DETAILED BUILDING RECONSTRUCTION FROM AIRBORNE LASER DATA USING A MOVING SURFACE METHOD

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ABSTRACT:

The increasing demand for a fast, efficient and low cost algorithm for extraction of 3D urban features was the motive behind this work. In this paper we present a new technique to reconstruct buildings with detailed roofs in urban areas using airborne laser scanning altimetry data. We have tried to show that dense airborne laser scanning data is sufficient for detailed 3D reconstruction of urban features such as buildings. This concept is based on local statistical inferences. Least squares moving surface analysis with variable window sizes and shapes of laser-derived points was the key in determining building roof details. The consistency of the data with those surfaces determines how they will be modelled. After obtaining the roof facet orientation and approximate location, the roof boundary will be extracted by intersecting those facets. Consequently a complete wireframe of buildings is constructed. Results from an actual dense airborne laser data set collected over the Purdue campus are presented in the paper.

1. INTRODUCTION

3D city models are the final outcome of many photogrammetric applications. In this paper, the approach of reconstructing 3D building descriptions from LIDAR data is discussed. This approach can be applied to any DEM data regardless of its source. However, DEM accuracy plays a major role in defining the performance of this approach

With the availability of many sources of data such as conventional imagery, SAR imaging, IFSAR DEMs, and LIDAR DEMs, there are many avenues open to derive terrain and feature data in urban areas. Through much research, it has been shown that laserscanning data has the potential to support 3D feature extraction, especially if combined with other types of data such as 2D GIS ground plans (Maas, 1999; Brenner and Haala, 1999; Weidner and Förstner, 1995). Despite the fact that LIDAR data is attractive in terms of cost per high quality data point, the quantity of the data makes a challenge for storage and display (Vosselman, 1999). Acquiring 3D object descriptions from such data is a difficult problem and many approaches have been tried to solve it. Several of them have succeeded with some limitations. The principle idea of this research is to detect and reconstruct buildings form laser altimetry data exclusively.

In earlier work, (Alharthy and Bethel, 2002), we presented an algorithm to detect building footprints using LIDAR data. The building detection procedure described includes detecting and excluding other natural features such as trees. Many segmentation techniques such as thresholding determined by histogram analysis, the use of 2D GIS data, and multispectral inference have been tested together with LIDAR heights to determine building outlines (Brunn and Weidner, 1997). Using the second strategy, 2D GIS ground maps give the building footprints.

After obtaining building outlines itself, the raw data points in each building polygon will be counted and labeled accordingly. Processing point sets in each polygon will provide the necessary characteristics to rebuild the roof surface. In addition a refinement step to get precise roof details is presented. This step utilizes the roof planar parameters to partition roof surfaces into homogenous roof facets. The refinement procedure for roof segments starts with detecting homogenous roof surfaces and segmenting them based on their geometrical surface parameters. Roof outlines are extracted and roof planar facet breaklines are then determined and refined. After connecting extracted roof planes, a complete wireframe of processed buildings will be formed and a 3D view of them will be shown.

2. ESTIMATION OF GEOMETRIC PARAMETERS FOR MOVING SURFACES

Several algorithms have been suggested to extract roof faces using range data (Brenner, 2000; Brenner and Haala, 1999; Brunn and Weidner, 1997; Brunn, 2001; Vosselman, 1999; and many others). Surface normal segmentation is one of the major ones. However normal vectors tend to be very noisy due to the variability in the LIDAR points. In this work, a new technique to reconstruct buildings is presented. Least squares moving surface analysis with variable window sizes and shapes of laser-derived points was the key in determining building roof details. The consistency of the data with those surfaces determines how they will be modelled.

2.1 Least squares moving surfaces

A grid with a designed spacing (one meter is used with the test data here) is overlaid on the irregular LIDAR points in each building outline as shown in figure 1, where the small green crosses represent the irregular scattered LIDAR points. Then a window is moved through the grid cell by cell in both *x* and y directions. In each step, the LIDAR points are counted inside the window and if they exceed a certain limit in number, a plane fitting procedure is performed. The reweighted least squares adjustment procedure is used to estimate a unique set of plane parameters for the fitted points (Mikhail and Ackermann, 1976). In addition to the basic plane parameters, slope in x, slope in y, and height intercept, the RMSE of the fitted data over the given window is determined as well, in order to evaluate the soundness of the recovered parameters. Those parameters will be recorded at the center cell "pixel" of the window in order to use them in roof facet segmentation and reconstruction.

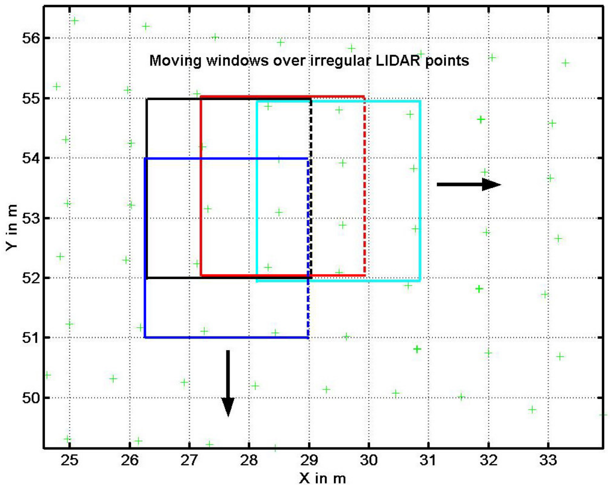


Figure 1: Moving windows for plane fitting over the irregular LIDAR points.

2.2 Key factors in designing moving surfaces algorithm

The grid spacing and fitting window size are two critical factors in this procedure. In case the data density is high, the grid spacing is based on the desired detail level and accuracy of the extracted roof facets. The reason is that grid spacing "cell size" defines the minimum precision that could be reached in breaklines between roof segments. However small cell size does not always yield fine details, especially if the data density is low. In addition to that, the smaller the cell size the higher the cost of computation. So in general, the data density sets the effective minimum limit for the cell size while the desired level of detail and accuracy defines the maximum limit. In this work and according to the available data with a density of approximately one spot height per square meter, the grid spacing "cell size" was one meter in both x and y directions. This spacing seems to be effective even though it is somewhat large. However, the main goal of this work is to test the suitability of LIDAR data for roof details reconstruction rather than their positional accuracy.

The other key factor is the moving window size used in plane fitting. The main factor that influences the window size is the data density since it controls the number of points inside each window. The window should be large enough to contain enough point observations to reliably estimate a unique set of plane parameters through the reweighted least squares adjustment. The number of points should exceed the minimum requirement in order to have redundancy in the adjustment. The redundancy helps to accommedate the inconsistency between data points and strengthen the soundness of the estimated parameters. In general the denser the data the smaller is window that can be used since there will be enough data to estimate the plane parameters.

During the plane fitting procedure, the estimated plane parameters are recorded at the center of the moving window. However, when gaps occur in data which consequently means not enough points fall within that window, the fitting procedure will not be applied and zeros for the parameters (slope in x, slope in y, and height intercept) will be assigned to that window center. In addition to that, a high RMSE will be assigned since the parameters are not valid. This high value is utilized in the best fitting search by giving an indication of bad fitting on that cell. After completing the plane fitting procedure and recording results, a best fitting algorithm is applied. In general, this algorithm minimizes the fitting error in each cell by assigning it to the plane which has the minimum RMSE among all planes containing this point (Alharthy and Bethel, 2002). Results of this procedure are used in the segmentation as discussed below.

3. SEGMENTATION OF PLANAR ROOF FACETS BASED ON THE ESTIMATED GEOMETRIC SURFACE PARAMETERS

In this research, the roof planar segments were extracted utilizing the estimated geometrical plane parameters resulting from the previous step. Starting from a small set of "seed" cells, region growing by a cell (pixel) aggregation technique was used to construct large roof facets. Steps of this procedure are discussed below.

3.1 Region growing segmentation by cell aggregation

Region growing is an approach for image segmentation, in which neighboring pixels are examined and added to a region if they have common characteristics. Those characteristics or parameters form the membership criteria (descriptors), based on which the decision will be made to include or exclude the cell. The region growing technique starts from defined seeds, which are known to be the center of the class (roof segment) and consists of a group of cells or "pixels" which are strongly homogenous. Those cells carry almost the same parameter values and the cost function between them is small. The key factor in this algorithm is the design of the membership criteria "cost function" and its computation. The way this technique is used in this work is similar to typical clustering or classification techniques, in which pixels are given the same label in a parameter space based on some similarity measures. However connectivity is required between pixels here unlike in general clustering algorithms. In this work starting seeds were defined based on the resulting RMSE from the plane fitting procedure. Low RMSE means excellent fitting and consequently good consistency among cells. The membership criteria and cost function used in aggregation are discussed below. However prior to that some preprocessing steps were performed on the estimated parameters that form the parameter space to fit the needs of the application.

3.1.1 Preprocessing steps to form the segmentation search space

There were three basic independent parameters (slope in x, slope in y, and height intercept) assigned at each cell inside each processed building polygon. Based on roof shape and direction complexity, one, two, or the three parameters could be used to form the parameter space and define the membership criteria for the region growing technique. As a preprocessing step, parameter magnitude range consistency was imposed over those parameters in order to make the parameter space uniform. Based on the knowledge of building roof facets, typical slope in both directions (x, y) does not exceed the value of one. Accordingly, the slope values were set to be with a range of ±1. Values out of this range are discarded since they are not realistic. The slope might have a high response during the fitting procedure due to the fact that the processed window may contain data points that lie in between two planar surfaces and do not belong to any. For example, at two discontinuous adjacent roofs with different heights, the laser beam might hit the wall between those two roofs. In such circumstances, the best fitting procedure will assign those points to one of the adjacent roofs even though in reality they do not belong to any which would result in high slope values.

Moreover, the height intercept also needs to have range limits as the other two factors. This scaling step is to make the parameter space homogenous. As in the slope parameters, a few spikes in the estimated height response were recorded. Unlike the slope case, limits on the height intercept cannot be predicted since roof height varies within the same building with a wide range. First a histogram of the height intercept of the processed area was constructed. Then values out of the range $\pm k\sigma$ (k can take any value from 0 to 2 based on the shape of the histogram and the outliers values) will be discarded since they don't seem to be valid and they are a result of points on edges as discussed above. This step centers the mean value of the parameter in the new range and reforms the spread of the data. Then the resulting values are scaled down to have the range from –1 to +1 as in the other two parameters. The trimming and scaling procedure are shown in equation (1) and (2). Figure 2 shows color-coded image of H of the same building before and after trimming and scaling.

$$Ht_{(x,y)} = \begin{cases} \mu + k\sigma & \text{if} \quad H_{(x,y)} > \mu + k\sigma \\ \mu - k\sigma & \text{if} \quad H_{(x,y)} < \mu - k\sigma \\ H_{(x,y)} & \text{elsewhere} \end{cases} \tag{1}$$

$$Hts_{(x,y)} = \frac{Ht_{(x,y)} - \mu}{2\sigma} \tag{2}$$

where H : height intercept
Ht : trimmed value of H
Hts : trimmed-scaled value of H
μ : mean value of H inside a building polygon
σ : standard deviation of H inside a building polygon

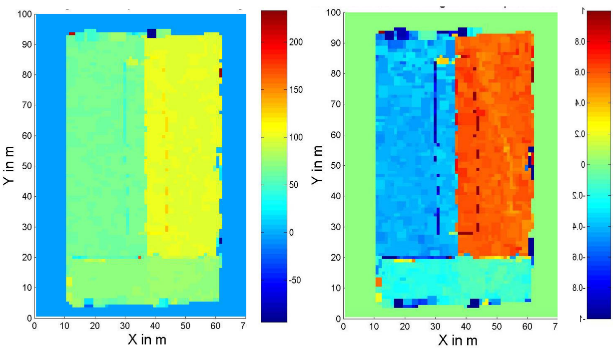


Figure 2: Height intercept color-coded image before and after the trimming and rescaling procedure.

3.1.2 Membership criteria (cost function)

The membership criterion between two cells to define whether they belong to the same roof segment or not is the Euclidean distance in the parameter space between the two points. If the cost function between the center of the seed (cell i) and the processed cell (cell j) is less than a defined threshold of the membership criteria, then they belong to the same roof segment. However, at the beginning as is known in the region growing segmentation, the candidate cell or pixel should share an adjacent boundary with the growing region.

3.1.3 2D parameter space

For simple gable roofs, slope in x and slope in y can form a satisfactory parameter space for the roof features. This is due to the fact that gable roof pair segments have well defined reverse slopes as shown in figure 3(a). The 2D search space of the same building is shown in figure 3(b) where its first axis X is the slope in x and the second axis Y is the slope in y. Figure 3(c) shows the raw result of the region growing segmentation procedure and the labeled roof segments in the parameter space. As shown in the search space, some pixels are not labeled (red crosses, figure 3(c)) since they don't belong to any class based on their parameters. However, those cells will be assigned to the nearest roof segment in term of position in the object space not in the search space as shown in figure 3(d). However, in a complex roof structure, these two parameters are not always capable of discriminating between all of the segments. Another parameter may be added as in the following section.

3.1.4 3D parameter space

In more complex roof structures, a third parameter is desirable to add to the parameter space to increase its information content and consequently detect a more complete and precise set of roof segments. Slope in x, slope in y, and height intercept form the 3D parameter space and shape the membership criteria. This dimensional increment improves the seprablity between classes (roof segments regions) in the parameter space, which enhances the possibility to detect roof segments with same slope but with different heights. Figure 4 shows the procedure and results of the roof facet segmentation utilizing the estimated surface parameters resulting from the least squares moving surfaces. As it shown clearly below, the third vector (height intercept) enables the system to detect the four elevated rectangular structures in the lower part of the building; while in the 2D parameter space (slopes in x and y) the system was not able to detect them.

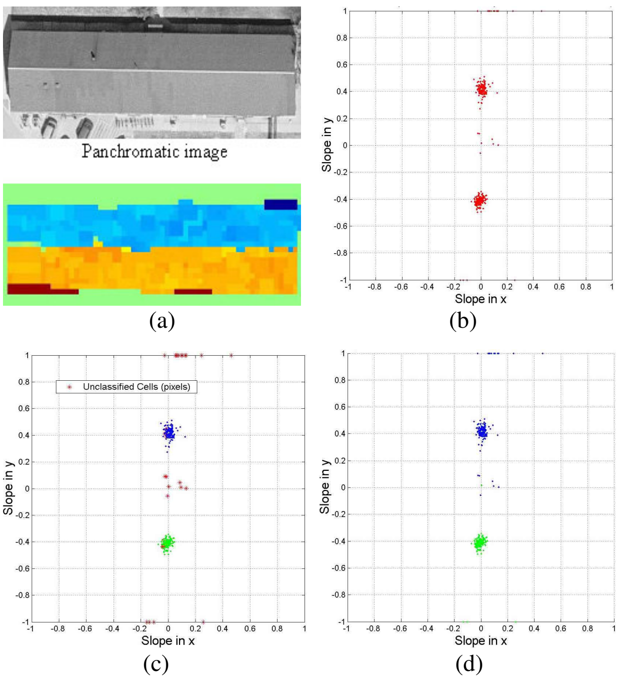
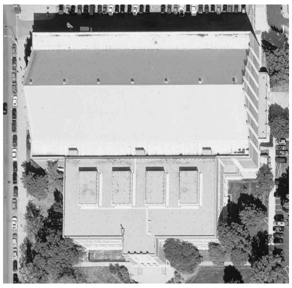
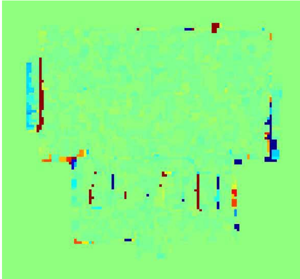


Figure 3: (a) Estimated slope in y for a simple gable roof building, (b) 2D search space based on slopes in both x and y directions, (c) Roof classes results

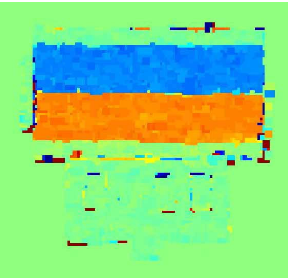
without gap filling, (d) Roof classes results after gap filling and refinement.



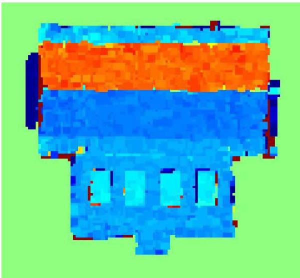
(a) Aerial image



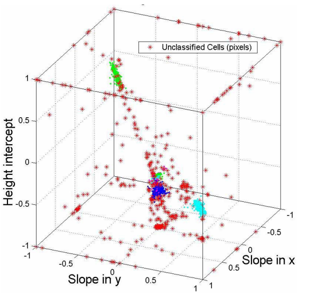
(b) Slope in x



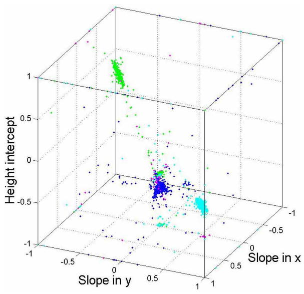
(c) Slope in y



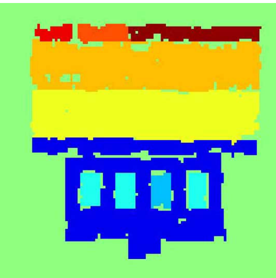
(d) Height intercept



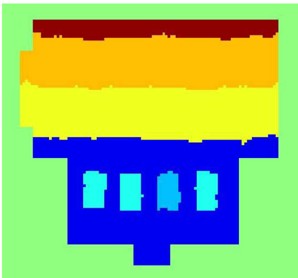
(e) Preliminary Clustering result



(f) Refined clustering result



(e) Raw segmentation results



(f) Refined segmentation result

Figure 4: Roof facets clustering in 3D search space.

4. EXTRACTION OF PLANE-ROOF POLYGONS

In this section, the procedure of translating the irregular roof facet regions to typical vectorized polygons is discussed. This procedure contains many steps to get the desired 3D polygons of the roof. Extracted roof regions will be transferred to 2D polygons first through raster to vector conversion that includes line extraction, connecting, joining, trimming, and segment adjacency determination. The geometrical plane-roof parameters, inclination and height, are then estimated based on the irregular LIDAR points inside each polygon. This enables the configuration of 3D roof facet polygons.

4.1 Extraction of plane-roof regions outlines

As a result of the region growing segmentation, roof facet regions were segmented and labeled as shown in the above section.

4.1.1 Simple roof structure

Simple roof structures mean here that the breakline between roof segments is uncomplicated and is parallel to one of the two dominant directions of the building footprint. In such buildings, the polygon extraction algorithm that was discussed in (Alharthy and Bethel, 2002) is applied to obtain roof segments outlines. The only constraint to this algorithm is that it can only extract lines in the two dominant directions of the building. However, the algorithm was very useful since all intermediate steps such as line extraction, connecting, trimming, and polygon formation, are embeded in it. And its main advantage and strength is the ability to preserve the squaring property of the extracted polygons. In general, the performance of this algorithm was excellent. Results of this step which show the extracted polygons (black lines) overlaid on the segmented roof regions are shown in figure 5.

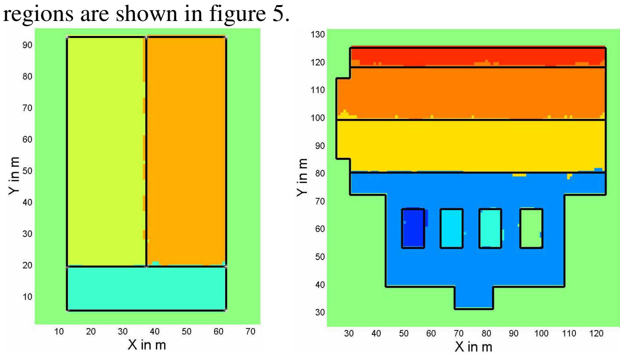


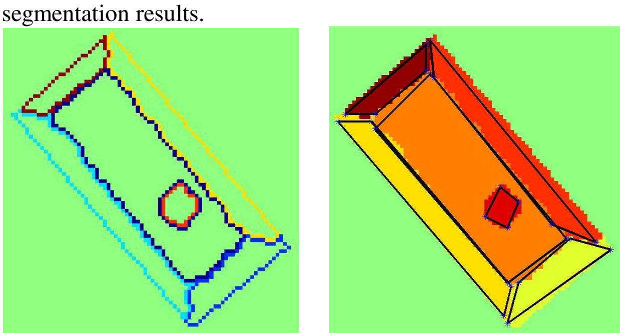
Figure 5: Extracted roof segments polygons

4.1.2 Complex roof structure

In complex roofs, breaklines between roof segments are not limited to be parallel to the dominant directions of a building, instead they might take any direction and roof segments might be in any shape. Based on that, the previous algorithm of polygon extraction would not work here. So, a modified prismatic algorithm was used to refine the segmentation results. A data driven model was used to connect and generalize these roof planar surfaces in order to extract standard roof polygons.

The approach is a modified version of an approach that was presented in a report in 1995 by U. Weidner, Institute of Photogrammetry, Bonn University, Germany. The approach treats each region segment individually. It starts with the boundary points by sorting them in clockwise mode starting from the upper left point as shown in figure 6(a). In addition to its position (x,y), each region boundary point will be given two labels, the first one tells to which roof segment this point belongs, and the second label tells its order among the boundary points of the segment. Now points will be considered as the polygon vertices that make polygons in vector format. In order to minimize the number of vertices, unnecessary points will be deleted. Then the procedure of eliminating discretization noise continues by testing the significance of each point in shaping the polygon. First, in order to keep only significant points and delete points on straight lines, all points with altitude close to zero will be eliminated. In previous similar approaches in (Douglas and Peucker, 1973; Weidner, 1995), the computed altitude was used directly as a criterion of point significance.

Consequently, points will be eliminated from the point set if their correspondening altitude is less than a fixed threshold. However, in order to suit the needs for standard roof polygons in this work, a modification was introduced to this criterion. The computed altitude was divided by the base of the processed triangle. This increases the probability of keeping corner points and minimizes the discretization noise resulting from the imperfection of region segmentation since the point elimination procedure is applied in a recursive way. The recursive mode comes from the fact that the elimination will start gradually from zero to the fixed threshold value. This prevents damaging the start point of elimination. If the elimination starts with high threshold directly, the start part and the arc after it will be damaged severely. Extracted polygons from the same example shown in figure 6 and 7 where they are overlaid over the roof segmentation results.



(a) Ordered border points. (b) Extracted roof polygons

Figure 6: Complex roof polygons extraction.

As shown in figure 6(b), the extracted polygons are isolated and not connected even though they belong to the same building. First, vertices located within a close proximity to each other were grouped together and this procedure starts with the external vertices. Since the building footprint outer primitive was defined precisely, those outer primitives were enforced in the extracted polygons to define the building geometrical borders. Another step was taken to enforce the alignment between nodes which appear to be in a line. This was done by computing the distance between each node and the closest line and if this distance is less than the prefixed threshold, the node will be shifted to that line. For interior nearby vertices, they were grouped together at an average location of their position.

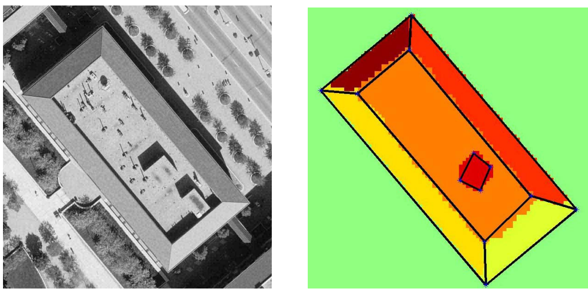


Figure 7: Connected roof polygons.

5. BUILDING WIREFRAMES

For each roof polygon, the plane-roof geometrical parameters are estimated by applying a robust 3D regression method on the irregular LIDAR data points inside each polygon. The reweighted least squares adjustment is used to estimate those parameters (inclinations in both directions x and y and height intercept) through plane fitting. The fitting includes all points inside each polygon collectively instead of the moving surfaces, i.e. each and every point will contribute to the adjustment and consequently in estimating the parameters. The point in polygon technique was used to obtain all data points inside the polygon in order to use them in the estimation. Due to the existence of outliers in the data and miss-located LIDAR points (being assigned to a roof segment to which it does not belong), in addition to data uncertainty, the reweighted procedure during the adjustment was used to diminish their influence on the results since weights are assigned based on each observational error in each of the adjustment iteration. The estimation of the plane-roof geometrical parameters transfers their polygons from 2D space to 3D space.

After finalizing the 3D polygons of the roof segments, the 3D coordinates of their vertices are computed based on the geometrical parameters of each segment. As a final refinement step, vertex heights within small close proximity will be clustered in order to have typical closed building wireframes. A thick plane will be dropped through each building and heights in close proximity will be combined. Also to get the building elevations, the terrain height was obtained for each building from a LIDAR derived DTM. This enables the reconstruction of building side polygons. The final result is the constructed wireframe of buildings as shown in figure 8 and 9.

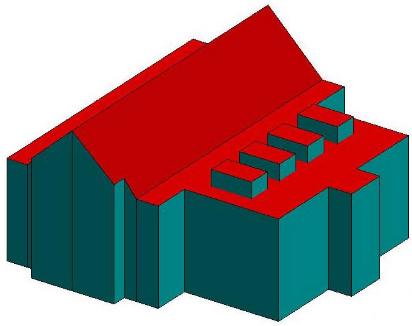


Figure 8: Reconstructed 3D view of the building processed in figure 4.

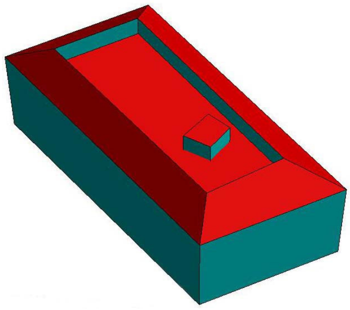


Figure 9: Reconstructed 3D view of the building processed in figure 7.

6. DISCUSSION

The aim of this work is to design a simple and fast method to reconstruct buildings in urban areas using LIDAR data only, which can be useful in many applications. We restricted the procedure to not require any other source of data other than the LIDAR heights. This was done intentionally to avoid the limitation of availability of other sources of information in some areas. Sources such as ground plans, imagery and multispectral data are not available for every desired site. The presented algorithm of detailed building extraction is very useful and effective in reconstructing large areas and it shows satisfactory results when the data was not so dense (one spot height per square meter only). More dense data might improve the extraction procedure, especially the roof details. However, some difficulties were encountered and they are discussed below.

Although the segmentation procedure shows successful results, it might fail to segment roof regions in some areas. Areas where the roof segment is not smooth or its size is not large enough to contain enough LIDAR points to estimate reliable geometrical parameters of the segment are some examples which might lead to inaccurate roof segments. Significant existence of small structures over a small roof region if added to the original noise in LIDAR data may cause the production of noisy parameters during the plane fitting procedure and consequently unreliable segmented regions. However, in such cases, increasing the data density might alleviate this obstacle to a certain extent. Another example of segmentation failure occurs where adjacent trees are extended over a large part of the roof facet that causes an occlusion where not all laser pulses can reach the building roof. This situation can be avoided by a good planning for the survey time where there are no leaves which would minimize occlusion.

In roof polygon extraction, the performance of the simple and complex roof polygon extraction was successful especially with large roof regions as shown in figures above. Roof polygons were extracted and successfully connected. However, some nodes might be shifted from their true position during the joining and connecting of the roof planar segments especially with complex buildings. On the other hand, the performance of the planar roof connecting algorithm deteriorates in the presence of very small close by roof regions. This is due to the fact that polygon vertices may be so close to each other that they incorrectly forced to coincide during the connection procedure.

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