ANALYSIS OF TIN-STRUCTURE PARAMETER SPACES IN AIRBORNE LASER SCANNER DATA FOR 3-D BUILDING MODEL GENERATION

A. D. Hofmann

Institute of Photogrammetry and Remote Sensing
Dresden University of Technology
Mommsenstr. 13
D-01062 Dresden, Germany
Alexandra.Hofmann@mailbox.tu-dresden.de
http://www.tu-dresden.de/fghgipf/forschung/BuildingDetectionAndModelling/default.htm

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ABSTRACT:

This paper presents a data-driven method for automatic building reconstruction from raw airborne laser scanner data. The method utilises a TIN-structure that is calculated into the point cloud. The parameters of every TIN-mesh are mapped into a 3D triangle-mesh parameter space, which is then analysed using a cluster analysis technique. By analysing the clusters, significant roof planes are derived from the parameter space while taking common knowledge of roofs into account. However, no prior knowledge of the roof as such as the number of roof faces is required. Analysing the intersected roof faces, the roof outlines are determined and the ground plan is derived.

The derived building models were evaluated for their correctness and geometric accuracy. Well-defined building roof planes can be extracted and reconstructed successfully, while disturbances such as dorms on buildings or geometric discrepancies in laser scanner data strip overlaps may significantly reduce the applicability of the technique.

1 INTRODUCTION

Airborne laser scanner data provides reliable and dense x,y,z-coordinates of a surface. With this data, exact information of roof shapes can be derived. Different methods have been published that use laser scanner data to obtain building parameters. Some of them are based purely on laser scanner point clouds, while others integrate additional information. The former method is more adaptable. Up to now there are two types of approaches that run without additional information and that derive the full 3D description of a building. The first kind, a model-driven approach, is parameter-based and was developed by [Maas 1999], who uses invariant moments. The method is, as described in the article, limited to simple ground plans, while it can handle relatively complex roof constructions. The second type is data-driven. [Rottensteiner 2002] and [Elaksher 2002] developed methods that group pixels in rasterised data that fit in a plane. The results are promising; however, interpolating the laser scanner data to a raster can hide valuable information. [Gorte 2002] and [Lee 2001] avoid this by applying a region-growing algorithm to a TIN-structure in raw laser scanner data. The difficulty here is to decide which neighbouring segments should be merged. [Vosselmann 1999] analysed laser scanner points of high density data and transformed them into a parameter space. In combination with a segmentation procedure the approach has encouraging results.

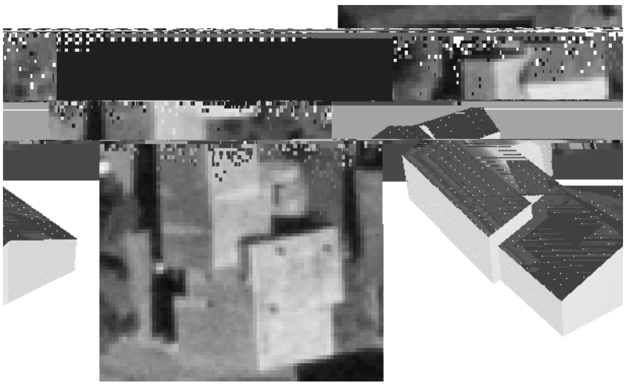


Figure 1-1. Building model reconstructed from airborne laser scanner data, orthophoto

This paper will discuss a further procedure for building model reconstruction. It works automatically and is not bound to simple roof types or to a certain point density. The method uses a TIN-structure that is calculated into a laser scanner point cloud that contains a building. The position of each triangle in space is expressed in spherical coordinates that are displayed in a Cartesian coordinate system. These coordinates are taken as parameters that, consequently, define a 3D parameter space. The distribution of points in parameter space (representing triangles in object space) shows a structure that is analysed with a cluster analysis technique. The clusters contain those points of the parameter point cloud that belong to triangles of roof faces. A plane is interpolated into the laser scanner points of the triangles of each roof face. The individual planes of each laser scanner point cloud are tested for valid intersections in order to complete the roof. The reconstructed roofs are then assessed for their correctness and accuracy.

2 DATA SET AND PRECONDITIONS

At the start, some preliminary information is provided about the data. The proposed method has been applied to two different data sets. The first data set has an average point spacing of 1.5m This point spacing means that smaller features of houses, such as dorms, cannot be mapped. The standard deviation of point coordinates within one stripe is in x and y about 30 cm and in z 20 cm. The data was taken in Switzerland in an alpine region and contains mainly gable roofs. The second data set is rasterised data with a point spacing of 1m. This data set covers several streets of Dresden, Germany, where buildings have rather complex roof structures.

For the study, 100 point clouds each containing only one building including some surrounding ground points**,** have been extracted from each of the laser scanner datasets. [Hofmann 2002] gives an example for the process of extracting such laser point clouds automatically. The extracted point clouds contain buildings with common roof types such as pent, gable and hip roofs. Some of the buildings also have combinations of them.

Figure 2-1. A building's point cloud with TIN-structure

3 BUILDING MODEL RECONSTRUCTION

The basic idea of the developed method is that all triangles of a TIN in the laser scanner points of a planar surface (in this case a roof face) should have the same position parameters in object space. Collecting all triangles with similar parameters should therefore gather all laser points of one roof face; a building modelling procedure can be applied to planes interpolated into the laser points of each roof face. The following section will describe the method of grouping laser points of roof faces and the building model reconstruction procedure. The following paragraph explains the basic parameters of the approach.

In many cases the selected laser scanner point cloud of one building contains data from multiple strips. In this approach the points of each strip have been analysed individually to avoid inconsistencies in the case of their strip discrepancies. In each strip's point cloud a TIN-structure is calculated with a Delaunay triangulation using the module Triangle [Shewchuk 1996]. Figure 2-1 shows an example. To obtain parameters for further analyses, the three points of each triangle are used to calculate parameters of the plane. In describing each triangles position in space uniquely, the following parameters were used: Slope, Orientation and the minimal distance of the triangles plane to the origin, below referred to as Distance. Figure 3-1 illustrates the chosen parameters.

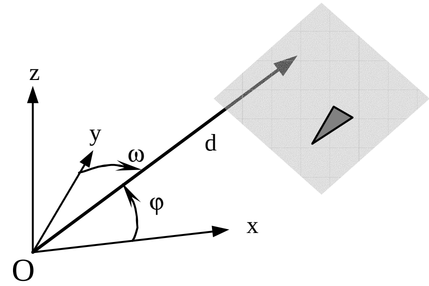


Figure 3-1. Triangle parameters φ slope, ω orientation and *d* minimal distance of the triangles plane to the origin O

Figure 3-2 shows the distribution of these triangle parameters for the building of Figure 2-1. Each parameter point in Figure 3-2 represents one mesh in the TIN-structure of Figure 2-1. The abscissas represent orientation values (0 to 360 degree), the ordinate of the upper image slope values (0 to 90 degree) and the ordinate of the lower image the distance *d* [m]. Within this parameter space two clusters with roof properties can be made out at a first glance. The next section will describe the algorithm that was used to group parameter points of roof triangles. The association of cluster points to single roof faces is discussed in section 3.2. The modelling of the roof itself is described in section 3.3

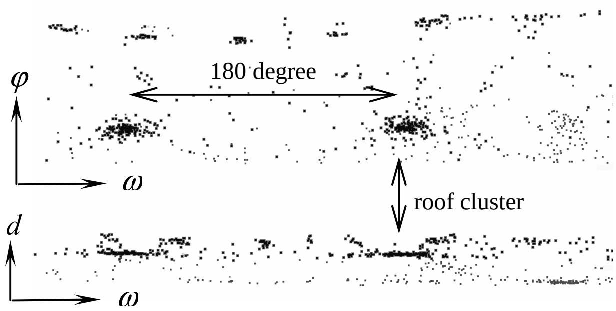


Figure 3-2. Example of a building's 3D parameter space

3.1 Cluster Analysis

There are several basic clustering techniques, such as partitioning, hierarchical, divisive, agglomerative or k-means methods, as described by [Anderberg 1973] and [Kaufmann 1990], which the researcher can choose from, while searching for the optimal application for its data. For this study it was decided to apply an agglomerative approach using single linkage. The procedure is as follows: Starting from a randomly chosen seed point, the distances to all direct neighbours in parameter space are calculated. If one distance is smaller than a certain threshold, the point is grouped to the seed point. This search is repeated until no direct neighbour of any point belonging to the group is found. Single linkage hereby means that the size of the clusters is not limited in any direction. The shape as well as the extension of the clusters is not relevant. After completing a cluster a new random seed point is chosen and the search starts again. Each point is treated only once. A cluster is only accumulated if a sufficient number of points are collected. Each cluster contains the parameter points of one planar surface. The cluster algorithm is explained in detail in [Hofmann 2003].

The single linkage is necessary, as the sizes of the clusters vary with the roofs inclination and position to the origin and with the laser scanner data accuracy in z. Here, the error model of the laser scanner data was simplified by making the assumption that within a small area planimetric errors are highly correlated as they are mainly caused by the GPS/INS system on board. Hence, for laser points of one flight strip within small objects, only the accuracy in z must be taken into account. With increasing inaccuracy of the laser scanner data and with increasing point density, the clusters swell in size and the borders of the clusters get fuzzier.

The single linkage connection also has the advantage that parameter points of triangles of not planar but continuous surfaces are collected in one cluster. In later analysis it will be possible to create multiple regions (smaller planes) from one cluster with the awareness that the planes should be connected. This may be advantageous for roofs with multiple inclinations.

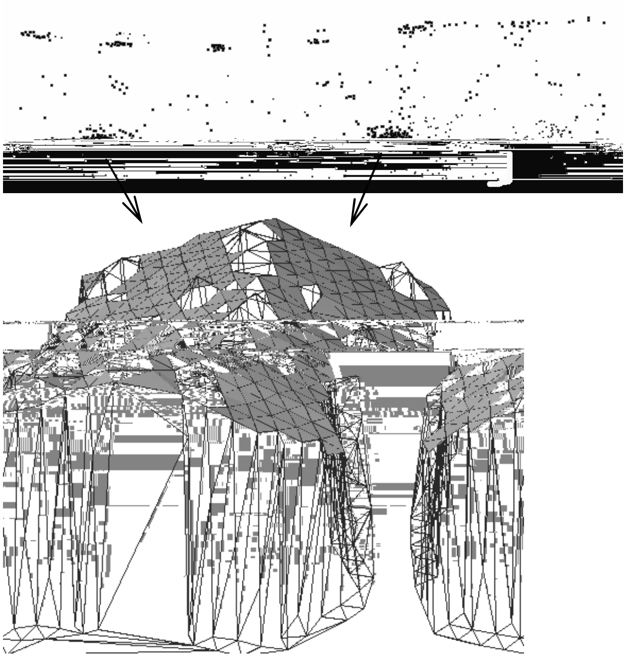


Figure 3-3. Association of parameter points to roof faces

3.2 Interpolate roof faces

At this stage of the analysis a number of clusters exists, that contain parameter points of planar surfaces. As can be seen in Figure 3-2, some parameter points originated from triangles representing walls group to clusters as well. These clusters are to be excluded from further analysis. The centre point of each cluster is calculated. If its slope in parameter space exceeds 75 degree, the cluster is rejected as a wall object.

The remaining clusters are now fed into the roof face interpolation process. The parameter points of each cluster are sorted in descending order by their distance to the cluster centre. The parameter point that is closest to the cluster centre is identified in the TIN-Structure. Following a simple region growing technique all neighbours of that triangle are evaluated whether they occur within the cluster or not. If that is not the case, but they still fit the clusters main properties the appropriate neighbour is added to the region. Each parameter point of a cluster is analysed only once. Figure 3-3 visualises the association of parameter points of a cluster to the according roof face. It can be seen that outliers of laser points resulting in triangles that do not fit the characteristics of the roof face are not included as potential roof points.

In the explained algorithm, multiple regions may be extracted out of one cluster. Figure 3-4 demonstrates that on the right roof face two regions have been extracted out of one cluster. This may happen when there are problems with the scan line registration. Complete rows of triangles have a different orientation in object space than the actual roof face. The advantage of the proposed method is obvious. A simple region-growing algorithm might not associate the single bright grey regions with each other without collecting too many triangles in other situations. Interestingly, this building's model has been reconstructed successfully (see Figure 4-1).

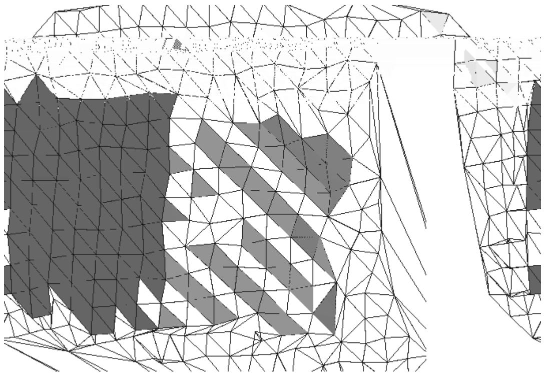


Figure 3-4. Multiple regions within one roof face, view from top

All regions extracted from one cluster are analysed on their mergence with other regions of this cluster. They should be merged in situations such as seen in Figure 3-4. If multiple larger regions have been extracted out of one cluster, they might belong to individual roof faces and should thus not be merged. A region that has one single triangle is, if possible, merged with a neighbouring region.

All laser scanner points that belong to triangles of a roof face large enough to be detected are now gathered to groups. In each group a plane is interpolated and a coarse bounding box is determined. Equation 3.1 shows the chosen plane equation. a, b and c correspond to the normal vector of the interpolated plane and d is the offset parameter. X, Y and Z are the directions of the object space coordinate system. The plane parameters a, b and c are derived by applying a principal component analysis to the point group. d can be calculated by applying a planes point to equation 3.1.

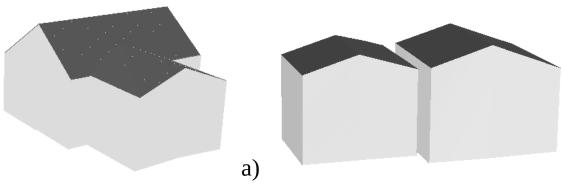
$$aX + bY + cZ + d = 0 \qquad (3.1)$$

The coarse bounding box of each region is necessary to aid the intersection procedure. It is created using the lowest and highest point and the points that are the resp. furthest on the left and right side of the region. Using the constraint that the lower edge (gutter) and upper edge (ridge) of a roof are very close to being horizontal, horizontal lines are fit in the according points. Perpendicular to them, lines are defined through the outer points of the region.

3.3 Intersecting roof faces

At this stage of the building model reconstruction procedure a number of plane objects exists, that still need to be associated and intersected. The ideal algorithm for this task should be able to give good results for any combination of roofs. The simplest application would be a gable roof and the more difficult one multiple detached houses with different roof types. The workflow of the intersection procedure consists of three steps: finding dormers, intersect ridges and intersect sides and bottoms. At each stage the intersected couple is assigned a code. There is the dormer type that means a smaller plane is located within the x-y-projection of a larger one. A couple would be two roof planes intersecting at the top forming a ridge. A neighbour would be any other adjacent plane. Also, a basic rule was set: Once gained intersection lines remain as they are. Only the corner coordinates can be moved on this line.

The task of the first step, detection of any flat dormers, is to find planes with similar parameters that are within each other. That means more than 80% of the laser points of the smaller plane are shared with the larger plane. If the lower edge of the smaller plane is at least 50cm above the larger plane, the smaller plane is intersected at the top creating a horizontal intersection line. Should these circumstances not apply, the smaller plane is discarded. The larger plane always remains as it is.



a) b)

Figure 3-5. Examples of buildings with sideways-connected roof faces

In a second step, those planes are associated that should be intersected at the ridge. In the case that two planes have been extracted a gable roof is presumed. The planes are intersected and the new corner coordinates of the ridge are saved. If there are more than two planes it is presumed that at least two of them form a gable roof. So, all roof faces are checked if there is/are one or more partners with opposite orientation that is/are within a certain distance and that has/have an overlapping area with the roof face worked on. These partners are listed in descending order by there overlapping area. Intersecting first those planes with the longest overlapping area will create the ridge of the two roof faces. Other bordering partners are intersected with the appropriate roof side. If no partner was found or none exists there will be, of course, no intersection. After the intersection of both planes the eaves at the gable side are trimmed. That means a least square line is calculated through the outer points of each gable side.

The third step is the intersection (Figure 3-5 a) and trimming (Figure 3-5 b) of sideways neighbouring planes. The difficulty here is to find a scheme that can be applied to any number of roof planes and the result will always be acceptable. The strategy that has been developed is as follows: First, all the roof planes are sorted in descending order by their size. To each plane the adjacent planes are detected and their connection type recognised. All neighbouring planes are also sorted by their size. The intersection starts with the largest plane and its largest neighbour. Basically, three different intersection cases can occur. Figure 3-6 illustrates them.

In cases a) and c) of Figure 3-6 all other adjacent sides have to be intersected. In case b) only the planes II and I are to be intersected. To accomplish this, the plane pair that is to be intersected is checked, whether one of the planes has a couple partner (forms a ridge with another plane) that is also an adjacent plane to the other plane or not. If not (Figure 3-6 c)) the adjacent sides are blended. In the other cases, for instance in Figure 3-6 b), plane II and I is a couple and both are adjacent to plane III. The same situation can be seen in Figure 3-6 a). Here, the plan is that plane III of Figure 3-6 b) should not be altered, but plane III of Figure 3-6 a) is to be intersected with the couple II, I.

Figure 3-6. Types of possible sideway intersection

As the algorithm has to make the decision without knowledge of the buildings shape, a rule has to be set defining when to intersect all three planes or just plane II and I. If after intersecting all three planes with each other, one of them is enclosed below the other two planes (that would be the case for plane III of Figure 3-6 b), this one should keep its original corner coordinates. Failing that, the appropriate sides of the three planes are blended.

Trimming planes is taken here as extending the sides of two adjacent parallel planes that are close to each other in a way that they can be connected with a vertical wall.

In some cases, such as storehouses, it is necessary to intersect the lower roof sides, the gutters, as well. This procedure is similar to the others. Planes next to each other with opposite orientations that are not a couple are intersected and the new lower end points are saved.

If all intersection steps are finished, walls are added to the building model. A wall element is created to each side of the roof faces that has not been intersected. The roof's eaves give the top line of the walls. The lower edge of the wall is derived form the DTM of the building's surrounding. The lowest point is chosen in order to please the eye in visualisations where also the terrain model is included. The reconstructed building model is now complete.

The ground plan of the building is obtained by creating a polygon that follows the top lines of the walls.

4 ACCURACY VERIFICATION

The reconstructed building model is valuable information for many visualisation tasks. For mapping agencies not just the 3D information of the building is of interest, but also the accuracy of the determined roof outline and ridge end points. This section will first give information about the success of the modelling procedure, measured by how many buildings have been reconstructed correctly. In the second part, the reconstructed roofs are verified regarding the geometrical accuracy of the corner coordinates of each roof face and the fittingness of the roof plane in the laser point cloud.

4.1 Correctness of reconstructed roofs

The results of the building model reconstruction were divided into three groups: correct, partly correct and incorrect. A roof model is correctly reconstructed if the number and outlines of each roof face corresponds to the real building. Figure 4-1 and 5-1 are examples of that. In a partly correct reconstructed building model at least half of the roof faces are correctly formed and parts of the other planes exists. An operator only would have to edit a few corner points. If less information is provided, the model is classified as incorrect. The reconstructed building model is of no value. A visual comparison of high-resolution aerial imagery and the analysed point cloud provided the information about the shape of the real building. Table 4-1 confronts the results for the two data sets that have been available.

Most of the buildings that have been correctly reconstructed are buildings with planar roof faces that do not have dormers. The majority of buildings in the Swiss data sets have gable roofs without dormers. Thus, they are easy to reconstruct. The result, given in Table 4-1, confirms this.

	Swiss data set	Data set of Dresden
Correct	70%	46%
Partly correct	17%	30%
Incorrect	13%	24%

Table 4-1. Statistics to the correctness of reconstructed roofs

The lower success rate of the Dresden data is a result of the constitutions of its roofs. The majority of buildings have hip roofs, whereby most of them are equipped with dormers and balconies, or smaller roofs are attached. Thus, numerous buildings have not been processed in their entirety. Roof faces that are too small (smaller than 10m²) could not be reconstructed at all and yielded to incorrect results.

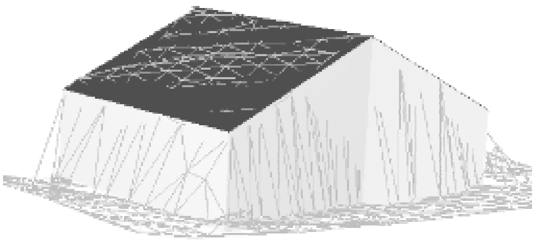


Figure 4-1. Example of building primitive reconstructed from the 3D cluster analysis information

4.2 Geometric accuracy of the reconstructed roofs

Beside the correctness of the reconstructed building models their geometrical accuracy is of most interest and will be discussed in this section.

Cadastral data have only been available for the Swiss data set. The outlines of 20 randomly selected reconstructed building models were compared to it. Here, the length/width ratio and the tilt angle of the main ridge directions have been analysed. Table 4-2 supplies these results. Taken this fact into account that cadastral data comprises the corner coordinates of walls and the exact overhang is not known the results are as expected. If one presumes a hangover of about 1m, which is typical for the majority of alpine houses in Switzerland, the laser scanner data would resemble the actual building quite well. The tilt can be negotiated, as it would only be of importance in large-scale applications.

	Mean difference	Standard deviation
Length/Width	+ 2m / +1.8m	0.7m
Tilt	0.8 degree	0.45 degree

Table 4-2. Mean differences as well as its standard deviation of the length and width of reconstructed building models in comparison to cadastral data.

High accuracy terrestrial measurements of the roof itself were available for a small sample of five building models of the Dresden data set. Statistically, this number is not meaningful, but it gives a general idea of the accuracy that can be expected. The correctly reconstructed buildings were evaluated by comparing the end points of the eaves and the ridge with the measured data. The achieved position accuracy of the ridge points has to be analysed separately from the end points of the eaves, as intersecting interpolated planes generated the ridge. The ridge points achieved a RMS-error in position of 0.4m and the corner coordinates of the roofs outline 0.9m. The worse accuracy of the corner coordinates mainly is an issue of the point density (1m). The accuracy in height, in terms of the eaves depends on the roofs inclination and position accuracy, is considered with 0.1m very good. It was expected to be around 0.2m according to the laser scanner data error in z.

To verify the single interpolated roof planes, the standard deviation of the perpendicular distances of the laser scanner points of each plane was calculated.

30 arbitrarily chosen building models of the Swiss data set and another 30 of the Dresden data set were analysed. The selection comprises small buildings as well as large storehouses. The mean perpendicular distance of the points that belong to one roof face to the interpolated plane is 4,78cm. The standard deviation of the distances off all points to their plane is 3.61cm. There was no trend recognised that interpolated planes of larger buildings fit better than those of smaller buildings. The main statistical results that table 4-3 summarises are considered as very good.

	Linear distance [cm]	Standard deviation [cm]
Minimum	2.01 / 0.5	1.4 / 1.2
Maximum	12.6 / 12.8	8.0 / 16.8
Mean	4.8 / 3.7	3.6 / 4.8

Table 4-3. Minimum, maximum and mean values of the perpendicular distance of points to the interpolated plane and standard deviation of the single distances for the Swiss/Dresden buildings

5 CONCLUSIONS AND OUTLOOK

With the proposed method a tool has been developed, that automatically generates building models from airborne laser scanner data with an acceptable percentage of correct results. The user only has to set parameters that define the mean point density and the laser point accuracy in z. The algorithm works quite fast. A machine operating with 700MHz and 512MB RAM computes 100 buildings, such as seen in the figures of this paper, in 3,2 minutes. The computation time increases, of course, with the number of laser points per point cloud, whereby most of it is the need of memory allocation.

The laser point cloud that the method requires can be obtained in different ways. The laserscanner data can be segmented with an image processing tool and the building polygons are than used to select the appropriate points. If ground plans are available, they can be used instead of the building polygons. An operator can also select point clouds manually. Thus, the method can be applied under various circumstances

Section 4 confirms that successfully reconstructed buildings models can be an alternative to photogrammetric models measured in normal aerial imagery. The accuracy in height is superior to these photogrammetric models. The position accuracy thought it depends on the point density, still has to be improved.

Furthermore, the algorithm is quite sensitive to errors in the laser scanner data. Poor data accuracy will prevent any result. For optimal results strip information should be supplied with the laser scanner data. If the strip information does not come with the data and the strips have not been adjusted sufficiently, the triangle structure will not represent the roof face properties; the roof is not detected. However, the method can also process rasterised data.

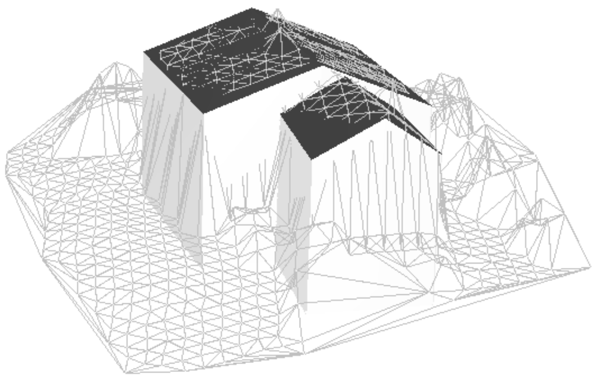


Figure 5-1. Example of building primitive reconstructed from the 3D cluster analysis information

In further work this approach will be extended to also be able to process flat roofs. This has not been yet possible because of the error definition of the laser scanner data. Occasionally it happens that only one roof face is detected and modelled. Still, a tool has to be written that checks the laser point cloud if there might be an opposite roof face.

Regarding the success of the method as a function of the mean laser point distance, further analyses have to be invested especially in the parameter space. Limits of the method such as minimal possible laser point density and minimal laser scanner accuracy that can be handled still have to be found. Within this analysis the accuracy of the resulting models has to be determined.

6 ACKNOWLEGMENTS

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