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May 25, 2019

DETECTION OF SPACE CONNECTIVITY FROM POINT CLOUD FOR STAIR RECONSTRUCTION

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Commission VI, WG VI/4

KEY WORDS: Stair Reconstruction, Stair Connection Space, Indoor Space, Space Connectivity, Point Cloud;

ABSTRACT:

Stairs are common features in indoor environments that play an important role in structured indoor reconstruction. Despite the rapid development of indoor reconstruction from point clouds, the problem of stair reconstruction is far from being resolved. The current staircase detection methods based on partial sensory data are not suitable for staircase modeling because they determine only the geometric structure of stair steps. As staircase model is among the most important components of an indoor model and stair space is a subspace of indoor space, the approach for indoor modeling should be able to determine the spatial extent of the stair connection space as well as its relationship with other subspaces. In this study, the semantic definition of stair space and stair connection space are defined and a novel stair reconstruction method by detecting space connectivity from the point cloud is proposed for stair reconstruction. The proposed method is verified on four datasets with different stair types. The results indicate that the proposed method is well suited for staircase modeling in multi-story indoor environments.

1. INTRODUCTION

Currently, there are growing interests and trends in modeling the digital three-dimensional world. 3D models of indoor scenes are in demand in many fields, e.g. the building information model (BIM), indoor navigation and positioning, emergency services, and architectural planning and simulations. Stairs are common features in urban environments (Tang and Lui et al., 2012), and automatically reconstructing stairs from point clouds is a problem that remains to be resolved. A staircase can generally be described as a series of steps (horizontal planes) placed at regular intervals in indoor space. The purpose of a staircase is to facilitate travel between different stories of a building. The stair space plays an important role in connecting adjacent stories in multi-story indoor space. Staircases often pose a navigational challenge to both visually impaired people and autonomous mobile systems (Tang and Lui et al., 2012). Staircase detection has been studied by many researchers in the computer vision and robotics communities. Localization and modeling of stairways by mobile robots can enable multi-floor exploration for those platforms capable of stair traversal (Sinha and Papadakis et al., 2015). Meanwhile, providing assistance to the visually impaired has been a relevant topic for many years, and many advances have been accomplished in some specific tasks (Perez-Yus and Gutierrez-Gomez et al., 2017).

Since this study focuses on the modeling of staircases, which is one of the most important components of structured indoor modeling (Ikehata and Yang et al., 2015), the current staircase detection methods from partial sensory data encounter some difficulties. As the stair space is a subspace of indoor space, the modeling of a staircase should determine not only the geometric structure but also the spatial extent of the stair connection space. The whole stair space is difficult to construct in a single moment because of the limited visibility of a camera.

Recent advances in laser scanning systems have provided an efficient way to collect 3D point clouds from indoor scenes. However, the camera information is often not available and the measurement results are often fused point clouds. It is hard to determine the spatial extent of the stair connection space because the point clouds acquired using either stationary terrestrial laser scanning (TLS) or indoor mobile laser scanning (IMLS) are often unstructured and semantically poor. The processing of raw point clouds to build a staircase model can be very expensive. In this study, we focus on the detection and modeling of stairs from fused point clouds. Viewpoint information is not available and multi-location point clouds are fused into a single point cloud.

This study proposes a novel stair reconstruction method by detecting the space connectivity from point cloud to perform staircase reconstruction. The stair space is defined and treated as a subspace of the indoor space at the semantic level. The spatial extent of the stair space is determined and the staircase point cloud is filtered with the prior knowledge of the stair space. Finally, a staircase geometric model is generated.

The remainder of this paper is organized as follows. Important related works are introduced in Section 2. The proposed method is described in Section 3. Experiments on the four staircase datasets are presented in Section 4, followed by a discussion in Section 5. Finally, the conclusions are drawn in Section 6.

2. RELATED WORK

The focus of this research is on the staircase modeling which is one of the most important structures of interior buildings. The discussion here is limited to those closely related topics. We first discuss the stair detection methods and then consider the related works on step plane detection methods for staircase modeling.

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2.1 Stair Detection

Stair detection is an important ability required by indoor robots, to enable for multi-floor exploration in 3D environments. It is also important for navigation to assist people with vision problems. Current research on stair detection often related to path planning systems in computer vision and robotics. Staircase detection is important for pathway finding and robot path planning. Stair identification has been widely studied in recent years, and laser or vision sensors are common used for stair detection.

A new minimal 3D map was used to represent point clouds obtained by RGB-D sensor. The step-like features were estimated and grouped based on adjacency for stair-case detection from point-cloud data to identify dominant staircase structures (Sinha and Papadakis et al., 2015).

A wearable RGB-D camera was used for stairs detection (Perez-Yus and Gutierrez-Gomez et al., 2017) from depth data to determine if the horizontal planes in the scene are valid steps of a staircase based on their dimensions and relative positions.

An ascending stairway was modeled from dense depth imagery to conduct the traversability analysis (Delmerico and Baran et al., 2013). Stairs were detected by a large and regular change in depth without considering the viewpoint information.

A two-level 3D data structure that allows pipelined and streaming processing of 3D data was proposed (Bansal and Matei et al., 2011). The point cloud was stored in a voxel grid and histograms were used for stairs detection.

Eilering et al. (2014) identified planar surfaces, with a specific focus on segmenting stair structures. The classification of each point was dependent on the local spatial features of the point cloud, but also on the classification of close points based on probability. With a trained dataset they achieved a success rate of approximately 75%. However, segmentation and the structural relationships between the objects were not considered.

From the stair modeling perspective, the camera often has limited visibility in a single moment, and the complete stair space is difficult to construct at any one time. Research using color image often achieves good results when deciding whether an object is a stair or not, but the spatial extent of the stair region cannot be determined, thus, these methods are not suitable for stair model reconstruction.

2.2 Primitive based Stair Modeling

The existing approaches focus on either stairway detection or traversal, and do not satisfy the demands of staircase modeling as a component of consistent indoor modeling. In such cases, the modeling of a staircase has three problems to be solved: (1) the extent of stair area, (2) the spatial relationship with other indoor subspaces and (3) the geometric model of staircase. The point cloud provides only geometric coordinates and viewpoint information is often unavailable, which makes stair detection a hard problem (Okorn and Xiong et al., 2010). Current studies often treat primitive based stair reconstruction problem as step plane detection problem. Most literature on 3D indoor modeling from point clouds and images focuses on the reconstruction of geometric elements, such as walls, floors and ceilings, including stairs.

A plane-based approach to the problem of staircase detection using depth data in inverse depth coordinates was proposed in (Tang and Lui et al., 2012). The random sample consensus (RANSAC) algorithm was used to detect the steps of a staircase iteratively relative to the ground plane on depth data obtained from a Kinect sensor. Such an approach not only allows for the detection of the presence of a staircase, but also allows us to identify the inclination of the staircase and model each detected step of the staircase as a plane model in 3D space.

Planar 3D modeling method (Sanchez and Zakhor, 2013) was used to construct building interiors from point cloud data. RANSAC was employed to find the best fitted planar primitive in terms of the least-square sense. Model-fitting and RANSAC, are capable of detecting large-scale architectural structures, such as ceilings and floors, as well as small scale architectural structures, such as staircases.

The approach in (Li and Su et al., 2018) attempted to solve the staircase modeling problem by using the step plane detection method. The NDT-RANSAC method (Li and Yang et al., 2017) was used to segment the large area planes and the region growing method was used for step plane segmentation. However, the method still suffers from the problem of unclear spatial extent of staircase, and is not suitable for consistent indoor model reconstruction.

The above studies often implicitly assume that the research region is stair. However, a point cloud is unstructured and contains plenty of planes. If the stair region cannot be determined; the step plane is difficult to identify. Moreover, the image feature-based method does not work well without viewpoint information. A staircase is part of indoor building; therefore, stair modeling is not only a stair and step detection problem but also a space recognition problem. and is an inseparable part of indoor space and indoor reconstruction. Moreover, the current work constructs only the single-flight staircases and is not suitable for double-flight or spiral staircases.

3. METHOD

In this section, we introduce our 3D staircase reconstruction method. We first introduce several semantic definitions adopted within our study. Some novel concepts like stair space and stair connection space are introduced here. The relationships between stair connection space and indoor space are clearly defined. The structure of an indoor building is defined on two levels, namely, semantic level and geometric level. The definition of room, wall, door and stair is at semantic level. To distinguish these semantic definitions from one another, the structural elements such as wall planar surfaces, ceiling planar surfaces and floor planar surfaces are defined at the geometric primitive level. The details are shown as follows.

A hierarchy of semantic classification for indoor spaces is defined in this study as shown in Figure 1. As Open Geospatial Consortium (OGC) IndoorGML has a complete definition of indoor space, we simplify and extend some representations in it to fulfil our research objectives. An indoor space is classified as either free space (open space) or occupied space. A free space is a navigable space and occupied space is a non-navigable space. The room space, wall opening space and stair connection space are three subclasses of free space.

With the hierarchical semantic definition of indoor spaces, each indoor space can be classified with semantic information. Meanwhile, an indoor space can be subdivided into a set of subspaces. A room space S^{room} is a continuous space enclosed by wall planar surfaces, a ceiling planar surface and a floor planar surface.

A slab space S^{slab} can be subdivided into a slab-occupied space S^{so} and a set of slab free space S^{sf}. The upper surface is a floor planar surface, and the bottom is a ceiling planar surface. A staircase connects the two vertically adjacent storeys. A slab free space S^{sf} is the intersection of a stair connection space S^{stconn} and a slab space S^{slab}.

$$S^{slab} = \{S^{so}, S_i^{sf}\}, i \text{ is the } i^{th} \text{ slab free spaces in the slab}$$
$$S^{stair} = \{S^{sto}, S^{stconn}\}, S^{sf} = S^{slab} \cap S^{stconn}$$

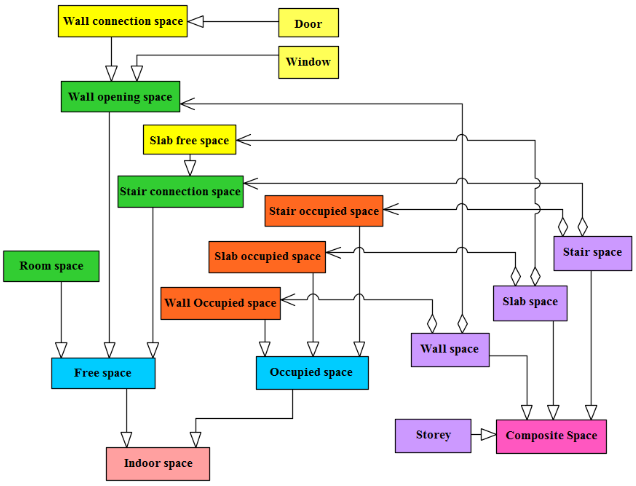


Figure 1. The semantic definition of indoor spaces.

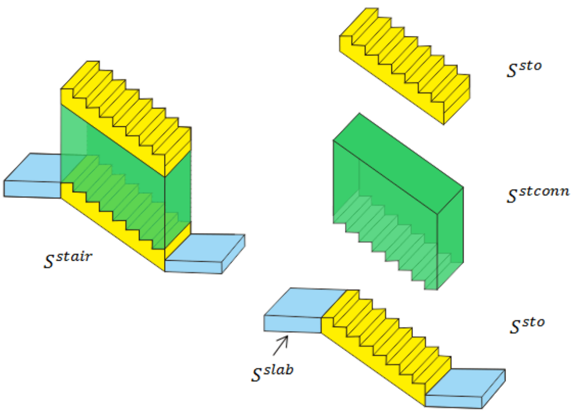


Figure 2. Illustration of semantic definition of stair space, it is the union of stair connection space (green) and stair occupied space (yellow).

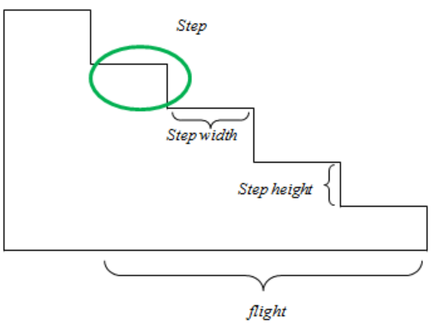


Figure 3. The concepts of staircase, it depicts the meaning of flight and step.

Many works have utilized the strong Manhattan world (MW) assumption (Fichtner and Diakité et al., 2018), which holds true for many indoor scenes that contain man-made architectural structures. However, this assumption fails in complex indoor environments with non-orthogonal walls. In this work, we refer to a weak MW, which assumes that vertical planes are parallel to the gravity vector and ground planes are orthogonal to the vertical direction. The horizontal planes of stair steps are orthogonal to the vertical direction. The close related parameters, e.g. flight, step width and step height are shown in Figure 3. A flight is an uninterrupted series of steps.

The input of our algorithm for stairs reconstruction is 3D point cloud, $P = \{p_i\}$, captured by stationary terrestrial laser scanning (TLS) and mobile laser scanning (MLS), where $p_i = \{x_i, y_i, z_i\}$ is the coordinates of point given via the world coordinate system.

As shown in Figure 4, the workflow of proposed method contains five steps: (1) Coarse segmentation of stair region; (2) Floor surface labeling; (3) Point cloud filter in the vertical direction; (4) Step-like growing for further filter; (5) 3D staircase modeling.

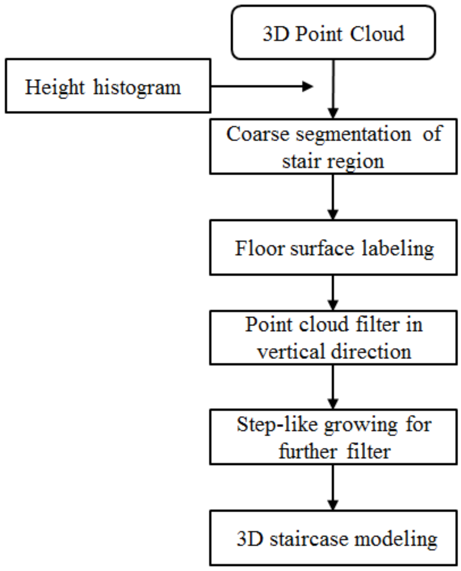


Figure 4. The workflow of the proposed method.

3.1 Coarse Segmentation of Stair Region

In the first step, the candidate region of the point cloud that contains entire staircase is segmented. Since we define the slab opening space S^{sf} as the intersection of the stair connection space S^{stconn} with the slab space S^{slab}, the vertical extent of S^{sf} is shown as the interval of histogram. A height histogram is created where the sample points are projected to a histogram in Z-coordinate direction (Oesau and Lafarge et al., 2014). Because the laser scan system can only measure the surface of object, the solid slab usually has two planar surfaces; the connectivity of the staircase area opens a hole in the solid slab and forms a connection space. Two adjacent peaks displayed on the point cloud height histogram correspond to the ceiling and floor planar surface. An example was shown in Figure 5, the peak of blue and yellow bin represent the floor and ceiling planar surface.

The input point cloud is subsampled using octree-based subsampling method to acquire relatively homogeneous point cloud in terms of density. As shown in Figure 5, the peaks at the highest increment of the histogram show the location of horizontal structures in the facility, and represent the locations of floors and ceilings. The slab opening space S^{sf} is extracted by nadirs between two peaks of floor and ceiling. According to the holes (slab opening space) extracted from the solid slab, the spatial scope of the staircase area is extracted. The point clouds including the stairs of the whole building are obtained by superimposing the acquired range of each floor and setting a certain buffer Δd area. In this step, the ceiling planar surface height $h_m^{ceiling}$ and floor planar surface height h_m^{floor} of story m (m = 1, 2,3, ⋯) are also extracted.

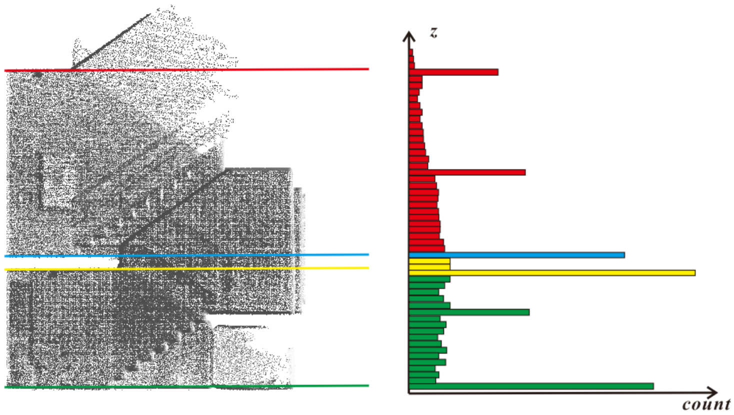
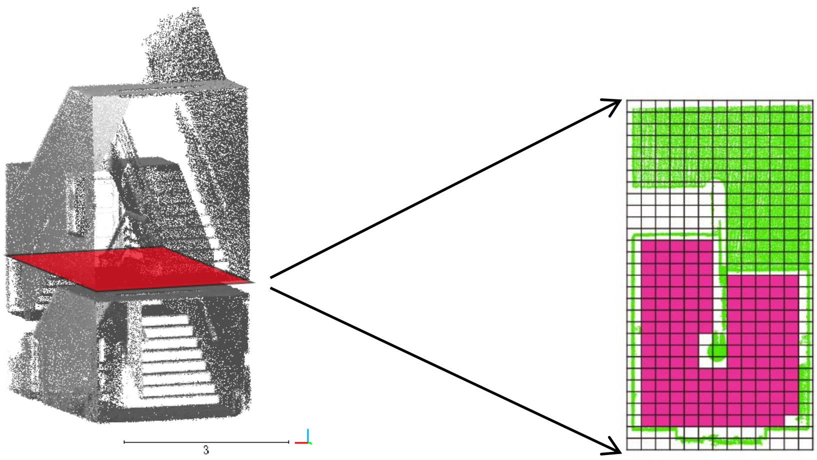


Figure 5. An example of height histogram.

3.2 Floor Surface labeling

Once the coarse segmentation of the stair region is completed, a candidate point cloud in stair region is obtained. A volumetric representation is used to model the occupied space and the free space with a grid of voxels. Using the extracted floor height h_m^{floor}, (m = 2,3, ⋯), the floor free space evidence is then generated in this step (Figure 6). The input of this step is the floor height h_m^{floor}, and a buffer distance d_{slab}. The value of d_{slab} should be smaller than the thickness of slab. The output is the floor free space evidence raster as shown in Figure 6 (b).

The outdoor empty evidence is filled with a flood-fill algorithm which is implemented in the OpenCV library. The seed pixel value equals zero. Then the floor free space is labeled using the region growing algorithm. Although the presence of furniture will generate occlusion during the laser scan process, an occlusion hole in the planar surface will obviously fail to connect the adjacent floors. In this case, the evidence of occlusion can be rejected. in multi-story building { S_i^{story}, i = 1,2,3,4, ... }, the algorithm iteration starts from the second floor.

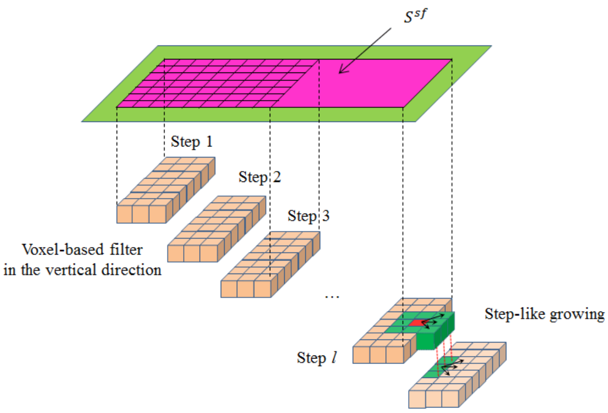


(a) (b)

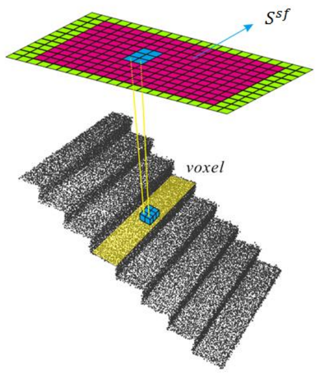
Figure 6. Floor planar surface labeling. (a) Floor surface (red), and (b) Floor point cloud labeling, the connection space is labeled in pink.

3.3 Point Cloud Filter in Vertical Direction

The next step is to filter out the point cloud of stair region. The stair connects stories vertically. The slab free space is labeled, after which the 2D extent of the slab opening space in the XOY plane is extracted. A voxel-based filter method is designed to filter out the scan points of steps (including the stair landing) in the vertical direction. Figure 7 shows the floor planar surface labeling result and the slab opening space is labeled with pink. The floor plane separates the stair connection space into two parts. The filter is accomplished in dual direction, i.e. up and down. In this step two point clouds are created, namely the point clouds are distributed in the bottom and upper boundary of stair connection space.



(a)



(b)

Figure 7. Point cloud filter in the vertical direction, the connection space is surrounded by steps. (a) Illustrate of the voxel-based filter algorithm; (b) An example of filtered stair point cloud.

3.4 Step-like Growing for Further Filter

The 2D extent of the slab opening space may not be equal to that of the stair connection space in the XOY plane; in this case, the extracted stair point cloud may be incomplete. Thus, a further filtering step is needed to all the occupied points occupied by on the steps. The basic principle of this approach is also that of region growing, but the difference is that the seed-occupied voxels are those at the lowest place extracted in the above step. The seed grows in the horizontal plane. The algorithm is terminated in the up direction when the distance between the occupied neighbour voxel and the current seed is larger than zero and less than the given threshold. Similarly, the algorithm is terminated in the down direction when the distance between the current seed and the occupied neighbour voxel is smaller than the given threshold ΔH. Since the distance is measured in the vertical direction and the region is growing from voxel to voxel, it is a step-like growing algorithm.

3.5 3D Staircase Modeling

After the step-like growing, the entire stair point cloud is filter out. We use the connect component algorithm to cluster the distinct piece, and clusters with a point number less than given threshold n are removed. The robust median absolute deviation (MAD) (Rousseeuw and ChristopheCroux, 1993; Leys and Ley et al., 2013) plane fitting algorithm is used to fit the step planes. The way MAD to find outliers is to mark as a potential outlier any point that is more than two standard deviations. Many researches use the histogram approach to reconstruct the stair. Obviously, it cannot be used to model the non-straight or spiral staircase. In this research, the α-shape algorithm is used to extract the boundary outline of each step followed by a boundary regulation step. Two cases of stair models are considered in this work: one is continue step surface and another is discrete step surface.

In the first case, a typical stair model usually consists of step planes, break lines, edges, and the corresponding vertices which are determined by intersecting the planar segments and are obtained based on the topological relationship between each pair of adjacent planar surfaces. Therefore, one of the main tasks in stair reconstruction is to get the correct topology of all steps. For a continue step surface stair, a graph is created to represent the step planes and the relationship between them. When the stair is a discrete step surface which means that the staircase only has horizontal step planes, the topology information can't be use, only the boundaries regulation step is adopt.

α-shapes

In this step, the points are projected to the fitted step plane and the step boundary outline is then computed and refined. The boundary outline is extracted via the CGAL α-shapes algorithm. In order to eliminate the introduced bias at borders and improve the computed raw outline, the user specified radius parameter α is used to determine the complexity and smoothness of boundary. As a further improvement, the extracted polyline α-shapes that do not fulfill predefined criteria are filtered out.

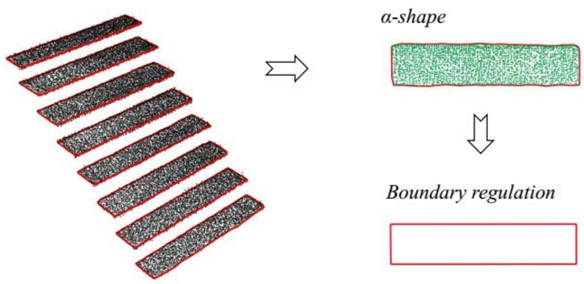


Figure 8. Boundary extracted using α-shapes algorithm

The steps are sorted based on their height. The current step to its next neighbor step determined the flight direction. The stair flights are classified. The shape of a step is general a rectangle; the long edges are extracted. The attributes including edge direction and length are extracted.

Boundary regulation

The α-shapes boundaries described above only produce a rough estimation of the true underlying object boundaries as shown in Figure 8. In order to get regularized boundaries, a RANSAC algorithm is used to robustly fit straight line segments to the refined α-shapes boundary. The assumption is that all steps of same-flight staircase share the same length, width and height. The median direction vector is taken as the line segments' direction of steps. Therefore, the unique step parameters are acquired. After the boundaries regulation step, the step plane primitives are extracted and the 3D stair model is finally generated.

4. EXPERIMENTS

We evaluated the proposed approach using four staircase datasets. The Dataset-1, Dataset-2 and Dataset-4 originate from the Matterport3D dataset (Chang and Dai et al., 2017). The Dataset-3 is from ISPRS benchmark on indoor modeling.

The Matterport3D dataset is a large-scale RGB-D dataset containing 10,800 panoramic views from 194,400 RGB-D images of 90 building-scale scenes. The data was captured with a Matterport camera in home environments. The point cloud was created from raw data in our research.

The ISPRS benchmark (Khoshelham and Díaz Vilariño et al., 2017) on indoor modeling is a laser scan dataset. This point cloud was captured in one of the buildings of the Technische University Braunschweig, Germany. The sensor Zeb-Revo was used to perform the survey across two floors connected by a staircase. The level of clutter in the point cloud is low. The relative accuracy is 2–3 cm. The parameters of the staircase datasets are listed in Table 1. The algorithm was implemented in C++. All experiments were performed with a 3.60 Hz Intel Core i7-4790 processor with 12 GB of RAM. The input parameters for proposed method are shown in Table 2.

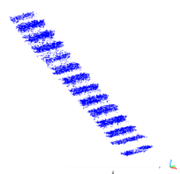
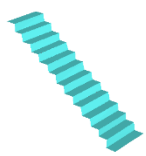
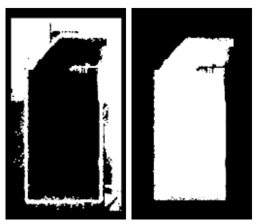
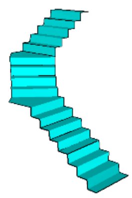
Test Sites	Stair Type	Length (m)	Width (m)	Height (m)	Points/m^2	From
Dataset-1	Single-flight	5.28	3.96	6.12	124,000	Matterport3D
Dataset-2	Three- flight	4.08	7.23	6.74	249,000	Matterport3D
Dataset-3	Double- flight	3.20	5.82	7.32	41,000	ISPRS benchmark
Dataset-4	Spiral	6.88	5.32	7.25	103,000	Matterport3D

Table 1. Description of the staircase datasets.

Parameters	Descriptions	Dataset-1	Dataset-2	Dataset-3	Dataset-4
s	The size of voxels	2.5 cm	2.5 cm	2.5 cm	2.5 cm
d_{slab}	The buffer distance of floor	8 cm	8 cm	8 cm	8 cm
n	The minimum number of point cluster of connect component algorithm	200	200	100	200
ΔH	The step height threshold	20 cm	20 cm	18 cm	20 cm
$\Delta width$	The step width threshold	22 cm	22 cm	25 cm	--
α	The specified radius parameter of α-shape algorithm	10 cm	10 cm	10 cm	10 cm

Table 2. The input parameters for proposed method.

In Table 3, we show the experiment results of our proposed stair modeling method. The original point clouds are shown in second column. The floor labeling binary image and connection space region image are shown in the third column. The filtered point clouds of stair area are shown in fourth column, and the last column is the reconstructed 3D stair models.

No.	Point Cloud	Floor surface labeling	Stair Point cloud filter	3D Stair model
1				
2				

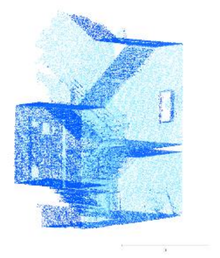
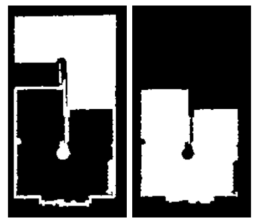
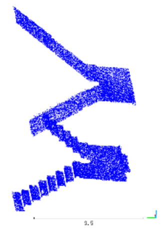
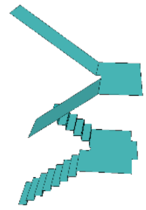
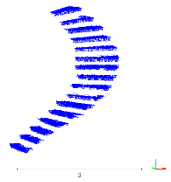
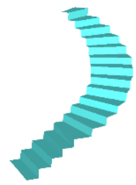
3				
4				

Table 3. The experimental results on four staircase point cloud.

As shown in Table 3, Dataset-1contains a single-flight staircase. It can be seen that all steps of single-flight staircase share the same length, width and height. The proposed method detected totally 12 steps. The average width of all steps is 102 cm and the average height is 19.2 cm. The Dataset-2 contains a three-flight staircase. The proposed method detected totally 17 steps. The average width of all detected steps is 118cm and the average height is 19.8 cm.

The stair shown in Dataset-3 is a double-flight stair. Two flights of this stair were joined by a landing. The shape of the staircase is like the alphabet Z. As shown in Table 4, totally 18 steps are detected. The average raise height of all detected steps is 17.6cm and the average width is 25.1cm.

There is a spiral staircase in Dataset-4. The experiment on this dataset detected totally 16 steps. The average raise height is 19.6 cm. The average length is 102.0 cm. Because the step shape of spiral staircase is not rectangle, the average width wasn't recorded here.

Test Sites	Total Steps	Average Height (cm)	Average Length (cm)	Average Width (cm)
Dataset-1	12	19.2	102.0	21.2
Dataset-2	17	19.8	118.0	21.3
Dataset-3	12	17.6	132.0	25.1
Dataset-4	16	19.6	102.0	--

Table 4. Description of the stairs reconstruction results on real datasets.

5. DISCUSSIONS

The above experiments suggest that our proposed stair reconstruction method is a potential method for automatic stair reconstruction. The stair space was defined and treated as a subspace of indoor space. When compare with the standard of IFC building model (Zhang and Shu et al., 2017), the free space is similar to the *IfcSpace*. The free space is further classified as room space and connection space to ensure the structured indoor modeling from point cloud. The extent of stair connection space is determined and the geometric model of staircase was built. However, some affiliation, for example the railing system cannot be reconstructed.

Point density has a big influence in histogram, so unambiguous point cloud is proper for our study. The input point cloud should subsample to be relatively homogeneous in terms of density. The precise of reconstructed model is still not very high. The reason can be divided into two aspects. First is the error from laser scan system. Second, the occlusion occurs sometimes, which causes the incomplete of scanned step point cloud.

Only the XYZ coordinates are used to detect stairs in this study. For stationary TLS or IMLS, the viewpoint of each scan can be used to calculate the 3D point evidence to get more reliable stair connection space. More cues (e.g., colour and intensity) and vision based methods can be used to detect the stair steps and obtain a more precise result. As the staircase model is an important part of indoor modelling, our previous work proposed a comprehensive segmentation method (Li and Su et al., 2018) to model interior building with multiple stories. It is easy to integrate this proposed approach to improve the modelling result of previous work.

6. CONCLUSIONS

In this work, a stair reconstruction method was proposed by detecting the connectivity of the indoor space. The semantic definitions of stair space and stair connection space are proposed and voxel based connection space detection method was used for the determination the extent of the stair region to serve the indoor model. The stair point cloud was filtered based on the space connectivity detected from the point cloud, and the step planes were fitted by the robust least square method. The alpha shapes and boundary regulation steps are used for the step boundary model fitting to construct the final stair model. The experimental results indicated that the proposed method is well suited for staircase modeling in multi-story indoor environments.

In this work, only the point geometric coordinates are used for staircase reconstruction. Further work includes the feature-based and vision combined methods for staircase modeling.

ACKNOWLEDGEMENTS

This study is funded by the National Key R&D Program of China (2017YFB0503701) and the National Natural Science Fund of China (41471325). The authors acknowledge the ISPRS WG IV/5 for the acquisition of the 3D point clouds. The authors would like to gratefully acknowledge Chang and Dai et al. (2017) for their help in accessing and processing the data.

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Revised May 2019