TOWARD AUTOMATIC RECONSTRUCTION OF INTERIORS FROM LASER DATA

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ABSTRACT:

So far, realistic models of interiors have always been designed manually with the help of dedicated software packages. However, the demand for indoor models for different purposes has recently increased, thus a higher degree of automation could better satisfy different applications and speed up the processes. We present a technique for the fully automated modelling of indoor environments from a three dimensional point cloud. The results we achieve are very promising and the method suggested may provide completion to the actual standard for 3D city modelling. Our approach is based on a plane sweep algorithm for the segmentation of a point cloud in order to recognize the planar structures of a room. At first the 3D points that belong to the horizontal structures are tagged by sweeping a virtual plane along the vertical direction and thresholding the distances of each point to the plane. All the points that are not chosen as either floor or ceiling are labelled as potential wall points and are being considered in the following segmentation step to detect the vertical faces. Finally, the floor plan of the room is estimated by intersecting the directions of the walls and finding the vertices that constitute the ground shape. The result generated is a 3D model in CAD format, which perfectly fits the original point cloud.

1 INTRODUCTION

Geometry and appearances of the urban reality can be currently represented in the international format CityGML, defined by the Open Geospatial Consortium (OGC). The model proposed by OGC supports five different levels of detail (LoDs) that provide a hierarchical description of building entities. A higher classification level corresponds to a more detailed representation of building features. The most elaborate representation is done at LoD4, which ensures the largest number of details for architectural models from the interior. Our research focuses on the implementation of an algorithm able to reconstruct an indoor room automatically according to the degree of resolution pointed to in LoD4. The motivation of this work lies in the convenience of achieving a 3D model, which incorporates internal architectural details. That means, structures and objects that are only detectable from inside, such as internal walls, doors or furniture may be automatically modelled.

For a long time within the geodetic community, automatic building model reconstruction has been restricted to the simple reconstruction of the outer shape of a building. However, it is obvious that for a full reconstruction, the interior of the building has to be considered as well. The availability of methods for automatic reconstruction of interiors could be useful in several applications, which may fit for different industries. Simple visualization purposes could be met, for example for virtual tours into indoor contexts like museums or expositions. The Computer Aided Facility Management (CAFM) would also benefit from the automation of indoor reconstruction. City's infrastructure management could include indoor models to monitor critical structures. Accurate 3D models of building interiors can be the starting point to generate so called production models, which give insight to the statics of a building (Schleinkofer, 2007). Disaster management, risk assessment and civil protection authorities could take advantage of indoor models, for example to plan and to monitor emergency routes and evacuation strategies (Hinks et al., 2009). If the models provide enough details and if they are geometrically accurate, they can be used for simulations by enabling realistic training scenarios for the localization of safety-relevant features (Kolbe et al., 2005). Today's digital globes can be extended not only to contain building's exteriors but also the interior. This allows for virtual stores and provides additional marketing potential. Bill Gates has already formulated this vision in a speech at the Internet Advertising Bureau's Engage conference in 2005 (Gibson, 2005).

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, cost-efficiency of the model generation can be guaranteed. This includes data acquisition, pre-processing and modelling. While data acquisition and low-level processing are already performed at a high automation level, model reconstruction of indoor scenarios is currently performed predominantly using manual approaches. This is in strong contrast to the successful application of automated approaches for the reconstruction of exterior building models (Brenner, 2004).

2 RELATED WORK

Current research concerning automatic modelling of internal scenarios deals with robotics and autonomous systems (Biber et al., 2005) as well as with pure automatic indoor modelling, for example for military purposes (Johnston and Zakhor, 2008). The difference between the method described in (Johnston and Zakhor, 2008) and ours is the data acquisition process, performed from outside the structure since military applications may require a model without even accessing the building. Of course, laser data measured from the exterior of the structure can somehow be incomplete because of the presence of obstructions.

The reconstruction of indoor models has mainly been dealt with in the context of cultural heritage applications, as well. Detailed models of the interior of tombs, temples, churches and other historic structures are a popular topic in heritage projects (Beraldin et al., 2002). However, in these scenarios the scene typically exhibits few regular structures and is rather dominated by ornaments and other irregular features. Therefore, it is usually assumed that the proper reconstruction method in these scenarios is dense surface meshing in combination with high-resolution texturing. Such an approach is suitable for singular structures, but is very difficult to be automated and thus cannot be adopted for widespread modelling.

A very specific area of indoor modelling, which has been the topic of intense effort for automation, is the reconstruction of industrial scenes. In these scenarios, scenes consist of repetitive elements such as beams and pipes. Especially in the chemical and petro industry, automated reconstruction of plants is a growing market. Current state-of-the-art in commercial reconstruction tools is manual pre-segmentation in combination with automated fitting. In the research area, the aim is to further automate the process (Rabbani et al., 2007).

Our approach to building reconstruction from a point cloud is led by the segmentation of the data. Points with different properties are segmented with a plane sweeping method. Such a strategy has already been adopted in image-based algorithms for the estimation of the precise position of façade planes in Digital Surface Models (DSM) (Zebedin et al., 2006). 3D reconstruction of roofs of urban areas from multiple aerial images is also a target application of plane sweeping (Baillard and Zisserman, 2000).

As mentioned above, the focus of the geodetic community has been on exterior building model reconstruction. Classical approaches rely on known cadastral data, which are used in combination with either aerial imagery or LiDAR data to extract building models. Typically, building models are assumed to be simple polyhedrons. A typical representative of these approaches is given in (Haala and Brenner, 1999). Further approaches are described in (Brenner, 2005). However, recent development in LiDAR technology has provided the research community with more detailed point cloud data, which has created the desire for more detailed models. Furthermore, street-side data available through mobile mapping system has sparked developments for detailed facade reconstruction (Böhm et al., 2007). These approaches share many properties (and problems) with indoor reconstruction. Generally, many of the algorithms useful for the reconstruction of exterior building models can be adapted for indoor reconstruction. Our approach specifically adopts the approach of cell decomposition, which has also successfully been used by (Kada, 2006) and (Sohn et al., 2008).

3 ALGORITHM OUTLINE

The specific procedure chosen to process the data in order to extract the 3D model is strictly connected to the laser measurements available, which provide a point cloud as an input for our algorithm. Such a point cloud is a collection of three dimensional points whose position in space is defined by Cartesian coordinates. The entire data set is the result of the registration of several scans along a hallway whose representation is shown in figure 1.

Our project assumes the laser scanner to be approximately levelled, so that the z-axis is aligned with the local vector of gravity; therefore the floor and the ceiling of the scene are parallel to the x-y plane. This is a characteristic property of the laser scanner used in the experiments; however similar features are also provided from other scanners or could easily be achieved using an electronic levelling device.

The real modelling process starts with a segmentation of the point cloud. Its goal is to optimally locate the faces that specify the main structures in the room by grouping points in planar regions with the same characteristics, for instance, the distance from the origin of the coordinates. Our segmentation technique is based on the computation of a vertical and a horizontal sweep. These are both evaluated by sweeping a plane linearly along a predetermined direction with discrete steps (Δu in figure 2) and counting the number of points that either lie on or have a small distance from that plane. Such a threshold operation is initially computed

Figure 1: The hallway

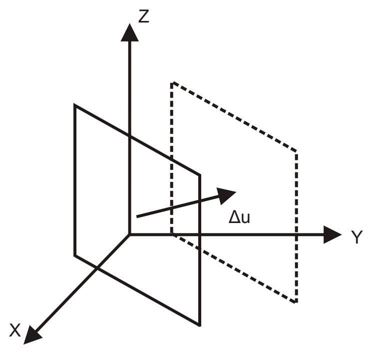


Figure 2: Linear sweep: Sweeping step

for every point in the point cloud since no information is available about the relationship of any 3D point with the structures of the room. Once a point is detected as being part of a particular structure, it is then tagged and removed from the point cloud in order to reduce the amount of data for the next calculation and optimize the speed performance of our algorithm. Whereas the segmentation of the point cloud is necessary to find the surfaces that constitute the room, the ground plan extraction is fundamental to design the correct model. The floor plan is computed by intersecting the directions of the main walls and finding the vertices of the polygons, which constitute the ground shape. Techniques based on half space modeling and cell decomposition are used (Kada, 2006). Namely, the space bounded by the walls is divided in cells, which may be either accepted as floor cells or rejected. The knowledge of the floor plan is important to establish the exact extent of the room, which is limited by the contours corresponding to the walls.

In our implementation, both the segmentation and the modelling algorithm are completely independent from the coordinate system. The axes' positions do not affect the computation of the plane sweep, neither do they about the floor plan extraction. The segmentation of the point cloud is described in section 4. Section 5 explains the rendering of the ground plan. An overview of the algorithm is given in figure 3.

4 SEGMENTATION PROCESS

The segmentation algorithm is implemented in two steps to optimize the recognition of interior faces that are fitted separately to horizontal and vertical planes. As it is a mandatory assumption that the floor and ceiling are horizontally positioned with respect to the world coordinates, their heights along the z-axis can be easily computed with a vertical sweep. Besides, a horizontal sweep

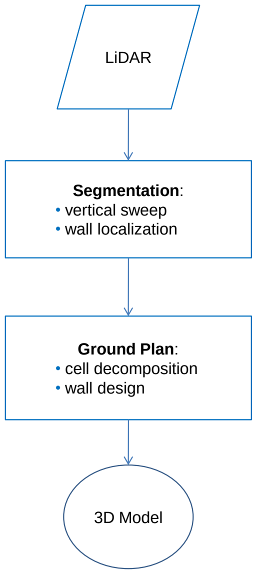


Figure 3: Block diagram of the algorithm

is used for the segmentation of the walls, which are assumed to be perpendicular to the ground.

4.1 Vertical Sweep

The general concept behind our sweeping algorithm is based on the idea of shifting a hypothetic plane along an arbitrary direction with discrete steps. The step width may vary with the point sampling density. The direction chosen for the sweep determines the type of structure which is meant to be detected. For the floor and ceiling extraction, a vertical sweep is computed. Therefore, the sweeping operation is performed along the z-axis.
The implicit form of the plane equation is considered:

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

where x, y and z are the Cartesian coordinates of a point in the 3D space, a, b and c are the components of the surface normal, and d is the distance of the plane from the coordinate origin. We consider a vertical sweeping direction for a consensus plane that is parallel to the x-y plane. Thus, the normal vector of such a surface is the z-axis itself, which corresponds to $(0, 0, 1)$ and leads to $a = b = 0$. By replacing such values in the equation 1, it becomes:

$$z = d \tag{2}$$

where d is actually the parameter, which determines the sweeping position along z.
While shifting the planar surface along the vertical direction by modifying the value of d, we collect points at each step. To store and visualize the results, we generate a histogram, which represents the number of points accumulated at each position of the sweeping plane. Figure 4 shows how most of the points are collected around two peaks whose values on the horizontal axis stand for the heights of the ceiling and the floor of our room. The parameter d ranges from -2 m to $+2$ m since the z value of the coordinate origin does not correspond to the floor level; hence the floor has a negative position. The positions of the peaks are computed through a non maximum suppression algorithm, which selects the histogram values whose amplitude is strictly greater than all amplitudes within a given window. The window size should obviously be smaller than the expected spacing between

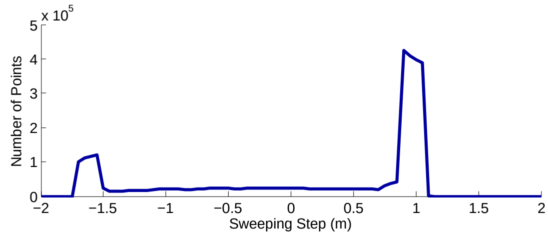


Figure 4: Peaks representing the floor and ceiling

the peaks. Additionally, all the histogram values, which are eligible to be maximal, should be higher than a certain threshold.
The result we achieve is validated by the distance that was found to separate the two peaks. In fact, two meters and a half may be considered a fair standard spacing between the ground and the ceiling. Because of the presence of undesirable objects on the ground, some areas of it have not been reached by the laser beam during the scanning process. Thus, the number of points accounting for the floor is reasonably lower than the number of ceiling points.

4.2 Wall Reconstruction

The geometry of the walls is reconstructed with the same principle used to localize the floor and the ceiling. However, an additional step is required since we now have two degrees of freedom, while in the vertical sweep the parameter d was the only unknown. The planes wanted for the walls are vertical by a clear assumption; therefore they are orthogonal to the floor and the ceiling, and have a normal vector whose z component is equal to zero. That allows us to think of the solution as a two dimensional projection of the problem. By setting $c = 0$ in equation 1, we obtain:

$$ax + by = d \tag{3}$$

where a and b are functions of the angle β between the wall and the x direction (see figure 5). Thus, we can express them as

$$a = cos\beta \tag{4}$$
$$b = sin\beta \tag{5}$$

if the normal to the walls is a unit vector. The angle β together with the value of d are the parameters to be considered in order to find the optimal position of the walls. Actually, by defining the coordinates of an arbitrary 3D point as (x_0, y_0, z_0), it is possible to write a parametric equation, which represents a sheaf of lines through that point as

$$ax + by = cos\beta * x_0 + sin\beta * y_0 \tag{6}$$

whose right hand side term gives the value of d, thus

$$d = cos\beta * x_0 + sin\beta * y_0 \tag{7}$$

with $cz_0 = 0$ since $c = 0$. The walls' dominant direction is then given by the direction of one straight line of the sheaf, which is computed with a threshold operation by means of a rotational sweep. A further linear sweep is meant to find a precise position for the walls by sweeping planes along their normal vectors.

4.2.1 Rotational Sweep

Combining equations 3 - 6 yields

$$cos\beta * x + sin\beta * y = cos\beta * x_0 + sin\beta * y_0 \tag{8}$$

where for each value of the parameter β a different plane through $(x_0, y_0, 0)$ is generated. Eventually, the goal of the rotational

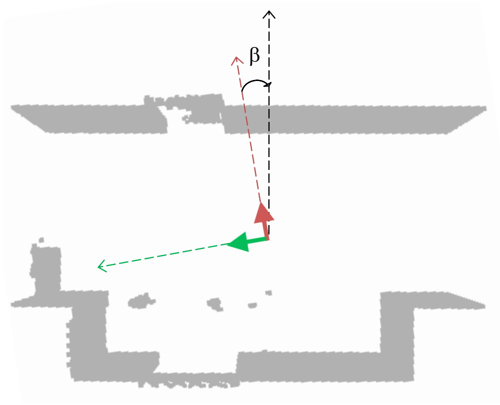


Figure 5: Rotation of the coordinates

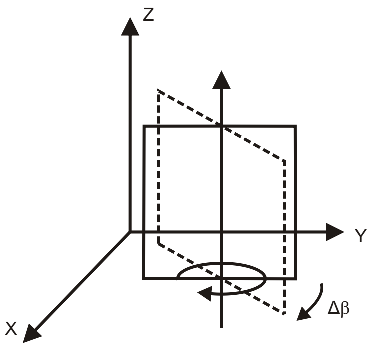


Figure 6: Rotational sweep: Sweeping angle

sweep is to find the optimal value of β by substituting a random given point with coordinates x_0, y_0 and $z_0 = 0$ in the equation 8. The condition for β to be optimal is the acceptance of a vertical plane, which has the normal vector at that angle and matches the highest number of points. Conceptually, to execute the rotational sweep means to rotate a plane, which contains the point $(x_0, y_0, 0)$, around a given axis with discrete angular steps. As shown in figure 6, the plane is rotated each time by a certain angle $\Delta\beta$ with respect to its previous position. At each step, the number of points, which belong to the current plane, is counted. 3D points that are considered close to the plane within a given threshold are also collected. To reduce computation time, the points to be checked for consensus with the rotating plane are only those in the radial neighbourhood of the random point. At the end of the process, after achieving a global rotation of 180 degrees, a two columns vector has been created. Such a vector stores the information about the current angles, that means the position of each plane in relation with the amount of points collected. It is obvious that the direction corresponding to the densest distribution of points is chosen as the dominant direction for the walls. Figure 7 shows that the dominant direction was found for $\beta \approx 3$ rad. The process is iterated several times, and each time a different random point is given at the top of the iteration. We decided to consider 50 loops. Thus, 50 planes through 50 randomly selected points are swept 180 degrees around a vertical axis before fixing the wall angle.

4.2.2 Linear Sweep After the computation of the angle β, a linear sweep is performed for the completion of the wall reconstruction process. This has the same mathematical properties of the vertical sweep computed for the localization of the floor and the ceiling. For ease of implementation, the point coordinates are

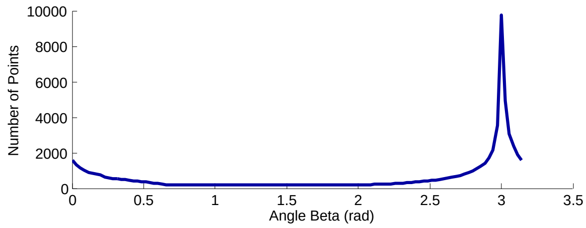


Figure 7: Peak representing the angle beta

rotated by an angle β in order to be able to perform the sweeping operations along the following directions:

$$x = h \tag{9}$$
$$y = k \tag{10}$$

by leaving only one degree of freedom to be determined for each direction. The adjustment of the coordinates for a clockwise rotation is given by

$$x' = -x\cos\beta - y\sin\beta \tag{11}$$
$$y' = x\sin\beta - y\cos\beta \tag{12}$$

where x' and y' are the new coordinates of a point in the reference system whose x- and y-axis are parallel to the normal vectors of the sought walls. All the points having coordinates $(x', y', 0)$ are checked for consensus with the planes in equation 9 and 10. The planes that fit a number of points above a given threshold are accepted as walls. The histogram for the linear sweep in the horizontal direction is shown in figure 8.

5 FLOOR PLAN EXTRACTION

The computation of the ground plan is about defining the ground shape, namely, the contours of the scanned room. These contours are easily obtainable from the positions of the walls, which were already computed in the previous step of the algorithm. The idea is to intersect the directions of the walls and partition the ground in several cells, which are later labelled as ground cells or non-ground cells. That is basically a split-and-merge approach since the ground is first split into quadrilaterals, which are later joined under a given criteria. The task is accomplished in two dimensions because we work on the ground level; thus the elevation along z can be omitted. The straight lines defining the wall traces on the floor are derived from the histogram peaks. Such peaks are initially computed along one direction and correspond to the plane in equation 9 which best fits the points tested.

Of course, all the walls in a room do not usually have the same direction. However, our data set is restricted to the case of a hallway with wall pairs, which are either aligned or rotated by 90 degrees to each others. This assumption allows us to look easily for one main direction, having the largest amount of wall points, while inferring the second one by a simple rotation by 90 degrees. If the assumption about the walls being aligned within two perpendicular directions is not valid any longer (a room may have any shape), then the angle β should be computed for every group of walls with equal orientation.

After the computation of the histogram peaks, we can write out cut lines for the implementation of the wall traces on the floor. Up to this point, the peaks that detect the walls are still given by the equations 9 and 10, which refer to the point cloud rotated by the similarity transformation in 11 and 12. Therefore, the calculation of the cut lines should consider the rotation parameters in order to create, as an output for the intersection procedure, points

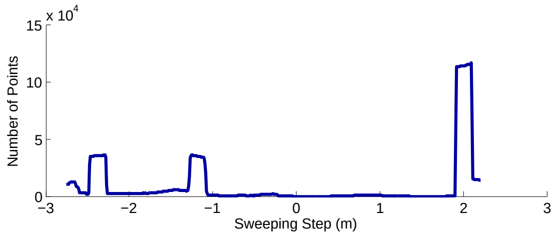


Figure 8: Peaks representing the walls

Figure 9: Partition of the floor in cells

with valid coordinates for the final model. Hence, the cut lines in the original coordinate system are written as:

$$-\cos\beta * x - \sin\beta * y - h = 0 \quad (13)$$

$$\sin\beta * x - \cos\beta * y - k = 0 \quad (14)$$

and are rotated by β with respect to the x- and y-axis. The result of the intersection of the cut lines in 13 with the cut lines in 14 is a set of points, which are further split into subsets representing single quadrilateral vertices. The criteria to accept or reject each quadrilateral as a ground cell is a simple threshold operation of the number of points contained inside the cell. Considering a whole data set of 800000 points, we expect each quadrilateral of the ground plan to contain at least 5000 points. Such a number is an absolute threshold decided after the observation of the point sampling density in relation to the area of the cells. In the data acquisition process, we achieve an average sampling density of 15 mm after registration. Also, the largest cell computed is about 3.2 by 4 m. Therefore it contains an amount of points equal to $3.2/0.015 * 4/0.015 \approx 56000$, which is highly above the threshold value. The result of the ground partition process with the related cells is shown in figure 9. The blue cell at the upper-left corner is discarded because the test with the 5000 points failed; therefore the cell does not belong to the ground.
The last step is to compute the contours of the ground. To do that, the union of the accepted cells is calculated and the external sides, which give the profile of the floor, are extracted. The walls are finally drawn along the resulting sides by raising them up to the level of the ceiling. A representation of all the steps necessary to create the final model is given in 10.

6 RESULTS AND DISCUSSION

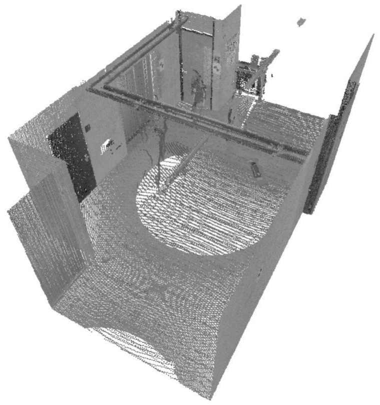
We have tested our algorithm on a data set of about one million points acquired with the Leica HDS3000. The plane sweep method is implemented with C++ code and runs on a PC with AMD Athlon dual core 2.4 GHz CPU. Our design choices are a compromise between the accuracy of the results and the speed performances. In accordance with that, we have set the variables of our project to values, which optimize the outcomes without affecting the computation time.
In the linear sweep, which computes the levels of the floor and the ceiling, we have set a sweeping step of 5 cm and a consensus distance of 10 cm for a point to belong to a moving plane. That means, if a point is found to be at a maximum distance of 10 cm from one of the sweeping planes, it is considered to be on that plane. Since we chose the sweeping step to be 5 cm and the agreement distance 10 cm, the same point may be counted as belonging to different sweeping planes. That generates a small error in the exact definition of the plane levels. Such an uncertainty is corrected by an average operation between the detected histogram peaks and their neighbouring values. After the correction, the floor and ceiling heights perfectly fit the original point cloud.
A numerical proof of the correction is also given in table 1. The levels of the floor and ceiling obtained with different methods are shown on each row of the table. The first row points out the floor and ceiling heights computed by using a least squares adjustment (Cyclone LS) to fit patches to the point cloud, which was manually segmented. The difference between the positions of the two planes, which represent the floor and the ceiling, along the z-axis is displayed on the third column. Such a difference corresponds to the real height of the ceiling if the floor is shifted to the origin of the coordinate system. We compare that difference for the three cases. The output of the least squares is taken as a reference for the other two results. It is observable that the floor height accuracy after the correction step is about 1 cm, while the same value without correction has a divergence of 13 cm. As for the rotational sweep, figure 6 shows the rotational angle $\Delta\beta$, which is set to less than 2 degrees. Precisely, it is required to compute a 180 degrees rotation of the plane by achieving the goal with 110 steps. The angle $\Delta\beta$ is then equal to $180/110 = 1.63$ degree. As already described in 4.2.1, the 180 degrees rotation is repeated for 50 randomly selected points, in order to find the best angles for the walls.

Algorithm	Floor	Ceiling	Difference
Cyclone LS	-1.599	0.988	2.587
Plane Sweep	-1.55	0.899	2.449
Correction	-1.6	0.975	2.575

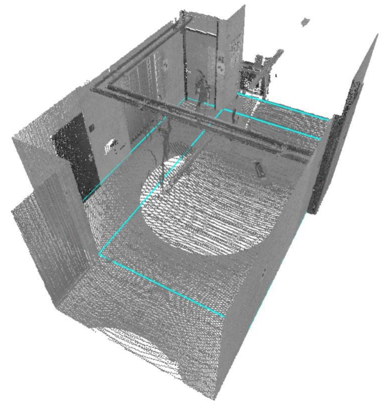
Table 1: Floor and ceiling levels (m)

7 SUMMARY

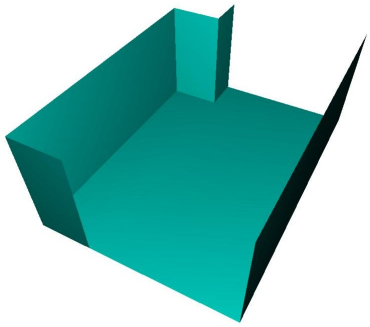
In this paper we described a method to reconstruct automatically the 3D model of indoor rooms. A plane-sweep-based approach is used to detect the positions of the walls, floor and ceiling. First, the horizontal surfaces are segmented from the point cloud by computing a vertical plane sweep along the z direction and thresholding the point distances. On the other side, the vertical surfaces are localized by means of a rotational plane sweep, followed by a horizontal sweep. The goal of the rotational sweep is to compute the wall directions with respect to the x- and y-axis. Finally, the ground plan of the room is computed and the 3D model is built.
Our approach to 3D modeling is robust and completely automatic since our program takes a binary point cloud as an input and writes the actual model on a CAD file. A priori information about the topology of the targeted room shape is not required. Only basic assumptions on the vertical axis and orthogonality are made. In the future, we expect to increase the functionalities of our algorithm by providing new capabilities for the automatic recognition of pieces of furniture and other critical objects, such as windows or doors.



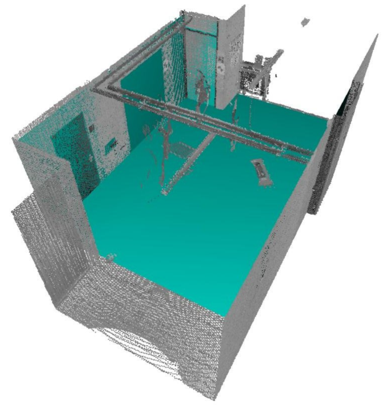
(a) Point Cloud



(b) Cell decomposition



(c) 3D model



(d) Point cloud and model

Figure 10: From the point cloud to the model

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