Automated 3D Reconstruction of Interiors from Point Clouds

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ABSTRACT

We present a new technique for the fully automated 3D modelling of indoor environments from a point cloud. The point cloud is acquired with several scans and is afterwards processed in order to segment planar structures, which have a noticeable architectural meaning (floor, ceiling and walls) in the interior. The basic approach to data segmentation is plane sweeping based on a hypothesis-and-test strategy. From the segmentation results, the ground plan is created through cell decomposition by trimming the two-dimensional ground space using half-space primitives. An extension in height of the ground contours makes the generation of the 3D model possible. The so-reconstructed indoor model is saved in CAD format for analysis and further applications or, simply, as a record of the interior geometry.

1. Introduction

Since the power of computers has joined the world of architecture, in the early eighties, the way of designing and developing architectural products has drastically turned into a more sophisticated process. In particular, the appearance of CAAD software packages as commercial tools has given new perspectives to the art of designing, constructing and managing a building [1]. Space partitioning and simulations are nowadays easily done by engineering applications, while the value of a manual drawing stays highly worthy for quickly communicating design ideas. On the other hand, the benefits of a computerized approach to architectural methods are diverse. The most attractive is the possibility of creating virtual environments and digital models, which support the design phase through allowing the end user to experience how buildings would look like or how they would interact with the surrounding external environment.

Each phase of the architectural design and construction process may take advantage of a modelling medium [2] for different reasons. During the preliminary design and the design development, the convenience of a CAD model consists in the fact that primitives can easily be visualized and combined with each other in an interactive way. The result is a detailed documentation of the entire design phase. In addition, a considerable advantage of computer-based drawings is the possibility of storing, automating and manipulating the information at every level of abstraction.

Looking at this preface, it is clear that the introduction of CAD techniques has been an absolute turning point in the way of thinking through an architectural design project. However, the efficiency in the pipeline of an architectural application may still improve further. Though CAD approaches are essential for the creation of detailed models, we believe that their full potentiality is still limited by the lack of automation. The core of our research is focused on increasing the level of automation for model generation.

Fundamentally different from conventional CAD simulation are contemporary approaches to performance-based design [3]. These approaches belong to an earlier stage of design of an architectural project, that means they involve the evaluation of the building performances when the building itself has not been defined at an ultimate level of resolution. Performance-based design is a modern methodology to optimize the usability of buildings. The significance of such an approach to digital design could grow in parallel with the value of digital models based on existing architecture.

Our work focuses on the computation of a three dimensional model of a building interior from scans of an existing structure. This definition implies that the construction phase of the interactive architectural process has already been completed. Therefore, our approach is considered as a tool to digitize actual structures of interiors and store real characteristics of buildings for further spatial analysis. The way in which the model is generated is fully automated and requires only a point cloud as an input, which contains a dense set of points acquired from the target room. The result is a 3D model in CAD format, which perfectly fits the original data set. So far, realistic models of interiors have always been designed manually. However, the demand for indoor models for different purposes (cultural heritage, preservation and documentation) has recently increased, thus a higher degree of automation could better satisfy different applications and speed up the processes.

1.1. Automatic modelling for 3D reconstruction

If we could add a new step to the total scope of an architectural project – beyond the architectural program, the design phase, the working drawings, the bidding phase and the construction – the technique presented in this article would find a proper placing at the top of the activities' list. Our software, in fact, automatically produces a 3D model of an existing structure; hence, we could label the new phase *re-construction* and execute it every time a building has to be analyzed in terms of forms and proportions or when it is used, for example, in a multimedia application. In the future, virtual experiences and multimedia adventures will be the usual environments for everyday's life practices, which are now purely driven by human action and interaction. In Bill Gates' digital vision of the incoming world:

> "You'll be walking in downtown London and see the shops, the stores . . . Walk in a shop and navigate the merchandise . . . in a virtual reality walkthrough." [4]

In light of what was pointed out by Bill Gates, current digital globes, such as Google Earth and Microsoft Bing Maps, can be extended to contain buildings' interiors in addition to the already available external shapes. This allows for virtual stores and provides additional marketing potential. However, for the widespread dissemination of indoor models, automation in the reconstruction process is essential. Only if a high degree of automation is maintained throughout the processing pipeline (from the acquisition of the building points to the modelling phase), cost-efficiency of the model generation can be guaranteed. Automated approaches bring also advantages in term of speed, and thus the time needed to deliver the final model of an indoor scene is drastically reduced in comparison with the manual CAD techniques.

At first sight, it looks like the automatic generation of the CAD model (once a building is already made) is somehow redundant. It appears in fact not necessary to compute a digital model as the design was also supported by digital techniques, thus a 3D model should already exist. Different reasons can explain this apparent contradiction. First of all, the model accuracy in the design phase is not ensured throughout the entire construction development. Therefore, a CAD model, which is computed on top of the process by observing the real world, may be used as a reference test for the validity of the original model. Second, building models must deal with a high probability of changes to their structures during their lifetime. Existing architecture are in fact objects of continuous modifications for different reasons, for example enlargement of spaces, renovation and so on. Unfortunately, such changes are not supported by the original CAD models, which are static and contain only initial shapes. Also, prototypes in CAD format, which are created at the very early stage of the architectural process, can entirely get lost (it would not be possible to look them up for reconstruction purposes). A dynamic reconstruction through the automatic computation of 3D models could provide a solution to these issues.

2. Previous work in 3D reconstruction

Reconstruction is the abstract operation of building or re-creating something that has been damaged or fragmented. Three-dimensional information related to architectural data is often complex, and thus it needs an acquisition method that extracts fine details in order to be able to describe every element of the target in the best way. The laser scanner is a very efficient details-catcher, either for architectural (civil engineering) applications or for cultural heritage documentation. However, after the data has been acquired with a TOF sensor such as a laser scanner, it is basically reduced to a list of information (coordinates of points, intensities . . .) without any internal structure. An essential part of the reconstruction is to interpret such an amount of information and bring it again into a configuration, which can be stored and visualized. Current research about 3D reconstruction cannot be restricted to a unique framework because of the variety of scenarios concerning the types of targets, the desired degree of automation and the acquisition tools. The following studies related to 3D reconstruction, which will be highlighted, all require a point cloud as an input for their algorithms.

2.1. Reconstruction from a point cloud

A very common and particularly fascinating use of reconstruction techniques for indoor modelling deals with the context of cultural heritage. Detailed models of interior of tombs, temples, churches and other historic structures are a popular topic in heritage projects [5]. In these cases, the scene typically exhibits few regular structures and is rather dominated by ornaments and other irregular features. Therefore, it is assumed that the proper reconstruction method for these kinds of scenarios is dense surface meshing in combination with high resolution texturing. Such an approach is difficult to be automated, and thus cannot be used for widespread modelling but only for individual structures.

Another very specific area of indoor modelling, which, unlike cultural heritage, has been the topic of intense efforts for automation, is the reconstruction of industrial environments. These scenes are characterized by repetitive elements such as beams or pipes. Current state of the art in commercial reconstruction tools is manual pre-segmentation in combination with automated fitting. In the research field, the goal is to automate the process further [6].

Currently, model reconstruction and visualization of generic indoor scenarios is still a difficult task [7]. In fact, the reconstruction of interiors is mostly performed using interactive or semi-automatic approaches (Cyclone, Pointools . . .), though our goal is to accomplish a full automation of the modelling process. It follows that the literature about automatic 3D reconstruction is quite poor since the generation of 3D model from point clouds was only worked out with manual methods. In contrast, automated techniques for the reconstruction of buildings' exteriors are nowadays successfully implemented by the geodetic scientific community [8].

Classical methods extract building models from the combination of cadastral information and either aerial images or LiDAR data [9]. Such models are assumed to be simple polyhedrons. Besides, recent development in LiDAR technology has provided more detailed point clouds, which raise the expectation of more detailed models. Also, street-side data delivered by mobile mapping systems allow for higher amount of details in façade models [10]. These approaches for the reconstruction of buildings' exteriors share many properties (and problems) with the issues associated with indoor reconstruction. Typically, many of the algorithms useful for the reconstruction of exterior building models can be adapted for indoor reconstruction, as well. Our approach especially uses the concept of cell decomposition, which is also found in [11] and [12].

The computation of 3D models for building digitalization is a classical task of photogrammetry and surveying. However, this is also a task in computer vision as well. In particular, the task of indoor reconstruction deals with robotics (navigation problems) and autonomous systems [13], as well as with pure automatic indoor modelling for military purposes [14]. Unlike our method, the laser data in [14] is acquired from outside the building, thus it could be incomplete due to obstructions. An additional method for surface reconstruction in indoor scenes makes use of a statistical approach to connect a finite number of cuboid shapes whose union gives the global representation of an office environment [15].

2.2. 3D models from floor plans

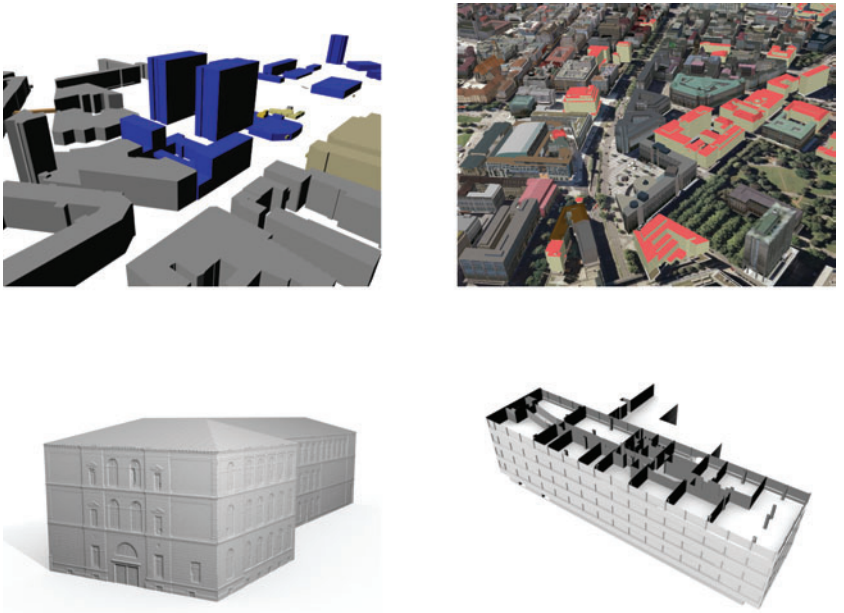
An automatic technique is presented in [16] to generate detailed 3D models from floor plans. Floor plans are two dimensional scale drawings of a horizontal section through a building. They portray building interiors by computing an orthogonal projection of the architectural elements. To achieve that, standardized symbols, which describe architectural details, are used. Floor plans can either be paper- or CAD-based drawings. The kind of floor plan greatly determines how complicated it will be to extrude the 3D model from the drawings [16]. In case of paper plans, raster images must be processed; consequently, systems using such floor plans must rely on image processing and pattern recognition algorithms to identify the graphical symbols, which stand for wall lines, window profiles, and so on. On the other hand, systems using CAD-based floor plans do not have to overcome the ambiguities caused by hand-sketched drawings and they can focus more on the model extrusion. In both cases, the floor plan complexity is crucial for the computation of a good model. Also, manual intervention is often required at some points of the processing pipeline.

Although the value of the approach in [16] is beyond question, we believe that a technique, which extracts the 3D model from a point cloud, may avoid all the problems encountered in the interpretation of floor plans and it may solve the problem of the lack (or loss) of the floor plan, especially in the reconstruction phase.

3. Architectural levels of detail

It is within the geodetic community that the definition of the architectural levels of detail (LODs) has become a significant topic concerning multiple representations of geometric and thematic characteristics of buildings. Currently, spatial properties and appearances of real urban environments can be classified through the international format CityGML, derived from the standard GML3 of the Open Geospatial Consortium (OGC). This open data model proposed by Kolbe in [17] was conceived for the storage and exchange of virtual 3D city models. It supports five different LODs that provide a hierarchical description of building entities. A higher classification level corresponds to a more detailed representation of building features. Figure 1 shows examples for LOD1 to LOD4.

► Figure 1. Representation of LODs from LOD1 (top-left) to LOD4 (bottom-right).



The first four levels of detail, ranging from LOD0 to LOD3, describe external characteristics of buildings and natural features, either from close range or from aerial images. In particular, LOD0 is a two and a half dimensional Digital Terrain Model (DTM). LOD1 is a block model, which represents houses as prismatic volumes (without roofs). The next LOD2 adds roof structures to LOD1 and may include vegetation objects. LOD3 is a detailed model of external architectural elements such as outer walls, balconies, bays and projections. Accurate vegetation items and traffic components may be also exhibited at this level, as well as high-resolution textures on the facades. The most elaborate representation is done at LOD4, which ensures the highest degree of detail for architectural models of interiors.

The goal of our reconstruction process is to automatically achieve an indoor model that is consistent with the degree of resolution typical for a model at LOD4. The motivation for this work comes from the convenience of having a 3D model, which incorporates internal architectural details. That means, structural information, represented by walls, and local architectural components, such as doors or furniture, may be automatically modelled.

Virtual 3D city models are also important for various aspects of disaster management. CityGML provides in fact a framework for augmented reality with interoperable access, whose characteristics may be helpful to monitor critical structures by enabling the visualization of different objects with accuracies up to 0.2 m in position and height. If the model is accurate enough, it can be used for simulations by reproducing realistic training scenarios for the localization of safety-relevant features [17]. Besides, in case of a severe destruction, caused for example by an earthquake, the reference data would allow for a faster rescue operation of the people involved or, afterwards, a better reconstruction of the damaged sites.

4. Case study

The paper describes our experiments concerning the automatic reconstruction of an architectural 3D model from a point cloud. This section gives an overview of the work flow and describes the early stages of point cloud processing. A point cloud is an unorganized list of 3D measurements produced as the result of a surveying operation. Each of those measures contains the coordinate of a single target point in a Cartesian reference system. Depending on the extent of the acquired architectural structure and from the sample density of the instrument, a point cloud may contain several millions of points. The amount of data, which we will refer to, is the adjustment of several laser scanning acquisitions and consists of about one million 3D points. The typical work flow of a laser scanning project suggests that the acquisition of the points, which is achieved with progressive strategic re-placement of the instrument, is followed by the registration of separate data sets. That means, point clouds coordinates related to different reference systems must be transformed into a common system. Only after such a registration, the scans are combined and the framework for the core modelling process is established. The modelling phase, which is the focus of the paper, is described separately in the next section.

4.1. Data acquisition

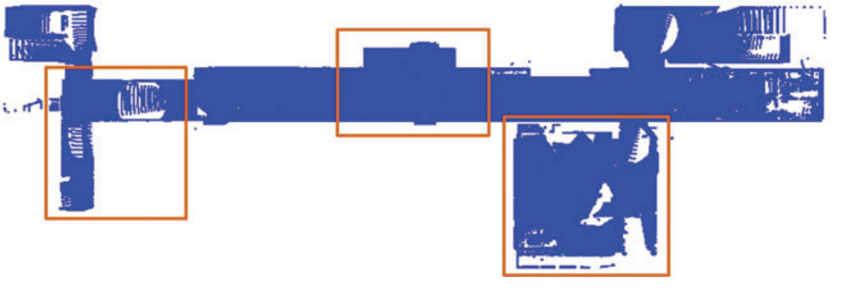
The first step that has to be done toward the setting-up of the reconstruction tool is the acquisition of a valid data set (Figure 2). In particular, our case study considers the point cloud of the basement of a university building in the city campus of Stuttgart, which is thought to be a suitable example for the experiments. Its floor plan presents in fact a basic geometry with the wall traces that are either orthogonal or parallel to each other. This property allows for an immediate verification of the correctness of the proposed method.

► Figure 2. Timeline of a laser scanning project.

A top view of the site of interest is given in Figure 3. The hallway is mainly composed of a long empty corridor, which varies in width, and a small side room whose floor and walls are partially covered with furniture. The laser beam can obviously only access non-hidden objects, making it a challenge to study the behaviour of the reconstruction algorithm in occluded areas. The acquisition is performed with the laser scanner Leica HDS3000, a time-of-flight (TOF) sensor that is able to capture up to 4000 points per second with a horizontal field of view of 360°, while the visibility along the vertical direction is limited to 270°.

The measurement consists of fifteen separate scans spread out along the hallway, each capturing portions of the interior. In order to combine the data acquired at each viewpoint, paper targets that signalize tie points are

► Figure 3. Top view of the point cloud representing the hallway. Three areas of further investigation are highlighted by boxes.



measured with high precision from adjacent scans. At least three corresponding targets are needed for the transformation of the related point clouds into a common coordinate system.

4.2. Registration

The goal of the registration is to compute a common reference system for point clouds, which are partially overlapped but refer to independent coordinate systems. For instance, the registration of two adjacent scans can be properly computed by the acquisition of homologous tie points whose coordinates are used for the estimation of the translation and rotation parameters. That means one of the two reference systems of the considered point clouds is taken as primary reference for all the points contained in the other one. For a successful conclusion of the registration operations, it is important to choose tie points that are in a proper geometric configuration in order to avoid unstable solutions [18]. Also, due to redundancy it is generally recommended to place the scans so that they share more than the minimum number of tie points required since the measurement of a tie point might fail. In our experiment, we computed the registration of all the fifteen scan worlds into a unique coordinate system with a final accuracy of one millimetre. We performed the registration using the software Cyclone from Leica. Cyclone is a widely used tool for visualizing, editing and processing point clouds.

5. Algorithm for 3D reconstruction

The procedure we propose in order to extract the model uses a 3D point cloud as an input for the algorithm. After the data acquisition, the main steps of the algorithm are segmentation (based on a plane sweep technique) and ground plan extraction (using half-space modelling). An overview of the two steps is given below.

Referring to the field of computer vision, segmentation is an image processing operation that partitions a digital image by grouping sets of pixels with relevant common characteristics. In this way, objects of interest are isolated from the rest of the image, which becomes more meaningful and easier to analyze [19]. 2D segmentation of images shares the same goal of our segmentation, which, although it is applied to 3D points and not to intensity pixels, aims to make different structures distinguishable within the input data set. The distances of such structures from the origin of the coordinates, together with their orientations (angles) in the reference system determine the type of planar region identified (floor, ceiling, walls . . .). To be precise, a plane sweep algorithm is used to collect and separate points describing the walls and the two horizontal faces, namely floor and ceiling. The approach is based on a hypothesis-and-test strategy. A hypothesis is made about the position of a plane, referred to as the sweeping plane, along its normal vector. The criterion for testing this hypothesis is a threshold on the number of points in the neighbourhoods of the sweeping plane. The plane is accepted when the number of points exceeds the threshold.

The second part of the algorithm extracts the ground plan through a half space modelling technique. According to this paradigm, the two-dimensional space is partitioned and shaped by repeatedly splitting it up into two half-spaces using straight lines. In order to recover the ground plan contours, the lines that are used to trim the ground space are those determined by the traces of the walls on the floor. As a result, a set of ground cells is found. As we mentioned above, the algorithm is able to estimate the geometry of the ground plan automatically without requiring any a priori information about its shape. This is a considerable advantage since the ground plan of buildings is not always available. In our case, we make the basic assumptions that the floor and the ceiling are horizontal, the walls are vertical and they are either perpendicular or parallel to each other.

Our project assumes the laser scanner to be approximately levelled so that the vertical axis of the Cartesian reference system is aligned with the local vector of gravity. This is a characteristic property of the Leica HDS3000 but similar features are also provided by other scanners or could easily be achieved using an electronic levelling device. In the implementation of our 3D reconstruction method, the result of the algorithm is independent from the coordinate system.

5.1. Segmentation

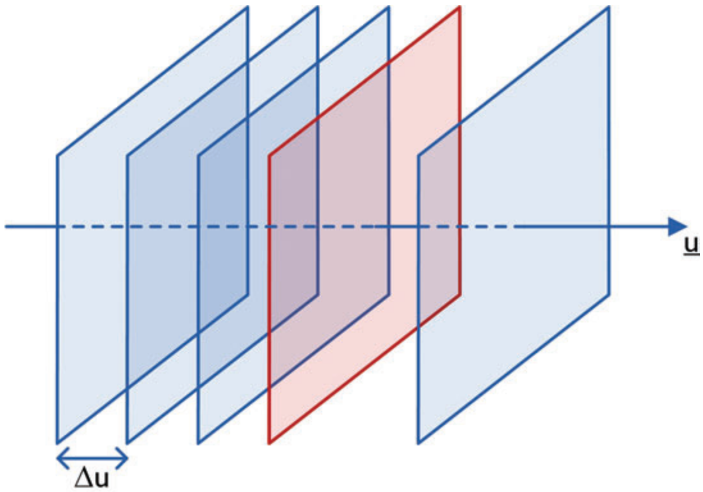
The segmentation algorithm consists of two steps, which separate the detection of horizontal and vertical planes. While they share the same mathematical properties, the detection of vertical structures requires additional computations.

Linear sweep

The segmentation of planar surfaces through linear sweeping is the first step toward the creation of the final 3D model. In principle, the linear sweep requires a plane

$$ax + by + cz + d = 0 \tag{1}$$

to sweep along its normal vector (a, b, c). The sweep is not continuous but discrete, characterized by steps whose width Δu (Figure 4) can be determined according to the point sampling density of the data set. At each step the number of points in the point cloud, which are within a consensus distance to the actual plane, is counted. The idea is to sum up the 3D points, which either lie on or have a small distance from the plane at a certain step position. A threshold is set to define the consensus distance.



◀ Figure 4. Linear sweep: Sweeping step.

At the end of the process, the planes associated to the maximum number of points are taken as representative planes of relevant surfaces in the room. For example, we wish to compute a plane sweep along the direction (a, b, c), supposing to find some structures perpendicular to it. We perform several sweeping steps , $u_i \in [u_i, u_n]$. The plane, which collects the highest number of points within the sweeping interval at u_i', has coefficients a, b, c, u_i', so it has distance u_i' from the origin of the coordinate system. Thus, we expect to detect a significant structure at the position u_i' along the sweeping direction. In order to store the position of the accumulation peaks (local maxima), a histogram of the occurrences of points is computed. The positions of the histogram peaks are then inferred through a non-maximum-suppression algorithm applied to the histogram values.

For every meaningful structure in the room we need to set the proper coefficients of the sweeping plane (in relation to the reference system). The plane coefficients are restricted using human knowledge about building characteristics [20].

Horizontal structures

If we segment floor and ceiling with a linear sweep, some useful assumption can be made:

- They are both horizontal thus,
- they are parallel;
- The ground is positioned at a lower level with respect to the ceiling.

The first two hypotheses above, together with the property of vertical alignment of the scanner simplify the definition of the sweeping direction. For the detection of both horizontal structures, it is in fact necessary to sweep a plane along the vertical direction **z**, which is (0, 0, 1). The third hypothesis allows us to distinguish the histogram peak corresponding to the ground from that one related to the ceiling. In conclusion, the constraints available for the vertical segmentation of the room reduce the problem of plane sweep to one degree of freedom.

Vertical structures

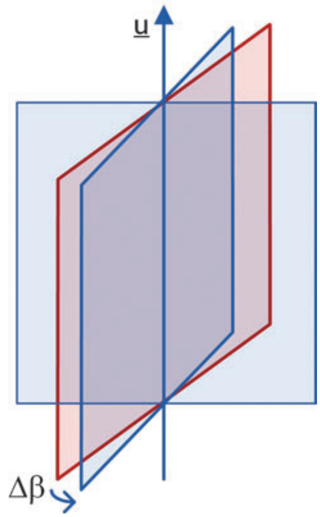
The computation of the wall positions is a little more complex since the only assumption that can be made is about the orthogonality of the walls to the ground (at least in standard buildings with no special claims to architectural originality). Thus, the problem has two degrees of freedom. One is the distance to the origin, as before. The other one is the horizontal angle β of the structure, which determines the sweeping direction (a, b, 0) by easy trigonometric calculations.

Since we restrict ourselves to the detection of either perpendicular or parallel walls as mentioned above, we search for only one major direction and we determine the second direction as the orthogonal one. To find the exact position of the walls, a plane is swept along these two orthogonal directions $(-\cos\beta, -\sin\beta, 0)$ and $(\sin\beta, -\cos\beta, 0)$ separately. The angle β is computed by means of a rotational sweep.

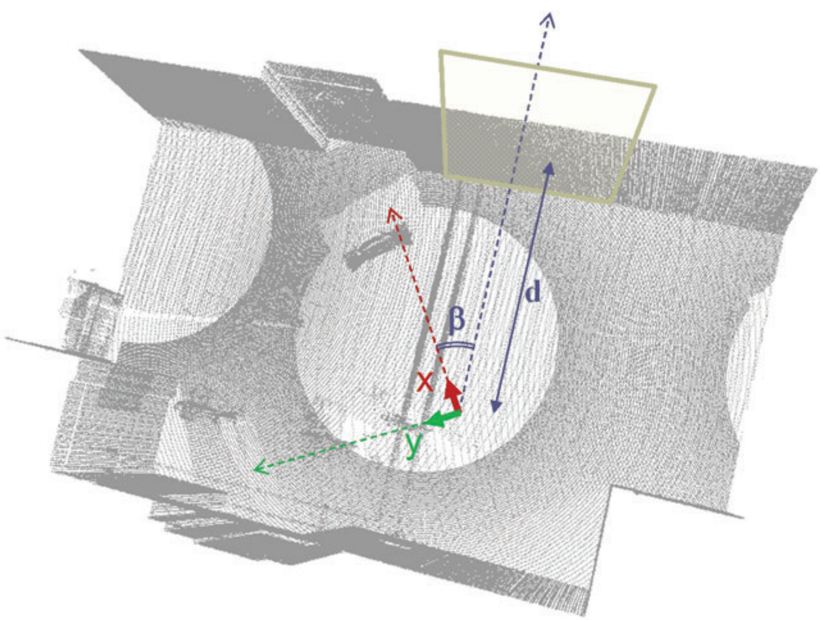
Rotational sweep

Conceptually, to execute a rotational sweep means to rotate a plane around a given axis (that lies in the plane) in discrete angular steps. The rotation axis runs through a randomly selected 3D point and it is vertical because we restricted the problem to the detection of vertical walls. The random point is chosen from a reduced point cloud obtained after discarding the floor and ceiling points, which were segmented through the linear sweep. As shown in Figure 5, the plane is rotated each time by a certain angle $\Delta\beta$ with respect to its previous position. At each step we count the number of points, which belong to the current plane. To reduce the computation time, only the points in a cylindrical neighbourhood of the rotation axis are checked for consensus with the rotating plane. Since we only consider the pure orientation of the wall and treat the topology in a later step, a rotation about the axis in the interval of $[0°, 180°]$ is sufficient. A rotation outside this interval would only change the sign of the normal vector.

At the end of the process, a histogram is created, which stores the information about the rotation angles in relation to the amount of points collected. The process is iterated several times; Each time a different random point is chosen and a new histogram is computed. The sum of all the histograms gives the global frequency of the directions of local vertical structures in the room. The largest peak of the histogram gives the dominant direction along which the main walls (in terms of point accumulated) are aligned. This corresponds also to the value of the angle β between the wall normal and the original coordinate system. In Figure 6 a graphical visualization of β (together with the distance $d = u_i'$ between the origin of the coordinate and one of the walls) is given.



◀ Figure 5. Rotational sweep: Sweeping angle.

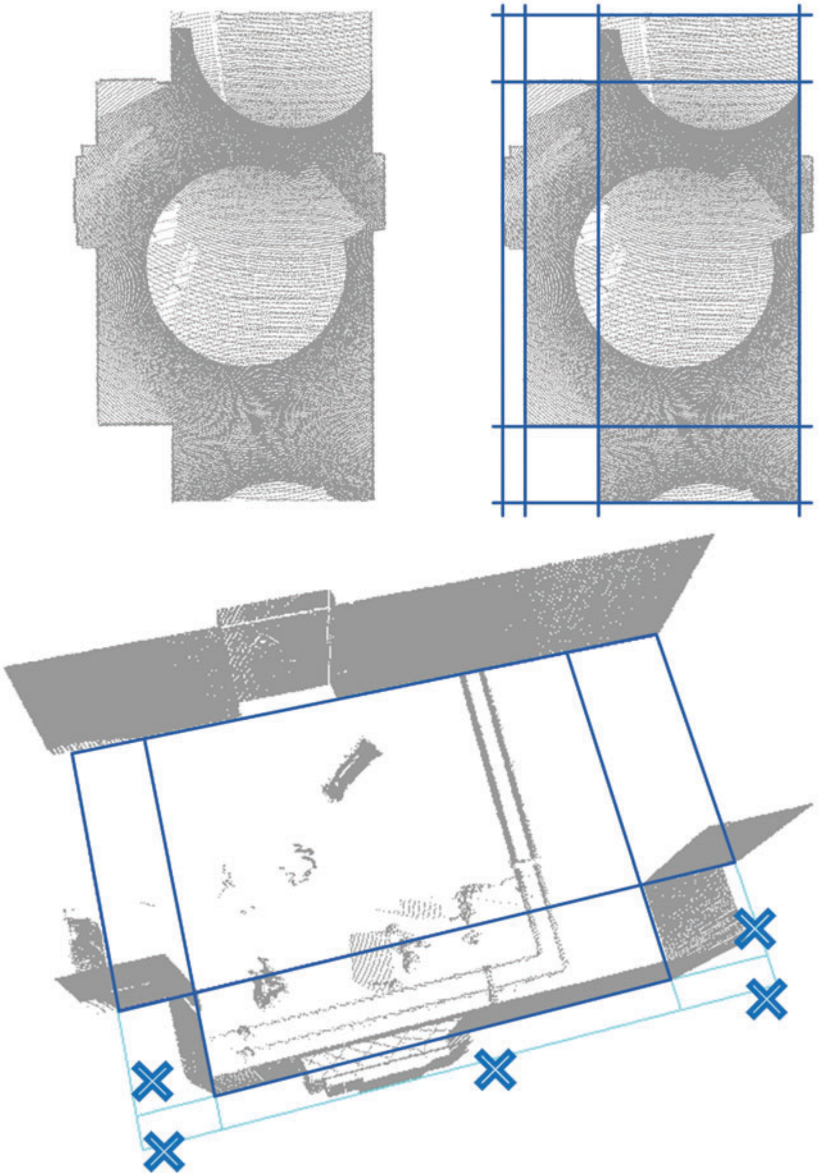


◀ Figure 6. Computation of the direction of the walls (top view of the laser data).

5.2. Ground plan computation

In the final phase we compute the ground plan, which contains the contours of the scanned room. The ground plan extraction is driven by the idea of half space modelling to derive cell decomposition. Cell decomposition is the first step of a split-and-merge approach. According to split-and-merge region detection algorithms, an area of interest is first partitioned (split) into uniform regions, which can later be merged again if they satisfy certain homogeneity criteria. A half space modelling method is used for dividing the horizontal plane into polygonal cells.

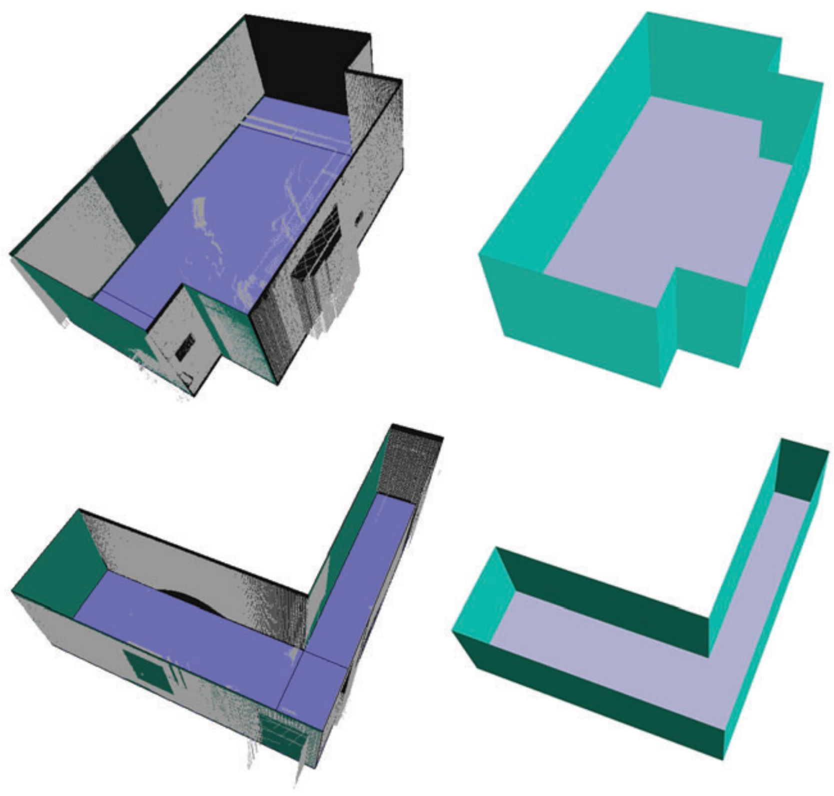
In order to perform the decomposition into cells, the space is trimmed using straight lines [21] also called half-space primitives. Since the floor is bound by the walls, the straight lines defining the wall traces on the floor are used as the primitives for the generation of the ground plan. They are derived from the histogram peaks resulting from the two orthogonal horizontal sweeps. The half space primitives with orthogonal directions generate rectangular cells as shown in Figure 7.



► Figure 7. Cell decomposition (top) and discarded cells (bottom).

In the following step, each cell is analyzed and only those cells that contain enough points are merged to shape the definitive ground plan. We set a threshold of the minimum number of points included in every ground cell. The threshold is selected from the point sampling density in relation to the area of the cells. The cells, which do not contain enough data points, are discarded.

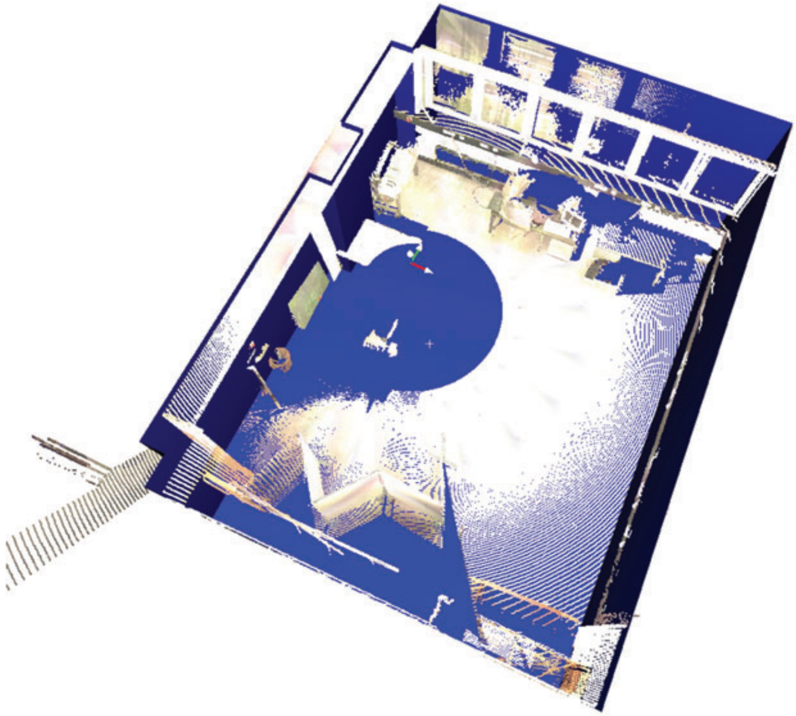
From the union of the cells labelled as accepted, the ground contours are extracted and the walls are subsequently computed as a protrusion of the contours from the floor up to the ceiling level. A representation of the final 3D model is shown in Figure 8 (the data refer to the areas highlighted by the central (a) and the left (b) rectangular boxes in Figure 3).



◀ Figure 8. Left: Models with the point clouds. Right: Final 3D CAD models.

The creation of 3D models from noisy data is also tested; in particular, Figure 9 shows the comparison between a point cloud, which contains spare information in addition to the basic structure of the room, and its model. The result is satisfactory since it turns out that our algorithm can build an accurate model (to localize the data, see the right rectangular in Figure 3).

► Figure 9. 3D model from noisy data.



6. Conclusion

We proposed a method to automatically reconstruct the 3D model of indoor scenes. The motivation comes from the utility of CAD models for 3D architectural reconstruction but also from the importance of the digitalization of the interiors to create virtual environments for the modern digital globes. A plane sweep approach is used to detect the positions of the floor, ceiling and walls. First, the horizontal surfaces are segmented from the point cloud by computing a vertical plane sweep along the z-axis and setting a threshold of the distances of the points from the plane. Secondly, vertical structures are localized through a rotational plane sweep, followed by a horizontal sweep. Finally, the ground plan of the room is computed using cell decomposition and the 3D model is built.

Our approach to 3D modelling is robust and completely automatic since a point cloud is given as an input to the software, which creates the actual model as a CAD file. Prior information about the topology of the interior room is not required, only basic assumptions are made. This makes the algorithm suitable in many situations where the original design model is not longer available.

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