3D LiDAR BUILDING ROOF REFINEMENT USING PHOTOGRAMMETRIC DATA

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Abstract

In this paper, a methodology is proposed for the geometric refinement of LiDAR building roof contours using high-resolution aerial images and Markov Random Field (MRF) models. The proposed methodology assumes that the 3D geometric description of each building roof reconstructed from the LiDAR data (i.e., a polyhedron) is topologically correct and that it is only necessary to improve its accuracy. First, the 3D LiDAR building roof contours are projected onto the image-space through well known photogrammetric procedures. In brief, first the collinearity equations are used, along with the exterior orientation parameters, to transform the roof contours into the photogrammetric reference system, and then, an internal camera model and the associated interior orientation parameters are used to add systematic errors and to transform the roof contours from the photogrammetric reference system to the LC-image coordinate system. The projection errors are estimated and used to build bounding boxes around the projected polygon straight lines. These bounding boxes enable the straight line extraction process to be focused only on limited regions of the image, avoiding the extraction of irrelevant information. We used the Canny edge detector associated with edge-linking and polygonization procedures. Second, straight lines defining projected polygons and ones extracted by the image processing techniques are used to construct an MRF model expressing the specific shapes of building roofs. MRF models have been increasingly used in image analysis because they enable the exploitation of the local statistical dependence of image features and also allow global optimisation to be accomplished through iterative local computations. This makes sense particularly in the context of roof building extraction because it is not necessary that all straight lines interact with one another. Instead, only a few straight lines that are spatially close to one another and with specific angular relations with one another need to interact. Using projected polygons and their projection errors, the neighbouring set of straight lines associated with each building roof can be further reduced. In the resulting energy function, each straight line is associated with a random variable, giving rise to an n-dimensional random vector, where n is the number of straight lines to be considered in the optimisation process. This random vector is the unknown in the optimisation process and the value of each component assumes either 0 or 1, where the unitary value means that the corresponding straight line belongs to a roof contour. Theoretically, the search space has two to the n-th power combinations to be considered in the global minimum computation of the energy function. The brute force algorithm, associated with some domain-related heuristics, proved to be effective to solve the optimisation problem. Finally, the last step consists in re-delineating the LiDAR building polyhedron outlines, assuming that all roof polyhedron faces are accurate enough. This is carried out in two steps: 1) straight lines groupings, resulted from the optimisation procedure, are backprojected onto the polyhedron face planes by using a new line-based photogrammetric model; and 2) vertical planes of the building polyhedrons are repositioned according to corresponding 3D straight line positions determined in step 1. The obtained results show that the proposed approach works properly. As expected, the integration of image data and LiDAR data allows better results to be obtained with the building polyhedron outlines, as compared to the results provided using only LiDAR data.

1. INTRODUCTION

Building extraction methodologies are very important in the context of spatial data capture and updating for GIS applications. These methodologies can be based on either LiDAR or photogrammetric data or even on a combination between them. Several approaches have been proposed to explore the synergy between LiDAR and photogrammetric data. Haala and Brenner (1999) combined multispectral imagery and DEM (Digital Elevation Model) derived from LiDAR data for separating building from vegetation. In Sohn and Dowman (2003) buildings are independently extracted from Ikonos imagery and DEM/LiDAR data and, then, the results are combined to remove inconsistencies. Vosselman (2002) combined LiDAR, plan view, and high-resolution aerial image data to automatically reconstruct 3D building. The plan view is used as reference to extract polyhedral building model from LiDAR data. The high-resolution aerial images are used to refine the roof boundaries. This paper presents a methodology for 3D LiDAR building roof refinement using photogrammetric data. Section 2 presents the proposed methodology. The preliminary results are presented and discussed in Section 3. Finally, the paper is finalized in Section 4 presenting some conclusions and outlook.

2. METHODOLOGY

The proposed methodology comprises preprocessing steps, extraction of groupings of straight line segments in the image-space, and backprojection of straight line groupings onto the object-space, and generation of complete building roof 3D models. In the following sub-sections, some details on these steps are presented.

2.1 **Preprocessing**

The preprocessing steps mainly comprise the projection of the 3D roof contours onto the image-space and the extraction of the image straight lines that are nearby the projected LiDAR roof contours. Techniques used in these steps are well known and, as such, only basic details are presented. In order to project the 3D building roof contours onto the image-space, two basic steps are necessary. First, the collinearity equations are used, along with the exterior orientation parameters, to transform the roof contours into the photogrammetric reference system. Second, an internal camera model and the associated interior orientation parameters are used to add systematic errors and to transform the roof contours from the photogrammetric reference system to the LC-image coordinate system. The projection errors are estimated in order to construct a registration error model. The registration error model is a simple bounding box constructed around each projected LiDAR straight line, which enables the straight line extraction process to be accomplished only on limited regions of the image, avoiding the extraction of irrelevant information. There is a large amount of research in the literature in the subject of straight line extraction. Examples of methods are the Burns line detector (Burns, et al., 1984) and the Hough transform based methods (Ballard & Brown, 1982). Our algorithm for straight line extraction is based on standard image processing algorithms and seems to be effective for the present application. First, the Canny operator is used to generate a binary map with thinned edges. Next, an edge-linking algorithm is applied to the edge map for organizing the edge pixels into sets of logically-connected pixel chains. In order to extract the straight lines, the edge contours are approximated by polylines through the recursive splitting method (Jain, et al., 1995). Very small straight lines (2-3 pixels length) and straight lines differing too much in orientation (e.g., 20^o) from the projected LiDAR roof contour are removed, since they are unlikely to be valid candidates for constituting roof contours. In the last step, simple perceptual grouping rules (i.e., proximity and collinearity) are used to merge collinear straight lines and then to further reduce the number of candidates for representing the roof contours.

2.2 **Extraction of groupings of straight line segments in the image-space**

Straight lines extracted from the aerial image are used to construct an MRF (Markov Random Field) model expressing the specific shapes of building roofs, having as reference the polygons resulted from the photogrammetric projection of LiDAR roof contours. The associated energy function is defined in such way that each straight line is associated with a discrete random variable (x_i) assuming binary values according to the following rule:

$$x_i = \begin{cases} 1 & \text{iff the } i^{th} \text{ straight line belongs to a roof contour;} \\ 0 & \text{otherwise.} \end{cases} \quad (1)$$

This rule gives rise to an n-dimensional discrete random vector **x=** $(x_1, x_2, \ldots, x_n)$, where n is the number of straight lines in the optimization process. This random vector is the unknown in the optimization process. Theoretically, the search space has 2^n combinations to be considered in the global minimum computation of the energy function.

The energy function can be finally expressed as follows:

$$U(\mathbf{x}) = \alpha_1 . \sum_{i=1}^{n} x_i . R(i) + \alpha_2 . \sum_{i=1}^{n} \sum_{j|j \in N_i} x_i . x_j . P(i, j) + \alpha_3 . \sum_{i=1}^{n} \sum_{j|j \in N_i} x_i . x_j . s_\theta(i, j) \quad (2)$$

where:

- α_1, α_2, and α_3 are positive constants;
- R(i) is the ratio of the length of a projected LiDAR straight line to the length of i^{th} image-space straight line, in which the former is nearest to the latter;
- P(i, j) is a distance metric between image-space straight lines i and j;
- $s_\theta(i, j)$ is an orientation metric between image-space straight lines i and j;
- N_i is the set of straight lines neighbouring the straight line i.

The distance metric P(i, j) is defined as follows,

$$P(i, j) = \frac{1}{2}(d_i^1 + d_i^2 + d_j^1 + d_j^2) \quad (3)$$

where:

- d_i^1 and d_i^2 are the distances between the endpoints of the straight line i and the projected LiDAR straight line that is nearest to straight line i;
- d_j^1 and d_j^2 are the distances between the endpoints of the straight line j and the projected LiDAR straight line that is nearest to straight line j.

The orientation metric $s_\theta(i, j)$ is defined by tanking into account the sigmoid function, i.e.,

$$s_\theta(i, j) = \frac{2}{1 + \exp[-\beta.(\theta - \theta_o)^2]} - 1 \quad (4)$$

where:

- $\theta = \theta_i + \theta_j$;
- θ_i is the angle between the straight line i and the projected LiDAR straight line that is nearest to straight line i;
- θ_j is the angle between the straight line j and the projected LiDAR straight line that is nearest to straight line j;
- β is a positive constant;
- θ_o is the optimal value (0^o or 180^o) of the parameter θ.

In order to obtain the optimal configuration ($\mathbf{x}_{\mathbf{opt}}$) it is necessary to find the global minimum of the energy function (U(**x**)). The global minimum can be found by the so-called brute force searching method. This method is a simple and general problem-solving technique, which consists of exhaustively searching for the best candidate among all possible configurations. It is simple to implement and, if a solution exists, it always finds it. The great problem of using the brute force method is that in many practical problems the number of candidates can be so large that the problem becomes intractable. In general, the brute force method can be used when the problem complexity is relatively simple or when there are problem-domain heuristics that can allow the search space size to be reduced properly. In order to avoid the combinatorial explosion, some heuristics can be used. For example, it should be imposed that that each projected LiDAR straight line must have only one correspondence or none. It is also reasonable to expect a minimum of correspondences for the problem in hand.

2.3 **Redrawing the 3D building model**

In order to redraw the 3D building model it is necessary to transform the corresponding image-space straight lines grouping onto the object-space. Figure 1 presents the geometric principle for the projection of a single straight line segment **ab**, defined by the image-space points **a** and **b**. The pre-existing 3D building model is supposed to be previously derived from a LiDAR data set. As shown in figure 1, it is assumed for simplicity a building roof with two planar roof faces, one of them being defined by points **A´**, **B´**, **C**, and **D**. The roof boundary side **A´B´** is represented in the image-space by the straight line segment **a´b´**. The corresponding straight line segment **ab** is found by the energy equation optimisation described in Section 2.3.

The backprojection of the straight line segment **ab** onto the object-space allows the determination of the object-space straight line segment **AB**. This straight line segment corresponds to the pre-existing side **A´B´** of the LiDAR 3D roof model and can be defined by the intersection of two planes (Figure 1):

- Plane defined by the perspective centre (**PC**) of the photograph and the image-space straight line segment **ab**: since the straight line segment **ab** is extracted in the photogrammetric coordinate system (PCxyz), three basic steps are necessary to establish the plane equation in the object-space. First, points **a**, **b**, and **PC** (please note that the coordinates of this point in the photogrammetric reference system is (0, 0, 0)) is used to formulate a vector normal to the plane containing those points. Second, the obtained vector is transformed into the object-space coordinate system (OXYZ) by a rotation transformation using the three camera attitude angles. Finally, the normal vector and the **PC**, both in the object-space, are used to formulate the plane equation in the object-space. The camera attitude angles and the **PC** coordinates in the object-space are known and can be determined in several manner, as for example by the space resection method (Wolf & Dewitt, 2000);

- Plane defined by the polyhedron face that contains the roof side **A´B´** and the roof ridge **CD**: Points A´, B´, C, and D are coplanar, thus any 3-points combinations can be used to formulate the plane equation of interest.

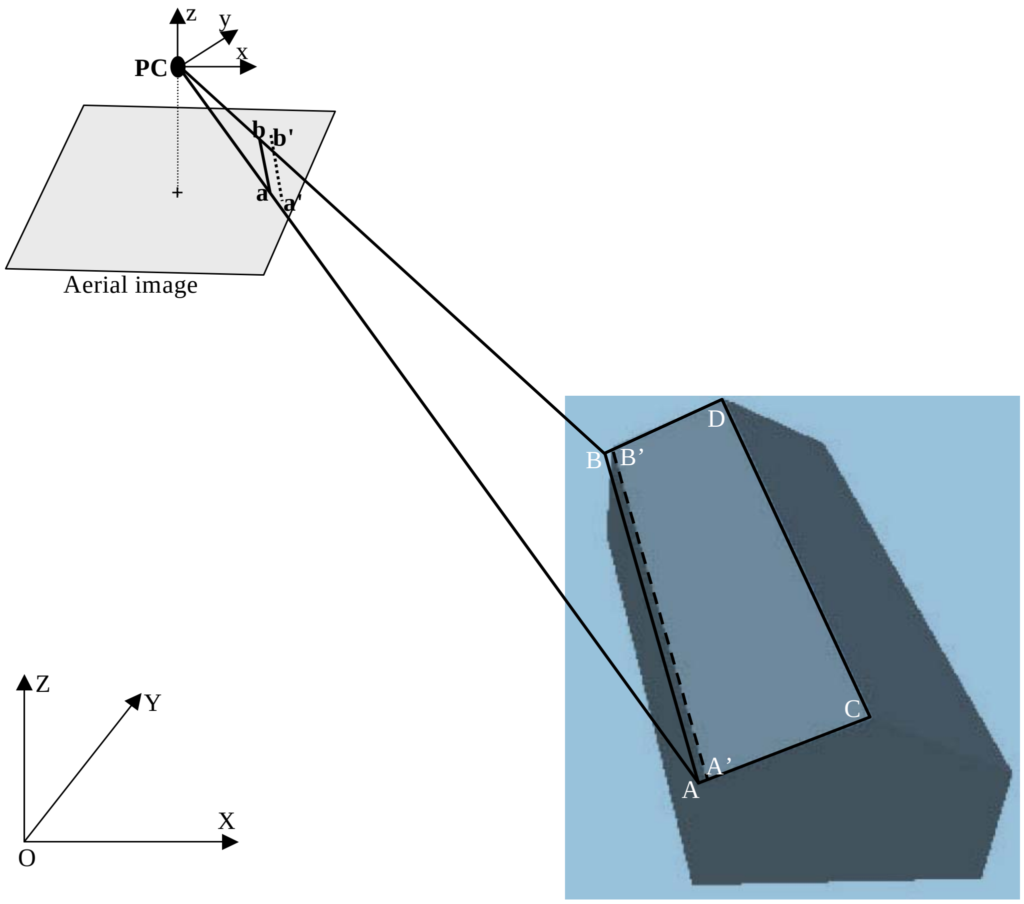

Figure 1 - Backprojection of the image-space straight line segment **ab**

The intersection between both planes generates a straight line equation in 3D, which in turn contains the unknown points A and B. These points are the new vertices of the building roof contour and their determinations can be carried out by the intersection of pairs of straight line equations obtained by means of planes defined as above.

3. EXPERIMENTAL RESULTS

The test data consists of a high-resolution aerial image and a 3D building model generated automatically by a pre-existing methodology that processes LiDAR point cloud. The test area is located in the city of Curitiba, Brazil. The image has 4500 pixels x 3000 pixels and the pixel footprint is about 20 cm. The interior and exterior orientation parameters of the image are available. Figure 2 shows the test building used in the preliminary experiment. This is an inverted E-shaped building, with a 19-side roof contour.

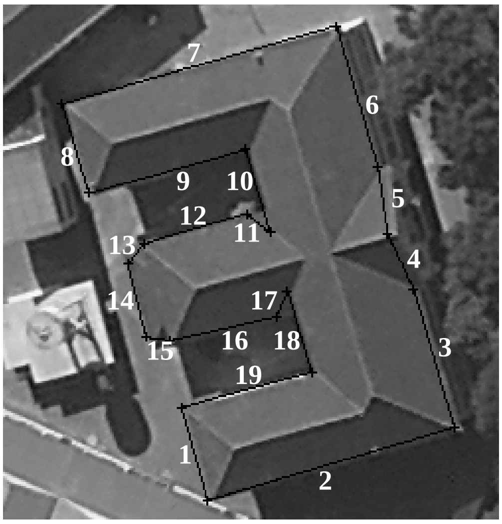

Figure 2 - Projected LiDAR straight lines

Figure 2 shows the projected LiDAR straight lines obtained through the projection of the 3D roof contour. The resulting polygon is relatively close to the building roof edges, as the registration error is about 5 pixels maximum. This registration error occurs with the LiDAR straight line 5. However, the LiDAR straight lines 13 and 15 do not approximate correctly the details that are nearby them.

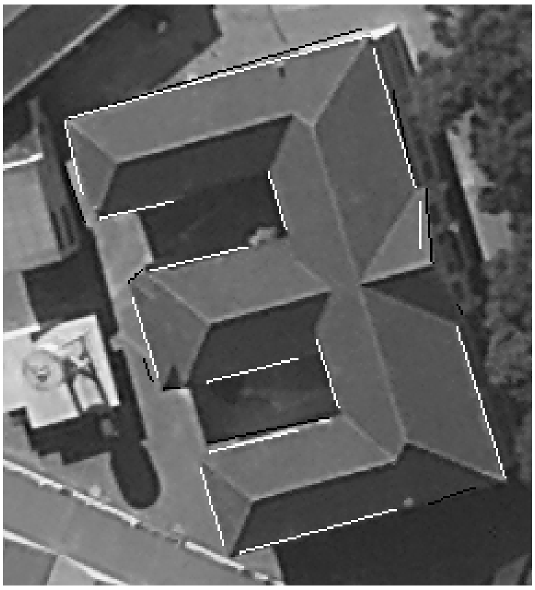

Figure 3 - Matching result

Figure 3 shows that the pre-processing steps extract twenty-four straight lines. The projected straight lines have the following number of candidate for matching: ten projected straight lines have only one candidate; seven projected straight lines have two candidate; and two projected straight lines have no candidates. This result shows that the pre-processing steps filter out irrelevant information properly. Straight lines that are successfully matched to the projected LiDAR roof contour are overlaid in white on the image. The remaining straight lines that are rejected by the matching process appear in black. As shown in figure 3, the methodology found fourteen (74%) correspondences, in which thirteen (69%) are correct and one (5%) is incorrect (false positive). Please note that the incorrect matching occurred because the matched straight lines is nearer to the projected LiDAR straight line 5 than the another candidate for matching. In addition, both candidates for matching have similar length and orientation related to the projected LiDAR straight line 5. Figure 3 also shows that the methodology did not find five (26%) correspondences (false negatives). All false negative cases are related to either the absence of candidates (i.e., the nearby LiDAR straight lines 11 and 17) or the presence of invalid candidates (i.e., the nearby LiDAR straight lines 4, 13, and 15). The projected LiDAR straight lines 4, 11, 13, 15, and 17 are kept because they do not have correspondences among the straight lines extracted by the pre-processing steps.

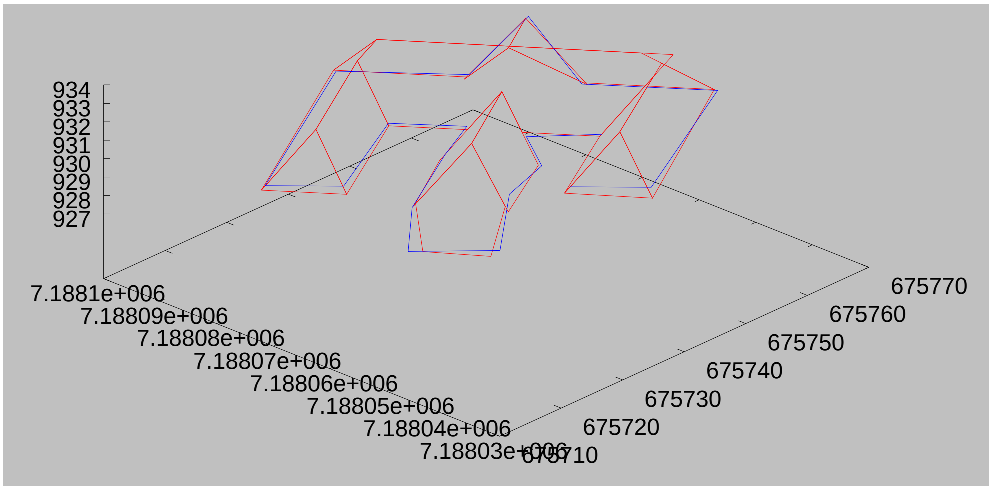

Figure 4 - Vizualization of the refiened 3D building roof contour

Figure 4 presents the refined 3D building roof contour (in blue) superimposed onto the LiDAR 3D building roof (in red). The vertex positions of refined building roof contour were determined to be about 0.67 m on average from the corresponding LiDAR building roof contour vertices. The maximum and minimum discrepancies were 1.41 m and 0.17 m, respectively.

4. CONCLUSIONS AND OUTLOOK

In this paper a methodology was proposed for geometric refinement of pre-existing 3D roof contour generated from LiDAR data set. The preliminary results showed that the proposed methodology is promising. Although only a test was presented and discussed, it involves a building with a relatively complex geometry and with a low contrast against the background. Using the image building outline as reference, it was possible to conclude the most sides of the refined polygon are geometrically better then corresponding projected LiDAR straight lines. The comparison between both building 3D models shows that the vertex positions of refined building roof contour were determined to be about 0.67 m on average from the corresponding LiDAR building roof contour vertices.

Some directions for future developments are the improvements of the energy function and the use of more appropriate optimisation methods (as, e.g., the simulated annealing algorithm) of the energy function, mainly to allow high-dimensional problems to be treated properly. The energy function can be improved tanking into account the shadow information, the corner information, and the laser heights, besides other cues.

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