

EXTRACTING WIRE-FRAME MODELS OF STREET FACADES FROM 3D POINT CLOUDS AND THE CORRESPONDING CADASTRAL MAP

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Commission III/3

KEY WORDS: 3D city modeling, 3D street reconstruction, 3D point cloud, terrestrial laser scanning, cadastral map, Hough transform.

ABSTRACT:

This paper presents an operational approach for extracting wire-frame models of street facades. Georeferenced terrestrial laser rawdata are acquired by a Mobile Mapping System (MMS). The MMS constitutes an adapted tool to massively collect accurate data at street level. After a filtering step of the 3D raw point cloud of street, the street point cloud is segmented into a cloud of dominant facade walls. Piecewise quasi-planar facade cloud are then extracted using an adapted Progressive Probabilistic Hough Transform (PPHT). At the planimetric level, a cadastral map issue from an urban database is employed to segment the cloud of planar clusters into residential facade portion. Finally, each portion is vertically delimited using heuristic approaches. The adapted PPHT allows the automatic modeling of facade outlines with a fine facade line detection and a low computation time. The adapted approach has been tested on a set of point clouds acquired in the city of Paris under real conditions. Examples and experimental results show the efficiency of the proposed approach.

1 INTRODUCTION

In cartographic fields, many research works deal with city modeling using aerial data. Aerial data are very useful for the coverage of large areas such as cities. Several aerial-based approaches have been developed. They provide 3D city models with a satisfying reconstruction at roof level.

However, in most aerial-based 3D models, the facades are coarsely fitted by planes. Indeed, the Level Of Detail (LOD) according to the 3D CityGML¹ standard is often limited in this case to the LOD2 modeling (e.g., simple polyhedral models) mainly due to the angle and to the scale of view. Moreover, the 3D limits of roofs from aerial-based models (gutters limits) generally do not model the 3D limits corresponding to the intersection of the facade walls and the roofs. Actually, some applications dedicated to the virtual navigation and to the urban planning require the generic extraction of facade limits with higher qualities and a better localization. For these reasons, we are interested in LOD2 terrestrial-based modeling (wire-frame models) and in LOD3 modeling (e.g., models with windows and balconies). The current work belongs to LOD2 modeling.

Consequently, we use terrestrial data to accomplish this task. The terrestrial devices of acquisition are either static, either mobile and the collected rawdata are image and/or laser. Static devices have been initially employed for modeling individual or block of buildings. These systems are well adapted for the cultural heritage conservation but not suitable for mapping building facades at large scale (streets, districts, cities). The acquisition of large areas implies the usage of Mobile Mapping Systems (MMS).

Indeed, the recent developments in MMS allows to rapidly acquire georeferenced laser and image data of facades. However, the acquisitions at large scale generate additional difficulties in the 3D facade modeling. The employed data are more complex due to the massive acquisition *under real conditions* (e.g. continuous acquisition, large quantity of data, diversity of shapes,

lots of mobile occluding objects, arbitrary sensor orientation, arbitrary trajectory of acquisition). More details about these constraints are given in (Hammoudi et al., 2009).

Hence, the performance of approaches for extracting detailed facade models requires a lot of improvements. In this paper, we address **the 3D modeling of street facades**, e.g extracting wire-frame models of residential facades (figure 1(d)) using georeferenced laser rawdata acquired in *dense urban environments* (figure 1(b)) and the corresponding cadastral map (figure 1(c)).

The paper is organized as follows: Section 2 states the motivation of the work. Section 3 describes various existing laser-based approaches for dominant building facade extraction. Section 4 presents the global strategy of the proposed approach. Section 5 to section 8 describe the major stages of the approach; namely segmentation, extraction, and delimitation of street facades using a georeferenced raw point cloud and the corresponding available cadastral map. Section 9 gives several results and evaluations of major steps.

2 MOTIVATION

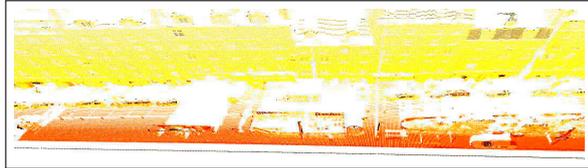
3D city modeling needs geometrical enrichments at street facade level. In this study, we aim to model 3D limits of street facades in order to bring improvements for some cartographic research topics. Several topics we are working on are mentioned below. These topics describe the potential use of these limits.

Updating building footprints. Many research activities on city modeling have focused on the automatic generation of 3D building models from aerial images. Firstly, most pipelines which have been developed for 3D city modeling employ two kinds of data in the focusing stage (i.e. the building selection stage). On the one hand, they use *building footprints* (individual or in block) coming from cadastral maps digitalized, vectorized and adapted (figure 1(c)). On the other hand, they employ building footprints generated from aerial images (manual selection or edge-based extraction). These ones lack precision due to the nature of the data and to the associated extraction methods. In these cases, extracting fine and more accurate building footprints is required. Hence,

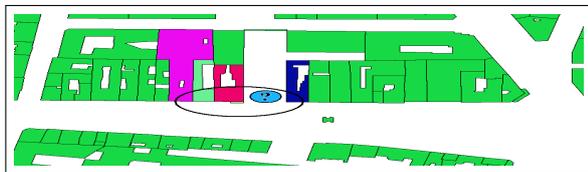
¹Link to the CityGML website: <http://www.citygml.org>



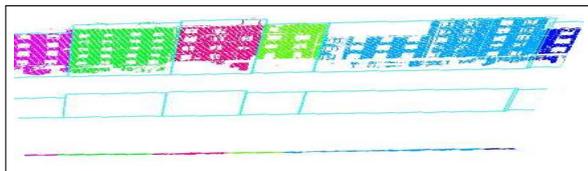
(a) A part of a panoramic image of a Parisian street under study of the 12th district.



(b) Street laser rawdata acquired by the MMS. Some laser shadow are observed. The black line represents the vehicle trajectory.



(c) Map of building footprints (based on a cadastral map) coming from a standard database of the French national mapping agency. Initially, this map has been made as input for aerial-based modeling pipeline. The facades marked by an oval are shown in figure 1(d).



(d) Outlined facade clusters at the top. Wire-frame model of the facades at the center. Planimetric footprint of each cluster at the bottom.

Figure 1: Illustration of the input/output of the proposed approach when applied on a given street laser data (b). Note that the optical image shown in (a) is included here for illustrating the scanned scene. The optical images are not used by our proposed approach.

the 3D limits that we estimate can be employed at planimetric level to generate the 2D building footprints at facade level, thus used as input of modeling pipelines. Secondly, the research on mapping tends also towards the automatic generation of cadastral map. The *cadastral map* (e.g. like figure 1(c)) is initially employed for the national taxation of each citizen according with the size of his dwelling. The generation of this map in a manual way requires many surveyors to make measurements in the terrain and stays very expensive. In this condition, the extraction of facade limits using laser data from a MMS can be employed to automatically update cadastral maps.

DEM's correction. Many urban modeling approaches employ as input Digital Elevation Models (DEMs) generated from aerial images. However, these DEM's can be inaccurate at facade limits (e.g. smoothed right angles) and undoubtedly need geometric correction. The fine extraction of the 3D limits will be useful to establish DEM's corrections at facade level.

Building modeling. The fine mapping of building facade from aerial-based framework is a complex task. Research works on city mapping tend to develop approaches for facade mapping at large scale from terrestrial acquisition. One of the aims consists in combining in a coherent way aerial and corresponding terrestrial data in order to finely model full facets of buildings (roofs and facades). In our case, the goal consists in modeling outlines of residential facades (i.e. a wire-frame model of street facades)

using a MMS at street level. The proposed method can be used for a district or for an entire city. The enhancement of the geometrical quality in city model at facade level is of great interest for applications like city planning or virtual navigation.

Segmenting street images. In the framework of our work, we dispose of a Google like web-based street viewer². This street viewer employs data collected by the MMS to provide to the general public, city visualization/navigation at street level through georeferenced panoramic images. The projection of the 3D georeferenced delimitations of each facade onto the corresponding georeferenced images allows the segmentation into street facades images and the remain of the scene. On the one hand, the facade images (facade areas) are of great interest for research on *urban scene semantization* (e.g. facade keywords extraction or facade retrieval in image databases). On the other hand, the facade images can be employed as input for *texturing* the generated wire-frame models (our approach) as well as existing 3D city models at facade level.

3 RELATED WORKS

This section briefly describes some *existing laser-based approaches for facade extraction*. The proposed approaches achieve the extraction of facade walls under various conditions and with different goals.

(Wolf et al., 2005) use a MMS for data collection and propose a method generating compact 3D maps of urban environments using a mobile mapping robot. The mobile robot acquires a 3D point cloud of building facades using a range laser sensor at alley level on a university campus (semi-urban environment). The buildings under study are isolated and have simple polyhedral shapes (rectangular footprints). The proposed approach employs a Hough Transform based approach to fit each facade wall into a plane using partially occluded (trees and bushes) 3D point clouds. The plane extraction step assumes that facade walls are large and vertical. Finally, the facade planes are delimited by fusing extracted planes. The authors generate approximated prismatic building models, i.e. elementary facade wall with constant height. The proposed approach is convenient for applications that do not require a high level of details (e.g. visualization of large spaces, path planning).

Another method is proposed by (Hammoudi et al., 2009) for automatic extraction of building footprints and corresponding dominant facade planes. They use ground-based laser data acquired in dense urban environment. A MMS turns around a block of joined buildings having simple planimetric shapes (polygonal footprints). The proposed approach employs a *K*-mean clustering in the Hough space in order to extract planar clusters of facades. This approach does not require previous knowledge of the number of facades in the input dataset and is relatively robust for the heterogeneous densities of facade points. Finally, dominant facade planes are implicitly delimited at a planimetric level by intersecting 2D facade lines (footprints extraction). One of the goals is the extraction of building footprints for the input of 3D building reconstruction framework using aerial images.

In (Alshawa et al., 2009) and (Boulaassal et al., 2009), an approach is presented to automatically segment and extract planar facades using a low cost laser mobile mapping system on large sites. A MMS acquires a 3D point cloud of building facades using a range laser sensor. The illustrations show the facade of a part of a street. The proposed approach uses a RANSAC algorithm applied sequentially to detect the planar clusters (doors, windows) and the dominant facade plane. A Delaunay triangulation is applied on the dominant planar cluster and edge points corresponding to the extremities of the longest sides in the triangulated network are extracted. These edge points characterize the

²Link to the ITOWNS project: <http://www.itowns.fr>

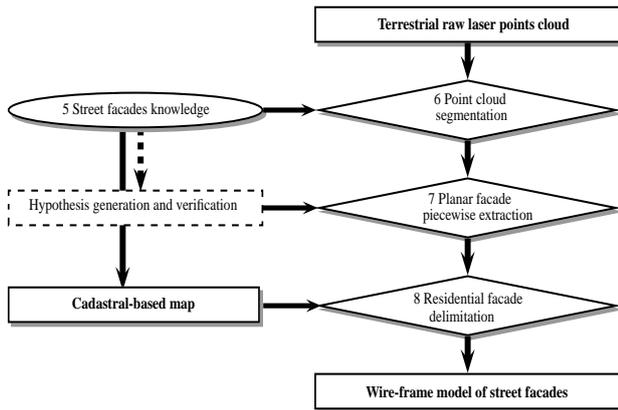


Figure 2: Flowchart diagram of the proposed approach for extracting wire-frame model of street facades.

outer edges (wall outlines) and the inner edges (holes like windows) of facades. The obtained edges can thus be reconstructed in order to produce a CAD model of building facades.

In (Rutzinger et al., 2009), an approach for automatic extraction of vertical walls from terrestrial and aerial mobile laser scanning is presented. The laser datasets correspond to a city street of residential buildings (separated buildings). A vehicle is equipped on the back with two rotating laser scanners. Data are also acquired with helicopter mounted scanners with forward, backward and nadir directions. The dataset contains static and mobile objects (vehicles, pedestrians). The vertical walls are extracted using the same segmentation and classification approach for both datasets. A growing region segmentation is performed to extract planar clusters. Seed surfaces are found by the usage of a 3D Hough Transform (HT). The usage of independent or combined aerial and terrestrial scans is discussed (completeness, accuracy, visibility) with the goal of optimizing datasets for 3D city modeling and map updating.

4 PROPOSED APPROACH

The proposed approach aims at automatically extracting wire-frame model of street facades using 3D point clouds of streets and the corresponding cadastral map.

4.1 Characteristics of acquisition

Our MMS is equipped with a Terrestrial Laser Scanning system (TLS system). This one is a 2D profile scanner oriented perpendicularly to the vehicle trajectory. The third dimension is induced by the vehicle displacement. The MMS is able to scan street facades with a density of hundreds of 3D points per square meter. The obtained 3D point cloud is sufficiently dense to recognize facade walls and also more detailed objects. More details on the device of acquisition are given in (Hammoudi et al., 2009).

4.2 Global strategy

The 3D modeling of urban objects is divided into three main stages. Namely, the focusing stage which allows the delimitation of the area corresponding to the facades. This stage includes a pre-filtering step and a segmentation step. Secondly, the features extraction stage, providing some geometrical features (straight segments, planar clusters) and finally a modeling stage consisting in the assembly into 3D facade models of these geometrical features and the delimitations provided by the cadastral-based map; namely a wire-frame model of street facades in our case. However, before all the stages, an important prior task is the analysis

of the input dataset (raw laser cloud of a street) and the collection of a priori knowledge related to the object of interest (street facades). Figure 2 shows the flowchart diagram of the proposed approach. The proposed approach employs a *hybrid bottom-up and top-down modeling strategy*. Indeed, on the one hand, the approach is composed of a feature extraction stage and a modeling stage for features assembling. On the other hand, the approach employs a priori knowledge of street facades to provide some geometrical facade characteristics and particularly an existing cadastral-based map (2D building models). Besides, the planar clusters are extracted by generating hypothetical straight lines with a Progressive Probabilistic Hough Transform (PPHT) based approach and estimated real lines are extracted by verifying conditions in part similar to the RANSAC (RANDOM SAMPLE CONSENSUS) algorithm. For this reason, our approach can also be classified into 3D modeling approaches using a *strategy of hypothesis generation and verification*.

The remainder of the paper is organized as follows: section 5 describes various a priori knowledge on street facades that can be useful for 3D street facade modeling. Section 6 describes processing steps for segmenting a street cloud into a cloud of facades. Section 7 explains in more detail the algorithm specially developed for the facade planar cluster extraction. Section 8 describes the stage of residential facade delimitation. Section 9 shows the results and evaluations of major steps. Section 10 gives conclusions and perspectives.

5 A PRIORI KNOWLEDGE ON STREET FACADES

The urban environment of the city of Paris is composed of street facades with various and complex architectural shapes (e.g. Haussmannian, contemporary). A major part of acquired street facades are entirely residential buildings. The remaining acquired facades include stores, coffee terraces, cinemas, theaters, hotels, scaffoldings at the ground level and sometimes at the lower levels. Facades with different styles of architecture are usually joined together for hundreds of meters in a row. For this reason, the facades have often walls with different *rough or granular surfaces* (rock, brick, coating, joint) and sometimes smooth surfaces (glass windows), i.e. a certain thickness (see figure 3(a)).

The segmentation of joined and aligned facades into a cadastral map is a complex task using laser data. We observe that aligned facades are sometimes separated by vertical gutters and downspouts. Alas, the distinctions between street facades at macrostructures level remain perceptible with difficulty in the street point cloud. The usage of a laser scanner providing a 3D point cloud with a higher density will be useful. Besides, a cadastral map can be employed at the planimetric level to segment the street facade into residential facade portions. The laser data are also employed for delimiting the facades at the altimetric level. A cadastral map is composed of simple polygonal shapes. Nevertheless, the laser data provide 3D points in facade withdrawals (see figure 3(a)). For this reason, a refinement of the building footprint is possible. Like many large capitals throughout the world, buildings have some common geometric characteristics. The walls of building facades are *vertically* constructed. The maximum height of facades and the minimum and maximum width of facade portions of the area under study can be known from existing urban databases. This knowledge can be used to *focus on the facade objects* at the altimetric and the planimetric level. The minimum width of streets can also be known. It can be used to *characterize holes in facade clusters*, e.g. crossroads or occlusions (see figure 3(a)).

These geometric characteristics of street facades coming from observations, ground truth (e.g. cadastral map, urban database) are very useful knowledge for generating geometric hypothesis for the street facade modeling approaches. In particular, the generic characteristics can thus be used to **roughly reduce the search**

space required for street facade extraction as well as for the choice of relevant parameters.

6 STREET POINT CLOUD SEGMENTATION

As we have previously mentioned, an overview of the pre-processing steps are described in (Hammoudi et al., 2009). This subsection presents a segmentation stage that can be divided into two main steps. First, the focusing step consists in defining the object space (facades area). The second step consists in the vertical facade cluster extraction.

6.1 Defining the volume of interest

A band is defined at planimetric level along the trajectory of the vehicle around the street facades (distance to the sensor). On the one hand, the facade walls are in general relatively far from the MMS. Thus, the 3D points close to the vehicle are partially removed from the dataset. These removed points mainly correspond to parked vehicles and/or pavement borders. On the other hand, the streets are processed one by one. Hence, 3D points belonging to other street facades are partially removed, i.e., these 3D points are too far from the laser sensor. One can coarsely delimit the space at the altimetric level from a priori knowledge from urban databases. This altimetric delimitation combined with the planimetric band will defined the volume of interest.

6.2 Street facades cluster extraction

Each 3D point of the dataset is vertically projected onto a 2D horizontal discretized map producing a 2D accumulation map. A global threshold is applied to the cells. 3D points having voted in cells with a low score are removed from the dataset. We assume that facade walls are mainly vertical according to building facade characteristics taken from urban a priori knowledge. The remaining 3D points correspond to cells having a high score. These cells are mainly facade points and sometimes points of tree trunks, street posts, streetlights or small artifacts. Moreover, precise coordinates of the rectangular bounding box of the street cluster are thus calculated.

The raw cloud of street points, i.e. partition $\mathcal{P}_{street_{raw}} \subset \mathbb{R}^3$ has been divided into a cloud of points out of the volume of interest $\mathcal{C}_{volume_{out}}$, a cloud of points having cells with a high altimetric density $\mathcal{C}'_{alt_density_{high}}$ (cloud with major facade points) and a cloud of points having cells with a low altimetric density $\mathcal{C}'_{residue}$ (points of ground in majority) such as:

$$\mathcal{P}_{street_{raw}} = \mathcal{C}_{volume_{out}} \cup \mathcal{C}'_{alt_density_{high}} \cup \mathcal{C}'_{residue} \quad (1)$$

7 PIECEWISE PLANAR FACADE EXTRACTION

At present, the work deals with the cloud $\mathcal{C}'_{alt_density_{high}}$. These 3D points are included into rectangular prisms due to the precedent discretization (3D extrusion of the 2D accumulation cells). The extracted 3D points of street facades and the corresponding planimetric points are coarsely aligned along the street and the cloud of major facade points is more or less thick (e.g. windows, balconies, decorations). This stage deals with the planar clusters extraction, reducing thus the geometric effect of the discretization by a *smoothing of the facade cloud* and an *extraction of the major wall points*.

In our field, several techniques allow the extraction of the 2D straight lines among a dataset of 2D points. A well-known technique is the Standard Hough Transform (SHT) (Hough, 1962). Recall that the 2D straight lines are equivalent to 3D planes since the facades are assumed to be vertical.

The principle is briefly recalled here. We make a Hough accumulation space in the discretized parameter space (ρ, θ) with the step

units $\Delta\rho$ and $\Delta\theta$. For each 3D point $P(x,y,z) \in \mathcal{C}'_{alt_density_{high}}$, the corresponding planimetric point (x,y) votes (all points) verifying the following constraint:

$$\rho = x \cdot \cos \theta + y \cdot \sin \theta \quad (2)$$

where ρ is the length of the perpendicular from the line to the origin and θ is the orientation associated to the normal vector. Each point (ρ, θ) is unique if $\theta \in [0, 2\pi]$ and $\rho \geq 0$. In this way, the dominant street line can thus be extracted.

However, neighborhood facades of the street often have walls with close orientations and positions. These geometric characteristics can be observed in the Hough space accumulator (in high resolution) as several close peaks. The segmentation of these peaks into dominant facade walls is a complex task. To achieve this task, we propose to use a non classic Hough Transform based on a probabilistic and randomized process. More precisely, we use an approach (subfamily of HT) based on the PPHT approach (Matas et al., 1998) to fit each planimetric segment to each corresponding dominant facade. The proposed approach employs a sequential algorithm and a random sampling scheme. In our case, the points are randomly selected one by one. Moreover, the probability to detect a potential line rapidly enhances in the sense that each selected point in the input dataset is progressively memorized in the Hough space. Thus, just a subset of points is employed to detect the lines. This voting strategy alleviates thus processing by reducing the number of voting points. The pseudo-code algorithm 1 describes the main steps employed for the planar facade cluster extraction.

Algorithm 1 The adapted PPHT.

- 1: **Input:** A set of N 3D points (filtered street cloud);
 - 2: Corresponding planimetric bounding box (rectangle);
 - 3: T_{peak} : Threshold of enough aligned points;
 - 4: $T_{thickness}$: Threshold of facade thickness;
 - 5: $T_{connectivity}$: Threshold of segments connectivity;
 - 6: $T_{density}$: Threshold of facade density.
 - 7: **Output:** 3D planar clusters;
 - 8: Corresponding dominant planes (from segments).
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- 9: **Pseudo-code:**
 - 10: **repeat**
 - 11: Select a 3D point randomly
 - 12: Select the associated planimetric 2D point.
 - 13: Vote of the 2D point in the Hough space using eq. 2
 - 14: **if** T_{peak} reached **then**
 - 15: Extract corresponding candidate peak line
 - 16: Intersect line and bounding box into segment
 - 17: Extract points close of the segment ($T_{thickness}$)
 - 18: Divide segment into segments ($T_{connectivity}$)
 - 19: Keep segments with enough density ($T_{density}$)
 - 20: Keep each corresponding planar cluster
 - 21: Remove associated 3D points from the dataset
 - 22: Zero the whole Hough space accumulator
 - 23: **end if**
 - 24: **until** Stopping criteria fulfilled
-

Some steps of the adopted PPHT algorithm are described in more detail here. Line 11, the 3D points are randomly selected one by one. At each selection of a 3D points, a sinusoid is progressively traced in the Hough space until the score of a cell exceeds the preset threshold (preferably a low value). In this condition, it means that a certain number of aligned 3D points having vote in this cell is reached and that these points are implicitly in the same plane. Considering the planarity of facade walls in general, there is a high probability that other 3D points are also aligned along the same plane. Moreover, the main streets are often relatively straight in urban environments. The threshold T_{peak} (line 14) behaves like a starter, which launches the core of entire process. As we have previously mentioned, the dominant facade walls have various surfaces. Thus, the dominant facade walls are quasi-planar structures. Nevertheless, the set of the 3D points associated with the dominant facade walls commonly has a roughness (thickness) defined by the upper bound $T_{thickness_{max}}$. For

this reason, $\Delta\rho$ is selected such as $\Delta\rho = T_{thickness_{max}}$. Moreover, a neighborhood is defined along this segment relative to the $\Delta\rho$ step of the Hough space. Namely, an additional parameter $T_{thickness}$ (line 17) allows retuning the thickness of the segment with a width inferior or equal to the $\Delta\rho$ step. It avoids to modify the discretization steps initially defined in the Hough accumulation space in the case of output adjustments. Furthermore, several planar clusters of facades can be extracted from one detected line. The points positioned inside the neighborhood, i.e. inlier points are divided into several segments respecting properties of connectivity between the parsed points. Line 18, $T_{connectivity}$ is defined according to the minimum width of streets from the a priori knowledge. For each segment, if the density of points belonging to the neighborhood is sufficient then the corresponding cluster is labeled as a facade part (see figure 3(b)). The criterion for stopping the process (line 24) is met when a preset number of random sampling no longer produces clusters or when the full dataset is extracted (other existing statistical criteria can be used).

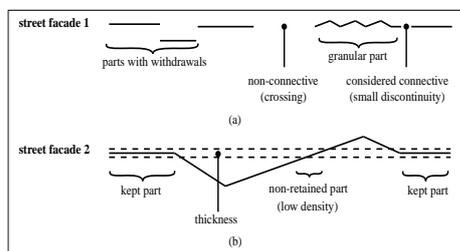


Figure 3: Comprehension scheme illustrating general characteristics of street facades in (a) and a step of segment keeping (one pass of the algorithm 1) in (b).

The adopted PPHT algorithm is employed like a fast 2D vectorization method. Dominant street facade planes and corresponding planar clusters of points are then extracted. This extraction stage can also be considered as a segmentation stage (figure 4(b) and 4(c)). Indeed, $C'_{alt_density_{high}}$ has been divided into dominant piecewise planar $C''_{piecewise_{planar}}$ and the remain $C''_{residue}$ (mainly windows) such as:

$$C'_{alt_density_{high}} = C''_{piecewise_{planar}} \cup C''_{residue} \quad (3)$$

8 RESIDENTIAL FACADE DELIMITATION

The output of the algorithm 1 is a set of planar clusters of street facade $C''_{piecewise_{planar}}$ and the corresponding fine planimetric segments. In this study, we dispose of a cadastral-based map (figure 1(c)). This map is an adaptation of an original cadastral map (e.g. digitalized, vectorized, deformed, simplified). Moreover, the laser data and the cadastral-based map (external data) are georeferenced in the same coordinate system using different devices and/or approaches; and thus suffer of absolute positioning errors. Currently, we have no studies allowing to define which of them is the best ground truth. For this reason, the geometric registration between them is a complex task. In our case, we aim to segment the cloud of points provided by the algorithm 1 with the help of a standard cadastral-based map. To simplify the evaluation (image-based) of this segmentation, we fused the planar clusters into a global cloud of points that are piece-wise planar (see figure 4(b)). The stage 7 is only used here for the *cloud smoothing*, not for the fine extracted segment. Thus, the level of detail is simplified for the evaluation since just cadastral boundaries are tested. Nevertheless, we assume that the misalignment between laser data and cadastral-based data is small. At the planimetric level, the georeferenced cadastral-based map is applied by segmenting the points of the global cloud having their planimetric coordinates included inside the band orthogonal to each cadastral-based segment. The segmentation onto the global cloud can be

slightly shifted. Surplus of points $C''_{residue}$ (cloud with very small size) are removed from $C''_{piecewise_{planar}}$ providing a cloud with planimetric adjustment of boundaries $C'''_{map_{cadastral-based}}$ (figure 4(d)) such as:

$$C''_{piecewise_{planar}} = C'''_{map_{cadastral-based}} \cup C''_{residue} \quad (4)$$

At the altimetric level, *three strategies* are proposed to model the ground limit by an horizontal line. A global strategy consists in selecting the altitude of the points having the minimum height in the filtered point cloud. This solution is not very robust if the street is sloped. Local strategies can estimate the height from the altitude of the points having the minimum height for each cluster. In case of an observed discontinuity for a given facade, we reset its minimal height to the interpolation of the two neighboring facades. Indeed, obstacles like vehicle parked sometimes occlude a facade. The height of the bottom limit can also be computed subtracting the vehicle height to the laser sensor altitude for each cluster and adding the height of a standard border pavement. The limit of facade top consists in computing the 3D bounding box of each cluster and to fit the facade top by the horizontal line of maximum height.

Finally, the extracted facade planes are delimited at altimetric and planimetric level by an assembly of four straight segments. The approach provides rectangular wire-frame model of street facade.

9 RESULTS AND EVALUATIONS

Here, several results and evaluations are provided corresponding to the different stages of the proposed approach.

9.1 Intermediary results of the approach

The georeferenced raw street data depicted in figures 1(a) and 1(b) present several static and mobile occlusions. Notably, we observe some occluding objects; namely trees, parked vehicles, posts, bus shelter or newsstands. These objects cause some facade holes (missing parts, heterogeneous facades) that make the street facade extraction and delimitation complex.

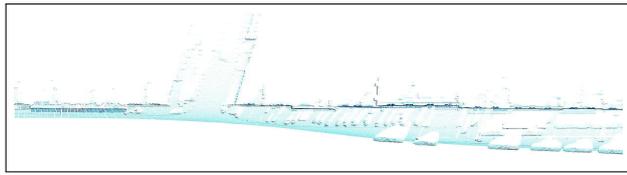
Figure 4(a) shows the 3D point cloud belonging to the preset volume (see section 6) mapped onto the 2D accumulator. Since the laser sensor acquires points perpendicularly to the vehicle trajectory, walls corresponding to the slight recesses, in the sides of front walls, are poorly represented (low density). These walls do not appear in the filtered laser data illustrated figures 5. The dominant facade points are well-extracted (figure 4(c)).

Figures 5 show at the top the representation of outlined facade clusters provided by the proposed approach. and underneath, the wire-frame model of facades (3D meshes) and the associated planimetric footprint. Points of facade withdrawals are well-extracted at planimetric level (see the footprints of the clusters). The large missing part at the left street side corresponds to a crossroad. The cadastral-based map is sometimes incomplete. Indeed, we remark missing footprints in map (see figure 1(c)) due to oversights of cadastral map vectorization (e.g semi-manual process) or new buildings. Hence, our approach provides 2D and 3D maps with new buildings updated.

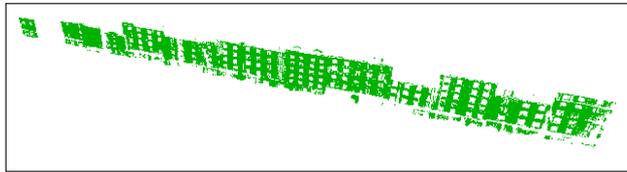
9.2 Evaluations of accuracy and reliability

The evaluation of outlines accuracy is a complex task in the sense that it depends on the laser sensor, vehicle georeferencing, calibration accuracies, cadastral-based map deformation and projection. In the context of our work, we dispose of a Google like web-based street viewer. This street viewer employs data collected by the MMS to provide to the general public, city visualization/navigation at street level through georeferenced panoramic images. The projection of the 3D delimitation of facade polygons onto the panoramic images allow the *segmentation of the panoramic images* into street facades and other urban objects.

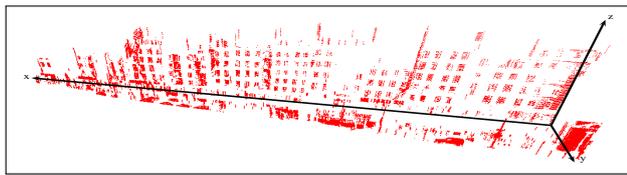
For this reason, the accuracy of the 3D outlined planar clusters at the planimetric and altimetric level is analyzed qualitatively by



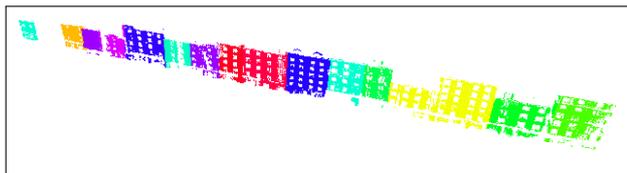
(a) 3D point cloud ($\mathcal{P}_{streetraw}$) projected onto a 2D accumulation map.



(b) High density points ($\mathcal{C}''_{piecewiseplanar}$) that are retained by the algorithm 1.



(c) High density points ($\mathcal{C}''_{residue}$) that are rejected by the algorithm 1.



(d) Cloud ($\mathcal{C}'''_{mapcadastral-based}$) derived from ($\mathcal{C}''_{piecewiseplanar}$) using the cadastral-based map. Each facade cluster is visualized with a colorful randomly selected in HSV space.

Figure 4: Results of the segmentation of a complex street cloud into a cloud of residential facades.

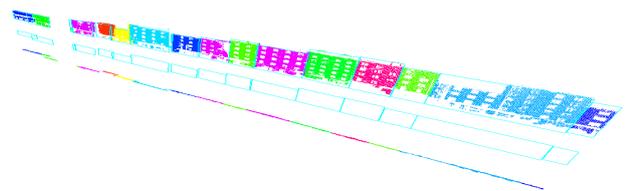


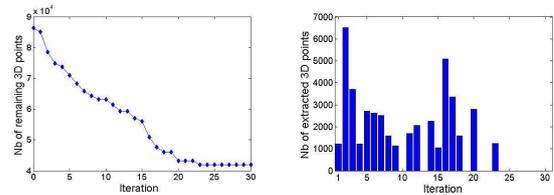
Figure 5: Wire-frame model of street facades with the top delimited by the maximum height of each cluster.



Figure 6: Wire-frame model projected onto a panoramic image.

inspecting their projection in a corresponding part of the **georeferenced panoramic images**. We show here the delimitation at ground level using the minimum height of the global street cloud. We observe in figure 6 a proper and robust delimitation at ground level in spite of the missing parts caused by the parked vehicles and the bus shelter (laser shadow). The estimated upper boundary of the facades give a satisfying limits in the sense that attic windows are included in the modeling process if they are very close

of the dominant facade wall. The 3D reconstruction of rectangular wire-frame (simple shapes) provides an homogeneous representation of the scene.



(a) Graph of convergence. (b) Histogram of clusters density.

Figure 7: Behavior of the adopted PPHT.

The laser dataset deals with all the 12th district of Paris. The approach speed allows to map a street in 20 to 30 seconds for 30 iterations; near real-time in the sense that the time for the data acquisition of a street is higher than the processing time. An iteration of the algorithm 1 is achieved when the threshold T_{peak} is reached. In other words, the facades outlines can progressively be modeled street by street along the acquisition by the MMS. Figure 7(b) shows the number of points extracted at each iteration. The extraction process stops when the size of the dataset is stabilized (see figures 7(a) and 7(b)).

10 CONCLUSION

In this paper we have presented an approach combining laser data and a cadastral-based map for the automatic extraction of residential facades outlines in very dense and real urban environment. We stress the fact that the use of the extraction method based on Progressive Probabilistic Hough Transform has two advantages. First, it provides fine estimation of planar facades (there is always some misalignment between the georeferenced laser data and the cadastral map). Second, it can update already existing cadastral maps by incorporating or removing some building facades. Moreover, the approach uses fast filtering and feature extraction techniques that can be run in real-time in the case of a street by street mapping. Thus, the approach offers a fast 3D vectorization method and provides a wire-frame model of street facades. Experimental evaluations show the efficiency of the approach to map large streets from terrestrial MMS. The approach allows to made an updated map. The outlined facades extracted with rectangular shapes are reasonably well-delimited at planimetric and altimetric level. A database of georeferenced facade contours are generated providing undeniably street features of great potential the city modeling improvement at facade level.

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