From Point Cloud to as-built BIM: automated Detection of Openings in existing Buildings

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Abstract: Nowadays, point clouds acquired from laser scanning have become one of the main sources for building modeling. The generation of as-built BIM models for existing buildings brings benefits for building energy analyze and information management. However, the acquired point clouds may contain unwanted elements placed in rooms, which results in clutters and occlusions in the extracted wall structures. Thus, how to extract the correct information of openings from the occluded walls is a challenging task for the indoor modeling. This paper proposes a methodology to detect the information of openings, such as windows and doors, from occluded walls and generate the BIM components automatically. To extract the features of openings, the gradient based maximum likelihood algorithm with shape grammar is used. The corresponding BIM component can be generated using the scripts created by visual programming language. The proposed approach is evaluated with a case study and the obtained results are discussed. The paper concludes with a summary and an outlook of future investigation directions.

Keywords: Building Information Modeling(BIM), as-built BIM, Point clouds, 3D Reconstruction, Automation

1 Introduction

With the more frequent and practical use of Building Information Management (BIM) model in built environment, generating building models from existing buildings is getting more attentions nowadays. The major information sources for BIM modeling of existing buildings are point clouds acquired by laser scanners. However, many methods focus on extracting wall structures (without openings) from point clouds. Fewer attentions are paid to the reconstruction of openings on the wall structures in the BIM model, which is important and worth investigating. For example, in the research of energy consumption analyze of existing buildings, the positions of windows and doors play an important role in the energy consumption simulation. However, the acquired point clouds may contain unwanted elements placed in rooms, which can result in clutters and occlusions in the extracted wall structures.

Thus, how to extract the correct information about openings from the occluded walls is a challenging task for the indoor modeling.

The state-of-the-art researches working on openings' extraction are based on neural networks. However, neural networks have two main drawbacks. First, the pre-training needs a huge amount of training examples (point clouds), which may not be easy to get. Second, the performance of neural network degenerates easily on noisy and low-quality point clouds.

To address these two problems, we propose a novel method based on maximum likelihood estimation to precisely detect the information about openings (such as windows and doors) from occluded walls and then generate the BIM components automatically by using visual programming language Dynamo. We made three main contributions in our proposed method, namely:

1. We extract the information directly from the raw input point cloud without using enormous amount of training examples like neural networks,
2. Our method performs reasonably good on low-quality point clouds,
3. We can achieve effectively and highly precise automatically modelling by combining Python, Dynamo and Revit.

This paper is composed of five chapters, including this introductory chapter. At first, a literature review of the development of scan to BIM methods in aspect of structure segmentation as well as information extraction of openings. Chapter three begins by laying out the developed methodology for processing of point cloud and semi-automatically generating of openings in BIM model. We show the use case and results in the fourth chapter. The last section provides a summary and future researches.

2 Literature Review

Comparing with point cloud data, BIM has the ability to provide not only a 3D geometry model of the building components, but also a comprehensive set of semantic information. [1] The research of [2] also identified that the integration of point cloud with BIM is one of the hot topics after analyzing the research trends between 2007 and 2020.

Many researches have studied on reconstruction of building interiors and exteriors using laser scanner. Tang [3] have reviewed the overall process of creating as-built BIMs. Recently, Xu [4] also provided a thorough review of the state-of-the-art acquisition and processing techniques for building reconstruction using point clouds. The core operations include geometric modelling, object recognition, and object relationship modelling. The most common used method of planar surface detection is Hough transform[5], [6] or RANSAC algorithm [7], [8], and with the development of artificial intelligence, machine learning methods. However, using RANSAC may cause so called 'bad-segmentation' problems. The reason is that points constituting the maximum consensus may be derived from different objects, according to Previtali's research[9]. Macher with the group did a series of researches on how to transform the building structure from a point cloud model into BIM model semi-automatically. [10]–[12] The process proposed in [10] included plane segmentation, point classification and BIM model reconstruction. Instead of using the RANSAC algorithm, a more precise algorithm with the same sampling strategy was used for plane segmentation. After that, the points were classified into different objects. To create the BIM model, the extracted structures were firstly transformed into .obj format and then created an IFC file using the FreeCAD software. The same method of creating BIM model with IFC file was also used in Thomson's research [7]. Various attempts have auch been implemented to detect the openings from the wall structures.[12]–[14] However, the developed methods by using energy function and radiometric information need high-quality data. To better overcome the problem with cluttered and occulated environment, Muraet.al combined the operation process both in 3D space and in 2D projection[6]. The basic room detection was performed in the 2D projection, while the patch detection and the occlusion-based pruning and the final fitting were performed in 3D space. The process costs more time while increasing the accuracy. The developed method by combining histogram and shape grammar approach[15].The work showed an approach to generate building elements in a hierarchical structure by using shape grammar approach. The Approach consists of 6 rules, which can also analyze and extract the topological relation such as containment, adjacency, and connectivity. With the rapid development of artificial intelligence, many machine learning technologies can be used for scan to BIM. Bassier et al. [16] presented a method using random forests to identify and classify of structural elements automatically, which showed a good performance in feature labeling in different buildings. Similarly, Sahebdivani et al. [17] used the PointNet deep learning network for semantic segmentation in the point cloud data. The PointNet neural network is a novel type of neural network developed in 2017 [18] for object classification and segmentation of 3D point cloud data. Currently, it has been developed to PointNet++[19].

Since using machine learning methods require high quality of data and large amount of training data, this paper attempt to analyze the raw point cloud data even with a high level of clutter without training process. The developed method is implemented by combining maximum likelihood estimator and shape grammar to extract the openings of wall structures even with low quality of data.

3 Methodology

The input data of the methodology is the segmented information as well as the created BIM model of wall structures by using the proposed method from the previous work [20]. Figure 1 shows the overview of the method. To extract the potential positions of openings apart from clutters or occlusions, we implement the gradient based maximum likelihood algorithm on the point clouds firstly. After that, we use the shape grammar rules to get the geometrical information about each opening from the potential positions. Then, the corresponding BIM components can be generated using the scripts created by visual programming language Dynamo automatically.

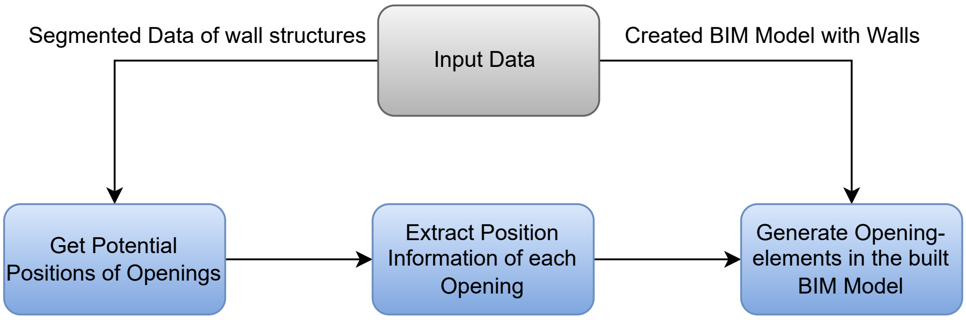

Figure 1: Overview of the developed Methodology

3.1 Using gradient maximum likelihood to detect the potential positions of openings

The potential positions of openings can be detected by using gradient-based maximum likelihood. Algorithm2 shows the workflow. Using Maximum likelihood estimation with histogram has been proven as a convincing method for wall segmentation of the point cloud [20]. It can also be extended to extract the information of openings. Different from the data distribution of wall structures, which has a significantly dense distribution at each potential position, the data distribution of each opening changes significantly at the start and end point. Therefore, we can use gradient-base maximum likelihood estimation with histogram to get the potential positions of openings. The start and end point can be identified by the calculated value by checking whether it is positive or negative.

Algorithm 2 Get Potential Positions with Gradient-based Maximum Likelihood

Require: Point cloud of each wall elements Wall_i, $i = 0 \cdots N$

$n \leftarrow 0$
while $n \leq N$ **do**
  Implement Histogram in corresponded axes of wall_n: xy and z;
  Get the positions and count values: P_{axis}, C_{axis} ;
  Calculate gradient-based count values: $g_{C_i} = (C_{i+1} - C_i)/\mathrm{mean}(C)$;
  Select Index with Maximum Likelihood: Idx_{axis} = Where $(|g_{C_i}| > \mathrm{mean}(g_{C_i}))$;
  Get Positions with selected Indexes: $P_{S_{axis}} = P_{axis}[\mathrm{Idx}_{axis}]$;
  $i = 0$;
  for $i \leq \mathrm{len}(P_{S_{axis}})$ **do**
    if $P_{S_{axis}}[i] < 0$ **then**
      i+= 1
    else if $P_{S_{axis}}[i+1] > 0$ **then**
      i += 1
    else
      export $P_{S_{axis}}[i]$
    end if
  end for
end while

3.2 Using Shape Grammar to get the information of openings.

It is critical to get the extracted information of each opening only with the information of potential positions. Since the combination possibilities of different coordinates are more than one. As figure 2 shows, with two pairs of potential positions in z-axis and in x-axis, there are already 4 possibilities of combinations. To classify whether the potential position is an opening, the shape grammar is implemented. In Tran's research [15], there is a formulated grammar rule for die classification, which can be reformulated to do the windows and doors classification. The Rule is formulated as equation 1. With the calculated value, we can get the geometrical information about each opening, the openings can then be classified as window or door based on the positions in z-axis.

$$R_{class} : A \rightarrow A[type] : cond, \qquad I_{PoF} = n/A \tag{1}$$

with the variables are:

I_{PoF} Index for Point of Face
n Number of points that fall into the surface A
A The area of the evaluated place

Figure 2: Possible combinations of openings based on the same distribution.

3.3 BIM Model generation of openings

The BIM model (including the opening elements) is created based on the extracted information. The input data in this step is the build wall model in Revit. Instead of creating the elements manually, a more efficient method is implemented for modeling, which is parametric design with Dynamo visual programming for Revit.

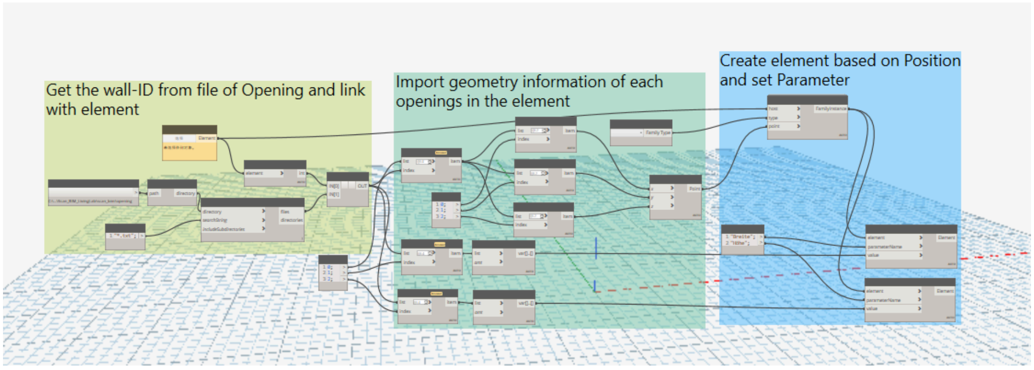

Figure 3: An illustration of a Dynamo diagram

Figure 3 demonstrates the model (with openings) generation process. The extracted opening information is imported into dynamo at the beginning. The opening of corresponded wall element is linked by the ID number of the wall element. Finally, a Revit opening element is created based on the geometry and the element type. Since the process of each can be created using the same processing method, a more automated and efficient way is implemented in this step. Instead of filling the required information separately, a python script with a loop function is written in dynamo to create all opening elements automatically.

4 Case Study and Results

One of the data set provided from ISPRS Benchmark on Indoor Modelling is used to evaluate the performance of the developed method. The ISPRS Benchmark [21] provides a public benchmark data set including six point clouds to enable performance evaluation and bench marking of indoor modelling methods. Since the point cloud of Fire Brigade contains 9 rooms on the same level, 10 doors and 53 windows with a high level of clutter, it is a challenging task to test the performance of our methodology. Figure 5 shows the reconstructed windows and doors in the BIM model. Since the detection of openings from point clouds is no longer the process of segmentation, it is critical to evaluate the process with precision and recall. Totally, 55 windows and 8 doors are extracted with the proposed method, which means 2 doors were classified as windows.

5 Conclusion and Outlook

In this paper, we propose a novel algorithm to address the two main problems of automatic building modelling, namely: 1. precisely extract the information by using the raw inputs, 2.efficiently modelling

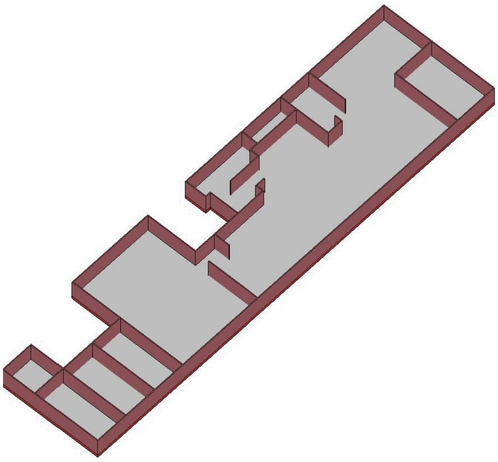

Figure 4: Reconstructed Wall Structures

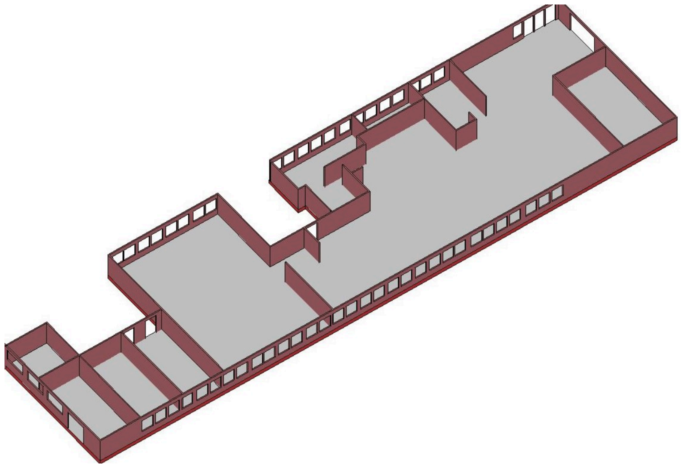

Figure 5: Reconstructed Openings in the BIM Model

based on the extracted information. By formalizing the raw inputs as a model represented by math equations, We rely on the maximum likelihood estimator to extract the parameters of the windows and door structure based on the gradient map of the acquired information. To the best of the authors' knowledge, this is the first work which directly handles the raw input point clouds, which doesn't rely on deep neural network or the generated pictures from the point cloud. The case study results show the preciseness and robustness of this proposed method. In summary, Our methods can deal with raw inputs without training data and also have no requirements of the point cloud quality. It can have a reasonably good performance on low-quality point cloud. The whole modeling process is automatic.

For the future work, combining the already well-trained neural network with our proposed method is an interesting way to go, in which we can make use of individual strengths by combining them. Another interesting point is using the generated model to perform the energy consumption prediction. Last but not least, the provided results of benchmark data set by [22] was measured only for wall elements. To evaluate the results of opening reconstruction process, the completeness, correctness and accuracy also need to be implemented to the opening detection.

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