URBAN MODELING BASED ON SEGMENTATION AND REGULARIZATION OF AIRBORNE LIDAR POINT CLOUDS

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ABSTRACT:

This paper presents an approach to process raw lidar 3-D point clouds over urban area and extract terrain, buildings and other urban features. In the initial step, "non-ground points" are separated from ground points using a one dimensional filtering process based on the slope between two consecutive points in the point cloud and the terrain elevation in the vicinity of the points. In the next step, the non-ground point dataset is processed to segment individual buildings. This is accomplished by using a 3-D regional growing approach. At the end of this step, each lidar point is attributed to a building. The first step towards building reconstruction is to obtain an approximate footprint of the building, which is accomplished by extracting the points on the building boundary by a modified convex hull algorithm. Once the footprint boundary points are found, their edges are regularized by using a least squares model to form the final building shape. Mathematic formulation of 3D region growing and boundary regularization is presented. Tests results of reconstructed buildings over complex urban areas are reported.

1. INTRODUCTION

Lidar (Light Detection And Ranging) records dense 3-D point clouds over the 3-D reflective terrain surface. Combined with GPS (Global Positioning System) and IMU (Inertial Meaurement Unit), these point clouds are georeferenced. Therefore, they can be used to model urban environments, create city models, and obtain 3-D topographic surface information (Ackermann, 1999; Balsavias, 1999). The first step in generating city models is to remove all the points that do not represent buildings from the dataset. Since it is easier to mathematically define the ground than other features, lidar returns from ground are first separated from non-ground features. In this process, we can also generate bald ground DEMs (Axelsson, 1999; Sampath and Shan, 2003; Schickler and Thorpe, 2001; Sithole, 2001; Vosselman, 2000; Vosselman and Mass, 2001). The rest of the work is then to segment each individual building from the building class and reconstruct it one by one based on certain building models.

In this study, we present an approach to segment and extract buildings from raw lidar point data. Most approaches to feature extraction from lidar data make use of the differences between DEMs generated using raw lidar dataset, and the dataset that is generated after non-ground points have been filtered. This will give the footprints of buildings. The problem of converting these footprints to vectors is addressed by assuming two orthogonal dominant directions for each building and then constraining the building edges to lie along those directions (Al-Harthy and Bethel 2002). Rottensteiner and Briese (2002) apply a morphological filter over the building footprints to get a binary image of planar regions. A connected component analysis then reduces these regions to smaller buildings. Another approach to this problem would be to use the detected building points and the surrounding ground points to interpolate the building boundaries. This is achieved after determining the internal 3-D breaklines of the buildings (Morgan and Habib, 2002).

In this paper, we discuss the process by which we detect, segment, regularize and reconstruct building shapes from raw lidar data. After briefly discussing the initial processing stage, where the raw point dataset is classified into two classes: buildings and non-buildings (mainly bald ground), we present a region growing algorithm to segment individual buildings from the building point dataset. Next, we propose a method to select the building boundary points based on a modified convex formation approach. These points are then used to determine parametric equations for lines that represent the building edge.

Section 5 discusses the steps that are taken for reconstructing the buildings in 3D. In the first step, regularized boundary of the selected building is obtained using a least squares model. This gives us the final building footprint. The third dimension is visualized by slicing the buildings at various levels of elevation, for roof structures that are flat. Each sliced segment can, in turn, be regularized to obtain the roof model. Buildings that have sloping roofs are a bit more complicated. Such cases are handled by segmenting out those points that belong to each face of the roof, and then regularizing them.

Buildings over Baltimore, MD, USA and Toronto, Canada are used in our study. Their quality is evaluated by comparing the lidar generated results with ortho-images.

2. SEPARATION OF BUILDING FROM GROUND

A few airborne lidar datasets are used in this study. They include downtown Baltimore, Maryland and Toronto. Their average point density is one point per 5.5 square meters and 2.25 square meters, respectively. Details about the datasets can be found in (Shan and Sampath, 2004).

An algorithm to separate ground and building points from raw dataset was suggested in our previous work (Sampath and Shan, 2003). The proposed labeling approach is based on slope and elevation assessment and is implemented along the lidar profile in two opposite directions. A local linear regression along the lidar profile is then followed to further remove possible non-ground points remained from the labeling process. Tests over three urban areas with different complexity show that over 96% of the lidar points can be correctly labeled. For the details and the performance of the proposed approach we refer to (Shan and Sampath, 2004). In the following studies, we will use the building point clouds separated from this step.

3. BUILDING SEGMENTATION

Each of the lidar points that have been labeled as belonging to building class through the previous step can only belong to one single building. That is, there is a one-to-many correspondence between the buildings and the 3D points, with each building having many points and each point belonging to one particular building. The Segmentation process assigns each point to a unique building. A 3-D region growing algorithm, which starts from a single point and successively collects points belonging to the same building, is presented. This algorithm consists of the following steps:

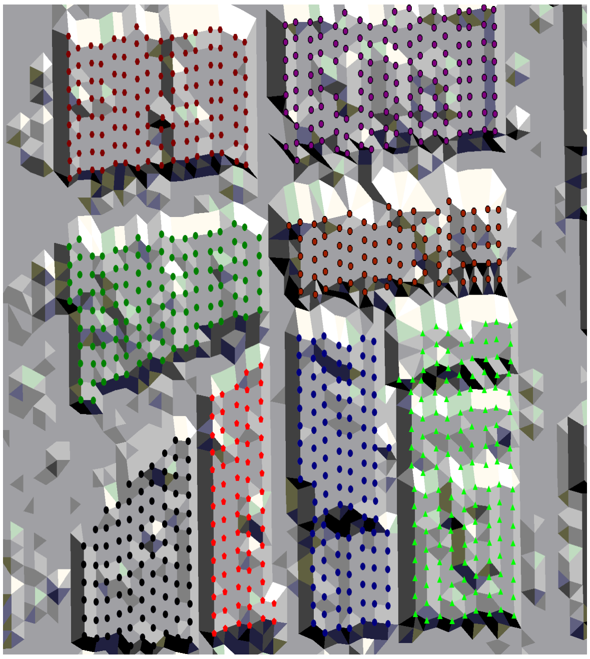

Figure 1. Segmented Building Points

1) Start from a building point P_0.
2) Centre a 3-D window (cube) on the point and collect all the points $A = \{P_1, P_2, \ldots P_k\}$ that fall within the window.
3) Move the window to P_1
4) Collect the points that fall within the window and store them in a temporary set, say tempPoints= $\{tP_1, tP_2, \ldots, tP_r\}$.
5) Move to point P_2 and place the window over it. Append the newly collected set of points to the variable tempPoints, and in the process making sure that no two points are the same.
6) Continue the process till the window has been placed over all the points $P_1, P_2, \ldots P_k$
7) Merge points in A and points in tempPoints and store them in B. i.e. $B = \{B \cup A \cup tempPoints\}$. Initially B is a null set.
8) Replace points in A with points in tempPoints such that the newly populated set A is equivalent to $\{A \cup tempPoints\}$.
9) Go back to step 3.
10) Stop when no new points are added to the set B.

In this way, the points in the building class are further segmented into points belonging to individual buildings. The proposed segmentation approach does not require any special data structure. The initial input into the algorithm is a 3-D point cloud, which is basically a set of X, Y and Z coordinates. Also, the number of searches progressively reduces as more and more points are assigned. Figure 1 shows a portion of the segmentation results over the test area, where different segmented buildings are color coded.

4. BUILDING BOUNDARY TRACING

Once each point has been mapped to a particular building, the next step is to determine the footprint of the building. In this section and the next, we explain a series of steps to parameterize the edges of the segmented buildings as a series of orthogonal straight lines. We call this step “regularizing”. Our assumption here is that most buildings have only two mutually perpendicular, dominant directions. In Figure 2, we demonstrate the first step in regularizing the footprints, where we determine points that belong to the outer boundary of the building. In the second step, parametric lines are drawn to represent the boundary edges of the building.

A convex hull algorithm, for a given set of points, determines the smallest convex set containing the points. It can be regarded as a rubber band wrapped around the set of points. To determine the building boundary points, we use a modified form of the convex hull algorithm. Figure 2 shows a convex hull for the building points. Clearly, it does not represent all the boundary points of the building, nor does it bring out the shape of the building accurately. The algorithm determines the hull points by selecting the left-most point and then successively determining those points that make the least angle with the last generated convex edge. To accomplish this, the algorithm compares the slope of the last edge that is generated with lines formed by connecting the current point with all the other points.

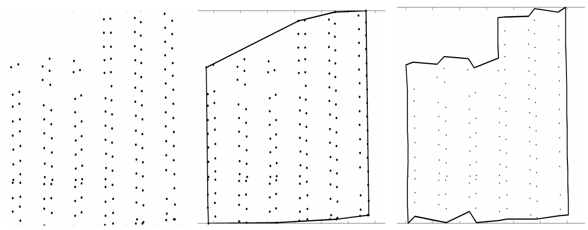

Figure 2. Building points (left), convex hull around the points (middle) and the actual boundary points (right)

To determine the boundary points for a building, we adapted this algorithm. The steps are given below:

1) Start from an extreme point that is necessarily a boundary point (say P).
2) Select all points that lie within a threshold distance from this point, say $Pts = \{p_{1,} p_2, ...p_k\}$. The threshold distance was the point density of the data-set.
3) Determine the slopes of all the line segments that connect the current point P, with the set of selected points in Pts.
4) Determine the point $\mathrm{p_r}$ in Pts which has the least angle from the Y-axis.
5) Move to this point and consider this to be the next current point $P_c^{'}$ and determine the slope of the line (say L_c) connecting this point with the previous point.
6) Select all points that lie within the threshold distance from $P_c^{'}$, determine the point/line segment which makes the least angle with line L_c. Append this point to the boundary point set and make this point the new $P_c^{'}$.
7) Continue till the first selected point is reached.

The result is shown in Figure 2. Many algorithms that can determine the convex hull of a give set of points exist. The problem in directly applying the convex hull algorithm is that buildings are not necessarily in convex. But, if we restrict the search space of the algorithm to a smaller area, given by a threshold distance, the algorithm will give us an accurate outline of the border points on a building. As can be expected, the result of the algorithm depends on the threshold distance that is assigned in steps 2 and 6. This distance, in turn, is proportional to the point density or the point spacing of the 3D point cloud. In most point clouds, the distance between two points lying on (or parallel) the X-axis will be different from the distance between two adjacent points lying on(or parallel) to the Y axis. Therefore the threshold distance mentioned in steps 2 and 6 should be adjusted accordingly. The convex hull algorithm is implemented as it is a well known algorithm and is easy to implement as well as to adapt for our purposes.

5. BUILDING REGULARIZATION

As seen in Figure 2, the above steps give us a set of adjacent points lying on the boundary of the building. Assuming that most buildings have only two dominant directions that are also mutually perpendicular, we can use the points to determine these directions, and fit parametric lines that represent the edge or the footprint of the building. As can be seen in Figure 2, not all line segments that we obtain from lidar data are perpendicular. However, likely longer lines seem to be very close to being mutually orthogonal. It is then safe to assume that these line segments represent the dominant directions of the building. These larger lines represent the basic frame of the building footprint. This idea is the basis of our method to determine the footprint of a building and a global solution based on the least squares criterion is proposed to square the building boundary so that the extracted buildings are regularized.

There exists a one-to-many correspondence between boundary edges and the boundary points. Each point lies on a single line, unless it is a point that lies where two lines intersect. Based on the assumptions mentioned above, the first step in regularizing a building is to extract the points that lie on the longer edges of the building. This is done by sequentially following the boundary points, and looking for positions where the slope between two consecutive points e.g.,$(P_i, P_{i+1})$is different from(P_{i+1}, P_{i+2}). The set of points is mapped to the line segments $\{l_1, l_2, ...l_n\}$ Then, the longest set of these lines (e.g., $\{l_i, l_j..l_m\}$) were selected, along with their corresponding sets of points, say

$$A=\{(p_{11,}p_{12},.. p_{1k1}),(p_{21,}p_{22}, ...p_{2k2}), ... (p_{n1,}p_{n2}, ...p_{nkn})\}$$

Then, the least squares solution for these lines are determined, with the constraint that the slopes of these lines are either equal (the lines being parallel), or their product is equal to -1 (in which case, the lines are perpendicular). The solutions consist of a set of parameters that describe each of the line segments $\{l_i, l_j..l_m\}$. In particular, we have the following set up for our building squaring problem. For each line segment,

$$A_i x_{ij} + B_i y_{ij} + 1 = 0 \qquad i = 1,2...n; \quad j = j(i) = 1,2,....m_i \tag{1}$$

where n is the number of line segments, m_i is the number of points on line segment i. Line segments of a building are grouped based on their slopes. Lines that are parallel within a given tolerance are sorted as one group with the same slope. Let *K* be the number of parallel line groups, then lines in every group should meet the following condition

$$\frac{A_s}{B_s} + M_k = 0 \qquad k = 1,2,...,K \quad s = s(k) = 1,2,....,n_k \tag{2}$$

where M_k is the slope of parallel line group k, n_k is the number of lines in the *k-th* parallel line group. Similarly, for the line groups that are perpendicular, we can write the following condition equation

$$M_u M_v + 1 = 0 \qquad u, v = 1,2,3....,K; \; u > v \tag{3}$$

The least squares criterion is used to solve the above equation systems. The unknowns include all the line segment parameters A_i and B_i $(i = 1,2,...,n)$, and the slope $M_k (k = 1,2,...,K)$ of parallel line groups. In the current study, only two groups of parallel lines, namely horizontal and vertical line segments are considered. This leads to only one conditional constraint in Equation (3).

To determine the parametric line segments, a hierarchical approach is designed. This approach starts with relatively longer line segments detected in the lidar points. In the next step, relatively shorter line segments are introduced and their parameters are determined based on the slopes of the line segments obtained from the previous step, keeping in mind that we consider only two possible directions for each line segment. Figure 3 shows the determined parametric line segments for the building boundary. The final squared building and the original building points are also shown in Figure 3, with the original lidar points overlaid atop. Presented in Figure 4 are examples of regularized building footprints with their ortho image displayed beside.

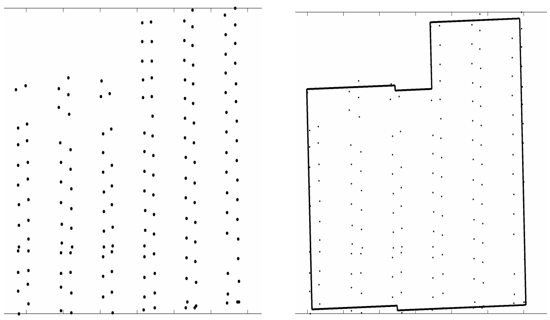

Figure 3. Boundary points (left) and parametric lines overlaid with original lidar points (right).

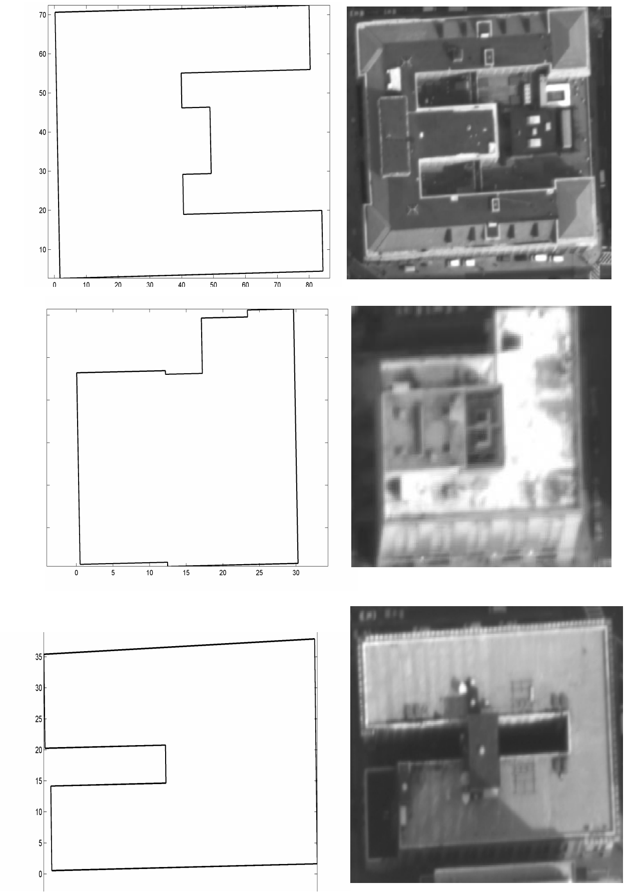

Figure 4. Some examples of regularized buildings

There are several characteristics of this least squares based hierarchical building squaring approach. First, it is robust to possible errors in building segmentation and boundary tracing. This is because of the hierarchical implementation of the solution, shorter line segments being processed after longer lines. Second, the errors of final extracted building can be evaluated through the least squares adjustment process, using either the residual values between estimated coordinates and the observed coordinates of the points or determining the distance of each of these points from the parametric lines. Third, it provides a global optimization solution to the building squaring problem. No points or line segments are taken as fixed reference. The longer line segments receive larger weights than shorter ones. All points and line segments are subject to certain adjustment in position depending on their contribution to the line segments Figure 4 present the results of several squared buildings along with their ortho-images. They are obtained from the above described regularization process.

Once the building footprints have been regularized, we can use the “Z” dimension of lidar data to obtain elevations for the parametric lines of the edges that we have determined. The 3D visualization of buildings that have flat roofs or “multiple layers of flat roofs” is accomplished by segmenting those portions of the roof that have similar “Z” values. Then these segmented parts are individually “regularized” in the manner described above. The parametric lines that define the regularized segments of the roof are given elevation values based on the average elevation of that segment of points.

As for the ridge buildings, a similar process is developed. In this case, slopes of each roof points are calculated based on a triangulation of roof points. Points with similar slope will be used to model the slant roof plane. The similar regularization is applied to form the slant roof plane. Reconstructed 3D buildings are shown in Figure 5.

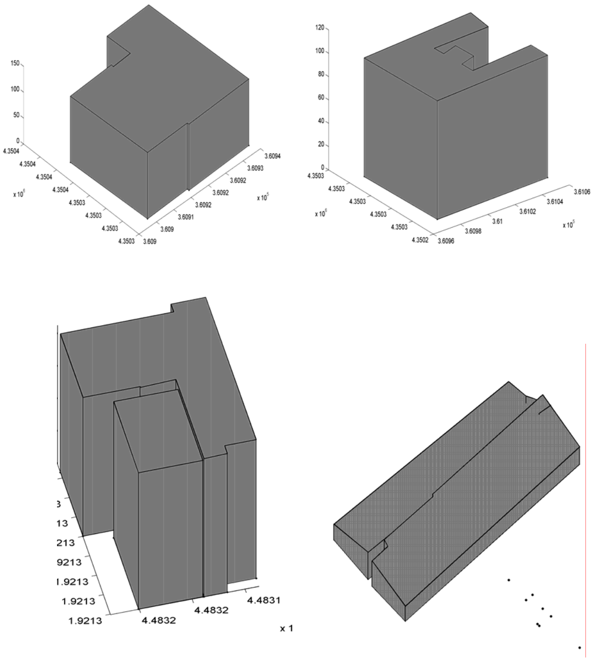

Figure 5. 3D reconstructed buildings

6. CONCLUSION

We have tried to show that lidar data can be used as a tool to model the urban environment. The series of steps described above can process raw lidar data and can be used to create building models that closely resemble the reality.

We used a novel approach to initially label the data as ground and building points. Then, we described a series of steps to segment the building point dataset, such that 3D points can be mapped to each building. This building detection and segmentation algorithm assumes that spatially separated clusters of point clouds representing separate buildings, and the distance between these clusters will be at least greater than the resolution of the dataset.

Then, the procedure to "regularize" is described. The first step in regularization is to select a set of points representing a building, and extract those points that represent its boundary. This is accomplished using a modified convex hull algorithm. A least squares based hierarchical building squaring approach is introduced. A series of steps that determine parametric equations for building edges have been suggested. In all this, an assumption has been made that the edges of the buildings have only two, mutually perpendicular directions. Since shorter line segments are processed after longer lines, errors from previous steps are minimized. In this approach, no line segment is chosen as fixed and all are subject to certain levels of adjustment in direction and position, depending in general on the length of the line segment. Such hierarchical strategy ensures our solution to be robust to the lidar data resolution and the possible non-building points mistakenly included in the previous steps.

Our experience shows that reliable segmentation is necessary for a quality building squaring outcome. Buildings with more than two principal directions and non-rectilinear edges need certain modification and adaptation of the reported hierarchical strategy.

The limiting factors in this process can be the resolution of the data. To accurately model an urban environment, the point density of the 3D point clouds should be as high as possible, and ideally the spacing should be higher than 1 meter in X and Y direction.

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