3D BUILDING MODEL GENERATION FROM AIRBORNE LASER SCANNER DATA USING 2D GIS DATA AND ORTHOGONAL POINT CLOUD PROJECTIONS

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ABSTRACT:

Human operators use an intuitive procedure of rotating laser scanner point clouds into specific projections when trying to understand the structure of buildings contained in the data. This procedure has been formalized and incorporated into an automatic building model reconstruction procedure. The method derives the building orientation from the analysis of height histogram bins. Using the orientation, orthogonal 2D projections of the point clouds are generated, where roof planes occur as lines of points. These lines representing planes are extracted by a line tracking algorithm. In subsequent processing steps, the lines are extended to planes, and the planes are analysed for deviations from rectangular shape. Two or more neighbouring planes are grouped to generate 3D building models. Existing 2D GIS data may be used in the process to provide a reliable segmentation of airborne laser scanner datasets and to generate hypothesis supporting the actual building reconstruction.

The method of 3D building model generation based on airborne laser scanner data and 2D GIS data has been tested on a dataset containing 250 buildings of different complexity. The success rate of correctly modelled buildings was close to 100% in simple regions with new-build residential buildings and dropped to below 50% in rather complex inner city areas or industrial areas.

1. INTRODUCTION

Beyond its primary application for the generation of high quality digital terrain and surface models, airborne laser scanner data has proven to be a rather powerful source for a wide range of 3D GIS object tasks. Among these tasks, the automatic generation of 3D building models as an integral part of 3D city models of topographical databases has found special interest. A number of approaches has been developed over the past 8-10 years. These methods can roughly be categorized into model-driven methods, which try to fit some kind of synthetic building model into the data, and data-driven methods, which try to find planes in the laser scanner data point clouds and group them to buildings. An early example of a model-driven approach was presented by (Haala/Brenner, 1997), who determine parameters of building primitives by a least squares adjustment approach. (Maas, 1999b) presents a closed solution for the determination of building model parameters based on the analysis of invariant moments of point clouds. Model-driven approaches are usually limited to simple building models; complex ground plans may be split into parts, which can be modelled individually (Haala et al., 1998). A data-driven approach based on a modified 3D Hough transform has been presented by (Vosselman, 1999). (Hofmann et al., 2002) show a data-driven approach based on the analysis of the cluster space of a TIN structure of a segmented point cloud. (Rottensteiner/Briese, 2002) extract roof planes by a region growing approach based on the local surface slope.

The method presented here was first suggested in (Schwalbe et al., 2004). It simulates the intuitive data handling of a user, who tries to recognize the structure of a 3D point cloud by rotation it into specific projections. This intuitive user interaction has been formalized and incorporated into an automatic building model reconstruction procedure, which firstly determines the orientation of a building, then detects 2D lines representing planes in orthogonal projections of the data and groups these planes to buildings. The method has been extended to use existing 2D GIS data to improve the segmentation and to generate hypothesis supporting the building reconstruction process.

In the following, the use of 2D GIS data for the segmentation of airborne laser scanner datasets will be outlined (chapter 2). Beyond the use for segmentation, chapter 3 will discuss possibilities of deriving hypotheses supporting the actual building reconstruction process from ground plan data. Chapter 4 will present a method for 3D building model reconstruction based on specific orthogonal projections of segmented point clouds. Finally, chapter 5 will show the results of a practical test based on a dataset containing a total of 250 buildings of different type and complexity.

2. 2D GIS DATA FOR SEGMENTATION

A proper segmentation of airborne laser scanner datasets forms a crucial pre-requisite for the successful application of 3D building model generation approaches. Basically, the segmentation of laser scanner data can be performed purely on the basis of the data itself, or incorporate other sources of information such as existing 2D GIS data or high resolution aerial images.

In the ideal case, buildings can be detected in laser scanner data performing a simple height thresholding combined with an analysis of first and last pulse differences for each point of the dataset, assuming that buildings and trees will have a height significantly larger than the terrain and that there will be a significant difference between first and last pulse on high vegetation (Maas, 2001). If applied to the raw data, buildings can be detected and segmented by a connectivity analysis in a TIN structure. If applied to laser scanner height data interpolated to a regular grid (for reasons of compatibility with existing software packages), the procedure generates a mask for cutting point clouds representing individual buildings from the data. In regions with non-flat terrain, the thresholding and the first-last pulse difference approach can be applied to a normalized digital surface model (nDSM), which is basically a highpass-filtered digital surface model (e.g. Straub et al 2001, Niederöst 2000). In regions where this simple procedure does not lead to a satisfactory segmentation, the additional analysis of height texture measures such as slope, local variance and anisotropic texture measures may significantly improve the segmentation results (Maas 1999a, Oude Elberink and Maas 2000). A segmentation approach based on the application of a shape-based classification tool is shown in (Hofmann et al., 2002).

The quality of the segmentation obtained from approaches purely based on the laser scanner data is limited by the complexity of the dataset. In regions with rather complex terrain, dense vegetation close to buildings or in inner city areas the success rate of these methods will be rather low, posing a limit to the applicability of automatic 3D building modelling schemes. A very powerful source of information for the segmentation process is given by existing 2D GIS data. In many regions this kind of data is available, either from cadastre data or from digitized maps. The great advantage of the data is the fact that interactive operator interpretation has been invested into the formation of the original data source, leading to a high reliability. On the other hand, the potential of this technique is limited to areas where complete, precise and reliable 2D GIS data exist, and to the update-level of this data. Moreover, a segmentation procedure purely based on such data will not be able to recover from generalization schemes, and it will mostly not consider roof overhang. Ground plans from 2D GIS data have for example been used for by (Haala et al., 1997).

In Switzerland, digital 2D cadastre data with decimetre accuracy are available for wide areas. This data was used for the segmentation of the airborne laser scanner data in the study area. The segmentation was realized by treating each building ground plan polygon individually and testing data points on their containment in the polygon. As the study area is characterized by buildings with large roof overhangs, a 5 meter buffer was defined around each polygon in order not to discard roof points in overhang areas (Figure 1). At the same time, the buffer allows the reconstruction procedure to recover from generalization effects contained in the ground plan. The procedure was implemented as a plug-in in ArcMap. Additional ground or vegetation points contained in the enlarged segments are eliminated during the actual building reconstruction procedure. The ground points can also be used for defining the terrain level in the reconstruction procedure. Connected neighbouring ground plans interrupt the buffer, with only ground points in the vicinity of neighbouring buildings possibly preliminarily being shared between two segments.

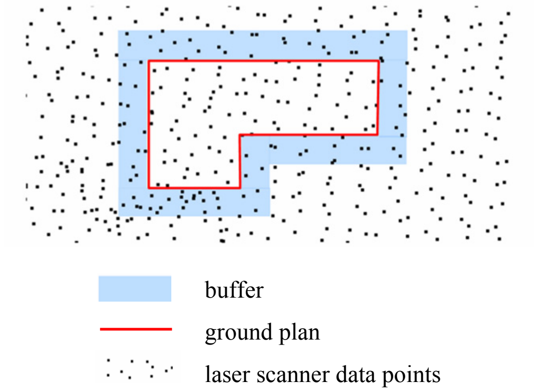

Figure 1. Segmentation with ground plan plus buffer

3. 2D GIS DATA FOR BUILDING ORIENTATION HYPOTHESIS GENERATION

Beyond the obvious use of the ground plan data for point cloud segmentation, additional information supporting the building reconstruction process can be derived from the ground plan data. (Vosselman and Dijkman, 2001) show a technique to partition complex ground plans and to use these parts to restrict the search area for a 3D Hough transform to extract roof planes. Like (Haala and Brenner, 1997), they use the assumption that the roof faces are parallel to one of the edges of the segmented ground plan. This assumption reduces the parameter space of the 3D Hough transform for the detection of planes to a 2D Hough transform for the detection of lines.

In the approach discussed here, roof planes are detected by specific orthogonal 2D projections of a segmented point cloud and a subsequent line detection procedure (see chapter 4). This approach needs information on the orientation of a building, which can be derived from the laser scanner data itself by an analysis of the results of a line search in height histogram bins (Figure 2, Schwalbe et al., 2004).

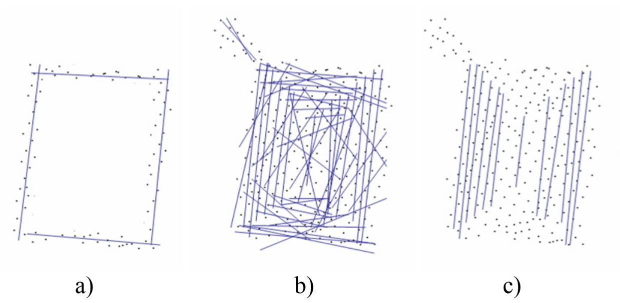

Figure 2. Building orientation determination from histogram height bins
a: lines detected in one bin
b: lines detected in all bins
a: dominant lines defining the main roof direction

This procedure may produce weak results in cases of flat roofs or roofs with many superstructures. In these cases, a building orientation derived from the building ground plan may support the roof reconstruction process. For this purpose, a length-weighted azimuth cluster analysis is performed, yielding the primary orientation of the building defined by the longest lines in the ground plan (Figure 3).

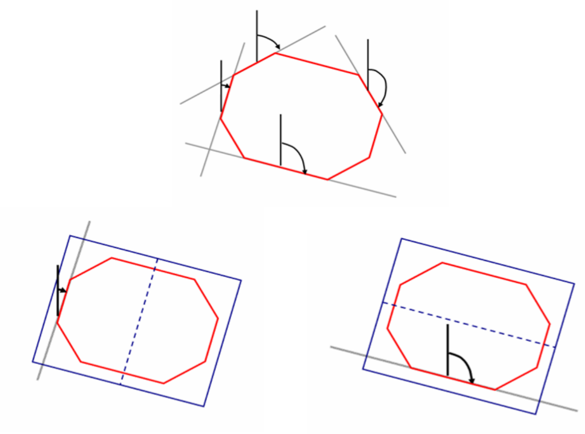

Figure 3. Building orientation determination from ground plan

This building orientation angle derived from the ground plan may either be used solely for the further reconstruction process, or it may be used to verify the orientation derived from the height histogram bin analysis. As the procedure as shown above will not always detect the correct primary orientation in cases of complex ground plans, the latter procedure will produce more reliable results. In cases of a clear maximum in the height histogram bin direction analysis the ground plan orientation closest to the orientation angle derived from the height bins is chosen as the primary building orientation, while in cases of a weak result of the height histogram bin direction analysis the primary building orientation is taken purely from the ground plan analysis.

4. BUILDING RECONSTRUCTION FROM SPECIFIC ORTHOGONAL POINT CLOUD PROJECTIONS

The basic idea of the automatic approach of 3D building model reconstruction presented here is derived from the manner of interaction of a human operator when interpreting a point cloud representing a building: The user will rotate the point cloud (for example in a VRML viewer) into orthogonal projections parallel to the roof ridges in order to recognize the roof structure. Roof planes are projected into lines in this projection, allowing to recognize the width and tilt of the planes. This goal-oriented procedure of human interaction is copied by the approach for building reconstruction in a processing scheme consisting of the following steps (see (Schwalbe, 2004) and (Schwalbe et al., 2004) for more details on the approach):

- **Elimination of ground points:** Ground points remaining from imperfections of the segmentation procedure or from a buffer defined around a building ground plan are eliminated by a local height histogram analysis, making use of the histogram minimum in the height range of the building walls to derive a height threshold.

- **Determination of the primary roof orientation:** The primary roof orientation, which is required for the specific orthogonal 2D projection of the point cloud, can be obtained from a height histogram bin analysis or from an analysis of the ground plan as described in chapter 3. The point cloud is rotated by the building azimuth and projected into the X-Z plane (Figure 4).

  A second orthogonal projection into the Y-Z plane is performed by 90° added to the building azimuth. When assuming a building with only one or two orthogonal roof ridge directions, these two projections will show all roof planes as lines in one of the projections. Optionally, more projections adding multiples or 45° can be added to cover more complex roof shapes.

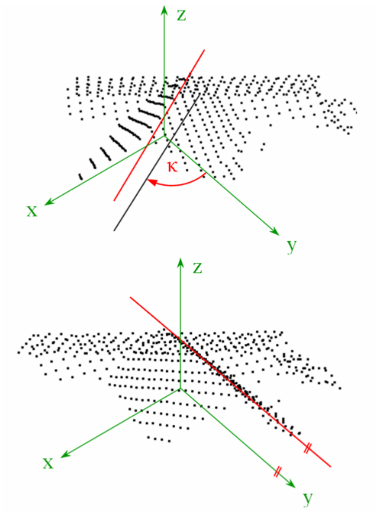

Figure 4. Azimuth rotation of a segmented point cloud

- **Detection of lines in 2D projections:** A line search is performed in the 2D projections of the point clouds in order to detect lines representing roof faces (Figure 5). The line search starts at the lowest point of the local point cloud after ground point elimination. If the number of points in a box centred above this point exceeds a certain threshold, a line is fitted into these points, using robust estimation techniques. In a next step, this line is extrapolated to collect additional points contributing to the line. If the lowest point does not produce a line, the process is restarted at the next point.

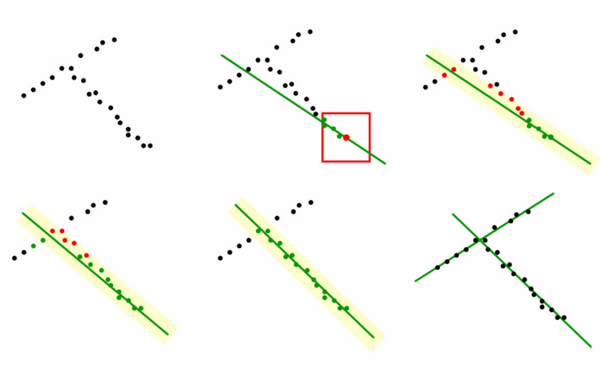

Figure 5. 2D Line extraction process

Gradient and length of a line define inclination and width of a roof plane (Figure 6). Lines representing neighbouring roof planes intersect in a point. The intersection point represents the ridge of the roof. The length of the extracted lines ending in the vicinity of a ridge is shortened or elongated to the intersection point.

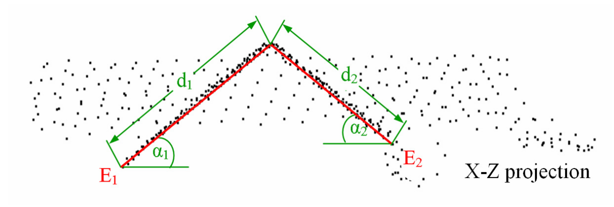

Figure 6. Lines representing roof faces

- **Generation of roof planes**: All points belonging to a line are rotated by the roof inclination α and projected into the Y-Z plane, where they form a horizontal line. The length of this line represents the length of the roof face. Figure 7 shows the extracted 3D polygons of roof faces derived from a single projection.

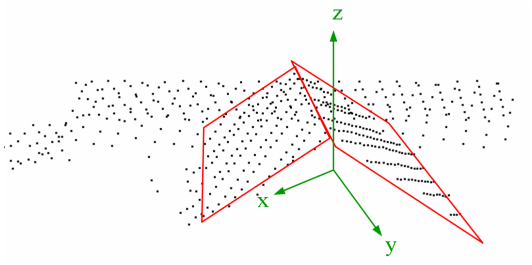

Figure 7. Extracted roof planes

- **Non-quadrangular roof planes:** The rectangular roof faces generated by this procedure are subsequently examined for cut-outs by a stripwise analysis for the presence of points after a projection into the X-Y plane, taking into consideration the average point density of the dataset (Figure 8).

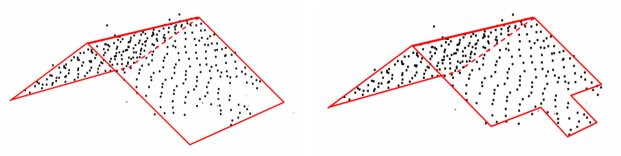

Figure 8. Modelling non-quadrangular roof faces

- **Building model generation:** The individual planes can be combined to a roof structure in a next step. For that purpose, neighbouring roof planes sharing a ridge line are intersected (Figure 7). In addition, planes stemming from two orthogonal projections have to be intersected. This concludes the modelling of a roof.

  In a next step, the walls of the building are reconstructed by projecting the roof edges onto the terrain model. For simplicity, the lowest point in the vicinity of the building is chosen to represent the building footpoint height. For visual purposes, the roof overhang can be considered in the reconstruction of the walls. If ground plan information is available, the size of the roof overhang may be derived from the difference between roof outline and ground plan. Alternatively, the walls can be reconstructed from the ground plan itself. If no ground plan information is available, an average roof overhang may be assumed.

  The polygons are grouped to a polyhedral building model and are visualised as a VRML model (Figure 9).

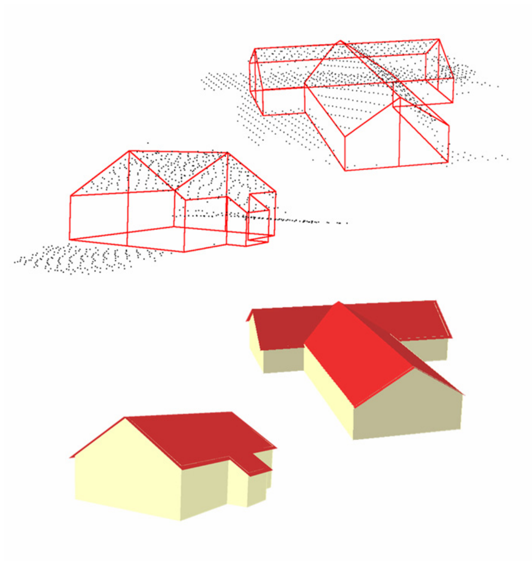

Figure 9. Reconstructed buildings

5. PRACTICAL VERIFICATION

The methods shown in chapter 2, 3 and 4 have been practically tested on a laser scanner dataset from the map sheet of Lucerne from the Swiss topographic map. The dataset is characterized by an average point density of one point per 1.5 square meters and a standard deviation of 20 cm in height. From this dataset, six probes with a total of 250 buildings representing different types of building types and building arrangements were chosen. 2D digital cadastre data was available for the whole test area and used for segmentation and building orientation determination as described above.

		Quality of reconstruction	
Area characteristics	number of buildings	using laser scanner data only	using ground plan information additionally
Residential area with small buildings	50	55%	59%
Residential area with flat roof buildings	20	35%	59%
Residential area in slope terrain	70	74%	76%
Residential area with new-built buildings	50	98%	84%
Industrial area	20	47%	44%
Inner city area	40	38%	35%
Total average	250	64%	64%

Table 1. Success rates of building reconstruction in test dataset of the map sheet of Lucerne

As expected, the quality of the reconstruction varies strongly, depending on the type of buildings and the complexity of the building arrangement. While a rate of almost 100% correctly reconstructed buildings could be obtained for a residential area with new built houses, the rate dropped to only about 40% in an industrial area and in an inner city area. Furthermore, table 1 shows the different success rates of the method applied to pure laser scanner data on the one hand and the method supported by ground plan information on the other hand. In the second variant the ground plans are used to improve the determination of the buildings orientation. Indeed, this is not reasonable for each of the analysed areas. The use of ground plan information yields better success rates especially in areas with small buildings and flat roofs because the determination of the buildings orientation from laser scanner data only is too uncertain. Otherwise, in areas with large buildings where the roof faces are rather steep and represented by numerous points the orientation can be derived more accurately from laser scanner data than from ground plans. Due to this fact in some cases the use of ground plan information even decreases the success rate. Figure 10 shows the reconstructed buildings from two of the test areas.

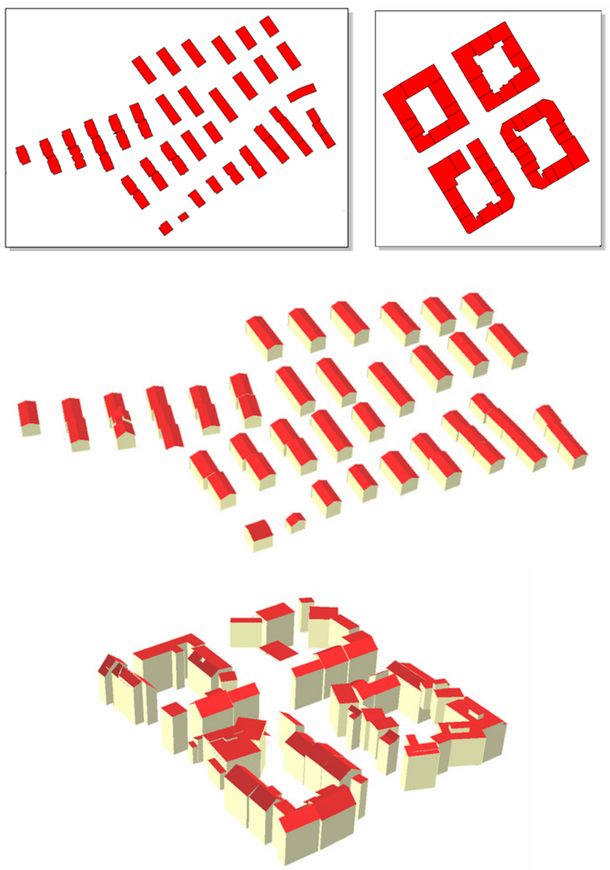

Figure 10. Map and reconstruction results of a new-built residential area and an inner city area

6. CONCLUSION

The method of 2D line search in specific orthogonal projections of segmented laser scanner point clouds has proven to be a versatile and powerful tool for 3D building model generation from airborne laser scanner data. Existing 2D GIS data may be used as a reliable tool for the segmentation of laser scanner data into local point clouds representing single buildings to be modelled by the approach. 2D GIS data may also be used to support the 3D building reconstruction process by orientation hypotheses generation.

The success rate of correctly reconstructed buildings is between 40-50% in regions with complex buildings and close to 100% in new-built residential areas. Future work will extend the use of 2D GIS data to the determination of roof overhang, the improvement of the shape determination of non-quadrangular roof planes and the generation of plane grouping hypotheses. The basic method of plane detection via line search will be expanded to a region growing and plane fit method.

7. ACKNOWLEGMENTS

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