

REFINING EXISTING 3D BUILDING MODELS WITH TERRESTRIAL LASER POINTS ACQUIRED FROM A MOBILE MAPPING VEHICLE

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KEY WORDS: Terrestrial, Laser scanning, Building, Model, Registration, Adjustment, Point Cloud, Matching

ABSTRACT:

This paper presents a method to automatically refine existing 3D building models with laser points acquired from a terrestrial mobile mapping system (MMS). 3D models derived from aerial imagery are in general less accurate than 3D information derived from terrestrial laser scanning. Therefore, point clouds are used to refine these models in order to make them precisely correspond to the scanned façade geometry. After a preliminary global registration using the ICP algorithm, each visible façade is individually processed and compared to a filtered point cloud containing only the façade points. First, an individual registration fits the façade plane to the laser points. Then the façade corners are detected in the point cloud by analysing changes in the gutter height. As façade contours can be skewed by lateral cornices, the latter are also detected to refine delineations. Finally, façade corners are adjusted in order to restore original connections between buildings. As a result, each façade of the model is accurately positioned and delineated thanks to the laser point cloud, whilst respecting the structure and the topology of the original model. The façade number and verticality are preserved. This algorithm was tested on several data sets from different MMS and showed satisfactory results, without any preliminary adjustments from the user.

1. INTRODUCTION

City modelling is an expanding subject of study, stimulated by the advent of virtual worlds devoted to the general public such as the ones provided by Google Earth or Visual Earth. First 2D, then 3D, the city models are expected to be increasingly accurate and complex. The refinement of existing models is therefore an important area to explore. Terrestrial laser point clouds are very appropriate for the geometrical refinement of existing models. Terrestrial mobile mapping systems (MMS) are experiencing considerable development. As they are most frequently equipped with high resolution cameras, laser scanners and very precise geo-referencing systems, they are a major source of information for modelling urban environments. Such systems provide geo-referenced 3D data with an accuracy of a few decimetres, depending on the GPS signal quality (Barder et al., 2008, Haala et al., 2008). Most studies related to terrestrial laser scanning focus on the production of 3D models from laser data (Früh et al., 2005, Pu and Vosselman, 2009a). However the massive production of city models based on terrestrial laser data is not yet mature, due to the potential complexity of the models and their environment. A solution consists of producing coarse building models using aerial LIDAR or aerial imagery, then refining them with terrestrial laser scanning. In the literature, the refinement of building models often refers to adding details such as roofs, windows and doors onto the façade planes of previously generated 3D building model (Becker and Haala, 2007, Pu and Vosselman, 2009b). This paper focuses on another aspect of the refinement, which is the accurate positioning and delineation of the façades.

Siradel has produced many 3D city models, from all around the world, using stereo aerial imagery. These data have a metric accuracy. This study aims at refining the façade positions and delineations in order to improve the 3D model accuracy. The

reference data are georeferenced terrestrial laser points acquired from a mobile mapping vehicle. The originality of the method is the preservation of the initial model structure during the process. In particular, the number of façades stays unchanged.

Section 2 introduces previous work about registration of 3D models against point clouds. Then our method for refining 3D building models is presented in section 3. It consists of two main stages: the registration of the two data sets, detailed in section 4, and the delineation of the façades, described in section 5. The results are presented and discussed in section 6. Finally, conclusion and future work are presented in section 7.

2. RELATED WORK

Little literature can be found about refining the accuracy of 3D models using georeferenced terrestrial laser points. However several studies have tackled the inverse problem of georeferencing laser point clouds by registration against existing 3D models (Haala, 2004). In both cases, the issue is to register two data sets acquired with different geo-positioning systems.

Rigid registration consists of finding the parameters of the six degrees of freedom transformation connecting two 3D data sets. The registration of 3D models against laser points can be carried out through different methods. One approach consists in first extracting planes from the point cloud, using the Hough transform for instance, then finding correspondences between planes (Koshelham and Gorte, 2009, Dold and Brenner, 2008). However the most popular algorithm to register 3D data is the Iterative Closest Point (ICP) introduced by Chen and Medioni (Chen and Medioni, 1992) and Besl and McKay (Besl and McKay, 1992). It is particularly well adapted to 3D model registration on laser point clouds (Schumacher and Böhm,

2005). It is also independent of possible errors induced by plane extraction. ICP is an iterative algorithm. At each iteration, the algorithm selects points $p1_i$ in the first set and their closest match $p2_j$ in the second set, then computes the rotation \mathbf{R} and translation \mathbf{t} minimizing the distance between the points:

$$E(\mathbf{R}, \mathbf{t}) = \sum_{i=1}^{N_1} \sum_{j=1}^{N_2} w_{i,j} \|p1_i - (\mathbf{R}p2_j + \mathbf{t})\|^2, \quad (1)$$

where N_1 and N_2 are the number of points in each point set, and $w_{i,j}$ is the weight associated to the point match $(p1_i, p2_j)$. This algorithm always converges monotonically to the nearest local minimum of a mean-square distance metric (Besl and McKay, 1992). The ICP algorithm needs a good initialization to converge to the best solution, which is not an issue in this study because both data sets are geo-referenced. ICP was improved through many versions, differing in the point selection method, the determination of the closest match, the weights, the rejection of correspondences, or the error metric (Zhang, 1994, Rusinkiewicz and Levoy, 2001, Bae and Lichti, 2004, Gruen and Akca, 2005).

3. PRESENTATION OF THE APPROACH

After introducing the input data and the pre-processing steps, the workflow of our method is presented.

3.1 Input data

The 3D models are derived from aerial geo-referenced images. The laser point clouds are acquired by various terrestrial mobile mapping systems equipped with lateral laser scanners. The laser points are geo-referenced thanks to a very precise geo-referencing system composed of a Global Positioning System (GPS), an Inertial Measurement Unit (IMU) and an odometer. The point position is corrected using Kalman filters.

3.2 Pre-processing

Before processing, the input data need to be filtered. Firstly, relevant façade polygons and relevant laser points are selected, then each selected façade is associated to its corresponding laser points.

3.2.1 Façade polygon selection Within the process two kinds of façades are distinguished: the "frontal" façades, that can be scanned by the mobile mapping system, and the "lateral" façades, often perpendicular to the road axis, that are not clearly visible in the point cloud. The lateral façades can skew the results of registration by introducing unreliable points in the process. In order to limit errors, only frontal façades are selected from the model and further processed. These façades are selected according to the following criteria:

- they are not parallel to the scan axis of the laser beam;
- they are within the area scanned by the laser (threshold on distance);
- they are oriented towards the street.

3.2.2 Façade point selection As the laser point cloud contains points representing building façades as well as points representing pavement, trees, cars, pedestrians or any other kinds of occluding objects that would skew the process, most irrelevant points are filtered out.

The filtration of the point cloud is carried out through the study of an accumulation image. In this image, each pixel represents a small area on the ground, and allows the storage of both the number of laser points projected on this area, and the maximal elevation of these points (as shown in Figure 1). A double threshold on point density and elevation is applied on this image. A pixel is said associated to a façade if:

- its maximal elevation is high enough to characterize a wall rather than a low object;
- its density value is high enough to characterize a vertical object.

The first criterion discards points describing low objects. The second criterion discards most points related to trees. It was clearly observed that walls accumulate many laser points in a small ground area, whereas tree leaves collect laser points on a large but not dense area. As the point cloud density decreases with the distance to the laser scanner, the threshold on density varies with the distance between the laser source and the area represented by the pixel.

The filtered accumulation image of one of the test areas is presented in Figure 2. In the following, the resulting filtered point cloud will be used instead of the original cloud, and it will be referred as the "reference" point cloud.

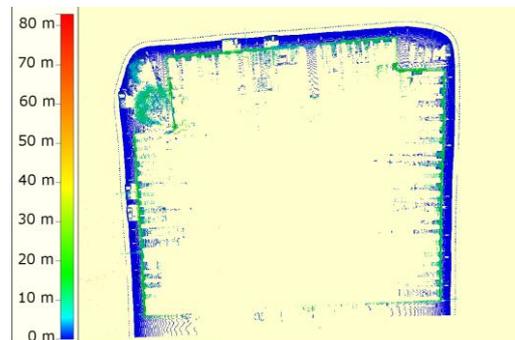


Figure 1: Image of point elevation.

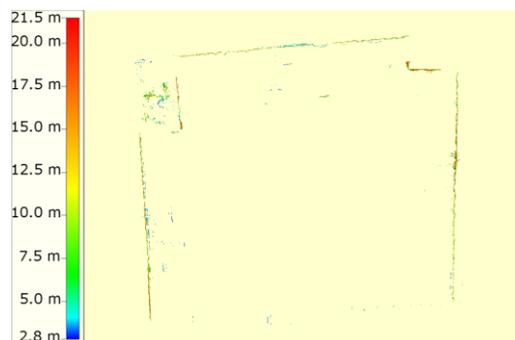


Figure 2: Image of point elevation after filtering. Ground and small objects points are removed. In this example, walls are kept but one tree is kept too.

3.2.3 Façade to point association Frontal façades of the 3D model are finally associated to their corresponding laser points. For a given façade, the selected points are distant of less than 50 cm to the façade plane, and their orthogonal projection on this plane is located inside the façade polygon.

3.3 Method overview

Following the pre-processing stage, the façade refinement process consists of two main steps, as shown in Figure 3. First

the model is registered against the laser points, including both a global and a local registration of the façade planes (see section 4). Then the façades are delineated and topologically connected (see section 5).

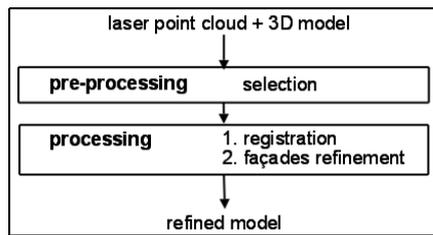


Figure 3: Process workflow.

4. REGISTRATION

The model-to-point registration is performed within two steps: first a global registration of the two data sets is performed, then each façade plane is locally registered to the laser points.

4.1 Global registration of the 3D model

The first step to refine a 3D building model with a laser point cloud is to register the two data sets. As each type of data was geo-localised with a different geo-positioning system, there is a shift induced by individual positioning errors. Therefore a rigid registration is performed.

4.1.1 Model registration The global rigid registration is performed with the ICP algorithm. The initialization is given by the geo-positioning of the 3D vectors. In order to use the ICP algorithm, a "target" point cloud is first derived from the model, by sampling the frontal façades. This target point cloud is then registered against the reference laser point cloud using ICP.

4.1.2 Model verticality constraint As the input 3D model describes buildings, a verticality constraint has been introduced on the registered model: the façades should stay vertical. Only the heading is allowed to change, whilst the pitch and roll should be kept to 0°. As ICP works on six degrees of freedom, the resulting model can be rotated and thus will no longer respect the model verticality. Therefore, after each ICP iteration, the whole model is rotated so that the final orientation respects the model verticality constraints.

4.2 Individual registration of the visible façades

At the previous step, the 3D model has been globally registered against the point cloud. Each frontal façade is then independently registered against the reference laser point cloud using again the ICP algorithm. As previously, the registered façades are subsequently rotated in order to respect the model verticality constraint (cf. section 4.1.2).

Importantly, the topological connections between lateral and frontal façades are preserved. Lateral façades that are originally connected to two frontal façades (from a single building or from two different buildings) are adjusted in order to stay connected to these façades (cf. figure 4). The lateral façades that are originally connected to only one frontal façade are also adjusted to stay connected to the façade, whilst keeping their original orientation (their normal vector stays the same). The lateral façades provide a way of detecting and correcting major registration errors: if their orientation has significantly changed

during registration, then the local registration is discarded and one of the refined façades is moved back to its previous position. Figure 5 shows a 2D view of a model at different steps of the registration.

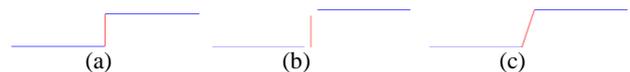


Figure 4: Connections between a lateral façade (red) and two frontal façades (blue). (a) Original positions. (b) Positions after individual registration. (c) Positions after restoring connections.

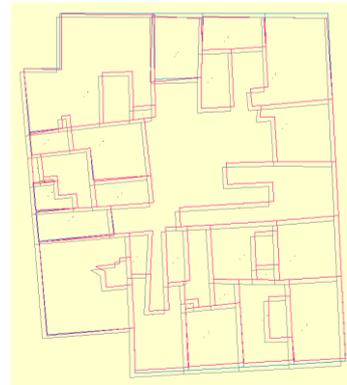


Figure 5: 2D views of the model : original model (grey), model after global registration (blue), and model after individual registration (pink).

5. FACADE DELINEATION REFINEMENT

At this stage, every frontal façade of the model has been fitted to the best corresponding plane in the point cloud. However the façade boundaries of the model do not exactly match the real building boundaries (see Figure 6), and the original topology is not preserved. We propose to refine façade delineations within four steps:

1. Façade top boundary detection;
2. Façade lateral boundaries detection;
3. Façade bottom boundary detection;
4. Façade connection.

5.1 Façade top boundary detection

In the original model, two buildings are distinct if the gutter heights differ from more than two meters. The height of each building was measured at the gutter level. In order to delineate buildings in the point cloud, it is therefore necessary to detect gutters and their changes in height.

The gutter altitude is derived from the laser points for every façade. It is determined through the study of an elevation histogram computed over the associated point cloud (see Figure 7). Due to its prominent shape, the gutter is characterized by a peak in the histogram, followed by an area without points. In this histogram, the class containing most points within the research interval is identified as the "gutter peak". The top of the gutter is then inferred as the highest downward gradient after the gutter peak in the histogram. Each scanned façade is then associated to a reference gutter altitude derived from the laser cloud. The maximal altitude of the laser points associated to a façade is also recorded: it corresponds either to the gutter altitude itself, or to the dormer altitude.

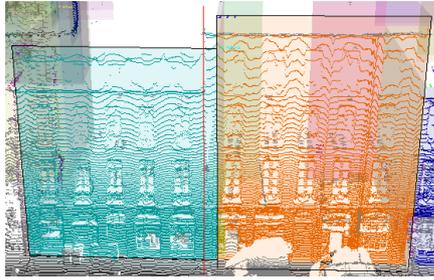


Figure 6: Example of façade boundaries (in black) that do not match the real façade geometry given by the point cloud (delimited in red).

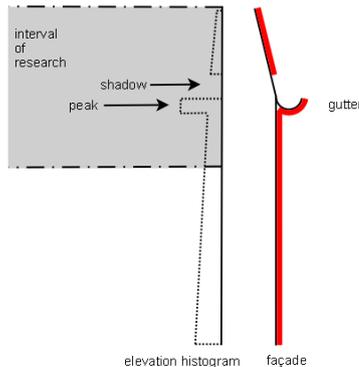


Figure 7: Diagram of the gutter detection principle. On the right is a representation of a façade profile, with the scanned area in red, and on the left is the associated histogram.

5.2 Façade lateral boundaries detection

The laser points neighbouring the original façade boundaries are studied to detect changes in the gutter altitude and locate the real lateral boundaries.

5.2.1 Inside exploration The first step consists in exploring the laser points associated to the façade itself in order to detect any local change in height. Along the façade, the maximal altitude of each scan line is individually analysed. This altitude can be the one of the current façade (gutter or dormer altitude), the one of an adjacent façade, the ground altitude, or the altitude of an occluding object. This altitude is recorded whenever it is different from the gutter height or the maximal height of the current façade.

5.2.2 Outside exploration If the façade width is underestimated, the façade real boundaries are located outside the input façade polygon. Thus the second step consists of studying the laser points located outside the façade near the façade boundaries. The outside exploration is performed in the same way as the inside exploration.

5.2.3 New façade lateral boundaries From the information collected during exploration, new lateral boundaries are determined for each façade. During this operation, the lateral façades stay connected to the frontal façades.

5.2.4 Façade lateral boundaries refinement The lateral boundary detection is based on the analysis of changes in the gutter elevation. However it can be affected by lateral cornices that artificially enlarge the façade width.

The chosen approach for correcting artefacts due to cornices is similar to the one used to detect façade corners (see Figure 8). The scan lines are analysed in turn, starting from the lateral border and going inside. Only scan lines associated with points regularly distributed over the building height are valid. The lateral boundaries of the façade are refined accordingly.

When the lateral boundaries of the frontal façades are modified, the boundaries of the adjacent façades (frontal or lateral) are modified too, in order to respect the model initial topology.

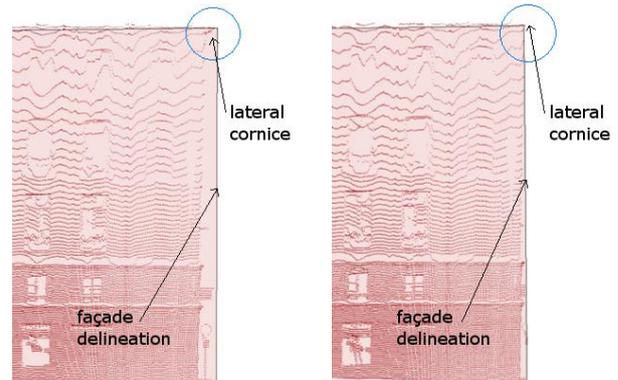


Figure 8: Example of a façade boundary before (left) and after (right) cornice detection.

5.3 Façade bottom boundary detection

The bottom boundary of each façade is determined as the intersection between the façade plane and the ground surface, derived from the original point cloud. The determination of the ground surface is achieved by combining histogram analysis and region growing techniques. More details about the method will be provided in a subsequent paper.

5.4 Façade connections

At this stage, the building geometry and topology may be corrupted, and the topology is not necessarily preserved. For example, some façades in the resulting model can be superimposed or topologically disconnected although adjacent in the original one. In order to correct these errors, each façade is studied with respect to its originally connected neighbouring façades. If the façades are no longer connected, the connection is restored by joining the lateral edges, as shown in Figure 9. Note that the plane orientation can be slightly modified by this operation.



Figure 9: 2D views of façades before (left) and after (right) façade connection.

6. EXPERIMENTATION

The method was tested on several laser data sets acquired with different mobile mapping systems and different kinds of laser scanners. In order to maximize automation and avoid any user intervention, the parameter values are either automatically computed or common to all data sets.

The results are illustrated on a data set covering three sides of a building block in the old town of Rennes, in France. The streets are narrow, and composed of buildings from the 18th century aligned with different heights.

Figure 10 shows the initial data and the results of model refinement at different steps of the process. Figure 10(a) shows the reference point cloud. It was acquired at a speed close to 40km/h. The laser scanner has a 180° wide aperture and recorded one point every degree. In the point cloud many façades are occluded by cars, pedestrians, trees, etc. Figure 10(b) shows the input 3D model. The building heights were captured at the gutter level. The ground level was imported from a Digital Terrain Model. Initially, most of the model buildings do not match the laser point cloud as seen in Figure 10(c). After global registration, approximately half of the façades match the point cloud but the model still needs to be refined as shown in Figure 10(d). After individual registration of the frontal façades, Figure 10(e) shows that every scanned façade matches a plane in the point cloud. However, the façade delineation is not correct. Finally, after the refinement stage, the façades exactly match the building delineations in the laser point cloud, as shown in Figure 10(f).

Figure 11 illustrates some results on another data set. Despite the fact that the top of the buildings was not scanned by the system, the façade are correctly delineated by the algorithm.

Most problems come from occlusions, trees in particular. Not only do they significantly disturb the façade scan homogeneity, but they also introduce biases in the detection algorithms. A specific algorithm for detecting trees in the point cloud should help making the process more robust. The method also occasionally fails in finding cornices, resulting in slightly mislocated lateral boundaries.

7. CONCLUSIONS AND FUTURE WORK

In this paper we have presented a process to automatically refine the façade boundaries of an existing 3D building model without changing its structure or topology. The reference data are laser point clouds acquired with a terrestrial mobile mapping system. An algorithm based on ICP registration and geometry analysis has been designed. This algorithm was tested on several laser data sets describing dense urban areas, without requiring a fine tuning of the parameter values. The resulting models show a good correspondence between the façade boundaries and the point cloud geometry. The process is fully automatic and does not require any manual intervention. More data sets are currently being tested and the improvement of the resulting 3D model accuracy will be numerically assessed. Future work will focus on further refinement including tree detection and façade subdivision.

ACKNOWLEDGEMENTS

The authors would like to thank the MATIS laboratory of the French national geographic institute (IGN) for providing one of the experimental laser data sets.

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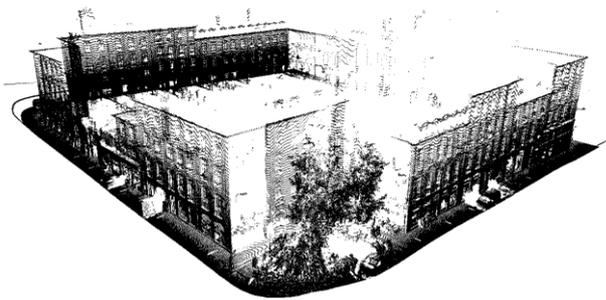
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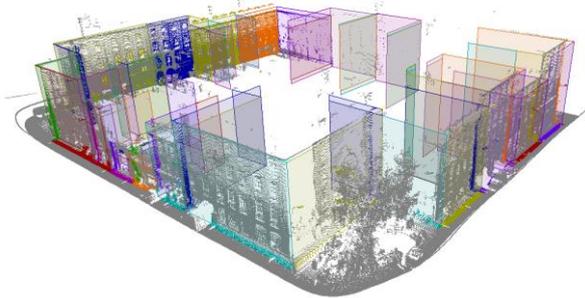
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(a) Laser point cloud.



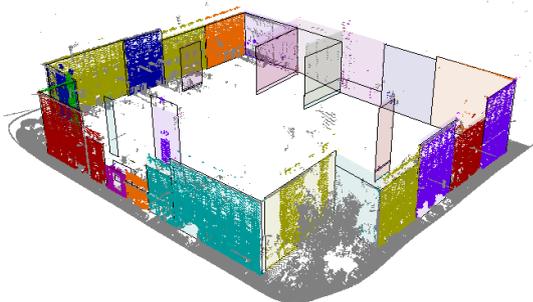
(b) Initial 3D model.



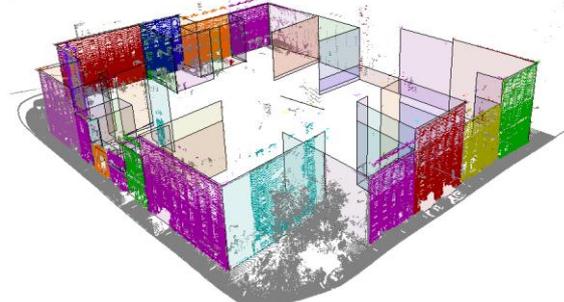
(c) Initial relative positions of laser points and 3D model.



(d) Relative positions after global registration.

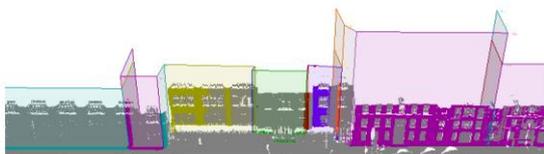


(e) Relative positions after individual registration

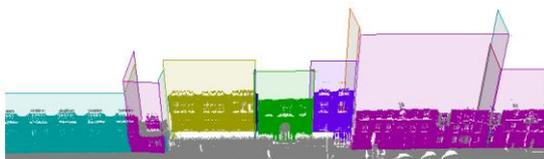


(f) Final relative positions after the refinement process.

Figure 10: Relative positions of laser points and 3D model at different steps of the refinement process (matched points are coloured, unmatched points are grey).



(a) Initial relative positions of laser points and 3D model process; (the building top was not scanned by the system).



(b) Relative positions after the refinement the façades are correctly delineated.

Figure 11: Illustration of the results on a data set from Paris (matched points are coloured, unmatched points are grey).