EXTENDING THE SHAPE GRAMMAR FOR 3D INDOOR MODELING

ZIWEI CAO
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ABSTRACT

Indoor navigation gradually gains its popularity along with the development of building. Currently, most indoor navigations are based on 2D maps. However, information provided by 2D maps cannot satisfy users' specific requirements. For instance, routes for the disables should have avoided stairs and obstacles. To solve these problems, it is necessary to develop a 3D indoor navigation system. Accordingly, the below three factors are concerned in achieving the 3D indoor navigation, including the 3D indoor model, the location and the path planning. Amongst those, the indoor model is the basis of indoor navigation. The 3D point cloud data, which reflects the actual indoor environment, is an adequate data source to reconstruct the 3D indoor model. Therefore, this research focuses on developing a method to reconstruct the 3D indoor model from point cloud data.

So far, some methods have been developed already. However, most of them aim to reconstructing the geometric information of navigable indoor space, while non-navigable indoor spaces and the relation between indoor spaces are not included. In this thesis, some improvements about 3D indoor reconstructing model of navigable spaces are introduced. Besides, this thesis further extends this model to reconstruct non-navigable spaces and proposes a method to obtain the topologic information between indoor spaces.

In addition, a method to acquire the non-navigable spaces and the topologic information between indoor spaces is proposed. The shape grammar indoor model is used in this research to adapt the real point cloud data and to reconstruct the non-navigable indoor spaces. A method to solve the problem caused by varied point density of the point cloud data is proposed to improve the shape grammar method for real point cloud data. Also, a place rule and a connect rule are applied to reconstruct the non-navigable indoor spaces. The topologic information including the adjacency and connectivity between the navigable indoor spaces can be detected from the data. The model result is finally exported as gbXML geometric model and topologic information graphs.

As a result, both the navigable and non-navigable indoor spaces are correctly detected from simulated and real point cloud data. Furthermore the adjacency and connectivity between navigable indoor spaces can be correctly detected. The overall accuracy of the indoor model reconstructed from simulated data and real point cloud data are 4.4 and 4.5 centimetres respectively.

In conclusion, this research provides a method to automatically reconstruct a 3D indoor model using point cloud data to meet the requirement of indoor navigation in both navigable and non-navigable spaces.

Key Words: point cloud data, 3d indoor model, indoor navigation, shape grammar

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1. INTRODUCTION

1.1. Motivation

3D indoor models have a wide application range. With the development of cities and advanced technology, buildings are becoming larger and taller nowadays, especially the buildings for public use. The architecture of buildings is getting increasingly complex at the same time. Therefore, people tend to spend lots of time finding their way inside an individual building. To solve this problem, more indoor geo-information should be provided to the general public. In the following paragraphs, three representative applications of 3D indoor models are described.

First of all, 3D indoor model can be used for navigation in large public buildings with multiple floors, for instance, airport terminals, shopping malls and large hospitals. So far, most navigation information is only shown in 2D maps with a name list, which is not enough to help people find a specific location efficiently. When a destination is located on a different floor from where the user is, it is difficult to plan the path between the user and the destination. Indoor modelling can help to provide a 3D model which can be used to calculate and indicate the route from the current location to the destination within the building with multiple floors. With the topologic 3D indoor model, a route through multiple floors can be calculated. Following the route, people can find their way to their destination intuitively and efficiently.

Secondly, 3D indoor model with topologic information can even help to calculate the route for specific groups of users, such as disabled people using wheelchair. Based on a 3D indoor model, navigation system can plan a route which avoids the stairs or abrupt slope, and the width of the doors involved in the navigation path should be larger than the width of the wheelchair.

Last but not least, indoor modelling can help to calculate the escape route in real time when an emergency occurs, for example, fire or terrorism. Currently, only a given evacuation plan can be provided for each building. If the escape route is blocked by fire or terrorist, the given evacuation plan will become useless. However, by using the indoor model, the escape route can be dynamically calculated in real time with fire spreading or terrorist movement. Therefore, the location of the fire or terrorist can be avoided accordingly.

1.2. Problem statement

Since the actual state of 3D indoor environment can be expressed by point cloud data, it can be used in 3D indoor model reconstruction. Current research has already acquired the geometry information of 3D indoor models from point cloud data. A shape grammar method proposed by Stiny (2008) mentions that complex geometry can be modelled by simple geometry. The rules that express how to combine the simple geometries is shape grammar. A geometric 3D indoor model has been developed using shape grammar by Khoshelham & Díaz-Vilariño (2014). In this approach, some cuboids were put in the 3D point cloud space and the cuboids would be adapted to the point cloud data by some rules. Finally, the 3D indoor geometric model would be represented by the combination of cuboids described by some simple rules. An example is showing in figure 1-1 and figure 1-2. The 3D indoor model in figure 1-2 is reconstructed from the point cloud data, which is shown in figure 1-1. This model can automatically obtain the geometry model from point cloud data without precedent knowledge. Besides, this model can describe the division of indoor space. Last but not least, this model can avoid the problem caused by walls during the process of topologic information development. Only the indoor space available for using remains. This is helpful on 3D indoor model reconstruction, especially the topologic information development. Therefore, this research of deriving 3D indoor model is based on the grammar 3D indoor model developed by Khoshelham & Díaz-Vilariño (2014). However, an integrated 3D indoor model for navigation requires not only the information of navigable spaces, but also the non-navigable spaces and the topology between indoor spaces. In the indoor model developed by Khoshelham & Díaz-Vilariño (2014), the non-navigable spaces and the topology between the indoor spaces are missed. Therefore, to develop an integrated 3D model, these information should be reconstructed from the point cloud data.

My research is trying to add necessary information for indoor navigation to complete the model. For instance, the topologic information between spaces should be added. Considering the practical use in reality, it is time-consuming to add these information manually. Thus, these topologic information should be detected automatically. In summary, this study aims at finding out the necessary information required for indoor navigation and develop a method to obtain this information automatically.

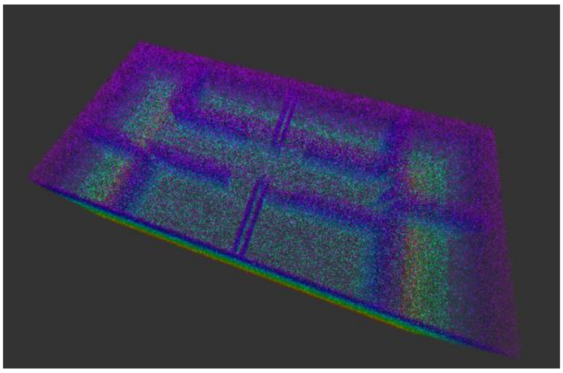


Figure 1-1 Point cloud data

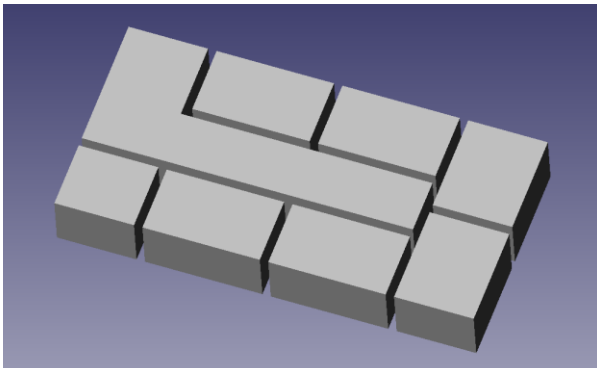


Figure 1-2 3D indoor model

1.3. Research objective and question

1.3.1. Research objective

To meet the requirement for indoor navigation, this study aims at providing a 3D indoor model with topologic information and thus developing geometric and topologic information of the indoor model. Two objectives are included:

- The first objective is to find out necessary information which is required for indoor navigation and should be derived automatically. Among different information, topologic information between different spaces plays an important role in the indoor navigation. Therefore, it has to be included in the indoor model. Besides, some other information may be necessary. But not all of these information can be derived automatically. To find out which semantic information should be derived automatically is an objective of this study.
- The second objective is to develop a method to derive the necessary information for indoor navigation automatically. This study aims at providing a 3D model with necessary information for indoor navigation as the result.

1.3.2. Research question

Three research questions are included in this research.

- What information should be included in a 3D indoor model for navigation? Some information like topology is necessary for indoor navigation. The question is to find out all information that meet the fundamental requirements for indoor navigation.

- Which information can be derived automatically? Not all information can be derived automatically and precisely. Thus, this study only focuses on the information that can be automatically derived.
- How to detect this information automatically from a point cloud data?

1.4. Innovation aimed at.

The innovation aims at the grammar-based 3D topologic indoor modelling. In contrast to the other 3D indoor modelling methods, this research is trying to develop a volume-based indoor model with topologic information. Not only the navigable spaces is reconstructed in this model, but also the non-navigable spaces, for instance, walls. Besides, the necessary information for indoor navigation can be automatically detected from the point cloud data. No prior knowledge such as the floor planning is required. In addition, the model will be exported as grammar rule and gbXML file, which can be easily ran in the common software.

1.5. Thesis structure

This research includes 7 chapters. The first chapter is the introduction and motivation and following by the second chapter, which is the literature review. The next chapter describes the shape grammar indoor model which is developed by Khoshelham & Díaz-Vilariño (2014). The forth chapter illuminates the methodology of extracting the non-navigable spaces and detecting the adjacency as well as the connectivity between the navigable spaces. Chapter 5 describes the implementation and results. Chapter 6 analyses the selection of threshold and discusses the result. The chapter 7 draws a conclusion on the research and provides recommendation for further research.

2. LITERATURE REVIEW

This research aims at developing a 3D model for indoor navigation. Since the 3D model is used for indoor navigation, some specified information is required. Currently, some methods for reconstructing 3D indoor model are developed. However, some of these models have shortcomings in the geometric expression while the others lack of some necessary information for indoor navigation. Therefore, this research focuses on developing the method to reconstruct a 3D model that satisfied the requirement of indoor navigation.

In this chapter, the prior work about the indoor models for indoor navigation is introduced. In the first section, both of indoor navigation and the required information are introduced. In the next two sections, the existing methods for indoor model reconstruction are discussed. Furthermore, the standards to express the indoor model are introduced. After that, some required knowledge of the research is shown.

2.1. Indoor navigation

Indoor navigation has three main factors, including 3D model of the indoor environment, the localisation and the navigated path algorithm. Amongst these, the 3D model of indoor environment is the basis of indoor navigation. To achieve the requirement of navigated path calculation, the indoor model should include some specified information i the indoor environment. Liu & Zlatanova (2011) mentioned that the indoor model for indoor navigation should provide the semantic indoor model with connectivity information, obstacles and the dynamic changes. In this case, the semantic indoor model includes the topology within the indoor environment. To specify the requirement of topologic information, Brown, Nagel, Zlatanova, & Kolbe (2013) proposed 15 topographic space requirements under different navigated situation. For instance, to calculate a path between two separate spaces within a single storey requires the usage information of spaces, connectivity between spaces and the information of doors. These 15 requirements can be mainly classified into four categories as following: information of indoor environment, information of indoor space, information of transfer space and information of indoor obstacle space.

Since this research is in the initiative step of reconstructing the indoor model, only the indoor spaces and relations within an individual storey are considered in this case. Therefore, in summary, the required information can be classed into information of solid indoor spaces and information of relation between the indoor spaces.

After clarifying the required information, the method to reconstruct the indoor model and obtain the necessary information should be considered. In the next two sections, some existing methods to reconstruct the indoor model as well as their advantages and disadvantages are introduced. These methods are divided into manual methods and automatic methods. In section 2.2, the manual reconstruction methods are introduced followed by the section 2.3 which describes the existed automatic reconstruction methods.

2.2. Manual reconstruction from point cloud data

Software can be applied in the process of manually reconstructing the indoor model from point cloud data. A commercial software named Autodesk Revit can extract both of walls and solid spaces from the point cloud data(Autodesk Knowledge Network, 2013). During the process, the point cloud data can be imported to the software directly and the reconstructed BIM model can be exported as gbXML file with plug-in application. Besides, another commercial software name AutoCAD Architecture is able to extract the building elements from the point cloud data as well. Point cloud data can be directly imported to the software and the reconstructed model can be exported as gbXML file as well.

2.3. 3D model for indoor navigation

Currently, several geometric indoor models reconstructed from point cloud data have been developed. These models can classified as following: surface-based and volume-based.

Regarding to surface-based models, an automatically approach is presented by Xiong, Adan, Akinci, & Huber (2013) by which planes of the indoor environment are detected and classified into different semantic categories such as, walls, floor and ceiling. However, the result of this approach consist of visualizing the indoor constructive elements. The indoor spaces are not considered, therefore, the division of indoor environment and the relation between them cannot be derived.

Some volumetric based models have been developed as well. Budroni & Boehm (2010) and Budroni & Böhm (2010) describe a plane sweeping method to reconstruct the 3D indoor model from point cloud data. This method is based on the assumption of Manhattan-World spaces. The model which sweeps a plane is parallel to the axis in order to detect the location of the wall. Then they use the location of walls to decompose indoor spaces. In the next step, the decomposed cells are selected as indoor spaces if they contain enough points inside. Finally, the 3D indoor model is stretched by the ground plan consisting of the valid cells. However, the result of this method is influenced by the varied point density of the point cloud. Besides, this model only reconstructs the geometric information, which is exports as 3D CAD models. The relation between indoor spaces is not considered. Another reconstruction method for volume-based indoor model from point cloud data is proposed by Khoshelham & Díaz-Vilariño (2014). This approach considers an indoor space such as, a room or a corridor, as an entity. Navigable spaces can be easily expressed by using this model. Besides, a volume-based indoor model was developed by Oesau, Lafarge, & Alliez (2013) and Oesau, Lafarge, & Alliez (2014). This method firstly detects the direction of walls by technique of Hough Transform and secondly uses the detected walls to divide the indoor environment. Last of all, the spaces are labelled as indoor or outdoor. This method is not restricted by the Manhattan-World assumption, but it relies on the point density of the point cloud data. However, the division of indoor space cannot be expressed in this model and the relation between different indoor spaces cannot be described. For instance, this model can only show the whole storey of indoor environment but the rooms within this storey (if it exist) cannot be divided. Another limitation of this method is that the problem caused by varied point density of the point cloud data exist when applied the method on the real point cloud data.

Besides, Peter, Becker, & Fritsch (2013) describe a method to reconstruct the 3D indoor model from photographed evacuation plans. This methodology firstly divides the indoor environment based on the photographed floor plan and then stretched it into a 3D model. Not only is the geometric information reconstructed in this model, but also the relation between indoor spaces. Adjacency is expressed as grammar rules. However, this reconstructed method is based on an evacuate plan as prior knowledge to retrieve the structure of the building, therefore this model cannot reflect the actual indoor environment. Only the primitive adjacency is considered and connectivity between the indoor spaces is not included. Another grammar based 3D indoor model is reconstructed by Philipp, Baier, Dibak, & Dürr (2014) and Becker et al. (2013). The model firstly divides the indoor environment into indoor spaces in 2D, then stretch it into 3D model. However, the source data used in this model is the track route. The floor plan can be derived from the trace path in this model.

In summary, advantages and disadvantages of the indoor modelling approaches mentioned beyond are listed in the table 2-1.

Table 2-1 The advantages and disadvantages of existent indoor modelling methods

	Not restricted to Manhattan-World	No prior knowledge required	Volumetric based model?	Can express the division of indoor spaces	Can express the relation between indoor spaces	Detect the doors in the model	Not rely on point density
Planar detecting model	Not mentioned	Yes	No	No	No	Yes	No
Plane sweeping model	No	Yes	Yes	No	No	Yes	No
Shape grammar model	No	Yes	Yes	Yes	No	No	No
Floor plan based grammar model	Yes	No	Yes	Yes	Yes	No	Not related to point clouds
Traced based grammar model	No	No	Yes	Yes	Yes	No	Not related to point clouds

Since this research aims at developing a 3D model for indoor navigation, the chosen geometric 3D indoor models should satisfy the requirements mentioned in section 2.1. Considering the requirement of expressing the indoor environment, the model should represent the indoor spaces in solid. Thus, volumetric model is chosen as the geometric model in this research. Besides, as section 2.1 mention, the subdivision of the indoor spaces and the relation between these indoor spaces should be described in the indoor model. Therefore, the model should be able to express the division within the indoor environment. In summary, the shape grammar method is chosen as the geometric modelling of this research. However, the relation between indoor spaces are not included in this model, thus, this research focus on including the relations between indoor spaces to satisfy the requirements of indoor navigation.

2.4. Models for expressing the required information

After extracting the required information from point cloud data, the information should be expressed in a model that can be easily understood and visualized. Both the geometric and the topologic information should be included in the exported indoor model. Currently, the indoor model mostly represented as Building Information Model (BIM). Li & He (2008) introduced a method to express both the topologic information and semantic information by combining the geometric 3D model and topological graph. Liu & Zlatanova (2012) developed an indoor navigation space model to express the geometric and semantic indoor model by two level. The first level includes the rough division of indoor spaces and topology is expressed by a logical graph. In the second level, the detail semantic information such as obstacles is shown in a visibility graph. Besides, other factors for indoor navigation are included in this model, for instance, the elevator, the doors and the windows. The relation between indoor spaces is expressed in this model as well. However, this model is not a volumetric based indoor model and it does not contain the geometric information of the indoor spaces. Therefore, this model is not easy to express and visualize the indoor space for navigation. Meijers, Zlatanova, & Pfeifer (2005) developed a 3D semantic model for evacuation. This model includes the information of doors and eventual exits of the building. However, this model is surface based. Therefore, the indoor spaces cannot be expressed well. Another indoor model is designed to express the geometric and topologic information by combining the CityGML or IFC model and adjacent graph. In this model, the indoor space is expressed as solid. Another method to express the topologic information of indoor space is developed by Lee (2004).

Except the existed models, some standards for expressing the indoor model have been published. The Industry Foundation Classes standard defines a data schema for BIM model (BuildingSMART International Ltd, 2007). This standard includes the attribute to hierarchically express the semantic information of the building, for instance, the walls, the doors and the windows. The topologic information within the indoor environment cannot directly expressed(S. Daum, Borrmann, Langenhan, & Petzold, 2014), however, it can be expressed by querying the attribute of the entities. Some methods to search the topology is described in Daum & Borrmann (2014). Besides, a standard named Green Building XML (gbXML) is widely used in common commercial software (gbXML.org, 2014). The geometric, topologic and semantic information of building elements are considered in this standard. The gbXML format represents the walls by surfaces and express the indoor spaces by a set of surfaces. Recently, a candidate Open Geospatial Consortium(OGC) standard to represent the indoor model of the building named IndoorGML is proposed (Lee et al., 2014). Comparing to the other standards, this standard focuses on modelling indoor space for navigation. Therefore, it gives a solution to express the topologic information of indoor spaces. Two kind of models can be used in representing the adjacency and connectivity of the building. The first one is thin wall model. In this model, only the navigable spaces is considered. The walls are not considered as solid. The second one is thick wall model. In contrast to the thin wall model, the non-navigable spaces, for instance, walls, are considered. Two adjacency graphs, which are showing in figure 2-1and 2-2, can express the difference between these two models. However, this standard is not currently supported in most common commercial software.

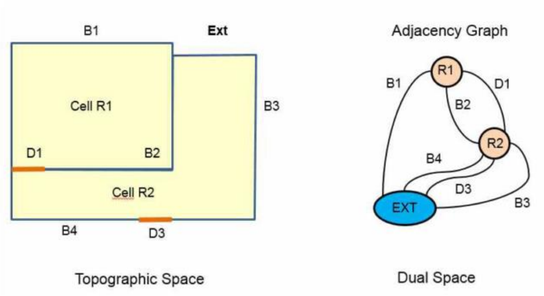


Figure 2-1 Thin wall model

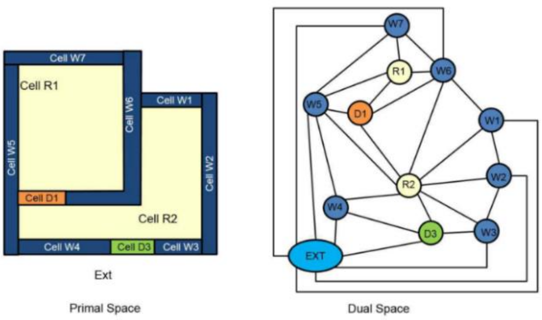


Figure 2-2 Thick wall model

In summary, both the IFC format and the gbXML format are available in expressing the required information of 3D model for indoor navigation. However, gbXML can be directly imported into the common commercial software while IFC XML, which has a smaller file size than IFC 2×3, are not directly supported. Since that, this research choose gbXML as the exported format for the model. In addition, the IndoorGML format may be used in further research after its official publish.

2.5. Shape grammar

Since the shape grammar based indoor model is chosen as the base of this research, the knowledge related to the shape grammar is introduced in this section. Shape grammar method expresses the complex shapes by combining the simple polygon (Stiny, 2008). For example, multiple square are combined to express irregular shape. The shape grammar consists of the starting shape, the non-terminal shape, the terminal shape and the rules. Figure 2-3 shows an example of combining the simple shapes. The starting shape of this example is square. Two rules are applied to express the terminal shape from non-terminal shapes. The first rule shown in the upper left area is a place rule. In this place rule, a square is placed. In the upper right area, the place rule is repeated for three times. As a result, four squares exist. After that, a merge rule is applied to the squares in order to combine the separated spaces. In the left lower area, the merge rule is applied to merge two adjacent squares while in the right lower area, the merge rule is repeated. As a consequence, an irregular shape is generated by using the shape grammar rule. In this method, the simple shapes are combined through complying with some rules. As a result, the simple shape can express many complex shapes in reality. This method can be extended to a 3D space. In 3D view, 3D shape, such as cuboid can be used as the simple shape. Different combinations of the cuboids can express various 3D spaces.

In brief, the shape grammar can be used to express the indoor spaces by using the cuboids as the starting shape. By dividing the indoor environment into cuboids and combining the cuboids, various indoor spaces can be well described. This shape grammar has already been used in the shape grammar indoor model developed by Khoshelham & Díaz-Vilariño (2014). In this research, the shape grammar approach is maintained.

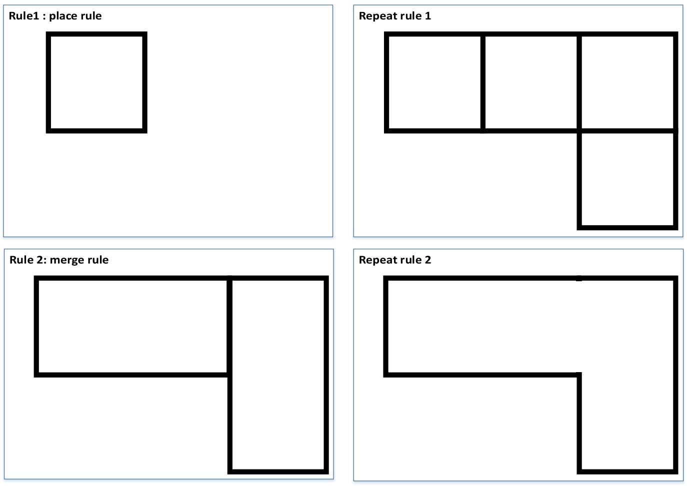


Figure 2-3 The example of shape grammar

2.6. Door detection

As mentioned in the summary of section 2.3, the relation between the indoor spaces is missed in the existing shape grammar based indoor model. This research aims to derive the relation between indoor spaces from the data. During this process, the locations of doors play an important role. For instance, the connectivity information is related to the doors. If a door is located between two adjacent indoor spaces, then these two cuboids are considered as connected. Therefore, to obtain the connectivity of the indoor spaces, the locations doors inside the building should be detected.

Currently, many methods to detect the doors have been developed. Derry & Argall (2013) illuminated a method to automatic detect the doorway by using only the depth data in RGB-D data. However, only the opened doorway can be detected by using this method. Díaz-Vilariño, Martínez-Sánchez, Lagüela, Armesto, & Khoshelham (2014) provides a method to detect the opened and closed door in 3D model by using both point cloud data and imagery. Besides, some door detection methods are included in the reconstruction method of the indoor spaces. For instance, a plane-based method is used to fit the point cloud data. If the planar satisfies some conditions, then the location of the planar is considered as a door.

In summary, various methods for door detection are mature and the accuracy of the results are acceptable in indoor modelling. Thus, door detection method is out of scope in this research. During this research, coordinates of doors are manually detected.

2.7. Summary

In this chapter, the required information of indoor navigation and existent methods to obtain this information are discussed. In brief, the geometric information of indoor environment and the relation between indoor spaces are necessary for indoor navigation. In comparison with the existent indoor reconstruction methodologies, an approach based on shape grammar is chosen as the basis of this research. Since the shape grammar indoor modelling approaches only contains the geometric information of indoor navigable spaces, this research focuses on extending the shape grammar in order to express the non-navigable spaces and reconstruct the relation between the indoor navigable spaces.

3. PRINCIPLES OF SHAPE GRAMMAR MODEL

A shape grammar methodology for indoor modelling is developed by Khoshelham & Díaz-Vilariño (2014). It includes 4 elements: the starting shape, the non-terminal shape, the terminal shape and a set of rules. The starting shape in this model is a cuboid and the non-terminal spaces are the cuboids with transform parameters. After applying the rules, indoor spaces are represented by terminal shape consist of a set of combined cuboids.

In this model, cuboids are chosen as the starting shape. The non-terminal cuboids are defined with 6 parameters: length, width, height and three transform parameters in x-axis, y-axis and z-axis. The length, width and height are detected by histogram analysis of the point cloud data during the placement rule. After the applying the merge rules, the terminal cuboids indicates the cuboids that cannot be further merged.

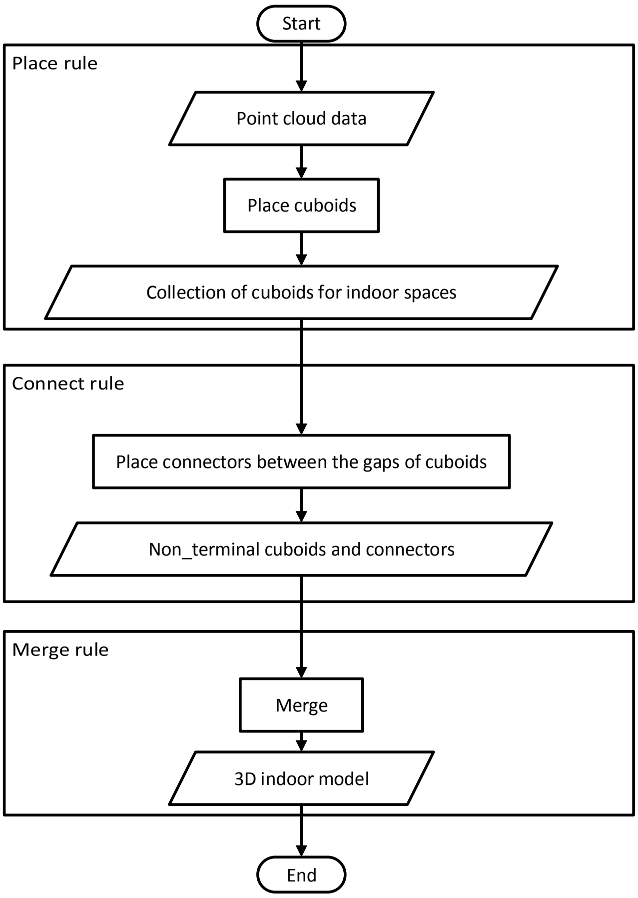


Figure 3-1 Process of navigable spaces reconstruction

This approach can extract the navigable spaces within an indoor environment and export the model as shape grammar rules. Three rules as following are included: placement rule, connecting rule and merging rule. The whole process of the shape grammar based modelling is shown in the figure 3-1. These three rules are applied sequentially, and a volumetric 3D indoor model is reconstructed as a result. During the placement rule, the point cloud data is imported to the program as data source and, after the placement process, set of non-terminal cuboids is derived as a result. The following step consist on placing the connectors between the non-terminal cuboids. Finally, the adjacent cuboids are merged together. An example is shown to explain this process. The point cloud data of the example is showing in figure 3-2.

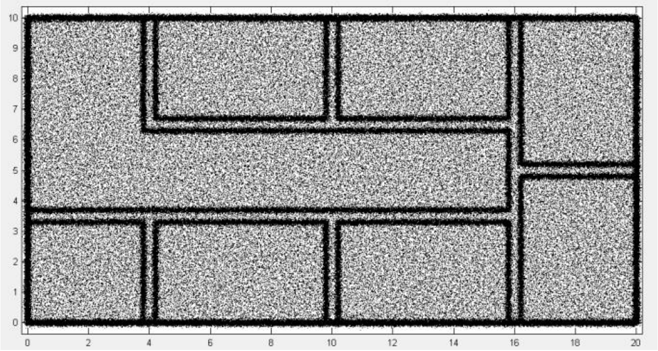


Figure 3-2 Point cloud data

3.1. Placement rule

The placement rule divides the whole indoor environment which satisfies the requirement of Manhattan-World space into various cuboids by analysing the histogram. For each space, cuboids are placed and it is checked whether the top surface of the cuboid touch the ceiling. If the candidate cuboid satisfy the condition of touching the ceiling, spaces are considered as indoor environment, then a non-terminal cuboid is placed. The process of place rule is shown in flowchart (figure 3-3).

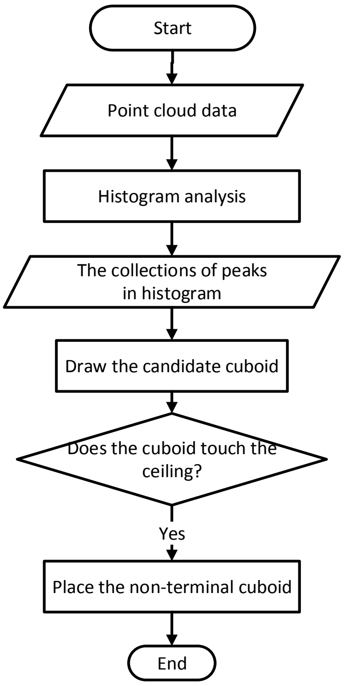


Figure 3-3 Flowchart of placement rule

During the histogram analysis, the coordinates of points are plot to three histogram in x-axis, y-axis and z-axis respectively. An example of the histogram is shown in figure 3-4.

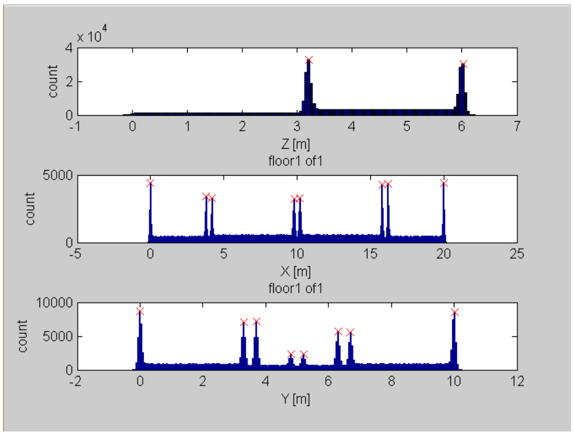


Figure 3-4 Histogram of x y and z axis

As shown in figure 3-4, some peaks are detected from the histogram. The distance between each two peaks determines the length of the cuboids in x, y and z axis. The distance between two peaks in z axis shows the height of the floor. This height and the coordinate in z axis can be used for the height and transform parameter in z-axis of the cuboids. For the histogram of x axis and y axis, if the distance between two peaks is larger than the maximum wall thickness, then the cuboid can be the candidate of the non-terminal cuboids.

After histogram analysis, the collection of peaks in x-axis, y-axis and z-axis are derived. For each pair of peaks in three axis, a candidate cuboid is considered. This candidate cuboid is considered as inner space of the building if this space touches the ceiling of the floor. In this model, touching the ceiling indicates sufficient points fall in the face of the ceiling within a small distance. To ensure the space touches the ceiling, an index named points-on-ceiling index is used (Khoshelham & Díaz-Vilariño, 2014). The formula is shown in equation 3-1.

$$I_{PoC} = \frac{n\delta^2}{A_{ceiling}}$$

Equation 3-1

The points-on-ceiling index I_{PoC} has three parameters as following: ceiling area $A_{ceiling}$, average point spacing δ^2 and the number of points n. Ceiling area indicates the total area of the ceiling which is represented as $A_{ceiling}$.The number of points is defined as the number of points that are falling in the ceiling space. The ceiling space refers to the closed ceiling plane within a vertical buffer. The average point spacing means the area represented by each points. This index is based on an assumption that the density of point cloud data is known and evenly. Thus, the area of each point represented can be given. If the space touches the ceiling, the number of points that fall in the ceiling space is large. Since the ceiling area is fixed, the more points fall in the ceiling space the lager index occurs. In this case, a threshold is set to decide whether the cuboid touches the ceiling. If the index of a space is larger than the threshold, the space is considered that touches the ceiling. The non-terminal cuboid is placed when the candidate cuboid touches the ceiling. Figure 3-5 shows the result of the placement rule. In the figure, the yellow area shows the placed non-terminal cuboids while the white area refers to no cuboid is placed. The black lines indicate the boundary of the cuboid.

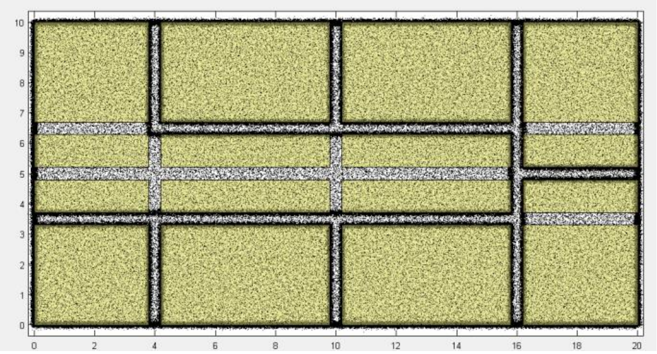


Figure 3-5 Result of place rule

3.2. Connecting rule

Because of the placement rule, some non-terminal cuboids are placed. Therefore, the main objective of connecting rule is to detect which non-terminal cuboids belong to the same navigable space. If two cuboids are not divided by a wall, they belong to the same navigable space. Thus, a connecting cuboid is placed between these two cuboids and the adjacent relation between them is stored.

Two conditions are used to determine whether a wall exist between two cuboids. The first one is whether the candidate gaps between two non-terminal spaces touch the ceiling. The points-on-ceiling index can be used. The other one is whether the candidate touch the walls. In this model, a cuboid touches the wall refers to sufficient points are within a small distance to the wall face. If the candidate touch the walls, then this candidate is considered as wall. Otherwise, the connector is placed.

To decide whether a space touches the wall, a points-on-walls index is used (Khoshelham & Díaz-Vilariño, 2014). The formula is shown in the equation 3-2 as below.

$$I_{PoW} = \frac{n\delta^2}{A_{wall}}$$

Equation 3-2

Similar to the points-on-ceiling index, the points-on-walls index I_{PoW} has three parameters: the number of points falling in wall space n, the average point spacing $\delta^2$and the area of wall A_{wall}. The average point spacing is decided by the point density. The area of wall indicates the area of closed wall plane and the number of points is defined as the number of points falling in the wall space with horizontal buffer.

As a result of connecting rule, the whole indoor space is filled with either non-terminal spaces or connectors. The result of connecting rule is shown in figure 3-6. In the figure, the yellow area indicates the non-terminal spaces while white area means that no cuboids have been placed. As the figure shows, the gap between the non-terminals spaces is filled while no connector is placed in the walls. In the model developed by Khoshelham & Díaz-Vilariño (2014), the connecting rule is only applied one luoop. Therefore, some gaps may still exist between the connector (showing in figure 3-6). These spaces are fixed by manually applying the connecting rule.

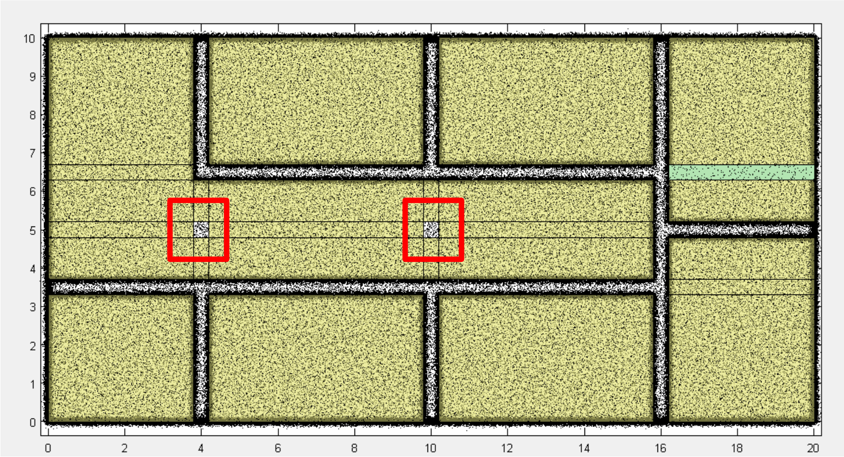


Figure 3-6 The result of connect rule

3.3. Merging rule

In the last step, the merging rule fuses the non-terminal cuboids with a connector between them. During the process of this rule, every two adjacent cuboids are merged. The merge process is iterated applied until all pairs of adjacent cuboids are merged. The maintained cuboids are labelled as terminal cuboids. The result of merging rule is shown in figure 3-7. The green area shows a sample of terminal cuboid.

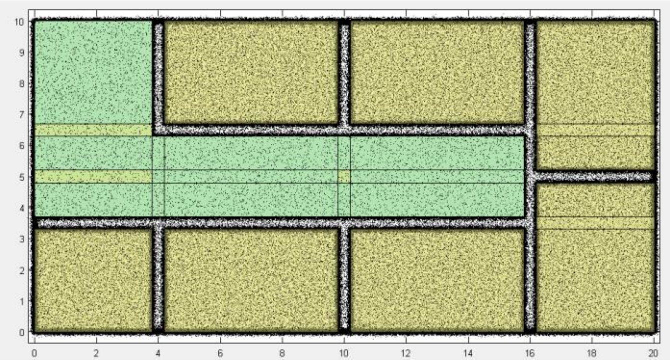


Figure 3-7 The result of merge rule

3.4. Exporting the model

After the reconstruction, the model is exported as shape grammar rules which can be run in the open source software name FreeCAD. The python code which can be read in FreeCAD is automatic generated. The model in FreeCAD is showing in figure 3-8.

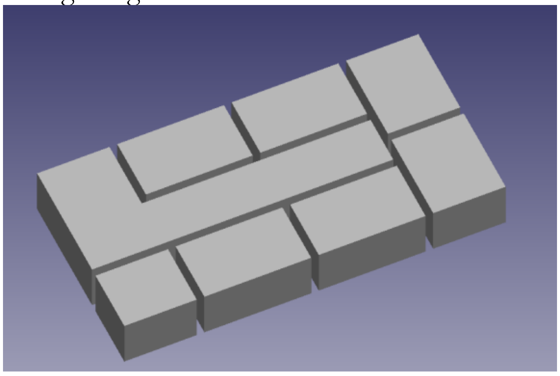


Figure 3-8 Exported indoor model in FreeCAD

3.5. The limitation of existing grammar method

This shape grammar method successfully reconstruct the indoor navigable spaces from the point cloud data. However, when applying this shape grammar model in the real point cloud data, some limitations occur. First of all, since the occlusions of data, the point cloud may not be correctly divided into cuboids by histogram analysing. Besides, because of the varied point density of the real point cloud data, the points-on-ceiling and points-on-walls index does not work well. Some mistaken decisions occur. Furthermore, after applying the rules, some cuboids may be mistaken placed because of the actual situation of the real point cloud data. Overall, since the limitations mentioned beyond, the shape grammar method should be improved.

Besides, not only the indoor navigable spaces, but also the non-navigable spaces and topology relation between the indoor spaces should be detected from the point cloud data to complete the 3D model for indoor navigation.

In summary, this research aims at improving the existing shape grammar method and extending it to reconstruct the non-navigable spaces and the topology relation between them.

4. METHODOLOGY

4.1. Introduction

In this research, the main objective is to find out the necessary information of a 3D model for indoor navigation and develop them. As discussed in chapter 2, the necessary information for indoor navigation is geometric information and relation between indoor spaces. This research aims at improving the geometric model and reconstructing the topologic relation between indoor spaces. Therefore, an indoor model for reconstructing the geometry indoor space from point cloud data is chosen as the basis of this research. According to the discussion in section 2.3, this research is based on the geometric model developed by Khoshelham & Díaz-Vilariño (2014). In the beginning, a simulated point cloud data is used to develop the 3D indoor model. After that, a real point cloud data is used to validate this research. The method of this indoor model development includes three main steps as following:

- To understand the necessary information of indoor navigation, the first step is to develop a 3D indoor model manually. After manually reconstructed the 3D indoor model, the limitation of manual method is learnt. In this step, a software named Revit would be used. The point cloud data is the input data in this step. Some necessary information for indoor navigation would be manually reconstructed by Revit. For instance, the information of walls and doors can be added to the original geometry model. As a result of this step, a list of information which is time-consuming or limited in manual method will be found out. This step aims to finding out the shortcoming and limitation of manual reconstruction method.
- The second step is to identify the necessary information that can be well and truly automatically detected. The information which has been developed in last step should be filtered. Only the information that can be precisely and automatically derived would be selected. For example, topologic information can be automatically obtained from the geometry model, and this relation between spaces is certain. Thus, the accuracy of this topologic information can be precisely. Then topologic information can be one of the information which would be developed in the next step. As a consequence of this step, some other information which should be developed in this indoor model is found.
- The last step is to develop the method for reconstructing these information. Once the information is selected, the geometry 3D indoor model is extended to topological model. For example, as a result of last step, the topologic information should be developed in this indoor model. To develop the topologic information, the first step is to reconstruct the wall from the point cloud data. After that, based on the wall, search the neighbour spaces for each individual space within the geometry model developed by Khoshelham & Díaz-Vilariño (2014). Then the number of neighbour spaces would be added to the attribute of corresponding space. Some grammar rules would be developed for this topologic information. This process would be implied by programming in Matlab. In the beginning, only information within a single floor is considered. In this case, the topologic information only contains the neighbour relation within an individual storey. Thus, the topology of above and below would not be considered.

4.2. Manually reconstructing the indoor model

In this step, a 3D indoor model is reconstructed from the point cloud data. In this research, the indoor environment with both geometric and topologic information can be reconstructed from the point cloud data manually. As discussed in the section 2.1, the required information for indoor navigation includes the geometric information and relation between indoor spaces. First of all, the geometric information considers both the navigable spaces and the non-navigable space. In this case, navigable spaces indicate the indoor spaces that are available for people to move while the non-navigable spaces refer to the spaces that are not able for people to move inside such as walls. Thus, both the indoor spaces and walls should be reconstructed from the point cloud data. Besides, regarding to relation information, many relation can exist between the indoor spaces, for instance, containing relation and topologic relation. In the case of indoor navigation, the adjacent relation and the connective relation play an important role on path planning. In this case, adjacency indicates two cuboids that are separated by the same wall and connective refers to a door existent in that wall. Without the adjacency and connectivity, the separated indoor spaces cannot be connected as a network for navigation. Thus, the adjacent and connective relation should be reconstructed from the data. Furthermore, since the location of doors is required for connectivity reconstruction, the coordinate of doors should be detected as well.

By using commercial software, the location of indoor spaces and walls can be precisely detected and the coordinates of doors can be extracted according to the point cloud data. Software named Autodesk Revit is used to help this manually reconstruction. During this process, point cloud data is imported directly as the data source. The tool of placing walls and placing doors are used. The parameters of walls and doors are pre-defined by the software. Only the location of walls and doors should be manually detected. After reconstructed the walls and doors, the navigable spaces are reconstructed by tool of placing rooms. By using the tool of placing rooms, the navigable spaces are placed within enclosed walls and doors. As a consequence of manually reconstruction, a 3D indoor model with navigable spaces and walls is built.

After the manual reconstruction, the model is exported as the gbXML file by the plug-in application of Revit. The result of manually reconstruction is showing in figure 4-2 and figure 4-4.

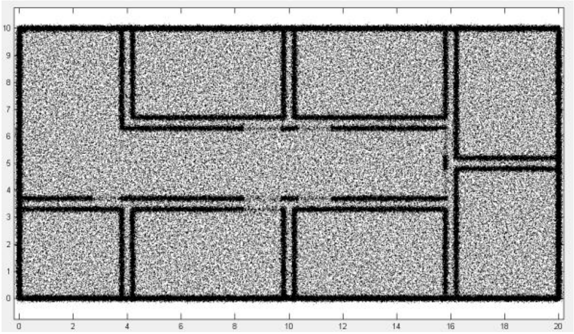


Figure 4-1 Simulated point cloud data

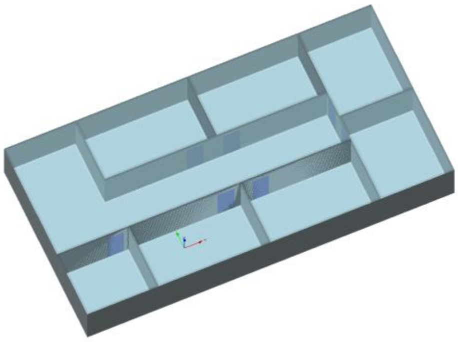


Figure 4-2 Manually reconstructed result of simulated point cloud data

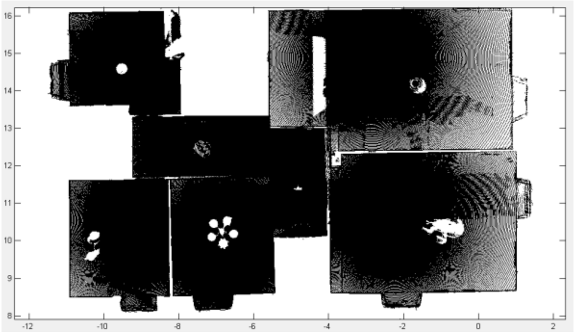


Figure 4-3 Real point cloud data

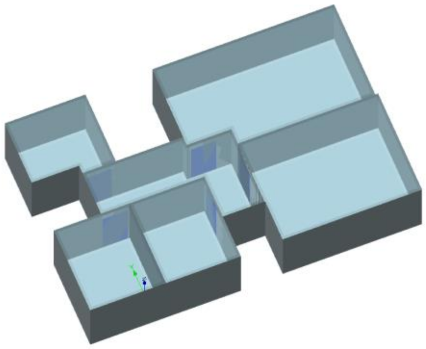


Figure 4-4 Result of manual reconstruction of real point cloud data

As a result of the process of manually reconstruction, the manually reconstructed information which is required for indoor navigation is listing as follows: the model of navigable and non-navigable spaces as well as the information of doors. Furthermore, the navigable spaces and walls can be manually reconstructed while the adjacency and connectivity cannot be reconstructed because of the limitation of the software. However, there is no doubt that the adjacency and connectivity is the required information for indoor navigation. Therefore, this information should be automatically reconstructed from the point cloud data.

4.3. Select the information to develop

As a result of the manual reconstruction process, the required information of indoor navigation can be listed as below: the model of navigable and non-navigable spaces, the coordinates of doors, the adjacency and the connectivity between navigable spaces. The navigable spaces have been reconstructed by shape grammar indoor model developed by Khoshelham & Díaz-Vilariño (2014). Thus, this research will focus on extending the shape grammar model for non-navigable spaces. In this case, the non-navigable spaces indicate the walls. However, since the indoor point cloud data can only provide the indoor environment and the information of outer walls is missed, the outer walls are not taken into consideration in this research. Only the inner doors should be reconstructed from the point cloud data. Besides, regarding to the coordinates of doors, plenty of mature methods for automatic door detection have been published. These methods can be easily applied in point cloud data. Therefore, the door detection is not considered as a goal of this research. The coordinates of doors from manual reconstruction in last step can be used in the connectivity development. In brief, this research emphasizes on the reconstruction of non-navigable space, the adjacency and the connectivity between navigable spaces.

4.4. Automatically develop the indoor model

As a result of Chapter 4.3, this research focuses on automatically reconstructing the non-navigable spaces, the adjacency and connectivity between navigable spaces. The flowchart of main processing is presented in the figure 4-5.

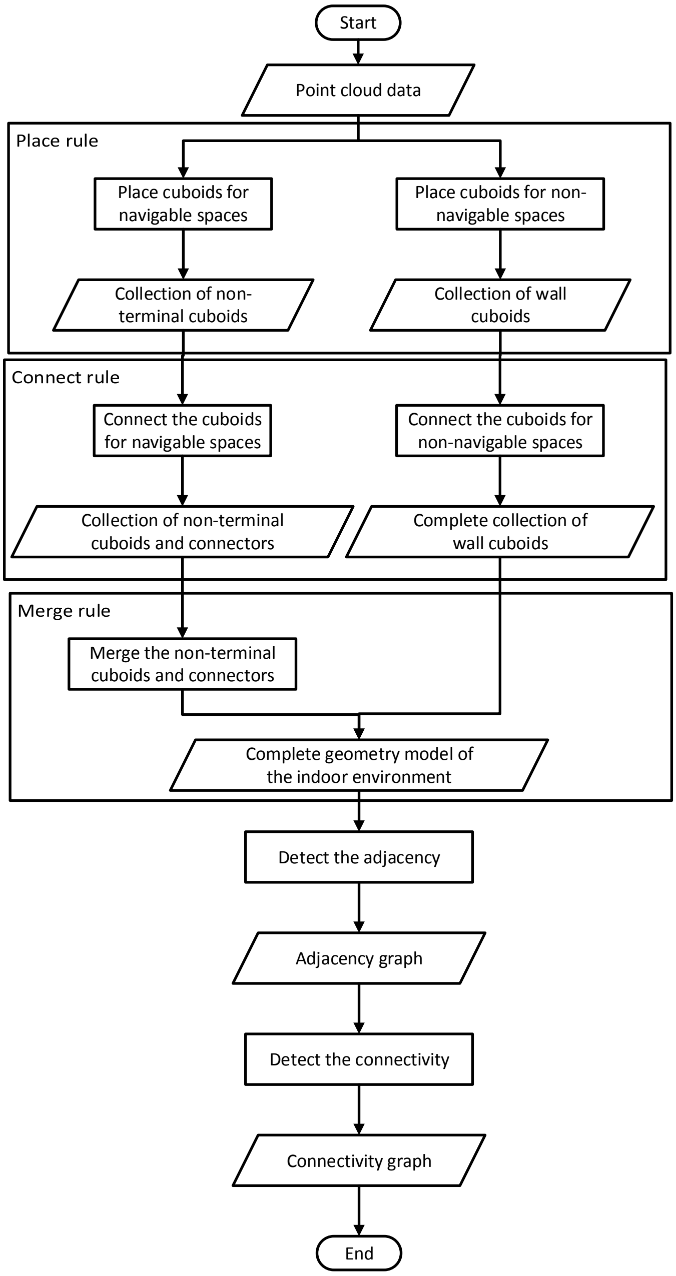


Figure 4-5 Flowchart of main processing

4.4.1. Improvement of shape grammar indoor model

The principle of shape grammar indoor model has been introduced in chapter 3. However, some limitations should be improved to apply the model in the real point cloud data. As mentioned in section 3.5, some limitations exist in the origin model. According to the limitations, 2 improvements are proposed in this research.

The first improvement is to change the z range of the histogram. By using the upper half area of the storey, the occlusion caused by furniture can be reduced. An example of occlusion caused by furniture is provided in figure 4-6. Considering the occlusions in reality, the histogram analysis may not be able to correctly divide the point cloud data into cuboids. A more precise result occurs when the area is changed from the whole storey into upper half area of the space. At the same time, the points-on-wall index is improved to only consider the upper half space of the whole storey.

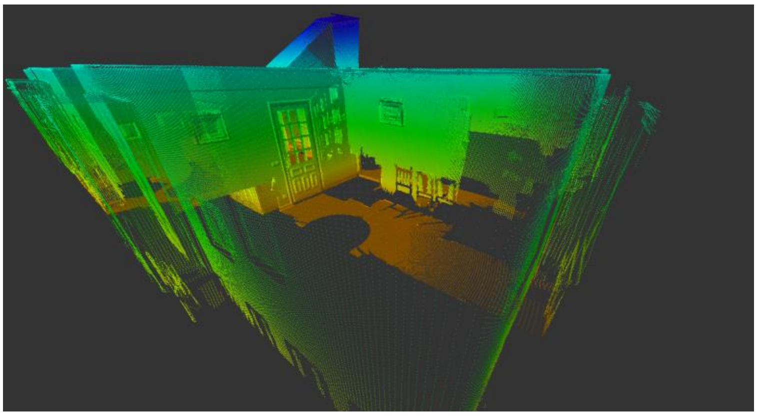


Figure 4-6 An example of occlusions in real point cloud data

Secondly, to avoid error caused by the varied point density, a thinning method is used to filter the point cloud data. The varied point density leads to the error while using the points-on-ceiling and points-on-walls index. Since the average point spacing is given for the whole point cloud data, when the average point spacing adapts to the lower point density, the area with height point density can easily leads to the high value in points-on-ceiling or points-on-walls index. An example is given in the figure 4-7.

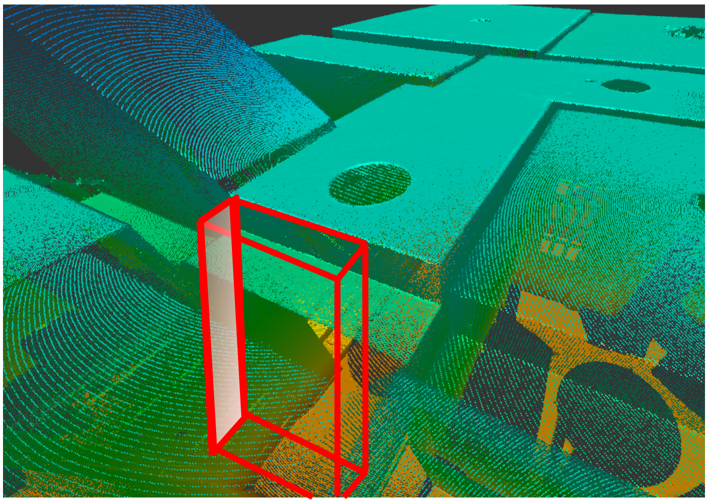


Figure 4-7 Example of error in points-on-walls index

When placing a cuboid in the area shown by the red lines, only small area of the cuboid (shown in white area of figure 4-7) touches the wall. However, since the point density in that area is very high, the number of points that fall in the wall area is high. As a result, the value of points-on-walls index is large and the cuboid is considered as touching the wall. To avoid this problem, it is necessary to thin the point cloud data through a 3D kernel. The thinning method uses a cubic kernel with a specified radius to filter the point cloud data. Within area of the kernel, a number of points are randomly selected to maintain while the others are removed. By using this method, the point density becomes more evenly and the average point spacing can be defined easily.

4.4.2. Reconstruct the non-navigable spaces

In this research, the indoor environment is divided into two types of spaces, including navigable spaces and non-navigable spaces. The navigable spaces indicate the indoor space that people can move. Oppositely, non-navigable spaces refers to the indoor area that is not available for people to move. In this research, the non-navigable spaces mainly indicates the inner walls of the building.

In this step, the inner walls within the indoor environment are reconstructed. The reconstructed processing is based on an assumption that the thickness of the wall is limited and known. Besides, the walls within an indoor environment should connected.
To reconstruct the non-navigable spaces, two rules are applied. The first rule is the placement rule. For the spaces that are smaller than a threshold and touch a wall, the wall cuboids should be placed. The second rule is the connecting rule. In this rule, the gaps between walls can be fixed. During the place process, some small walls may not be correctly detected. According to the assumption, the inner walls of the building should be connected. Thus, to fix the gaps, for each wall that reconstructed in the first step, the walls within a limited distance should be connected. This two rules are applied during the rule one and rule two of the grammar-based indoor model respectively. Therefore, the original shape grammar indoor model is extended to reconstruct the walls.

Figure 4-8 The flowchart of extended place rule

To apply the placement rule for non-navigable spaces, two conditions are considered. According to the assumption, the first condition is the thickness of the wall. A limitation of thickness is given. Only the spaces which are smaller than a given threshold are consider as the candidate of walls. The second condition is weather the space touches any wall. If a space can satisfies both conditions, this space is defined as the space of wall. A wall cuboid is placed. The process of the placement rule from shape grammar method is extended to contain the conditions to determine whether to place the wall cuboids. The extended flowchart is shown in the figure 4-8.

Regarding to the thickness of walls, if the length or width of the cuboid is smaller than the maximum thickness of the walls, this cuboid can be the candidate of the wall cuboids. Furthermore, a proposed number or empirical value should be given. To detect the length or width of the cuboid, the histogram of the point cloud data is used. Plot x, y and z value of all point cloud data in three histograms respectively, some peaks occurs as figure 4-9 shows. Similar interactive strategy with improvement of navigable space reconstruction is applied to the process of wall reconstruction. An example is shown in figure 4-10 and figure 4-11. In figure 4-10, the program ask the user to decide whether place the wall cuboid in the pink area which touches the lower threshold of points-on-walls index. In figure 4-11, the pink cuboid satisfies the requirement of size and the points-on-walls index but it is an outer wall. Therefore, this cuboid should not be placed.

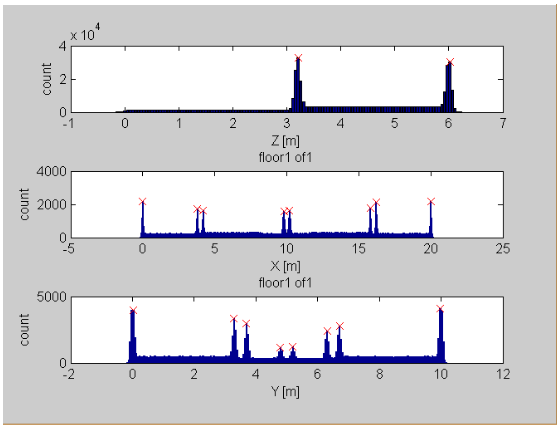
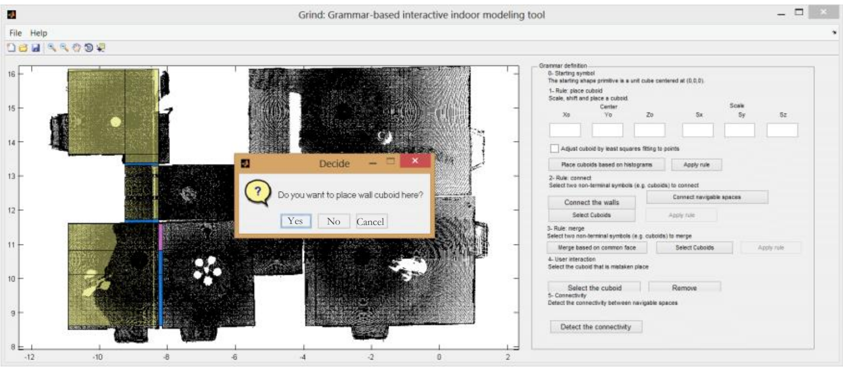


Figure 4-9 Histogram of simulated data



Do you want to place wall cuboid here?

Grammar definition

0- Starting symbol

The starting shape primitive is a unit cube centered at (0,0,0).

1- Rule: place cuboid

Scale, shift and place a cuboid.

☐ Adjust cuboid by least squares fitting to points

2- Rule: connect

Select two non-terminal symbols (e.g. cuboids) to connect

3- Rule: merge

Select two non-terminal symbols (e.g. cuboids) to merge

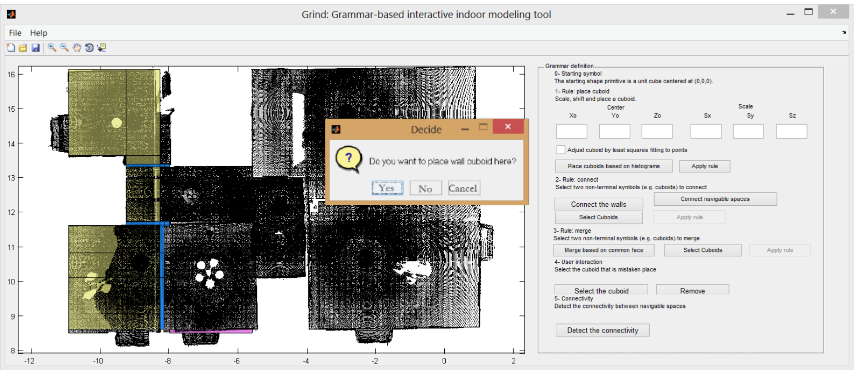
4- User interaction

Select the cuboid that is mistaken place

5- Connectivity

Detect the connectivity between navigable spaces

Figure 4-10 Example of interactive tool for wall reconstruction (place situation)



Do you want to place wall cuboid here?

Grammar definition

0- Starting symbol

The starting shape primitive is a unit cube centered at (0,0,0).

1- Rule: place cuboid

Scale, shift and place a cuboid.

☐ Adjust cuboid by least squares fitting to points

2- Rule: connect

Select two non-terminal symbols (e.g. cuboids) to connect

3- Rule: merge

Select two non-terminal symbols (e.g. cuboids) to merge

4- User interaction

Select the cuboid that is mistaken place

5- Connectivity

Detect the connectivity between navigable spaces

Figure 4-11 Example of interactive tool for wall reconstruction (not place situation)

After placing the wall cuboids, some gaps between the wall cuboids may occur. The reason of these gaps can be the incompleteness of the point cloud data or the varying point cloud density. To fix this problem, a connect rule is applied. If a cuboid within a maximum size exists between two wall cuboids, this cuboid is considered as the gap of walls. A wall connector is placed in this small cuboid.

However, after the automatic reconstructed process, some mistakes may still maintain due to the practical situation of the point cloud data. Therefore, an interactive tool of removing the cuboids that placed by mistaken is added. An example is shown in figure 4-12. In the highlight area of the figure, the wall cuboids are automatically placed since the width of the cuboid is smaller than the maximum wall thickness and the points-on-walls index is larger than the threshold. However, this wall is not an inner wall within the building. Therefore, this wall should be removed.

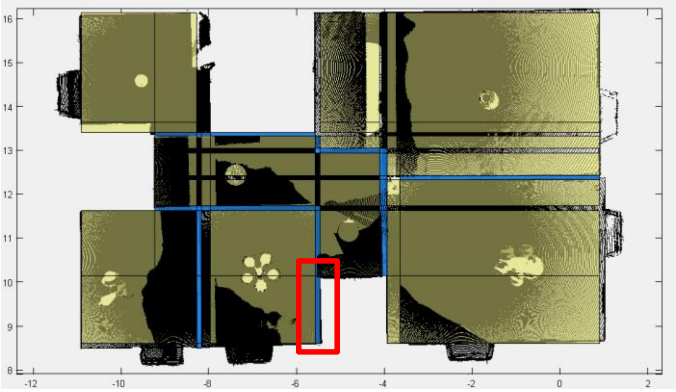


Figure 4-12 Example of error wall cuboids

4.4.3. Developing the adjacency relations between navigable spaces

The adjacency between navigable spaces indicates the adjacent relation between two navigable spaces with a wall between. If two navigable spaces are separated by a wall, these two spaces are considered as adjacent to each other. The method to detect this adjacency is to search the adjacent cuboids in both sides of the wall cuboids. If a cuboid x and a cuboid y are adjacent to the same wall, then x and y are considered as adjacent. This adjacent relation is only considered between terminal cuboids. The result of this step is stored in the attribute of the terminal cuboids.

4.4.4. Developing the connectivity between navigable spaces

The connectivity between two navigable spaces indicates the accessibility between two adjacent indoor spaces. In this case, the connectivity is based on the adjacency reconstructed in the last step. If a door is located in the wall between two navigable spaces, the connectivity between these two navigable spaces is true. In order to derive the connectivity, the location of the doors is required. Currently, various mature methods have been developed for door detection. In this case, the door detection is not an objective of this research. Therefore, the coordinates of vertices of the doors are manually detected in this research.

4.4.5. Export the reconstructed model

The reconstructed model from point cloud data should be exported as a common data format for visualization and navigation. Several data formats are mentioned in section 2.4. In this research, the gbXML file is chosen. The gbXML format is surface-based and the spaces are represented by a set of surfaces. Both the adjacency and the connectivity can be stored in the file.

To translate the reconstructed model into gbXML file, only the terminal cuboids with topologic information are used. The translate process consists of four main steps. In the first step, the surfaces of walls, ceiling and floor are developed by the vertices and faces which are stored in reconstructed model. During this process, the inner walls are deleted and the remaining walls are labelled according to their connectivity. In the second step, the ceiling and floors are restructured and the adjacency between walls are detected. Subsequently, the adjacent walls are merged to generate the indoor spaces and information, such as Location and SurfaceType are given. Last but not least, the duplication of surfaces is removed, the indices of spaces and surfaces are assigned and final xml file is written. As a result, a gbXML file can be directly imported into Sketchup through EnergyPlus plug-in.

5. IMPLEMENTATION AND RESULTS

5.1. Point cloud data

In this research, two point clouds are used. One of them is the simulated data generated by Matlab. The completeness of the simulated data is well, however some random error exists. Besides, the point density of this data is evenly. The data is shown in the figure 5-1. The colour is given by the height of the points.

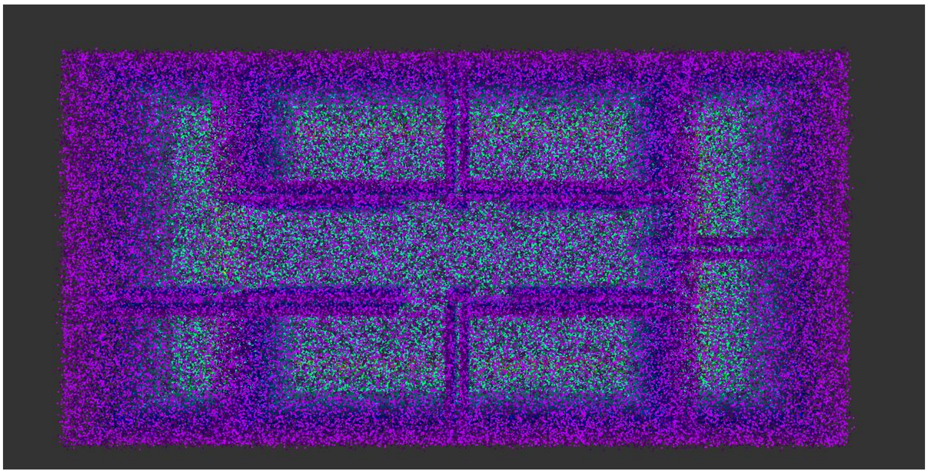


Figure 5-1 Simulated data

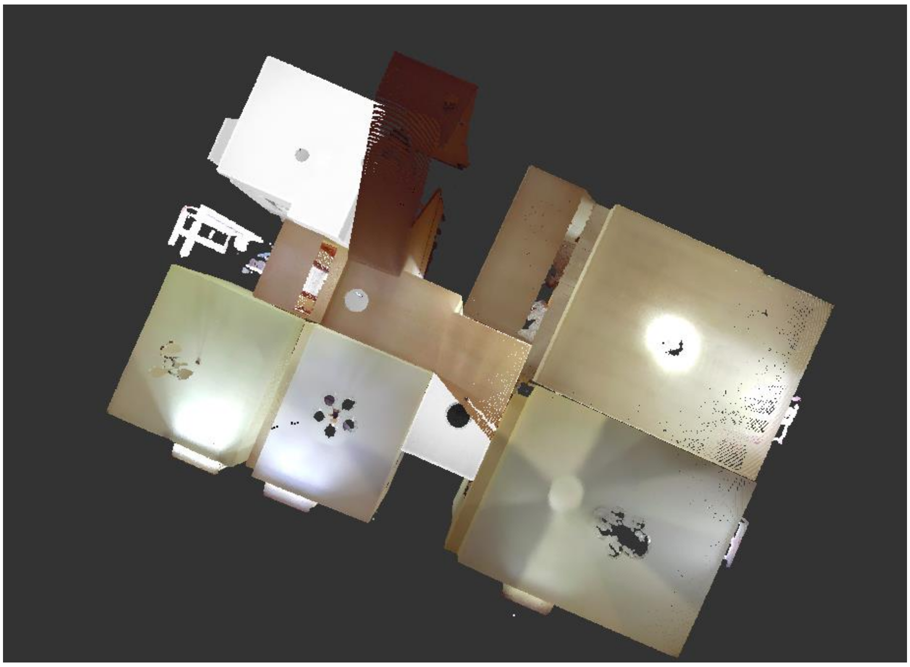


Figure 5-2 Real point cloud data

The second one is the real data of the first floor of a house. Data has been acquired with a Terrestrial Laser Scanner FARO Focus3D X 330 and the distance accuracy is up to 2 mm. The structure of this data satisfies the Manhattan-World principle, which is showing in the figure 5-2. However, some parts of the data do not match the Manhattan-World perfectly. Some small parts of the ceiling are not in the same plane with others (showing in figure 5-3) because of the beams. Besides, the shape of the bay windows is not precise rectangle. In addition, stairs are contained in the data. It does not match the requirement of Manhattan-World. In this research, only the relation within the same floor is considered. Thus, the stairs should be removed. Last but not least, the direction of the building is not parallel to x-axis or y-axis. The completeness of the real data is not as well as the simulated data (showing in figure 5-4). The problem of completeness is caused by two main reasons. The first one is some occlusion occurs because of the scanning location. The floor of scanner location is lack of points. The second reason is the furniture. While scanning the indoor environment, the furniture is scanned as well. The points belonging to the furniture affect the result of this research significantly. Since that, the point cloud data has been pre-processed to clean the furniture inside the building. Therefore, the occlusion problem becomes more serious in the area of lower half of the wall and the floor near to the walls. In addition, some small parts of the ceiling is missed. The accuracy of the real data is not satisfied to the automatically reconstructed model. Some parts of the point cloud data do not registered well. Comparing to the other part of the data, these parts are rotated a small angle across the z axis. Last but not least, the density of the real data is not evenly. Two main reasons caused this problem. Firstly, the distances between the scanner and the points are varied. Longer distance reduces the density of point cloud data. Secondly, some part of the building is scanned twice because of the occlusion. In summary, this point cloud data can be used in the automatic reconstructed model, but some pre-processing have to be done to avoid the problem.

Figure 5-3 Some parts of the ceiling are not in the same plane with the others

Figure 5-4 The occlusion of the point cloud data

5.2. Pre-processing of the data

According to the chapter 5.1, the simulated data can be used to the reconstructed model directly. Regarding to the real data, the problem of requirement of Manhattan-World and accuracy can be fixed by pre-processing. To match the requirement of Manhattan-World, the whole data should be rotate and the parts that do not match requirement of Manhattan-World should be removed. Regarding to the accuracy, the data register should be corrected.

5.2.1. Rotating the point cloud data

The problem of Manhattan-World includes the rotation of the data and the structures which are not satisfied the Manhattan-World. To fix the rotation problem, the real data should be rotated in order to be parallel to x-axis or y-axis. Regarding to the structures that are not match the Manhattan-World, these structures should be removed in this research.

The first step is to clean the structures that are not match the Manhattan-World. In this case, the stairs are removed. The second step is to rotate the data. Since the data only rotates across the z-axis in this case, a simple method is used to process the rotation. First, some points belongs to a plane are extracted manually by using MeshLab. Secondly, the equation of the plane is calculated from the points. After that, the line of intersection of plane $z = 0$ and the plane of the points is calculated. The angle between this cross line and x or y axis can be calculated by the equation of the line. By using this angle, the transform matrix can be derived. After this transformation, the point cloud data can be rotated to parallel to the x-axis. The result of this rotation is showing in the figure 5-5.

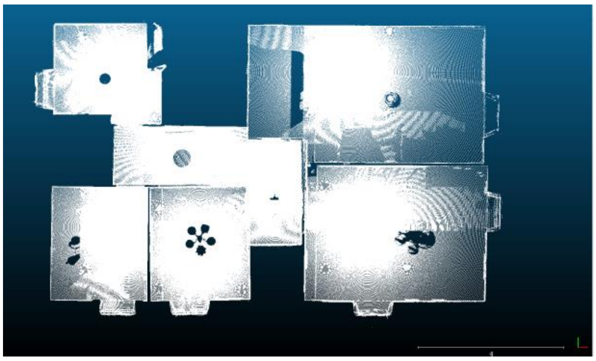


Figure 5-5 Real point cloud data after rotation

5.2.2. Correcting the registration errors

After the transformation, the point cloud data is almost parallel to the x-axis. However, the three left rooms are still rotated a little. To correct this problem, the second rotation have to be applied. Similar to the last rotation, the rotated angle is calculated by using the same method. After this correction, the result is available for the automatic reconstruction model. The result of this step is showing in the figure 5-6. However, the rotated angle is smaller than 1 degree, thus the change is not distinct in the figure.

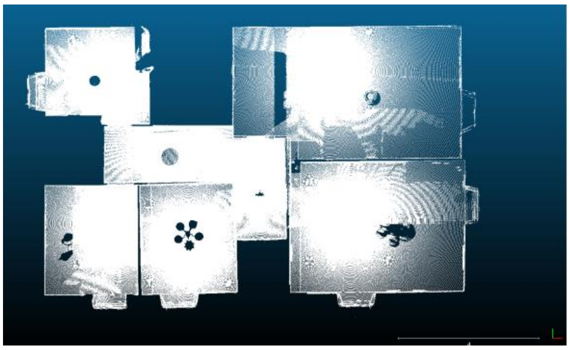


Figure 5-6 The real point cloud data after pre-processing

5.3. Application and improvement of navigable spaces reconstruction

The navigable spaces reconstruction method is developed by Khoshelham & Díaz-Vilariño (2014). The process contains three rules as follow: cuboid placement rule, cuboid connecting rule and cuboid merging rule. As mentioned in the section 4.4.1, an improved shape grammar indoor model is applied in both simulated data and real point cloud data.

5.3.1. Improvement of histogram analysis

As mentioned in chapter 3.1, the placement rule includes two main steps. The first one is dividing process and the second one is placing process. In the dividing process, the histogram mainly effect the result. Only if the peaks of histogram are correctly detected, the point cloud can be appropriate divided. During this process, the minimum peak distance and minimum peaks height are related. The second step is placing processing. Five parameters concerns this processing as following: maximum thickness of wall, average point spacing, precision of point coordinates, points-on-ceiling index and points-on-walls index. The first three parameters are related to the point cloud data. To correctly place the cuboids, the threshold of points-on-ceiling index and points-on-walls index should be appropriately determined.

First of all, the point cloud data should be correctly divided into cuboids. During this processing, the size of cuboids is detected by the histogram. For each axis, the distance between a pair of peaks decide the length of the cuboid. The x, y and z is determined by the corresponding histogram respectively. Ideally, every pair of adjacent peaks should be considered. However, in reality, since the noise and the quality of real point cloud data, not all peaks are considered. The peaks are selected only if the value is larger than the threshold. The threshold is set up for avoiding the small peaks.

In the case of simulated data, threshold for points-on-ceiling index is 0.20 in the simulated data. Besides, the minimum peak height is calculated by the median and the variance. The histogram and the result of the placement rule is shown in figure 5-7 and 5-8. In the figure 5-7, the yellow area represents the non-terminal cuboids while the white area indicates no cuboids placed.

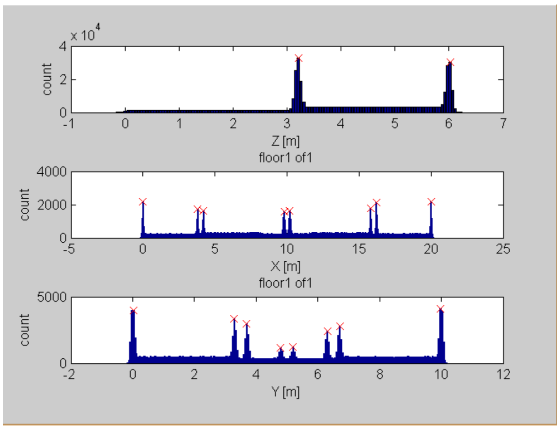


Figure 5-7 Histogram of simulated data

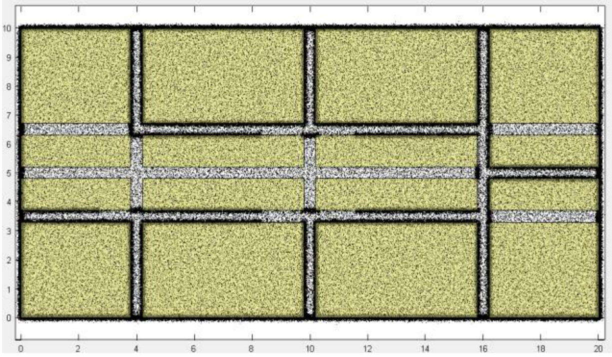


Figure 5-8 Result of place rule in simulated data

In the case of real point cloud data and due to the occlusion and noise caused by the furniture, the range that used to calculate the histogram is changed from the whole range of the floor into the upper half of the floor. The histograms of both ranges are showing in figure 5-9 and figure 5-10. The results under corresponding situations are shown in figure 5-11 and figure 5-12.

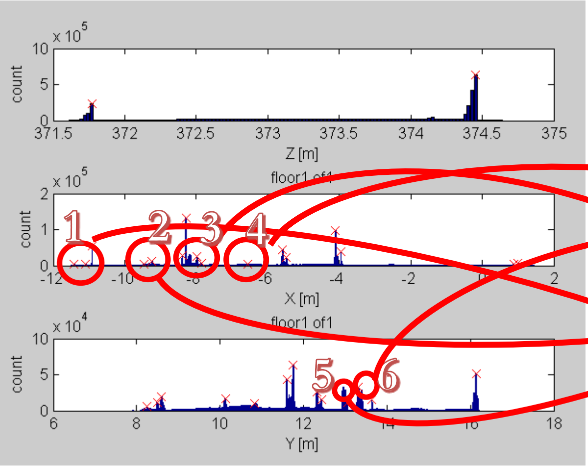


Figure 5-9 Histogram of whole range of the storey

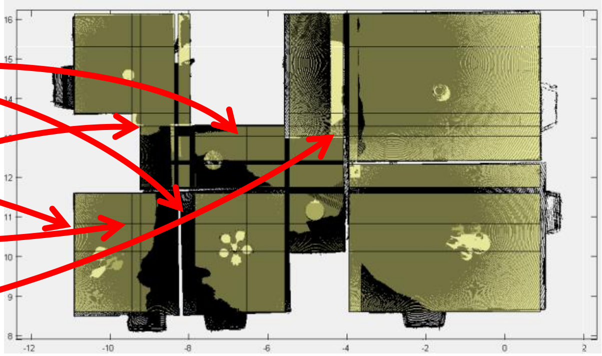


Figure 5-10 Result of whole range of the storey

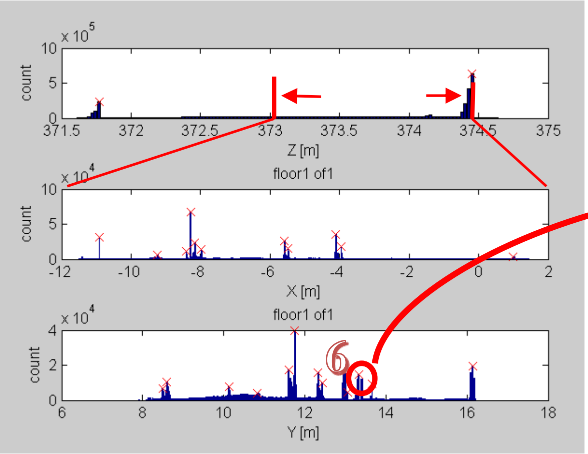


Figure 5-11 Histogram of upper half range of the storey

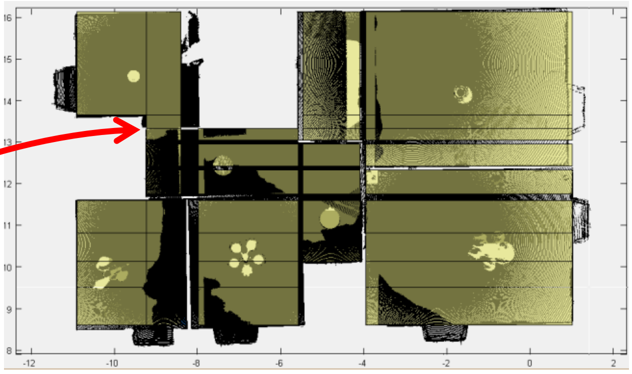


Figure 5-12 Result of upper half range of the storey

Figure 5-9 shows the histogram of the whole range of the storey and figure 5-10 shows the result of the placement rule for navigable spaces among the whole range. The 6 problem can be classified into two categories. The first one is the mistaken detection caused by noise or furniture. As the figures shows, in the location 1 in the histogram, two peaks around -12 to -11 are detected because the obey window located around – 11 in x-axis and 14 to 15 in y-axis. The corresponding area of the point cloud data is shown in figure 5-13.In location 2 and 4 in figure 5-9, similar situation occurs. The second problem is the omission of peaks, which is caused by the occlusion. In the locations of 3 in x-axis and 5 in y-axis, two peaks are missed since the value of peaks are too closed to the neighbour. The occlusion caused by furniture lower the peak value. Figure 5-14 is showing the occlusion caused by furniture around the location pointed out by number 5.

The problems mentioned beyond are improved by only using the points located in the upper half range of the storey. Figure 5-11 and figure 5-12 show the histogram and result of upper half range of the storey respectively. As shown in the figure, the problems that caused by occlusion and noise are corrected, however problem 6 still exists.

Overall, using only the upper half range of the storey leads to a better result of place rule.
In addition, spaces belong to the bay window is occluded in this research, because the shape of the bay window does not meet the requirement of the Manhattan-World spaces.

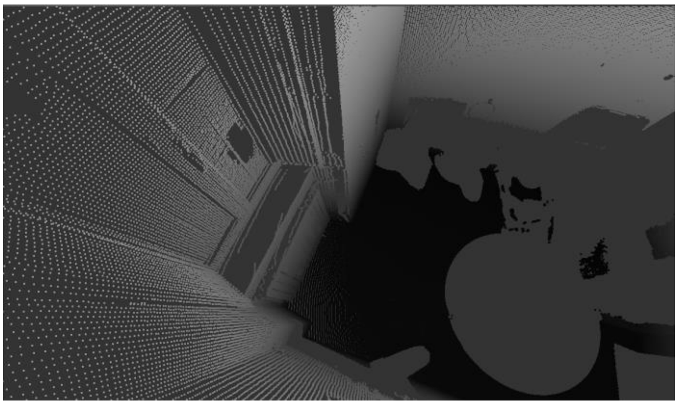


Figure 5-13 The obey window around -11 in x

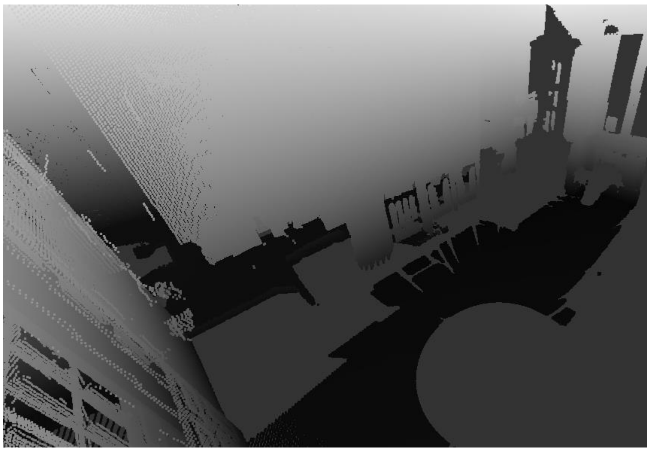


Figure 5-14 Occlusion caused by furniture

After correctly dividing the point cloud into cuboids, decision of whether place the non-terminal or wall-cuboids should be done. During the placing processing, three conditions are used to determine whether place the cuboids and which kind of cuboids should be placed. The first one is the size of the cuboids. Only the cuboids that larger than the threshold, the cuboids are considered as candidates of non-terminal cuboids for navigable space. The threshold is given by the maximum thickness of walls. Besides, the points-on-ceiling index is used to define whether the cuboid touches the ceiling of the storey. According to the equation of the points-on-ceiling index, the index related to average point spacing and the threshold of the index. The average point spacing is decided by the density of the point cloud data. In the case of simulated data, the average point spacing is 0.05 and the threshold is 0.6. The cuboids are correctly placed as figure 5-12 shown. In the case of real point cloud data, the average point spacing is 0.01 and the threshold is 0.5. However, since the varied density of the point cloud data, the result of the placing rule in real point cloud data is not ideal. In the area of high density, because of the given average point spacing, even if only small percentage area of the cuboid touch the ceiling, it results in at a high value of points-on-ceiling index. Therefore, the type the cuboids are mistaken decided.

5.3.2. Improvement of thinning the point cloud data

To improve the accuracy of the placement rule, a process of thinning the point cloud data is applied. The main method use a cube as the kernel and randomly selecting the specified number of points to maintain and removing the others. In this case, one point is kept within a cube with 1cm radius. The result and the corresponding histogram are showing in figure 5-15 and figure 5-16. After thinning the point cloud data, the density is evenly. The peaks caused by uneven distribution is reduced. Besides, after thinning, the points-on-ceiling index and points-on-walls index which are used later perform better accuracy. The final result of placement rule in real point cloud data is shown in figure 5-17.

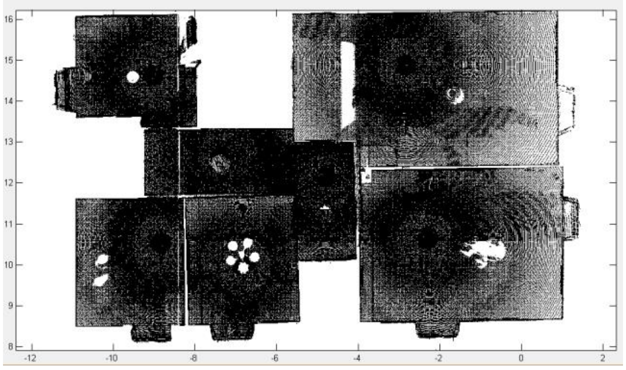


Figure 5-15 Result after thinner

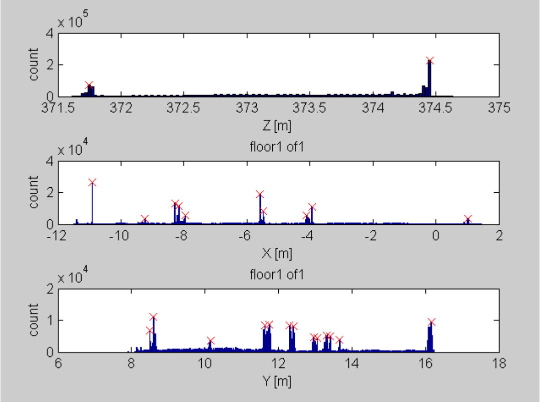


Figure 5-16 Histogram after thinner

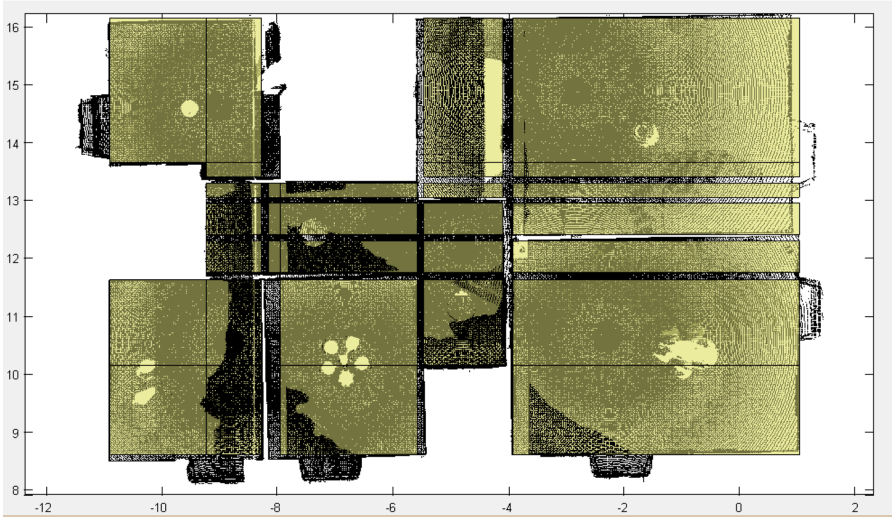


Figure 5-17 Result of place rule in real point cloud data

5.4. Non-navigable spaces and topologic information reconstruction model

The automatic reconstruction modelling method can reconstruct the non-navigable spaces, the adjacency and the connectivity between the navigable spaces. The reconstruction of non-navigable spaces is the basic of the adjacent and connected relation detection. Both the simulated data and the real data are used to test the model.

The reconstruction of non-navigable spaces is at the same time with the process of the reconstruction of navigable spaces. The placement rule and connecting rule are added to the corresponding step of process of navigable spaces reconstruction. After the non-navigable spaces reconstruction, adjacency and connectivity are derived.

5.4.1. Reconstruction of the non-navigable spaces

According to the discussion in chapter 4, the non-navigable spaces refer to the spaces of walls in this case. To reconstruct the spaces of walls, two rules are applied. The first one is the placement rule and the second one is connecting rule.

In the first step, the whole indoor environment is divided into cuboidal spaces. If the cuboidal spaces meet the specified conditions, the corresponding cuboid is placed. During the process of wall cuboid place rule, two situations are considered. The first one is the ideal situation, only if the spaces touch the walls and are thinner than the maximum thickness of the wall, the spaces are considered as wall spaces. Then the wall cuboid is placed. However, due to the data quality, an interactive function is added. When the points-on-walls index fail to satisfy the higher threshold but is larger than the lower threshold, the program will ask the user to decide whether place the wall cuboid. The process is applied during the placement rule of both the navigable spaces and non-navigable spaces. The decision process is shown in the figure 5-18

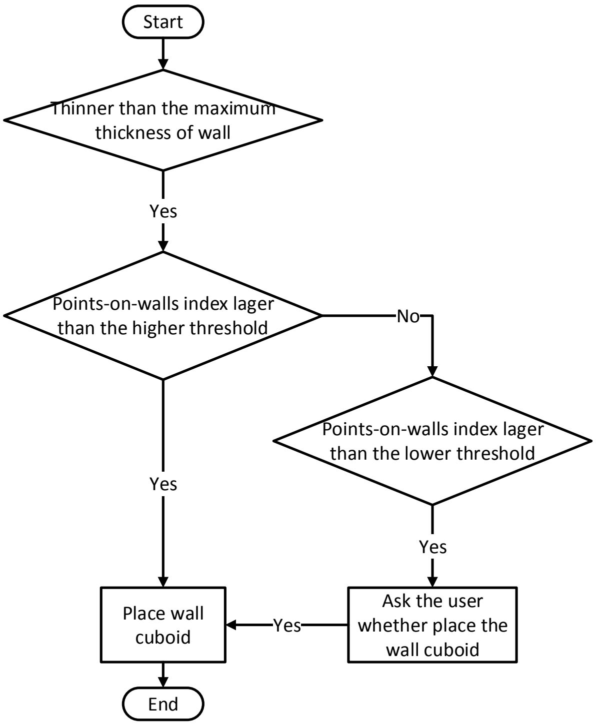


Figure 5-18 Flowchart of decision of place rule

To decide whether the cuboid meets the requirements, three indexes which are points-on-ceiling index, points-on-walls index and the size of the space are used in corresponding condition. These parameters are the same with the corresponding data in the reconstruction of navigable spaces. The results of both data are presented in figure 5-19 and 5-20.

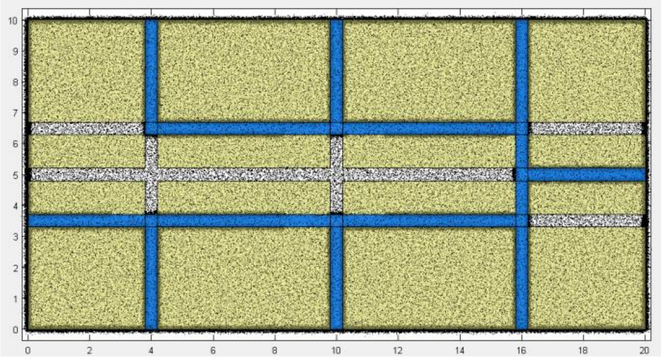


Figure 5-19 Result of placing wall cuboids of simulated data

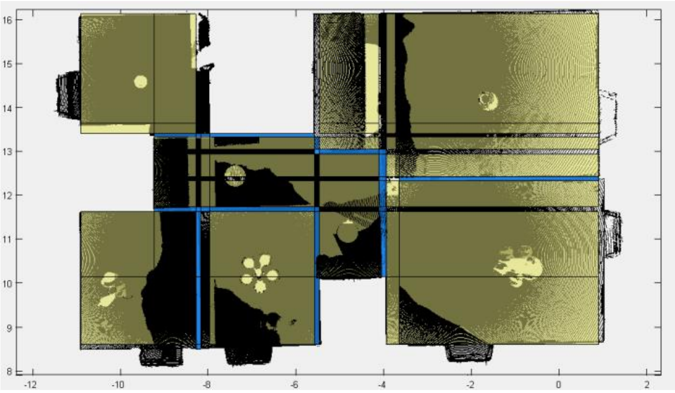


Figure 5-20 Result of placing wall cuboids of real point cloud data

In the case of real point cloud without the process of thinner the point cloud data, after placing wall cuboids, some gaps may occur due to the incompleteness of the data. Therefore, according to the assumption that the inner walls are connected, a connecting rule is applied. In this connecting process, the user can decide that whether to place the wall cuboid. No change occurs in the simulated data as wall cuboids are perfectly placed and no gap between the walls cuboids exist in simulated data. Regarding to the real point cloud data, the gap between the walls is fixed. The result of the connect rule is shown in the figure 5-21. The outer wall in the figure can be removed by interaction tool after applying connection rule of non-navigable spaces.

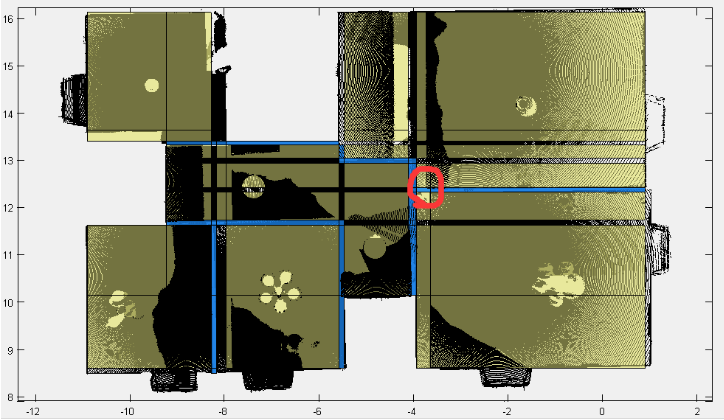


Figure 5-21 The result after connect rule of non-navigable spaces

5.4.2. Result of geometric model

After applying all 3 rules, both the navigable and non-navigable spaces are reconstructed in the geometric model. The results for both simulated data and real point cloud data are shown in figure 5-22 and 5-23. In both figures, yellow area shows the navigable spaces and the blue area refers to the non-navigable spaces. The green area is two selected terminal cuboids which are shown as examples in figures below. As the figures shows, the indoor spaces are correctly reconstructed from the simulated point cloud data. However, in the case of the real point cloud data, most of the indoor spaces are correctly detected except an omission caused by occlusion of the data.

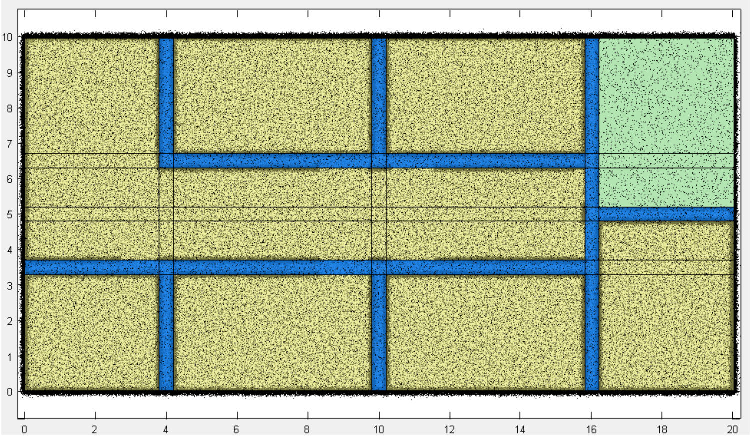


Figure 5-22 Result of geometric model reconstructed from simulated data

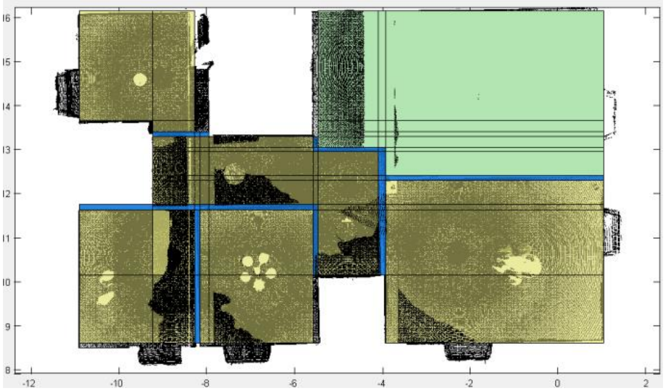


Figure 5-23 Result of geometric model reconstructed from real point cloud data

5.4.3. Detection of the adjacency between navigable spaces

The method to obtain the adjacency is to search the spaces on the both sides of the wall cuboids and then add the adjacent cuboid number of terminal cuboids to each other. After detection, the adjacency is stored as the attribute of cuboids. The results of both data are shown in the figure 5-24 and 5-25. The adjacency graph is built according to the result of automatic reconstruction from the model. To have a higher efficiency in indoor navigation, thin wall model is used in this research. The S number refers to the number of the navigable spaces, the lines between two spaces represent the adjacency. The w number shows the walls between two navigable spaces and the D number indicates the doors. The base map is the manually reconstructed model.

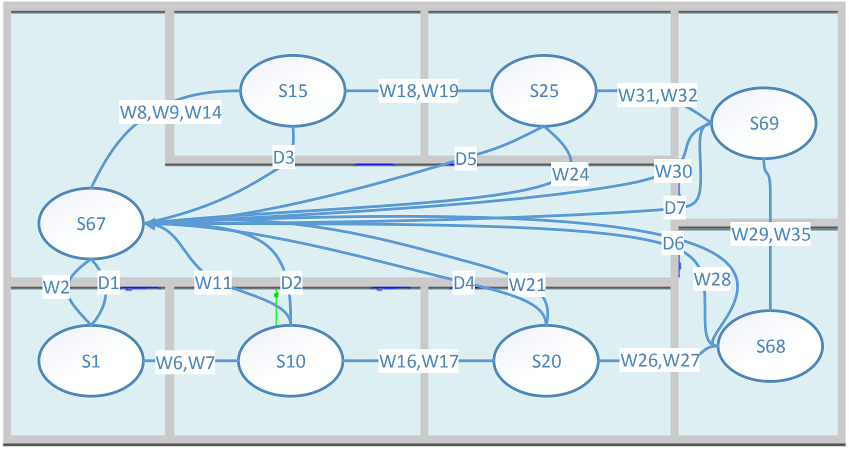


Figure 5-24 Result of adjacency detection of simulated data

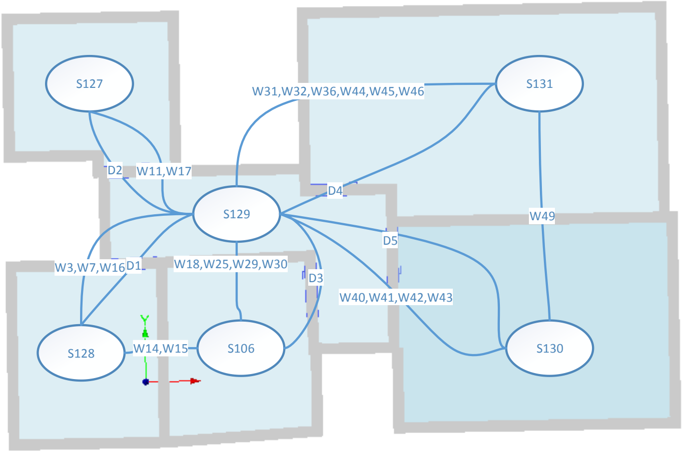


Figure 5-25 Result of adjacency detection of real point cloud data

5.4.4. Detection of the connectivity between navigable spaces

Two navigable spaces divided by a wall with a door is considered as connected. Therefore, the location information of doors has to be derived before reconstructing the connectivity. In this case, the coordinates of the vertices of the doors is manually detected. After importing the location of doors, the connectivity is derived based on the adjacency. For each adjacent relation, the one with a door between the pair of adjacent cuboids is marked as connected navigable spaces. This connectivity can be automatically detected. The result of connectivity reconstruction of simulated data is shown in the table 5-1 and figure 5-26.

Table 5-1 Connectivity of simulated data

	S1	S10	S15	S20	S25	S67	S68	S69
S1	Null	0				1		
S10	0	Null		0		1		
S15			Null		0	1		
S20		0		Null		1	0	
S25			0		Null	1		0
S67	1	1	1	1	1	Null	1	1
S68				0		1	Null	0
S69					0	1	0	Null

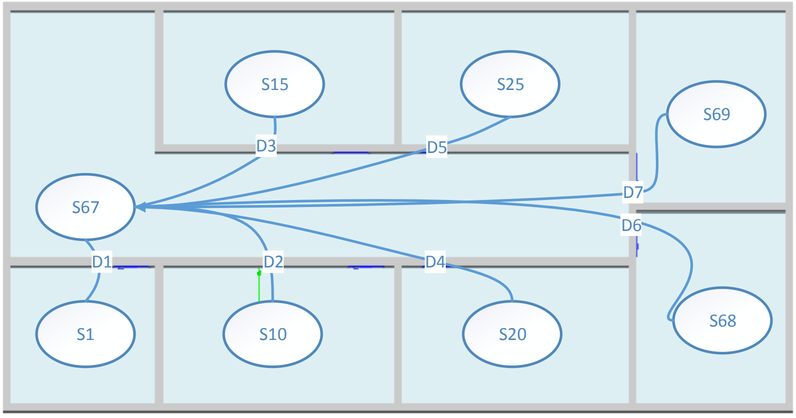


Figure 5-26 Connectivity of the simulated data

In the table, S-number refers to navigable spaces; number 1 expresses the connective adjacency while number 0 indicates the adjacency which is not connective. No value in the table means that the two navigable spaces are not adjacent.

Similarly, the result of connectivity reconstruction of real point cloud data is presented in table 5-2 and figure 5-27.

Table 5-2 The adjacency and connectivity table of real point data

	S106	S127	S128	S129	S130	S131
S106	Null		0	1		
S127		Null		1		
S128	0		Null	1		
S129	1	1	1	Null	1	1
S130				1	Null	0
S131				1	0	Null

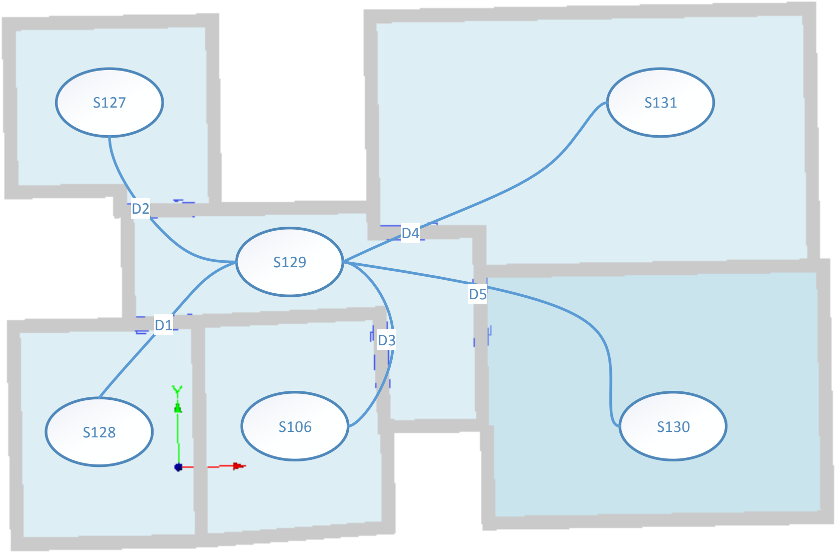


Figure 5-27 The connective graph of real point cloud data

As the adjacency and connectivity graph shown in simulated data and real point cloud data, the adjacency and connectivity within this indoor environment is completely and correctly obtained.

5.5. Export the model

After the reconstruction of the geometric and topologic information, the model is exported to gbXML format which can be visualized in the common software. The translated result are showing in figure 5-28 and 5-29. As a result, the translated gbXML file can be imported into SketchUp and Autodesk Ecotect.

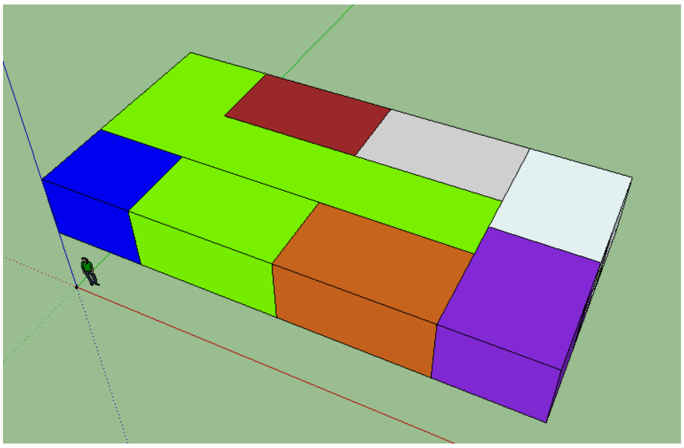


Figure 5-28 gbXML file translated by reconstructed model of simulated data

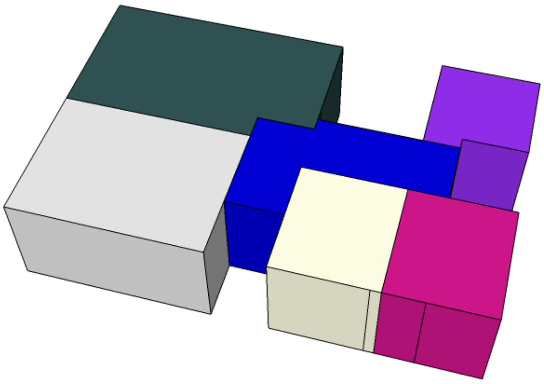


Figure 5-29 gbXML file translated by reconstructed model of real point cloud data

6. EVALUATION AND DISCUSSION

The completeness and accuracy of the automatically reconstructed model should be validated. To evaluate the completeness of the model, the manually reconstructed model is used as the reference. In comparison to the automatic reconstructed model and the manually reconstructed model, the completeness can be estimated. Regarding to the accuracy, the normal and the mean distance between points to the plane of the reconstructed model is calculated and compared.

6.1. Evaluation

6.1.1. The completeness of the model

Two models with navigable spaces and non-navigable spaces are manually reconstructed from the point cloud data by AutoCAD Revit and exported as gbXML. The models for both simulated data and real point cloud data are shown in figure 6-1 and 6-3. Besides, the automatically reconstructed models are exported as gbXML file and presented in figure 6-2 and 6-4 respectively. The doors are excluded in automatically reconstructed model.

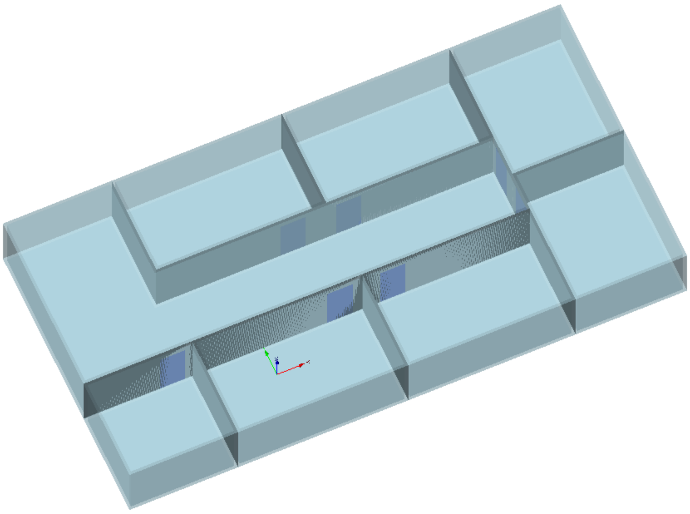


Figure 6-1 Manually reconstruction of simulated data

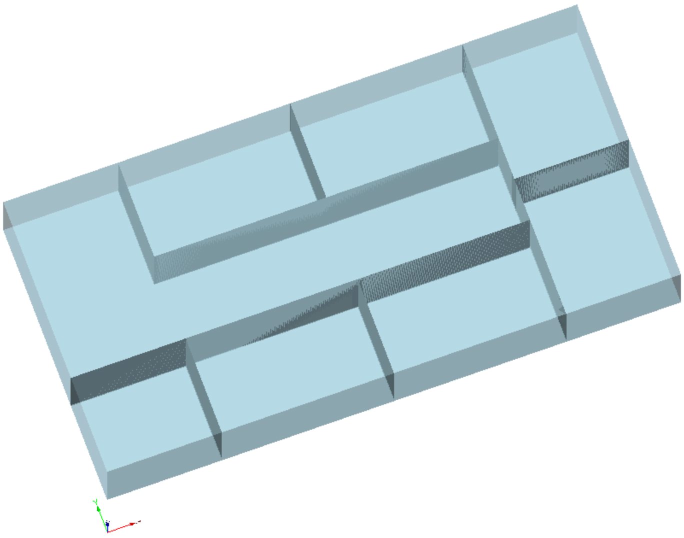


Figure 6-2 Automatically reconstruction of simulated data

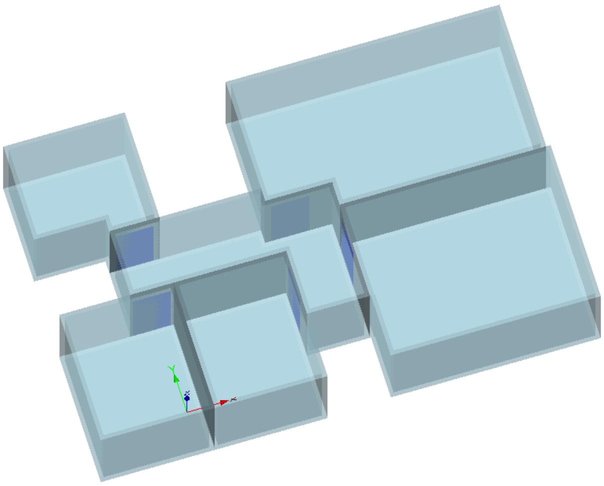


Figure 6-3 Manually reconstruction of real point cloud data

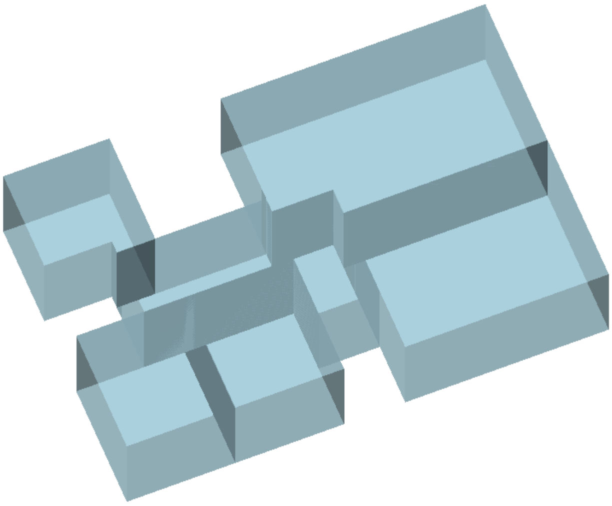


Figure 6-4 Automatically reconstruction of real point cloud data

In the case of simulated data, in comparison the figure 6-1 and 6-2, all the navigable spaces and non-navigable spaces are correctly detected. The adjacency and connectivity between non-navigable spaces are correctly derived as well (shown in figure 5-24 and figure 5-25). Regarding to the real point cloud data as shown in figure 6-3 and 6-4, all the navigable spaces are correctly reconstructed. After the interaction with user, the non-navigable spaces are correctly detected. Every adjacency and connectivity between navigable spaces is correctly obtained (shown in figure 5-26 and figure 5-27).

6.1.2. The accuracy of the model

The accuracy of the model is estimated by two indexes. The first one is comparing the normal of the reconstructed plane and the normal calculated from the points of the corresponding plane in order to ensure the direction of the plane is correct. The second one is the distance between points and the automatically reconstructed plane to ensure the location of the plane is correct.

The tables of deviation for both dataset are shown in table 6-1 and table 6-2 respectively. In the table, the planes are represented by the plane equation in equation 6-1.

$$X \times x + Y \times y + Z \times z - D = 0$$

Equation 6-1

In the plane equation, the X, Y and Z indicate the coefficients of x, y and z respectively. Besides, D refers to the distance from the plane to the origin. The coefficients of both plane calculated from point cloud data and the model are shown in the table 6-1 and table 6-2. In addition, the mean distances which refer to the mean distance between the points belong to the corresponding plane in the model is shown. The unit of D and the mean distance are meter. In the case of simulated point cloud data, the overall average distance between points and the plane is approximately 0.044 meters. Regarding to the real point cloud data, the overall average distance is about 0.045 meter.

Table 6-1 Normal and deviation between the data and the model for simulated data

		Simulated data				Model				
		X	Y	Z	D	X	Y	Z	D	Mean distance
storey	Front	-0.0003	-1	0.0044	0.0097	0	-1	0	0.0258	0.0312
	Ceiling	-0.0027	-0.0143	0.9999	5.885	0	0	1	6.0191	0.043
	Left	-0.9999	-0.002	0.015	0.0101	-1	0	0	0.0069	0.0374
	Right	1	0.0015	-0.0007	20.0093	1	0	0	20.0089	0.0366
	Back	-0.0004	1	-0.0008	9.9905	0	1	0	9.9729	0.0465
	Floor	0.0014	-0.0231	0.9997	3.1043	0	0	1	3.2111	0.0462
Room1	Back	-0.0065	0.9999	0.0128	3.3427	0	1	0	3.2913	0.0325
	Right	0.9992	0.0026	0.0392	4.0164	1	0	0	3.7961	0.0469
Room2	Back	-0.0004	0.9998	-0.0215	3.195	0	1	0	3.2913	0.0395
	Left	0.9988	0.0145	0.046	4.448	1	0	0	4.1964	0.0493
	Right	0.9999	-0.0139	-0.0093	9.7433	1	0	0	9.8008	0.0363
Room3	Back	-0.0085	1	-0.0024	3.1579	0	1	0	3.2988	0.0293
	Left	0.9995	-0.0192	0.0235	10.2824	1	0	0	10.2011	0.0435
	Right	1	-0.0098	-0.0015	15.7778	1	0	0	15.8056	0.0379
Room4	Back	-0.0011	0.9993	-0.0362	4.5987	0	1	0	4.7984	0.0442
	Left	0.9985	0.0016	0.0539	16.4483	1	0	0	16.2059	0.0513
Room5	Front	-0.0107	0.9996	0.0258	5.1254	0	1	0	5.2003	0.0409
	Left	0.9962	0.0185	0.0847	16.7107	1	0	0	16.2059	0.0646
Room6	Front	0.0103	0.9947	0.1028	7.2614	0	1	0	6.7075	0.0665
	Left	0.9997	0.024	-0.0069	10.386	1	0	0	10.2011	0.0444
	Right	0.9997	-0.0228	0.0058	15.6257	1	0	0	15.8056	0.043
Room7	Front	-0.0062	0.999	0.045	6.8697	0	1	0	6.7075	0.0459
	Left	0.9995	0.0188	-0.025	4.2645	1	0	0	4.1964	0.0464
	Right	0.9982	-0.0513	-0.0299	9.2508	1	0	0	9.8008	0.0548
Corridor	Front	-0.0018	0.9998	-0.0216	3.6184	0	1	0	3.6932	0.0532
	Back	-0.0018	0.9997	0.0248	6.3836	0	1	0	6.3056	0.0432
	Right	0.9989	0.0004	0.0476	4.0181	1	0	0	3.7961	0.0439
Overall										0.044385

Distribution of the distances of planes is shown of figure 6-5.

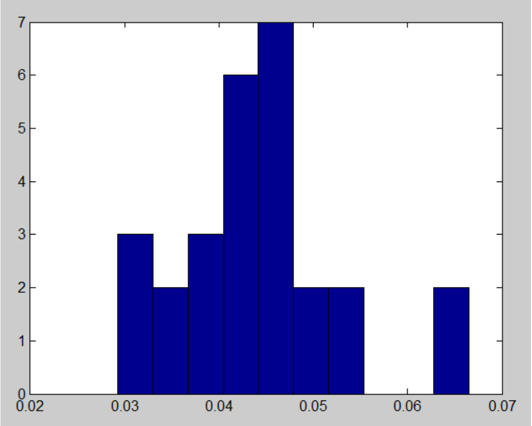


Figure 6-5 Histogram of deviation of points (simulated data)

Table 6-2 Normal and deviation between the data and the model for real point cloud data

		Real point cloud data				Model				
		X	Y	Z	D	X	Y	Z	D	Mean distance
Room1	Left	-0.9999	-0.0008	-0.0112	6.7102	-1	0	0	10.9128	0.0059
	Back	-0.0034	1	-0.0079	8.7132	0	1	0	11.6309	0.0191
	front	-0.0047	1	-0.0025	7.6322	0	1	0	8.5982	0.0941
	ceiling	-0.0121	0.0025	0.9999	374.5606	0	0	1	374.4513	0.0068
	right	-1	-0.0036	-0.0083	5.1387	-1	0	0	8.2845	0.0058
Room2	left	-0.9996	-0.0257	0.0068	10.4582	-1	0	0	8.1594	0.0332
	back	0.0229	0.9997	-0.0019	10.8471	0	1	0	11.6309	0.0894
	front	-0.0368	0.9993	-0.0063	6.4525	0	1	0	8.5982	0.0281
	ceiling	0.006	0.0095	0.9999	374.4766	0	0	1	374.4513	0.0084
	right	-0.9965	-0.0772	0.0322	16.7005	-1	0	0	5.5812	0.036
Room3	left	-0.9999	-0.0027	0.0148	9.4329	-1	0	0	3.9291	0.022
	back	-0.0159	0.9997	-0.0177	5.7337	0	1	0	12.3076	0.0184
	front	-0.0148	0.9998	-0.0132	3.7035	0	1	0	8.5982	0.0262
	ceiling	0.0086	0.0156	0.9998	374.51	0	0	1	374.4513	0.0299
	right	-0.9999	0.0036	0.0098	2.6954	1	0	0	1.027	0.0134
Room4	left	-0.9999	-0.0109	0.0058	12.9004	-1	0	0	10.9128	0.0097
	back	-0.0143	0.9997	-0.0197	8.8621	0	1	0	16.1673	0.0774
	front	-0.0168	0.9997	-0.0169	7.5114	0	1	0	13.661	0.0187
	ceiling	0.0067	0.0183	0.9998	374.531	0	0	1	374.4513	0.0573
	right	-0.9998	-0.0194	0.0059	9.905	-1	0	0	8.2845	0.2988
Room5	left	-1	0.0004	0.0056	7.691	-1	0	0	5.4811	0.1088
	back	-0.0224	0.9997	-0.0121	11.6843	0	1	0	16.1673	0.0253
	front	-0.0106	0.9999	0.0038	13.8512	0	1	0	12.4079	0.0166
	ceiling	0.0062	-0.0003	1	374.4167	0	0	1	374.4513	0.0079
	right	-0.9999	-0.0083	0.0067	1.4742	1	0	0	1.027	0.1356
Corridor	back	0.0616	0.9981	-0.0026	11.6626	0	1	0	13.3101	0.0523
	front	-0.0238	0.9996	-0.0121	5.7337	0	1	0	10.1522	0.0312
	ceiling	0.0072	0.0114	0.9999	374.5085	0	0	1	374.4513	0.0098
	right	-0.9997	-0.0254	0.0034	5.0495	-1	0	0	4.1044	0.0118
Overall										0.044755

Distribution of the distances is shown in figure 6-6.

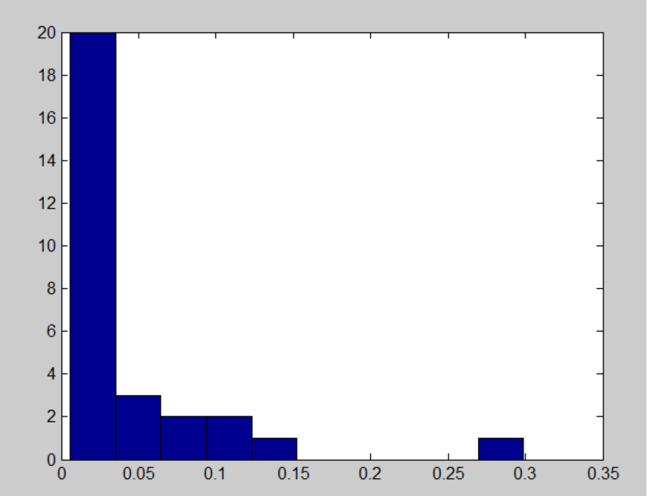


Figure 6-6 Histogram of deviation of points (real point cloud data)

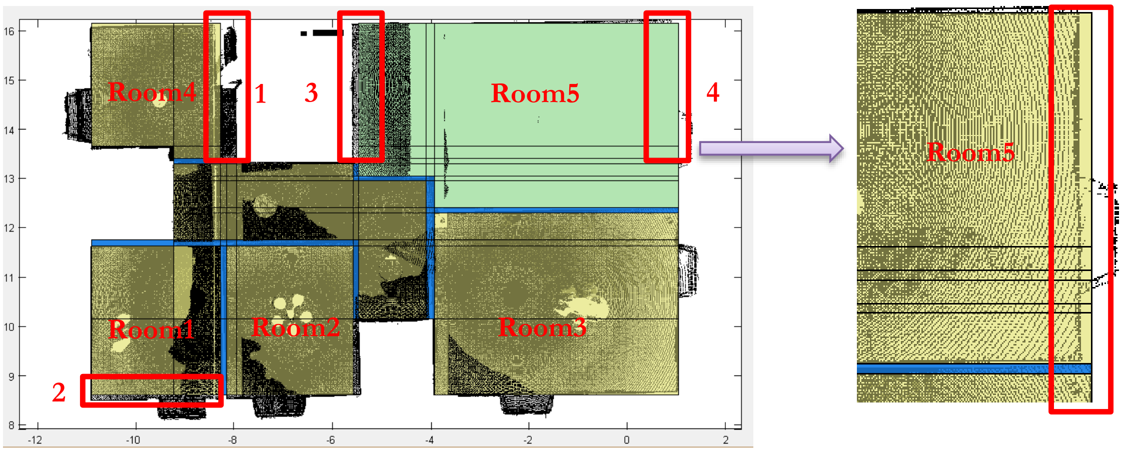


Figure 6-7 Result of both navigable and non-navigable spaces reconstruction

In the table 6-1 and table 6-2, comparing the normal of points belong to an individual plane and the corresponding face of cuboid, the normal of points is slightly sloping. Two reasons might lead to this result. The first one is the noise of the point cloud data and the second one is the algorithm used in calculating the normal of the plane. RANSAC is applied in calculating the normal from the point cloud data, therefore the result of the normal can be slightly different in every calculation. However, in general, the normal calculated from the extracted point cloud data is reliable. Comparing the normal of extracted point cloud and that of the face in reconstructed model, the main directions are consistent. In summary, the direction of the plane in the model is consistent with the point cloud data.

Regarding to the distances between the points and the plane, the histograms are shown in figure 6-5 and figure 6-6. In the case of simulated data, the deviation is broadly coincided with normal distribution. The average deviation is closed to the precision of the data. Thus, this result is acceptable. Refers to the real point cloud data, 75% of the distances are smaller than 0.04 meter. In other words, most of the planes fit the points well. However, some large deviations occur. In the case of the one of 0.3 meter, the reason of such a large deviation is the occlusion of the data. As the area 1 in figure 6-7, the room 4 has some occlusion in the right of the room, which leads to the omission of placing cuboid. Thus, the deviation is exceptional (around 30 cm). This situation happens in the area 3 as well. Besides, in the cases of area 2 and area 4, the deviations are around 10 cm. The reason of these deviations is that the data do not exactly matched to the Manhattan-World. A slightly lean exists. In summary, the overall deviation is around 4.4 centimetres. However, except the abnormal value mentioned beyond, the deviation may be caused by the precision of the point cloud data. Therefore, the overall accuracy which is less than 5cm is acceptable in this case.

6.2. Discussion

Although the overall result of the model is acceptable, some limitations exist. These limitation can be divided into three categories, including the problem caused by the grammar rules, the problem caused by learning the data and the shortcoming of this model.

6.2.1. The problem of grammar rules

The problem indicates the problems caused by the limitation of the grammar rules. While testing the grammar rules in the real point cloud data, some disadvantages occur. These problems can be fixed by improving the grammar rules.

The first problem occurs in the connecting rule of walls. This rule is based on the assumption that the walls within an indoor environment should be connected. However, in the process of placing the connector of wall, some small spaces are considered as the connector of wall by mistake. An example is shown in figure 6-8. In current stage, this situation is restrained through the interacting with the user.

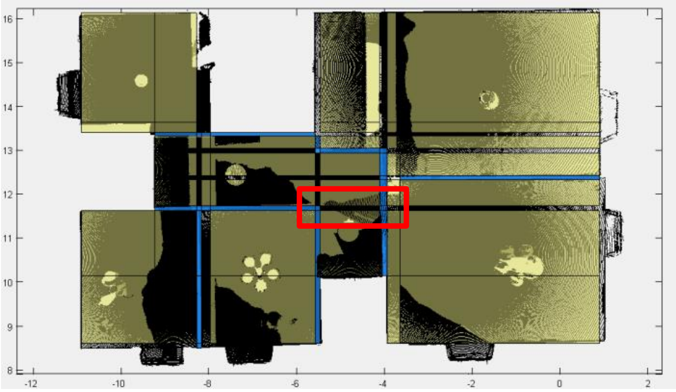


Figure 6-8 Problem of connecting walls

The other problem occurs during placing connector between non-terminal spaces. When the occlusion occurs in the spaces around the wall, the model omits to place a non-terminal cuboid in that space (presented in the red area of figure 6-9). Thus, no connector is placed between the omission and the neighbour non-terminal cuboid. Thus, this connect rule cannot correct the omission caused by the occlusion of the data. Interaction with the user is added to the program of this stage. The user can correct the place rule after every rule. For further research, a mechanism is meaningful to automatically detect and correct the error.

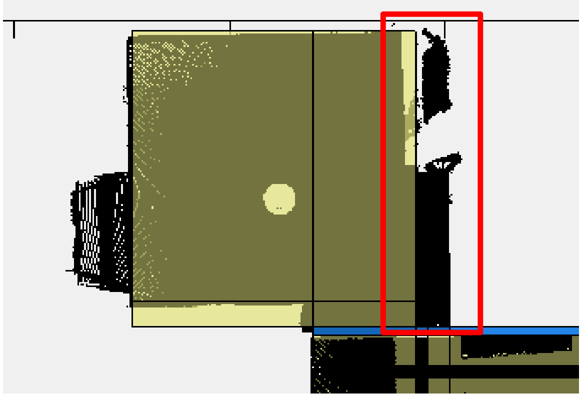


Figure 6-9 Error in place rule

Another problem of the grammar rules is that the two non-terminal cuboids divided by two small empty cuboids are not considered as adjacent cuboids. In the second rule, only the pairs of cuboids divided by one empty space are considered as the candidates of adjacent cuboids. Therefore the connecting rule is not applied in this case and the connector cuboids or the wall cuboids cannot be placed in this gap. For instance, as situation shown in the figure 6-10, there are two empty spaces between two non-terminal cuboids after the implementation of the placing rule, due to the variety of the wall thickness in the real point cloud data. If the model places a correct size wall cuboid for the thinnest wall of the data, in the cases of thicker wall, two wall cuboids are placed. In this research, this problem can be avoided by changing the threshold of the minimum peak distance to determine the minimum unit size of the cuboids. Enlarging the minimum unit size can help to avoid this problem but leads to lower accuracy of the model. Therefore, for further research, the improvement of connect rule should be considered.

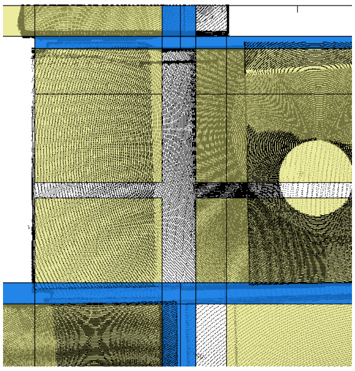


Figure 6-10 Error in place cuboids

6.2.2. The problem of learning the data

The main problem about the real data in this research is caused by the varied point density. The distribution of the points around the corridor is much denser than the points in the margin of the data. Since both the points-on-ceiling index and the points-on-walls index are based on the density of the point cloud data, the varied density leads to a number of problems. The first problem is that it is hard to decide the average point spacing. If the average point spacing is given based on the lower density, it leads to the index become larger than one in the higher density area. By using the same threshold to decide whether the points touch the ceiling or wall, some cuboids are considered to touch the ceiling or walls by mistake. In the opposite, if the average point spacing is decided based on the higher density, some cuboids that located in the margin of the whole data are considered as not touch the ceiling or walls by mistake. The second problem is that a large number of points fall in small area in the high density area leads to the incorrect decision of the points-on-ceiling and points-on-wall index. When the threshold fits to the lower density, the large number of points that caused by high density leads to result in a significant increase of the index, since the average point spacing is large. Therefore, for the further research, two solutions can be considered. The first one is to improve the index. If the index can be independent from the point density, this problem can be solved. Another possible solution may be applied to a function in order to normalize the point density from the point cloud data before using the points-on-ceiling and points-on-walls index.

During the implementation of the model, this problem is solved by thinning the point cloud data. This strategy helps to solve the problem of varied point density. Besides, this strategy can help to gain the parameter of average point spacing. Since the number of points with a given radius in a cube is known, the average point spacing can be easily calculated. So far, the radius and number of remaining points are defined manually. For further research, if the program can automatically detect the density of the point cloud data and give the suggestion of appropriate radius, the number of remaining points can help to improve this method.

Besides, the model has a mechanism to predict the cuboids. For instance, during the process of placing wall cuboids, if the cuboids fail to reach the requirement of the threshold but can stratify the alternative requirement, the program will ask the user to decide whether to place the cuboid. This mechanism is only used the threshold to estimate the potential cuboids in this research. For further research, the improved algorithm for prediction can be considered.

Furthermore, this model can only deal with the data that match the requirement of Manhanttan-World and parallel to the x-axis and y-axis. Therefore, in this case, the data have to be rotated first. If the model has a mechanism to detect the direction of the data and deals with this situation, the model can be more practical.

Last but not least, to adjust the parameters to point cloud data is time-consuming. For further research, if the parameters can be automatically adjusted to the point cloud data, this indoor model can be further improved. Since the strategy of thinning can help to define the parameter of average point spacing, a hypothesize value of the other parameters can be provided. After running the model, the direction of planes and the distances between points to the plane can be calculated. The hypothesize value and the iterative model are adjusted till the distances between the points and the plane are lower than an acceptable threshold. Then the parameters can be detected automatically.

6.2.3. The limitation of this method

The most important limitation is that this model is restricted to the spaces that meet the requirement of Manhattan-World. This limitation is caused by the method which decides the edge of the cuboids. The histogram can only be used to detect the edges that parallel to x-axis or y-axis. Therefore, the limitation of Manhattan-World can be improved by changing the method in order to detect the edge of the cuboid.

Furthermore, in this research, only two rules is applied for the non-navigable cuboids: the place rule and the connect rule. In this case, the connected walls did not merge together. For easier management of the elements within the building, the further research can focus on the merge rule for the non-navigable spaces.

Besides, in this research, the automatically derived topologic relation is restricted on the same floor. Since the indoor navigation within multiple floors is an important application of this model, the topologic relation and connectivity between floors should be developed in further research.

Last but not least, another limitation in this research related to the exporting data format. The gbXML can represent not only the indoor spaces but also the hierarchical relation of the elements within the building. However, the topologic information of every elements cannot be expressed directly. Both the adjacency and the connectivity cannot be directly represented in this data structure. Every time when the user request for the adjacent or connective information, the data research the walls around the target space and the spaces that around the walls on the fly. This method can express the adjacent relation in some way. However, a better solution occurs recently. As shown in the chapter 2, a new data standard named IndoorGML is proposed. In this standard, a solution to store the adjacency and the connectivity directly is given. The further research can focus on exporting the automatically reconstructed model in the IndoorGML standard after its official publish.

7. CONCLUSIONS AND RECOMMENDATIONS

7.1. Answers to the research questions

In this research, the required information for indoor navigation is found. To obtain the 3D indoor model that satisfies this requirement, the shape grammar method for reconstructing the navigable spaces from point cloud data is improved and the method to reconstruct the non-navigable spaces and topologic information is developed. As a result, the model is exported as gbXML file and can be used for indoor navigation.

1. What kind of information is necessary to provide by the 3D indoor model for the indoor navigation?
   The information of navigable space, non-navigable spaces, adjacency between the navigable spaces and connectivity are required for the indoor navigation.

2. Which of the necessary information can be automatically derived?
   The volumetric spaces of navigable and non-navigable can be derived automatically and corrected by the interaction with users. The adjacency and the connectivity between navigable spaces can be automatically derived from a correct model (the information of doors is considered as given). The completeness and accuracy of the detection of adjacency and connectivity is well performed.

3. Which method can be used to reconstruct the non-navigable space?
   The method used in non-navigable space reconstruction is the shape grammar based method. This method contains two rules as following: placement rule and connecting rule.

4. Which method can be used to derive the adjacency and connectivity between the navigable spaces?
   The adjacency and connectivity can be automatically derived by searching the navigable spaces in the both sides of the walls. For each pair of adjacent navigable spaces, the adjacent number is added to the attribute of the other one. Regarding to connectivity, for each pair of adjacent navigable spaces, if they are divided by a wall with door, the adjacency is considered as connective.

5. Which data format can express the volumetric indoor model with adjacent relation and connectivity between navigable spaces?
   The gbXML can hierarchically express the elements of the building. Even if the gbXML file is surface-based, it can express the indoor spaces. For further research, a new data model named IndoorGML can express the volumetric indoor model with adjacent and connective relation directly.

7.2. Conclusions

This research mainly focus on developing methods to reconstruct the non-navigable space, the adjacency and the connectivity between the navigable spaces. Besides, improvement of the shape grammar model is applied. The result shows this method to automatically reconstruct the non-navigable spaces, adjacency and connectivity is achieved. However, for the place rule of both non-navigable and navigable cuboids, some interaction with users is still required.

1. The shape grammar is a reliable method to reconstruct the indoor environment from point cloud data in reality. The exported shape grammar rule can easily be understood in the common commercial software related to indoor model.

2. The shape grammar rules used in this research are restricted to the spaces that meet the requirement of the Manhattan-World. Since that, well registration of the data is important to the model.
3. The adjacency between navigable spaces can be automatically reconstructed from the point cloud data without prior knowledge. The completeness and the accuracy is well performed. However, the detection of connectivity is based on the door detection.
4. The shape grammar model can be exported as gbxml file, which can store the topologic information. Besides, the gbxml file can be imported into common commercial software.

7.3. Recommendations

The recommendations can be grouped into three categories. The first group is related to improve the shape grammar rules. The second one concerns the learning problem in real data. The last one is about the limitation of the method.

First of all, the main problem of shape grammar rules is the connecttion rule. More situation should be considered and the rules can be expended.

Secondly, regarding the learning problem, two recommendations can be given. The first one is the problem of density can be solved by thinning the point cloud data. If the thinning can be automatically done while the place rule, it helps to derive a more accurate indoor model from point cloud data. The second one is that, after derive the first parameter from thinning processing, further research can focus on iterative adjusting the parameters by the programming.

Last but not least, regarding to the limitation in this model, several recommendations can be provided.

- To solve the problem of the restriction of Manhattan-World, the method of detecting the edge of the base shape can be improved. The base shape can be changed from cuboids into more flexible shape, for instance, triangular prism. The combination rule should be designed again as well.
- For development of the merge rule of the walls, the main problem may occurs in determine whether the walls should be merged. In other words, the standard to distinguish whether the wall cuboids belongs to the same wall in reality is the challenge of the merge rule of non-navigable spaces.
- According to the current knowledge, the IndoorGML standard can store the reconstructed information from this research such as adjacency and connectivity. Therefore, the further research can focus on develop the grammars for exporting the IndoorGML data format after its publish.

LIST OF REFERENCES

Autodesk Knowledge Network. (2013). Autodesk Revit Help. *Autodesk Knowledge Network*. Retrieved January 30, 2015, from http://help.autodesk.com/view/RVT/2014/ENU/

Becker, S., Peter, M., Fritsch, D., Philipp, D., Baier, P., & Dibak, C. (2013). Combined Grammar for the Modeling of Building Interiors. *ISPRS Annals of Photogrammetry, Remote Sensing and Spatial Information Sciences*, *II-4/W1*(December), 1–6. doi:10.5194/isprsannals-II-4-W1-1-2013

Brown, G., Nagel, C., Zlatanova, S., & Kolbe, T. H. (2013). Modelling 3D Topographic Space Against Indoor Navigation Requirements. In J. Pouliot, S. Daniel, F. Hubert, & A. Zamyadi (Eds.), *Progress and New Trends in 3D Geoinformation Sciences* (pp. 1–22). Berlin, Heidelberg: Springer Berlin Heidelberg. doi:10.1007/978-3-642-29793-9

Budroni, A., & Boehm, J. (2010). Automated 3D Reconstruction of Interiors from Point Clouds. *International Journal of Architectural Computing*, *08*(01), 55–74. doi:10.1260/1478-0771.8.1.55

Budroni, A., & Böhm, J. (2010). Automatic 3d modelling of indoor manhattan-world scenes from laser data. In *ISPRS Commission V Mid-Term Symposium: Close Range Image Measurement Techniques*. Retrieved from http://isprsserv.ifp.uni-stuttgart.de/proceedings/XXXVIII/part5/papers/137.pdf

BuildingSMART International Ltd. (2007). IFC2x3 Release Summary. Retrieved February 15, 2015, from http://www.buildingsmart-tech.org/specifications/ifc-releases/ifc2x3-release

Daum, S., & Borrmann, A. (2014). Processing of Topological BIM Queries using Boundary Representation Based Methods. *Advanced Engineering Informatics*, *28*(4), 272–286. doi:10.1016/j.aei.2014.06.001

Daum, S., Borrmann, A., Langenhan, C., & Petzold, F. (2014). CRCnetBASE - Automated generation of building fingerprints using a spatio-semantic query--language for building information models. In A. Mahdavi, B. Martens, & R. Scherer (Eds.), (pp. 87–94). doi:10.1201/b17396-18

Derry, M., & Argall, B. (2013). Automated doorway detection for assistive shared-control wheelchairs. In *2013 IEEE International Conference on Robotics and Automation* (pp. 1254–1259). IEEE. doi:10.1109/ICRA.2013.6630732

Díaz-Vilariño, L., Martínez-Sánchez, J., Lagüela, S., Armesto, J., & Khoshelham, K. (2014). Door recognition in cluttered building interiors using imagery and lidar data. *ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *XL-5*, 203–209. doi:10.5194/isprsarchives-XL-5-203-2014

gbXML.org. (2014). Software - Green Building XML Schema. *gbXML.org*. Retrieved February 14, 2015, from http://www.gbxml.org/software.php

Khoshelham, K., & Díaz-Vilariño, L. (2014). 3D Modelling of Interior Spaces: Learning the Language of Indoor Architecture. *ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *XL-5*(June), 321–326. doi:10.5194/isprsarchives-XL-5-321-2014

Lee, J. (2004). A Spatial Access-Oriented Implementation of a 3-D GIS Topological Data Model for Urban Entities. *GeoInformatica*, *8*(3), 237–264. doi:10.1023/B:GEIN.0000034820.93914.d0

Lee, J., Li, K.-J., Zlatanova, S., H.Kolbe, T., Nagel, C., & Becker, T. (2014). *Open Geospatial Consortium Inc.* Retrieved from http://xml.coverpages.org/OGC-07-026-RFC-Submission-GeoXACML-ImplementationSpecification.doc

Li, Y., & He, Z. (2008). 3D indoor navigation: a framework of combining BIM with 3D GIS. *44th ISOCARP Congress*, 1–10. Retrieved from http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:3D+Indoor+Navigation+:+a+Framework+of+Combining+BIM+with+3D+GIS#0

Liu, L., & Zlatanova, S. (2011, May 3). A "door-to-door" path-finding approach for indoor navigation. *Proceedings Gi4DM 2011: GeoInformation for Disaster Management, Antalya, Turkey, 3-8 May 2011.* International Society for Photogrammetry and Remote Sensing (ISPRS). Retrieved from http://repository.tudelft.nl/view/ir/uuid%3Ade84a1c2-6596-4888-a0dd-898886e1f48f/

Liu, L., & Zlatanova, S. (2012). A semantic data model for indoor navigation. In *Proceedings of the Fourth ACM SIGSPATIAL International Workshop on Indoor Spatial Awareness - ISA '12* (p. 1). New York, New York, USA: ACM Press. doi:10.1145/2442616.2442618

Meijers, M., Zlatanova, S., & Pfeifer, N. (2005). 3D geoinformation indoors: structuring for evacuation. *Proceedings of Next Generation.* Retrieved from ftp://ftp.ecn.purdue.edu/jshan/proceedings/topology_ucl2005/3D_indoor_geoinformation.pdf

Oesau, S., Lafarge, F., & Alliez, P. (2013). Indoor scene reconstruction using primitive-driven space partitioning and graph-cut. In V.Tourre & G.Besuievsky (Eds.), *Eurographics Workshop on Urban Modelling and Visualisation* (pp. 9–12). Eurographics Association. doi:10.2312/UDMV/UDMV13/009-012

Oesau, S., Lafarge, F., & Alliez, P. (2014). Indoor scene reconstruction using feature sensitive primitive extraction and graph-cut. *ISPRS Journal of Photogrammetry and Remote Sensing*, *90*, 68–82. doi:10.1016/j.isprsjprs.2014.02.004

Peter, M., Becker, S., & Fritsch, D. (2013). Grammar Supported Indoor Mapping. In *Proceedings of the 26th International Cartographic Conference.* Retrieved from http://icaci.org/files/documents/ICC_proceedings/ICC2013/_extendedAbstract/283_proceeding.pdf

Philipp, D., Baier, P., Dibak, C., Dürr, F., Rothermel, K., Becker, S., … Fritsch, D. (2014). MapGENIE: Grammar-enhanced indoor map construction from crowd-sourced data. In *2014 IEEE International Conference on Pervasive Computing and Communications, PerCom 2014* (pp. 139–147). doi:10.1109/PerCom.2014.6813954

Stiny, G. (2008). *Shape: talking about seeing and doing.* London: The MIT Press.

Xiong, X., Adan, A., Akinci, B., & Huber, D. (2013). Automatic creation of semantically rich 3D building models from laser scanner data. *Automation in Construction*, *31*, 325–337. doi:10.1016/j.autcon.2012.10.006