{d}x\mathrm{d}y = \frac{1}{12}L_X^3 L_Y,$$

$$m'_{00} = \int_{-L_X/2}^{L_X/2}\int_{-L_Y/2}^{L_Y/2} \mathrm{d}x\mathrm{d}y = L_X L_Y. \qquad (7)$$

Solving Eq. (7) for L_X and L_Y we obtain:

$$L_X = \sqrt{\frac{12\,m'_{20}}{m'_{00}}}, \quad L_Y = \sqrt{\frac{12\,m'_{02}}{m'_{00}}} \qquad (8)$$

For the computation of roof type and shape parameters, the height of the laser scanner data points is used as weight function in Eq. (7) and Eq. (2). Information on the roof type can be obtained from a comparison of the ratios of 2nd order moments of the height-weighted and the binarised data: If the roof is a flat roof, the ratio

$$r_q = \frac{M'_{20}/M'_{02}}{m'_{20}/m'_{02}} \qquad (9)$$

will be equal to 1. If r_q is larger than 1, a roof orientated parallel to the principal axis of the building can be assumed, while r_q smaller than 1 means a roof oriented perpendicular to the principal axis.

Assuming a standard gable roof type oriented parallel to the principal axis of the building, the height H and the slope of the roof α can also be derived from 0th and 2nd order moments. The height is expressed as a function of the y-coordinate in the local coordinate system after principal axis transformation (see Fig. 1):

$$H = H_{\mathrm{avg}} + \left(\frac{L_Y}{4} - |y|\right)\tan\alpha \qquad (10)$$

with the average building height

$$H_{\mathrm{avg}} = M'_{00}/m'_{00} \qquad (11)$$

and used as weight in the computation of the 2nd order moments

$$M'_{20} = \int_{-L_X/2}^{L_X/2}\int_{-L_Y/2}^{L_Y/2} x^2 H(y)\mathrm{d}x\mathrm{d}y = \frac{1}{2}L_X^3 L_Y H_{\mathrm{avg}}$$

$$M'_{02} = \int_{-L_X/2}^{L_X/2}\int_{-L_Y/2}^{L_Y/2} y^2 H(y)\mathrm{d}x\mathrm{d}y = \frac{1}{2}L_X^3 L_Y H_{\mathrm{avg}} - \frac{1}{96}L_X L_Y^4 \tan\alpha \qquad (12)$$

Solving, e.g., the ratio r_q (Eq. (9)) for α, the roof slope becomes

$$\alpha = \arctan\left(8\frac{H_{\mathrm{avg}}(r_q - 1)}{r_q L_Y}\right) \qquad (13)$$

Introducing this slope into Eq. (10), the roof height of the building can be computed:

$$H = H_{\mathrm{avg}} + \frac{L_Y}{4}\tan\alpha \qquad (14)$$

After the determination of these seven house model parameters, a goodness of fit can be determined by projecting the house model into the segmented point cloud and computing height residuals for every point. This allows for a rejection of the computed house model in case of bad fit and for the elimination of outliers in the data points.

3.2. Detection and modelling of asymmetries

The above considerations apply for the parametrisation of rectangular houses with gable roof or a flat roof. Higher order moments may be used for the determination of other roof types. In addition to that, higher order moments can also be used to detect asymmetries on gable roofs. A deviation from the standard gable roof type, which does occur quite often, is formed by dorms on the roof (Fig. 2). Basically, dorms can be described by four or five

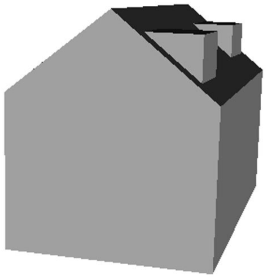

Fig. 2. House with two successfully modelled dorms.

additional parameters, which may be determined as closed solutions simultaneously with the parameters describing the standard gable house model by solving equation systems including third order moments. Already for a four-parameter dorm, however, the solution of the equation systems does become very complicated. Moreover, this approach does not take into consideration that there may be more than one dorm on a roof.

Instead, a different approach was chosen to model dorms by the analysis of moments: as a first step, a standard gable roof house model was determined. Then the differences between the points of the original point cloud and the model were calculated. Points above the ridge height were discarded as potentially lying on chimneys or antennae. Points below the ridge but significantly above the roof were assumed to belong to dorms. This new point cloud was segmented into parts belonging to different dorms by binning and connectivity analysis. For each of the subsets, binarised and height-weighted moments were then computed. As the number of points on the dorms was rather small (mostly less than 20), the height was assumed to be constant. The orientation of a dorm can be assumed to be perpendicular to the principal axis of the building. Thus a dorm is described by four parameters (a coordinate and a length along the roof axis, a distance from the roof edge and a height), which can be determined as closed solutions from ratios of moments m'_{20}, m'_{02}, m'_{10}, m'_{01}, m'_{00}. Optionally, a five-parameter dorm with an extra gable may be modelled in the same manner.

Also for the determination of house models with a non-rectangular ground plan, the derivation of closed solutions based on higher order moments seems not recommended. Instead, solutions for a number of roof types on a rectangular ground plan should be developed and applied to complex ground plans broken up into primitive units, thus going to prismatic building models as suggested by Weidner and Förstner (1995) and Haala and Brenner (1997).

4. House model reconstruction by intersection of planar faces

More generically, polyhedral models can describe most buildings. Therefore, planar faces describe the surface of a house roof. Because of the high density of laser scanner data, these faces can be recognised clearly and the parameters of the planes can be estimated accurately. The outlines of the faces of a roof are more difficult to determine. If the roof surface is continuous (e.g., there are no height jumps on the roof), the edges between adjacent faces can be reconstructed by intersection of the corresponding planes. Whereas the location of these edges will be quite accurate, the precise locations of edges at roof discontinuities and at the roof outline are difficult to derive from laser scanner data. In this section a data driven approach is presented for the derivation of polyhedral models of buildings with continuous roof surfaces. In order to improve the determination of the roof outline constraints are imposed on the orientation of the edges of the outline.

4.1. Detection of planar roof faces

Several techniques can be used to detect planar faces and determine their parameters. Haala et al. (1998) segment images of roof gradient directions. In order to reduce the noise in the gradient computation they fit a plane to a small area of the dataset and use information from a map to align the gradient directions with the roof outline. Another technique to robustly determine the planar faces is clustering. One way of clustering could be based on the meshes of a Delaunay triangulation. All triangles that are part of the same roof face should describe the same plane. Like the segmentation of gradient images, clustering of the plane parameters of the triangles will, however, be hampered severely by noise in the normal directions, since the triangles are very small due to the high point density. In contrast, clustering of

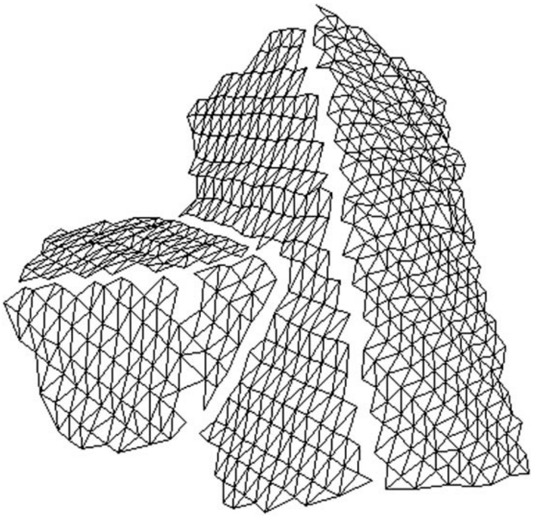

Fig. 3. Triangular meshes found by clustering and connected component analysis.

points does not suffer from this difficulty. We set up a 3-D cluster space described by two slope parameters (s_x, s_y) and a distance (d).

$$Z = s_x X + s_y Y + d \tag{15}$$

Each point (X,Y,Z) in the laser scanner data set defines a plane in this cluster space. By counting the number of planes that intersect a bin in the cluster space the planes of the roof can be identified as the bins with a large number of laser points. After the clustering the Delaunay triangulation is used to form connected components of the points in the same plane. If the area of such a component exceeds some threshold, a roof face is considered to be found. The example in Fig. 3 shows the meshes of the triangulation of four roof faces that are found by the clustering. To improve the precision of the plane parameters, a least squares fit is performed.

4.2. Intersection of roof faces

The outline of a roof face consists of two types of (straight) edges: edges that describe a common part of the outline of two adjacent roof faces and edges that are part of the contour of the whole roof. The first type of edge can be accurately reconstructed by intersection of the detected planes. To find these edges all pairs of detected planes are intersected. After the intersection the edge is defined as that part of the line of intersection for which both roof faces contain laser points that are near that line. In the same manner the edges of the roof faces that are part of the contour of the whole roof can be found by intersection of the roof face with the walls. For this purpose we now first have to determine the outline of the roof surface.

4.3. Determination of roof outline

From the triangulation and the segmentation of the laser points the connected component of triangles that belong to the roof surface is extracted (left drawing in Fig. 4). Since we are assuming polyhedral models a better description of the outline can be found by approximating the contour of this connected component by straight lines. Doing so with a Douglas–Peucker-like algorithm (Douglas and Peucker, 1973) will give results that are visually unattractive, since the resulting lines will not be exactly parallel or perpendicular. Therefore, another

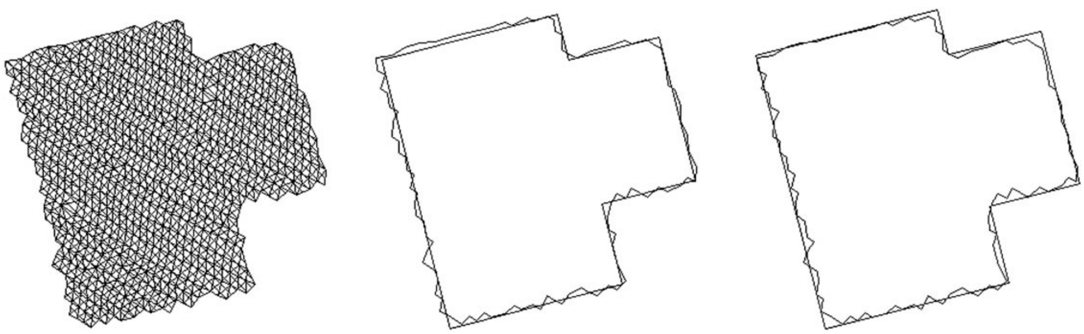

Fig. 4. Approximation of the roof outline by straight lines. Left: connected component of triangles on the roof surface. Middle: initial approximation of the roof outline. Right: final approximation.

approximation algorithm was used which strictly enforced the lines to be either parallel or perpendicular to the main building orientation. This orientation was obtained from the directions of the horizontal intersection lines between the roof faces. These ridgelines are usually parallel to lines of the roof outline. The algorithm to extract the roof outline first sequentially processes all points of the contour of the connected component. Starting at an arbitrary point the direction of the roof edge through this point is derived from the direction to the next point and adjusted using the house orientation modulo 90°. Further points of the contour are assigned to this edge until the perpendicular distance between a point and the edge exceeds some threshold. At this point a new edge is introduced which either makes a left or a right turn with respect to the previous edge. In this way all points are assigned to an edge. The resulting initial approximation (middle drawing of Fig. 4) corresponds to a segmentation of the contour. This segmentation is optimised by changing the assignments of points to the edges such that the least square sum of the distances of the points to the edges is minimised. The least squares fit of an edge to a series of points, however, does not give the optimal position of the roof edge. For a perfect laser scanner the best choice would be to determine the outlining polygon such that all points are on the inside of the polygon. Due to the finite spot size and the pointing jitter of the laser beam it is, however, likely that some data points will also be outside a correctly determined roof outline. In the presented result (right drawing of Fig. 4) the edges of the outline are determined such that 80% of the points on the contour of the connected component are on the inside of the roof outline.

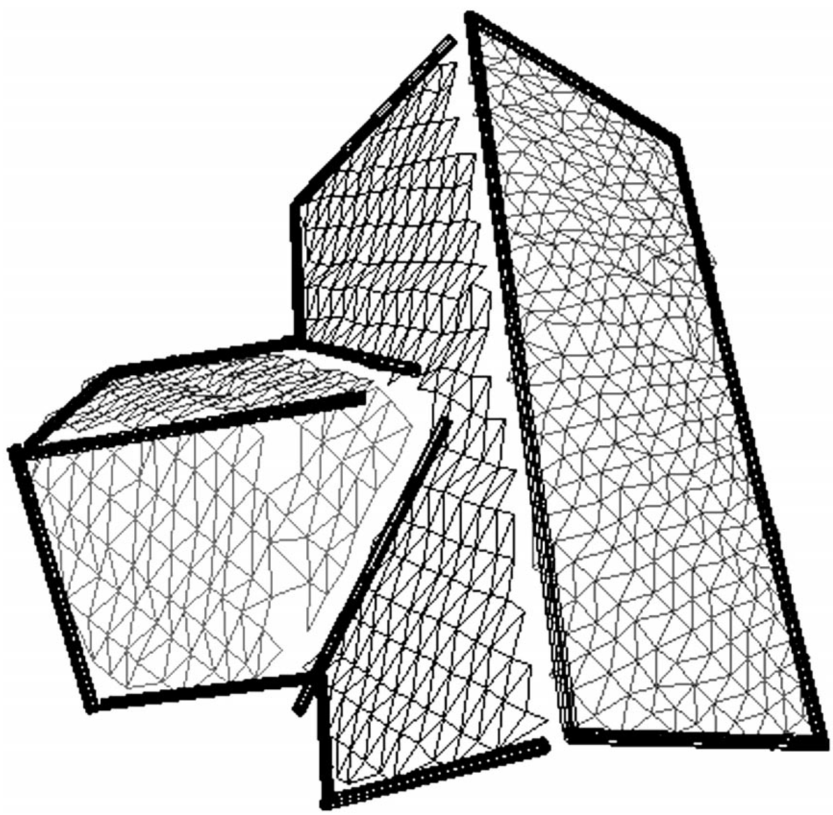

Fig. 5. Lines of intersection between adjacent roof faces and between roof faces and adjacent walls.

4.4. Reconstruction of the house model

Now that the roof outline is determined, vertical wall planes are constructed through all edges of the outline. These wall planes are intersected with the roof faces in order to find the remaining edges of the roof faces and to determine the height of the walls. An example of the edges that result from the intersections of pairs of roof faces and of the roof faces with the adjacent walls is shown in Fig. 5. All roof face edges are now determined. The complete outline of each roof face is reconstructed by intersecting the edges with nearby end points. Since all edges are in the same plane, there are no misclosures at the intersection point. At points where four or more different planes meet the reconstructed points are averaged to form a common node. Finally, the ground level of the walls was set to the height of the lowest point in the vicinity of the building.

5. Practical results

The techniques shown above were applied to a FLI-MAP laser altimetry dataset containing 51 buildings. FLI-MAP (Fugro-Inpark, see, e.g., Pottle, 1998) is a helicopter-based laser scanning system with 8 kHz sampling rate. It acquires 40 profiles/s with 200 points/profile. Range measurement is limited to first-pulse measurement at 20–200 m distance, thus providing a maximum strip width of 200 m at a scan width of 60°. Due to these system parameters, the point density is usually rather large (more than 1 point/m^2). Position and attitude parameters are determined by a set of four GPS receivers combined with a vertical reference unit. In addition to the laser range measurements, the FLI-MAP system is capable of delivering reflectance data.

Fig. 6 shows a part of a dataset acquired with the FLI-MAP system over an urban area in the Netherlands. The average point density within the laser scanner strips is in the order of 5 points/m^2. The application of height histogram analysis, morphological filtering, connected component analysis and the assumption of a minimum height and area per building turned out to be appropriate for segmentation of this data. The intensity values delivered by the FLI-MAP system are of very poor quality and could not be used in the segmentation process.

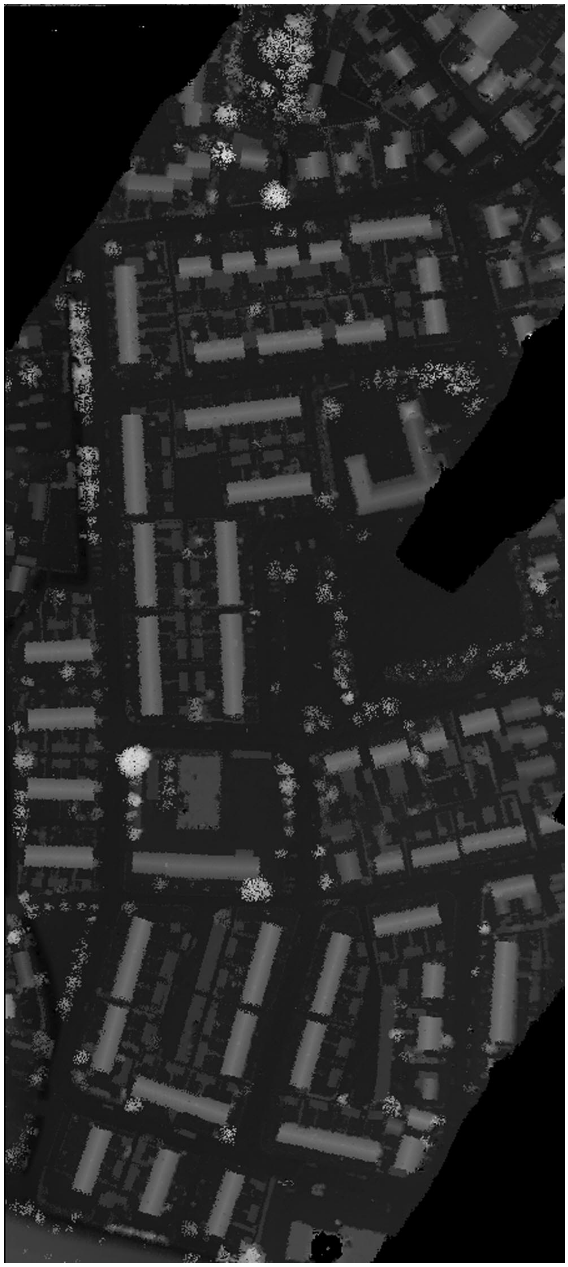

Fig. 6. Part of FLI-MAP dataset (grey coded binned height data).

5.1. Analysis of moments

Fig. 7 shows models of buildings in the area derived from 0th, 1st and 2nd order shiftand rotation

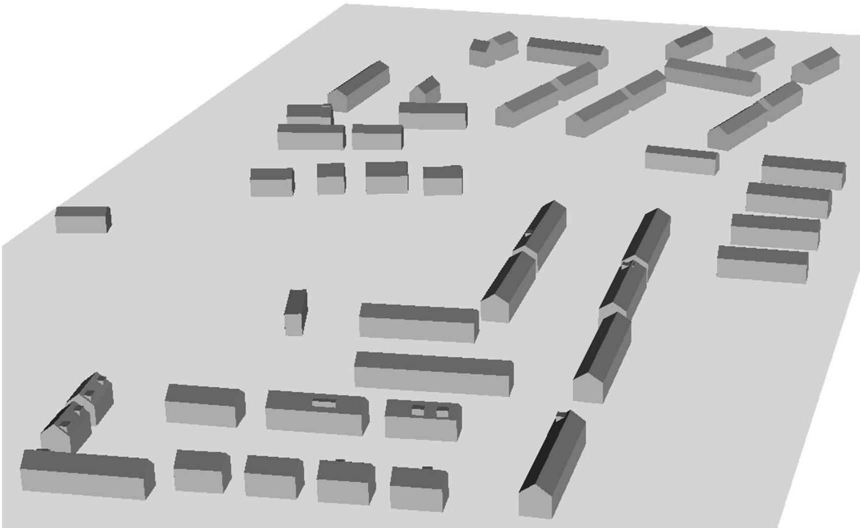

Fig. 7. Group of house models derived from invariant moments.

invariant in binarised and height-weighted moments. Most trees were successfully removed, either during the segmentation process or in the model fit analysis. Three of the 51 buildings could not be modelled due to an insufficient segmentation. In another attempt with a semi-interactive segmentation approach all buildings could be modelled.

As no ground truth was available, precision figures were only derived from the variance of the parameters within a group of buildings, assuming identical width, height, orientation and roof slopes for 10 houses which belong to a neighbourhood of equally designed buildings with varying length. The parameters and standard deviations within this group are listed in Table 1. The approach for modelling dorms turned out to work quite reliably: all dorms containing a minimum of about 10 data points could be modelled. Fig. 2 shows an example of a house with two reconstructed dorms.

Obviously, the point density of this dataset was uncommonly high. In order to be able to make statements on the applicability of the technique to less dense datasets, the data was thinned in several steps. A comparison of the results obtained from the analysis of moments applied to thinned datasets with the results obtained from the full density dataset indicates that — apart from the modelling of dorms — reasonable results can be expected from a point density of approximately 1 point/m^2. A point density in the order of 0.1 point/m^2, as it is being used in many airborne laser scanning projects today, is obviously insufficient for the parametrisation of roofs, unless building outlines can be obtained from available GIS data.

The computation of the building model parameters from moments assumes a homogeneous point distribution. Inhomogeneities in the point distribution will lead to biased parameters. Such inhomogeneities

Table 1
Average/standard deviation of house parameters within a group of 10 buildings

	Width	Height	Orientation	Roof slope
Analysis of moments	8.09 m/0.16 m	11.33 m/0.11 m	6.86°/0.8°	37.4°/1.6°
Intersection of planar faces	7.84 m/0.15 m	11.15m/0.07 m	6.84°/0.4°	35.7°/1.1°

may occur when points from overlapping strips are being merged. On buildings with their principal axis oriented not perpendicular to the flying direction of the aircraft, a laser scanner will deliver a higher point density on the roof side which is oriented towards the sensor, thus shifting the reconstructed building in this direction. The magnitude of this effect depends on the opening angle of the scanner, the relative position and orientation of the building with respect to the flight path and the roof slope. A numerical correction can be formulated to correct for the effect and has been applied to the results shown in Fig. 7. These problems will not occur when data interpolated to a regular grid is being used.

5.2. Intersection of planar faces

Fig. 8 shows two more complex house models that were reconstructed by intersection of roof faces. The left house is reconstructed correctly. The right house model is not quite correct. The assumption of a continuous roof surface is not fulfilled in this case. Two roof face edges could not be reconstructed by intersection. They were hypothesised by inserting an edge to close the open polygon of roof face edges that were found.

Forty-three out of 51 buildings in the data set could be reconstructed by intersection of planar faces. Due to the comparatively small amount of object knowledge, the algorithm is less robust than the reconstruction with the moment approach. Most problems occurred in the determination of the outline of the building, especially when trees are near the building.

Using the group of 10 houses mentioned in Section 5.1, the precision of the parameters listed in Table 1 was evaluated. The standard deviation of the ridge points, assuming the same height for all houses, is 7 cm. Despite the uncertainty in determining the outline of the houses, the standard deviation of the height of the eaves points is 9 cm. The standard deviation of the roof slope is 1.1°. The reconstructed roofs appear to be a little flatter than with the moment approach: the average ridge height is 18 cm lower and the average roof slope is 1.7° smaller. Possible explanations could be bias introduced by points on the walls of the building that were used in the calculation of the moments, or small errors in the assignment of the laser points to the detected planes in the other approach. The average width of the buildings is by 25 cm smaller. Setting the percentage of contour points within the roof outline as explained in Section 4.3 from 80% to 100%, the width becomes by 11 cm larger as compared to the width determined by the analysis of moments.

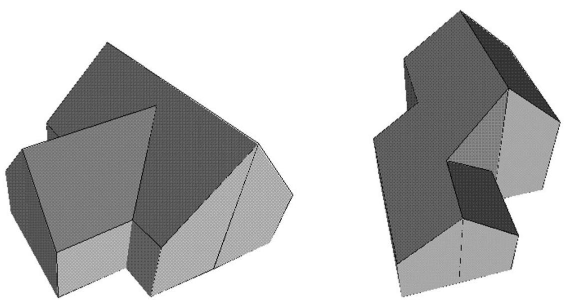

Fig. 8. Two house models reconstructed by intersection of planar faces.

6. Conclusions

Dense laser altimetry datasets with a point density of 1 point/m^2 or higher depict a very valuable source of data for the automatic generation of 3-D city models. Based on the computation of invariant moments, closed solutions can be formulated for the determination of the parameters of simple building models, yielding a precision of 0.1–0.2 m for the building dimensions and 1–2° for the building orientation and the slope of roofs. Going beyond primitive house models, techniques based on the analysis of moments do also allow for modelling asymmetric deviations like dorms on roofs. Using a data driven technique based on the intersection of planes fitted into triangulated point clouds, models of more complex buildings can be determined. Although the shapes of the reconstructed buildings look very regular, many model constraints that were part of the moment approach are not fulfilled. For example, the ridge and the eaves points do not exactly have the same height and the standard gable roofs are not exactly symmetrical. Further improvement of the models can be achieved by recognising and imposing shape constraints like collinearity and symmetry. Common to both approaches is the fact that they can be applied to point clouds of irregularly distributed laser altimetry data without the necessity of an interpolation to a regular grid. Furthermore, the use of additional information like 2-D GIS data is possible but not necessarily required to reconstruct the majority of the buildings.

Besides fusion with available GIS data, future work should concentrate on the fusion with photogrammetric imagery for a sharper modelling of edges and the fusion with multispectral imagery to support the segmentation process.

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