# GENERATION OF 3D CITY MODELS FROM AIRBORNE LASER SCANNING DATA

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## Abstract

Airborne laser scanners enable the geometric acquisition of the terrain surface, including objects like trees or buildings which rise from the terrain. Even though for a number of applications a so–called Digital Surface Model (DSM) representing the surface geometry by an object independent distribution of points is sufficient, the further qualification of the original scanner data is necessary for more sophisticated tasks like visualizations or high quality 3D simulations. In order to obtain a 3D city model, which is more suitable for these applications, an abstraction and interpretation of the surface model is required, e.g. buildings have to be separated from the terrain surface and represented by 3D CAD-like description.

Due to the very pretentious problem of automatic interpretation of height or range data, optimal results can only be achieved by using supplementary sources of information. Within the approach presented in this paper the segmentation of planar surfaces from the DSM, which is a prerequisite for the 3D reconstruction of the buildings, is supported by given ground plans. This type of information frequently is already available from a 2D Geo Information System (GIS). By introducing this type of information into the segmentation process the very high demands on the spatial resolution and quality of the DSM can additionally be reduced. The 2D building outlines are also used during the reconstruction step by deriving hypotheses on the possible roof shapes. This enables the combination of the segmented planes in order to obtain a 3D boundary representation of the building.

## 1 Introduction

Many tasks in the context of urban planning require 3D city models, which represent buildings separated from the terrain surface by 3D CAD models. These 3D city models are e.g. used to simulate the impact of noise to the surrounding buildings while planning new traffic routes, to define shadowed areas while simulation the propagation of electro–magnetic waves in order to determine optimal positions for transmitter stations, or they are required for 3D visualizations of urban areas e.g. to demonstrate the influence of a planned building to the surrounding townscape. Hence automated methods for reliable 3D building reconstruction are essential to many users of 3D city data, including urban planners, architects, and telecommunication and environmental engineers.

In principle airborne stereo image data is sufficient for the acquisition of buildings; a human operator is able to extract and reconstruct visible buildings solely using this data source. However due to the great complexity of image data the automation of this process poses many problems. Greyvalues are influenced by the object geometry but also by factors like illumination, surface material or texture. The large amount of information which is contained in images and the numerous factors influencing a greyvalue make it very difficult to separate important information from irrelevant details in the framework of an automatic interpretation process. One approach to enable an automatic interpretation process required for 3D building reconstruction is to use alternative data sources. These data sources are Digital Surface Models (DSM) and – at least for highly developed countries – existing 2D GIS information on the geometry and usage of buildings.

A DSM, i.e. a geometric description of the terrain surface and objects located on and above this surface like trees or buildings can be obtained by automatic image matching algorithms from aerial images or by airborne laser scanning systems. Image matching techniques have become standard tools for three-dimensional surface acquisition in open terrain. Still they suffer from problems in built-up areas due to occlusions and height discontinuities. In these areas the DSM quality mainly depends on the presence of texture at roof regions and on the amount of contrast between roof and terrain surface (Price & Huertas 1992). This results in considerable differences of DSM quality at roof regions, even in the same image pair.

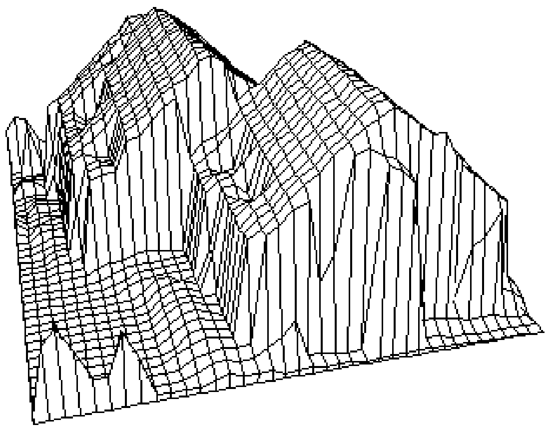

Figure 1: DSM measured by airborne laser scanning.

Alternatively three-dimensional points on the terrain surface can be determined dense and well-distributed using airborne laser scanning systems. Within this paper a data set provided by the TopoSys laser scanner-system is utilized (Lohr 1997). Terrain points were measured at approximately one point each $0.5 \times 0.5\,\mathrm{m}^2$ with an accuracy of 0.3 m in planimetry and 0.1 m in height. Direct height data acquisition by airborne laser scanners provides DSM of high and homogeneous quality in urban areas. Hence this data is very suitable for 3D building reconstruction. In figure 1 the sharp discontinuities at the eaves break-lines and the almost vertical walls of the building for this type of data can be noticed immediately. However, a surface description by a unqualified, i.e. object independent distribution of points results in great computational effort for applications like visualizations or other simulations. Therefore an abstraction and interpretation of the surface model is necessary, even though the measured points describe the surface geometry dense and accurate. This step is also required to transform the 2.5D DSM representation by the continuous function $z(x, y)$ into a true 3D description.

Frequently, ground plans of buildings have already been acquired and are represented either in analog form by maps and plans or digitally in Geo Information Systems (GIS). These ground plans are another – very reliable – source of information for 3D building reconstruction. An example for this kind of data is the digital cadastral map, which provides information on the distribution of property, including the borders of all agricultural areas and the ground plans of existing buildings. Additionally information on the names of streets and the usage of buildings (e.g. garage, residential building, office block, industrial building, church) is provided in form of text symbols. Procedures for the automatic digitization of maps and plans resulting in information similar to the digital cadastral map are e.g. given by Carosio (1995). Most users will require 3D data sets which are consistent and compatible to their existing 2D GIS. Hence, existing ground plans must be included into the process of generating 3D city models in order to achieve this consistency.

So far an automatic DSM acquisition was only feasible by stereo image matching. The limited accuracy of these DSM in built-up areas has prevented the direct usage of this data for building reconstruction. Instead, DSM have been used to support the aerial image interpretation e.g. for the coarse detection of buildings or as a means to get initial values for parallax estimation (Haala 1994). On the other hand, close range applications such as robot navigation and measurement and reconstruction of industrial objects have relied on active range sensors for quite some time (Besl 1988). The output of those sensors is a dense depth map of the object which can be compared directly to a DSM. The possibility to use this dense and accurate depth map for segmentation, reconstruction and object recognition has led to the discipline of range image understanding. The successful applications in this discipline motivated us to adopt these approaches for the 3D reconstruction of buildings using DSM data.

# 2 Segmentation of DSM

A large number of buildings can be represented by a polyhedron since the boundaries of most buildings consist of a number of planar surfaces and straight lines. For this reason a segmentation algorithm should aim on the extraction of geometric primitives which are likely to trace back to elements of a building like the planar surfaces or break-lines of a roof. The geometric accuracy of break-lines is limited because only a small area of the DSM in the neighborhood of a height discontinuity can be used for its definition. For this reason, in our approach planar regions representing larger areas of the DSM are extracted by the segmentation process and used for the following reconstruction.

## 2.1 Scan line grouping

In contrast to the general problem of range image segmentation, which aims at dividing the object surface into patches that can be described parametrically, e.g. as higher order bivariate polynomials, our segmentation can be restricted to the extraction of planar surface patches, because only this type of feature is utilized during the reconstruction. A framework for the comparison of range image segmentation algorithms together with an evaluation of four planar range image segmentation algorithms was given recently by Hoover (1996). The algorithm of Jiang & Bunke (1994) seemed to be ideally suited for our purposes since it is conceptually simple, fast and scored very well compared to other algorithms.

Figure 2: Planar segmentation for laser scanner DSM (overview), projected to ortho image

The algorithm is based on a region growing approach which uses straight line segments instead of pixels as growing primitives. The first step of the algorithm is to extract scan lines $z(x, y_0), y_0 \in I_N$ from the regular DSM grid $z(x, y)$ and divide them into straight line segments. This is realized by a simple split method that recursively divides each scan line into line segments such that the perpendicular distance of the points to their corresponding line segment is within a threshold. Since all points on a straight 3D line segment surely belong to the same planar surface a region growing process can be performed subsequently using the set of line segments instead of the individual pixels. Therefor a small number of lines segments satisfying an optimality criterion are selected as seed region and the region is expanded around the seed region. A line segment is added to the region if the perpendicular distance between its two endpoints and the plane equation of the region is within a second threshold. For threshold selection the noise of the underlying DSM is estimated.

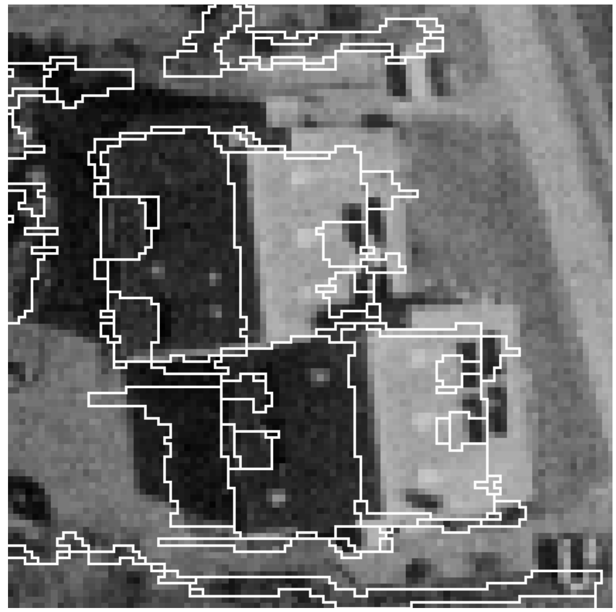

Figure 3: Planar segmentation for laser scanner DSM (detail)

Applying this segmentation algorithm to the DSM acquired by laser scanning showed promising results (figure 2). Even though the algorithm has no a priori knowledge about the location of planar roof faces, many of these faces are segmented correctly. Nevertheless, the problem of precise definition of the planar region boundaries, i.e. of roof break-lines still remains. In figure 3, which represents the segmentation results of the building also shown in figure 1, the irregular shape of segmented regions are clearly visible.

## 2.2 Compatibility of surface normals

This problem can be avoided and the requirements on the DSM quality, i.e. the density of measured laser points can be reduced. if ground plans of the buildings are utilized. In figure 4 a ground plan provided by the digital cadastral map is projected to the corresponding section of the ortho image. The given ground plan (black polygon) of course restricts the extension of the DSM area which has to be processed. The implemented segmentation is based on the direction of the surface normals of the DSM, which

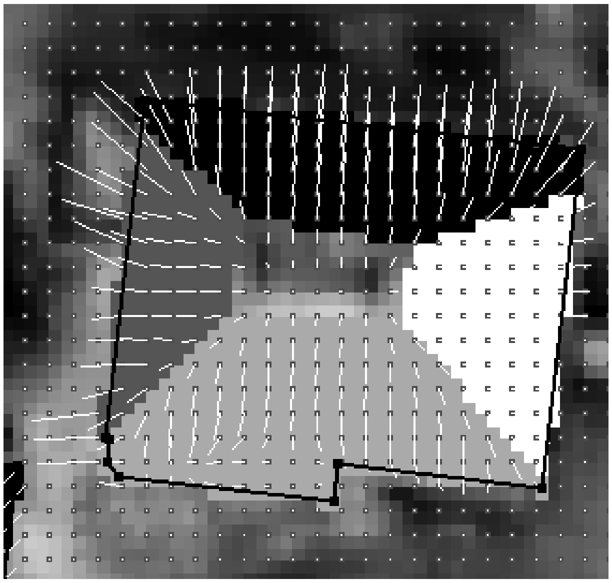

Figure 4: Building ground plan (black), DSM surface normals (white) and segmented planar surfaces

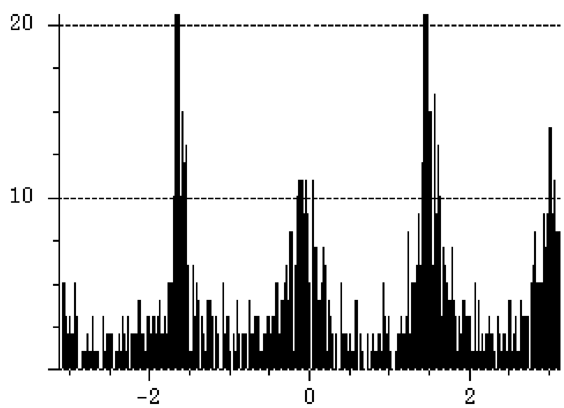


Figure 5: Histogram of surface normals for figure 4

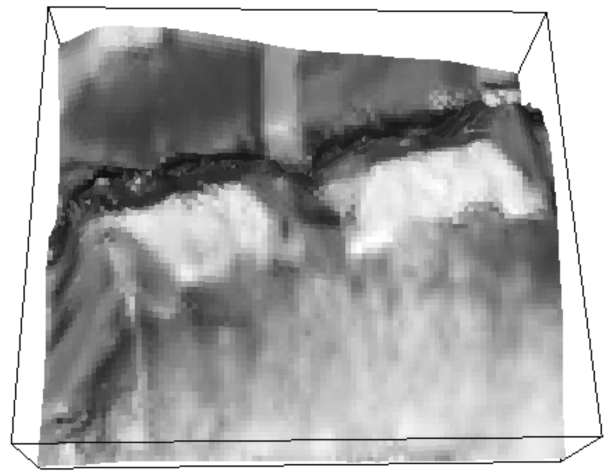

Figure 6: DSM from stereo image matching

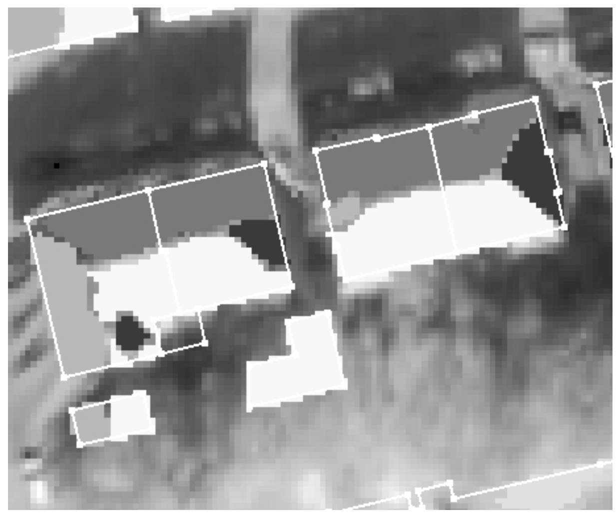

Figure 7: Planar surfaces and given ground plan

are represented by the small white lines in figure 4. Figure 5 shows the distribution of these surface normal directions occurring within the given outline of the building. The maxima of the histogram correspond to the four major axes of the ground plan. In principle the possible orientations of the planar roof surfaces can be extracted from the histogram. Nevertheless they are they are obtained by the analysis of the given ground plan, which is much more reliable. The direction of the unit normal vector of a possible roof plane emerging from an element of the ground plan has to be perpendicular to this segment. Hence, all orientations of the polygon are used to trigger the segmentation of a plane with a projected normal vector perpendicular to this element.

In order to make use of this knowledge, the surface normal for each DSM point is computed using the derivatives of a local bivariate polynomial fit. Afterwards, all points with a surface normal compatible to the examined ground plan direction are combined to a region which results in the segmentation represented by the shaded regions in figure 4. Hence, by utilizing the ground plan for the segmentation process planar regions can be extracted reliably, even though the DSM quality is limited. Figures 6 and 7 show another example of the segmentation process. For visualization, the corresponding image section is overlaid to the DSM in figure 6, figure 7 shows the utilized ground plans and the extracted compatible regions projected to the ortho image. Although the DSM in both cases was derived by image matching, the segmentation into normal vector compatible regions reflects the roof structure quite well.

# 3 Reconstruction

Generally, the use of primitives of restricted accuracy and reliability requires much a priori knowledge or in other words constraints for the process of object reconstruction. This can e.g. be achieved by applying a very rigid building model. Nevertheless, this limits the number of possible building types which can be represented by a single model. In order to deal with the large architectural variations of building shapes, the aim of our approaches is to use a very general roof model. Therefore, the building is represented by a general polyhedron, i.e. it is bounded by a set of planar surfaces. The only constraint implied in this model is the assumption that the coordinates of the given ground plan are correct and that the borders of the roof are exactly defined by this ground plan. As discussed earlier the exact definition of region boundaries is quite problematic for DSM data. Therefore only the center of gravity and the unit normal vector of each segmented region is utilized for the reconstruction. The surface borders, i.e. edges and corner points of the roof are determined afterwards by intersecting adjacent regions. This poses the problem of extracting topological relations between the segmented planes in order to detect which planes are adjacent and therefor have to be intersected. For that purpose ground plan information is also utilized.

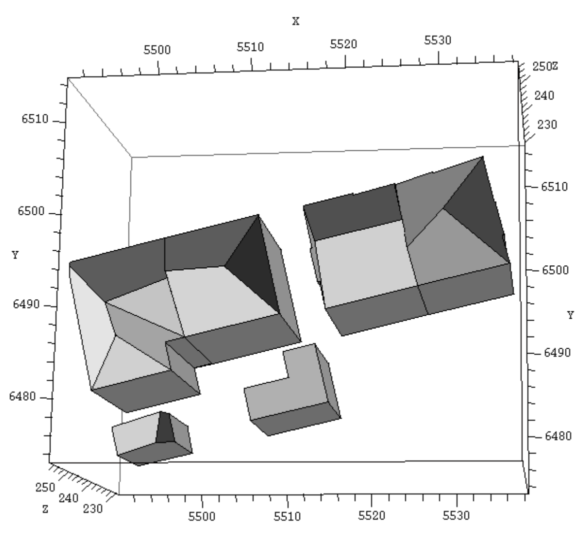


Figure 8: Reconstructed buildings, adjoining eaves lines forced to be collinear

In one approach, which is described in more detail by Haala & Anders (1997), the segmentation into normal vector compatible regions described above was used. Roof planes were estimated by a least squares adjustment while the walls were defined as verti-

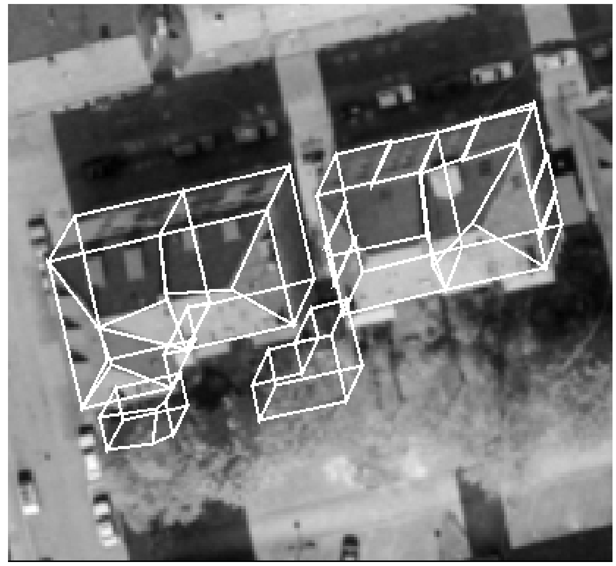

Figure 9: Results projected to corresponding image section

cal planes emerging from the ground plan polygon. An adjacency graph obtained by the analysis of the ground plan served to guide the intersection of roof and wall planes. The projections of crease lines given by the intersection of two roof planes were forced to pass through a ground polygon vertex, if the ground polygon was intersected. A more rigid model was additionally introduced by forcing all eaves lines to have the same height. Figures 8 and 9 show results obtained by this method using the DSM data and segmentation presented in figures 6 and 7. Obviously, the estimation of the plane parameters from the DSM acquired by image matching is not accurate enough to guarantee ridge lines that are sufficiently parallel to the corresponding ground polygon edges.

Both steps, segmentation and reconstruction require the analysis of the given ground plan. Hence by linking both steps in a somewhat more model-driven approach, which includes a combined hypothesize-and-test scheme, the performance and reliability of the algorithm could be further improved. The model used in this approach still is constrained by the assumptions that

- all walls defined by the ground polygon lead to a planar roof face. The slope of this face is variable. Saddleback roofs can e.g. be obtained by using vertical faces for individual parts of the roof.
- all eaves lines have the same height.

These assumptions are fairly general. However, one must keep in mind that any roof construction based

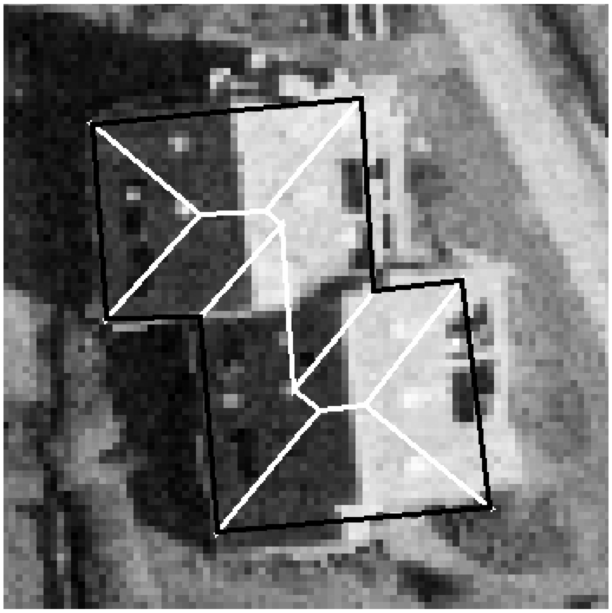

Figure 10: Given ground plan (black) and initial reconstruction (white), projected to ortho image

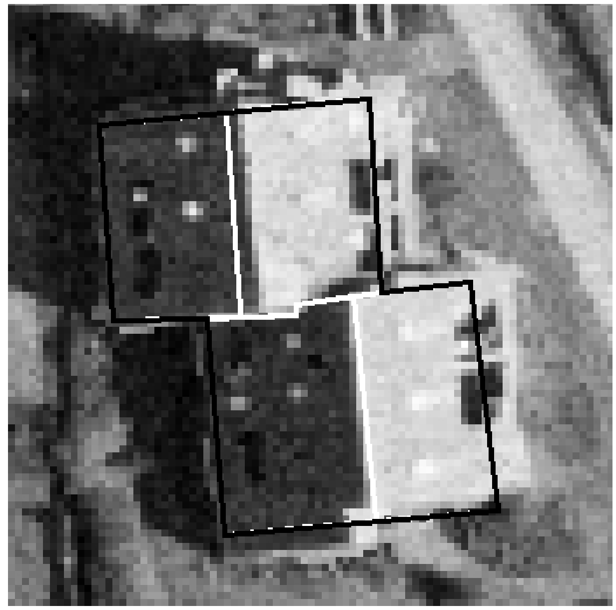

Figure 12: Given ground plan (black) and adjusted reconstruction (white), projected to ortho image.

Figure 11: Initial reconstruction, projected to DSM

Figure 13: Adjusted reconstruction, projected to DSM.

on this approach provides incorrect results if the roof structure inside the ground polygon does not follow the cues that can be obtained from the ground polygon. This can e.g. happen if more than one plane emerges from a single polygon element or if parts of the building like a bay which are entirely contained in a roof surface are not represented by the ground plan.

The implemented algorithm uses a simple *hypothesize–and–test* scheme. In a first step, a roof is constructed from the ground polygon assuming the same slope (e.g. $45^o$) for all roof faces. Since only the 2D projection of this roof is used in further steps, the actual slope can be set arbitrarily (except vertical and horizontal). This step is visualized in figure 10, where the utilized ground plan of the building (black) and the initial hypothesis of the roof shape (white) is projected to the ortho image. This step does not use any height information, hence the building shape constructed from the 2D ground plan will generally not fit to the measured DSM (figure 11).

In the second step inside each 2D region which is defined by the projection of a roof face, the normal vectors from the DSM are scanned for compatible vectors. In other words, from the initial roof construction, which defines a region of interest for each ground polygon edge, we get a set of roof surface elements that have normal vectors approximately perpendicular to that edge. This set is then used in a second step to adjust the slope of the roof face according to the slope extracted from the set of compatible normal vectors. If there is no sufficient number of compatible roof surface elements, the roof face is assumed to be vertical. After slope adjustment, the geometrical roof construction is invoked again to yield the final roof. The reconstruction is completed by a least squares adjustment of the roof height and the addition of vertical walls. Figure 12 shows the final reconstruction for the initial hypothesis shown in figure 10. In figure 13 the reconstruction is projected again to a 3D visualization of the laser scanner data; now the 3D building fits to the acquired DSM data.

Figures 14, 15 and 16 show some additional results obtained by the application of this algorithm to a laser scanning DSM. Figures 14 and 15 show the initial and final reconstruction projected to the ortho image, figure 16 shows a 3D visualization of the result. For these examples the ground plans were obtained by digitizing a map of scale 1:5000.

# 4 Conclusion

In this paper the segmentation of DSM and the use of the extracted primitives for building reconstruction has been shown. A planar segmentation algorithm yielded promising results for a laser scanning DSM of high resolution (approximately one point each $0.5 \times 0.5$ m$^2$), even though the exact definition of region borders still remained a problem. By the use of ground plan information a reliable segmentation of DSM data could be achieved, even by using a relatively poor quality DSM obtained by image matching. The segmentation supported by ground plans also resulted in less demands on the required density of laser points, i.e. in less effort during the height data acquisition.

The segmented planes are used as basic primitives to reconstruct a 3D boundary representation of the building. Due to the fundamental problems of region segmentation, which prevents the extraction of perfect region boundaries, the lines and corner points of the 3D representation have to be calculated by intersecting the extracted planar surfaces. This step requires knowledge on the topological relations between these planes, which can be gained by the analysis of the given ground plan. By the proposed approach the automatic extension of existing 2D GIS data to a 3D city model is available; the raster representation of airborne laser scanner data can be transformed to a qualified 3D vector representation for urban areas.

For the future the algorithm will be applied to larger data sets and the results will have to be compared to reference data acquired manually in order to evaluate the accuracy and reliability of the proposed method. Additionally the level of detail, which can be reached for a reconstion has to be examined depending on the density of measured laser points. Other topics of future interest are the extension of the algorithm to different eaves heights and a more thorough analysis of the ground plans, e.g. for adjoining or slightly incorrect outlines.

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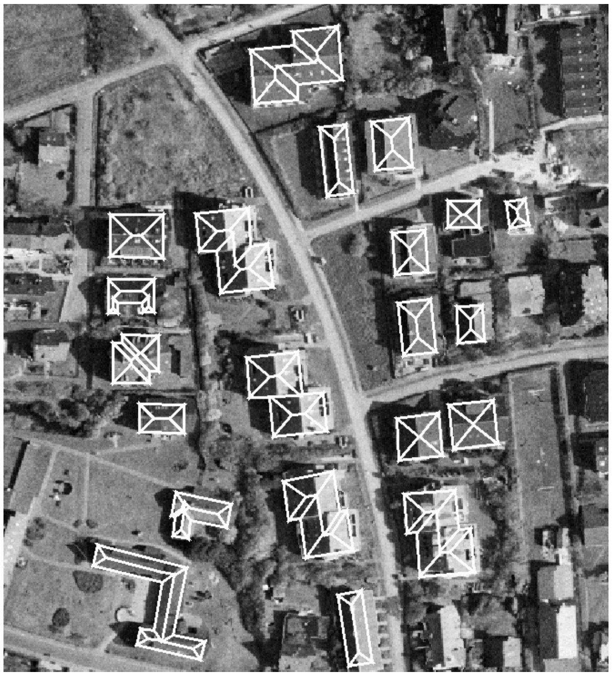

Figure 14: Initial reconstruction

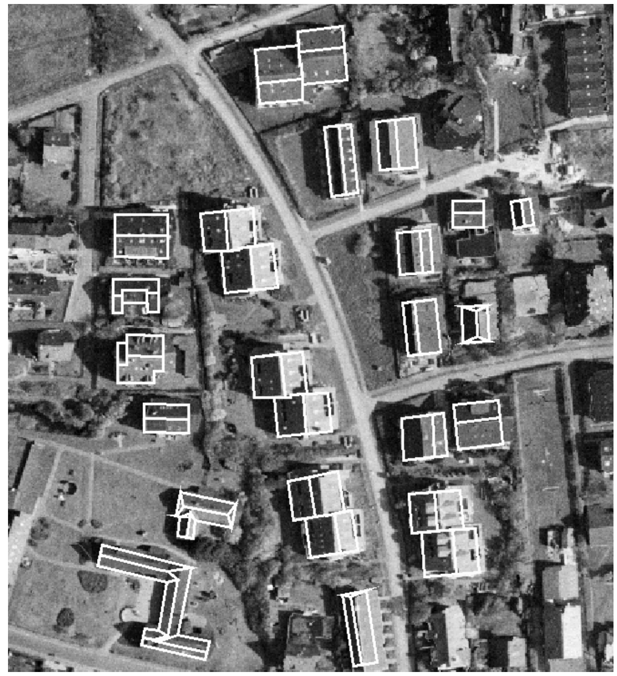

Figure 15: Reconstruction after adjustment

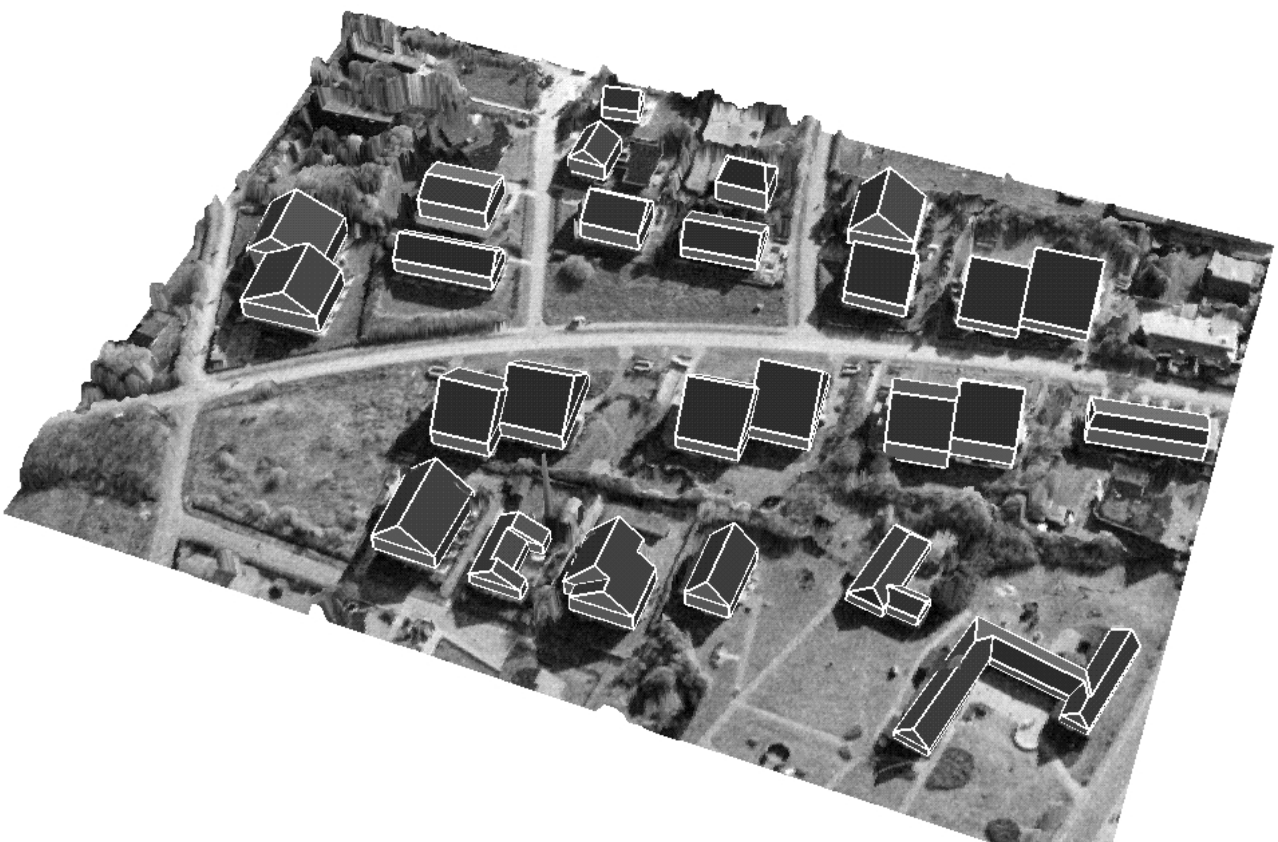

Figure 16: 3D visualization of reconstruction