Automatic Reconstruction of Aligned Indoor Building and Façade Elements from Point Cloud Data

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Abstract

The 3D building reconstruction from point clouds and images has significant applications in the field of built environment. Previous studies have investigated the methods of the indoor environment reconstruction and other studies explored the building façade reconstruction. However, limited studies have been conducted on aligningindoor and outdoor elements from point cloud data, which is critical for the building energy analysis and retrofitting plan during the operation stage. This research aims to develop a method that can automatically align the indoor building and façade elements from point cloud data. The results can enable the integration of buildings through the identified openings on both indoor and façade. The proposed method is validated on a real case and the experiment results show the effectiveness of the method. This research contributes to 3D reconstruction of the buildings with more details for automating building energy analysis and retrofitting design.

Keywords –

Point Cloud; Indoor Environment; Building Façade; 3D Reconstruction; Opening Detection

1 Introduction

Building reconstruction from point clouds and images has significant applications in the field of built environment, such as facility management, building performance analysis, and retrofitting design [1, 2]. Previous studies have investigated the methods of the indoor environment reconstruction and other studies explored the building façade reconstruction. For example, [3] proposed methods to reconstruct the indoor structural elements and generate geometric digital twin models. [4] presented method for the extraction of façade features from point cloud data. These methods are mainly focused on either indoor or façade data. Limited studies have been conducted to link the indoor and façade and integrate the building point cloud data as a whole.

3D laser scanning has been leveraged to capture the accurate as-is conditions of buildings, providing high-resolution spatial data that supports advanced modeling [5]. The BIM model can be then generated with processed point cloud clusters, which is known as the scan-to-BIM process [6]. Many studies have explored in this field to quickly and automatically generate BIM models from the point cloud data. For example, [7] presents the mobile laser scanning in reconstructing the indoor building environment and conduct semantic point cloud segmentation to reconstruct the buildings.

Despite advances in point cloud and image processing, as well as BIM-based workflows, detailed geometrical representations of indoor buildings often lackconnecting the indoor environment with building envelope enrichment. The integration of geometrical and spatial relationships between indoor spaces and façades into digital twin models remains a significant challenge. Achieving such integration is crucial for developing a more holistic understanding of buildings, enabling applications such as automated building energy analysis and retrofitting design. This research addresses this gap by proposing a novel method to align indoor building and façade elements from point cloud data, thereby contributing to more detailed and interconnected 3D building reconstructions.

2 Background

Previous studies have developed automatic methods for reconstructing indoor environments, primarily focusing on structural elements. For example, [3] proposed a method for creating geometric digital twins of buildings using a void-growing approach, which effectively identifies walls, ceilings, windows, floors, and doors. Similarly, [8] reconstructed indoor environments from point clouds collected by mobile laser scanners. Structural elements such as doors, windows, walls, floors, and ceilings were extracted based on geometric and semantic features. Furthermore, [9] presented an automatic approach for segmenting indoor point clouds and performing parametric reconstruction of structural elements, such as walls and floors. In summary, the segmentation of indoor point clouds has been extensively explored, with numerous algorithms and approaches proposed for identifying structural elements.

Other studies have investigated building façade reconstruction from point cloud data. For example, [4] identified openings in façades made of reflective materials and estimated their geometric properties and locations. [10] introduced a large-scale 3D point cloud dataset of building façades for semantic segmentation, enabling the identification of façade features. Additionally, [11] developed a method for generating building façade geometry from point clouds and implemented an automatic approach for building energy performance simulation. In summary, previous research has explored the extraction of building façades from point cloud data, with a focus on identifying façade openings.

The 3D reconstruction of the physical environment into a digital format enables multiple use cases, such as VR-based room tour, distant visualization of tourist spots and conservation of dilapidated cultural heritage sites. However, several challenges are faced when aligning outdoor and indoor point cloud data (PCD). Firstly, it is difficult to find common overlapping between indoor and outdoor environments since they are often disconnected [12-14]. Another challenge is the significant lighting variations when transitioning between outdoor and indoor environments [15, 16]. Traditionally, geometric models are constructed by laser scanning and photogrammetry. For example, Scianna and La Guardia [17] re-created the 3D model of the Manfredonic Castle of Mussomeli in Sicily leveraging the photos collected from drones. Despite the generation of the castle in 3D format, it focused solely on the external layout of the castle and had not yet connected to the internal castle features due to complexities and technical barriers. Kaminsky, Snavely [18] presented a preliminary algorithm that aligned indoor and outdoor structures observed in satellite photos and floor plans. Geotags were then assigned to the photos to match their locations.

After detecting common areas between indoor and outdoor elements, rough estimations were computed to match the scenes using an objective function. In order to match the indoor and outdoor environments, Yang, Fang [19] put forward a Semantic-Geometric Descriptor (SGD) that utilized both semantic and spatial information obtained from PCD. An indoor and outdoor alignment framework was presented after conducting empirical experiments with their experimental PCD and public PCD. It showcased the possibilities to align both indoor and outdoor areas by some shared building features, such as windows and doors which enhanced the accuracy and speed. To tackle slow and error-prone manual generation of as-built BIM models, Tang, Huber [20] reviewed the state-of-the-art as-built BIM model generation methods in recent years. Object recognition, parametric modelling and relationship modelling are the most common methodologies for as-built BIM automation. Although significant works have been carried out to reconstruct the indoor room layout inside BIM, there is still a gap to integrate the indoor room layout into the outdoor environment. Cohen, Schönberger [15] exploited the semantic information from detecting windows in various scenes by a pre-trained classifier. Separate window projections were computed altogether to enhance consistency and the results were evaluated by a cost function in their 3D reconstruction.

In conclusion, limited studies have been conducted on aligning indoor and outdoor elements from the point cloud data, which is critical for the building energy analysis and retrofitting plan during the operation stage. This research aims to develop a method that can automatically align the indoor building and façade elements from point cloud data.

3 Methodology

This research proposes an automatic openings detection and align the indoor and outdoor together from point cloud data. This alignment is based on the openings (e.g., windows and doors) between outdoor and indoor point clouds.

3.1 Wall Segmentation

The input of the proposed method consists of façade point cloud data and the indoor point cloud data. The first step is to identify the walls and separate the walls into individual planes. The region growing and RANSAC algorithms are adopted to segment the point cloud and identify the walls [21]. Since there are typically more walls in the indoor environment, the segmented façade walls are used as a reference to select the corresponding walls in the indoor environment PCD. The walls, after filtering, are then used for further detection of openings. This process is conducted for both the indoor and outdoor data. After the processing, the input point cloud data are processed to segmented walls with the openings.

3.2 Openings Detection

The second step is to detect the openings on the walls for both indoor and outdoor point cloud data. Compared with the indoor environment, the openings on the façade are more obvious than the openings in the indoor environment [4]. This is because there is more furniture in the indoor environment and can cause more occlusions of the point cloud. This makes it more difficult to identify openings in indoor environments.

Therefore, the proposed method starts by identifying the openings from the façade point cloud data, after the opening detection and the configuration of the openings on the façade, the results will be used to assist the refinement detection results of the openings detection in the indoor environment. The underlying principle of the opening detection is that openings appear as areas with no or very sparse points. Therefore, this research uses grid representation to detect the boundary of the openings.

To improve the accuracy of indoor environment data processing, a key step is to identify the openings from indoor and outdoor point cloud data. Since walls have a certain thickness, their indoor and outdoor surfaces represent two sides of the same structural element. The matching of indoor and outdoor point cloud data is based on their geometry features, such as the normal vector of the wall, and the coordinate position [19].

3.3 Openings Alignment

The final step is to align the openings on the same wall from indoor and outdoor point cloud data. Therefore, the indoor and outdoor building elements can be accurately matched. This aligned point cloud data can be further used for the 3D building reconstruction. Figure 1 presents the pipeline of the alignment of the indoor building and façade elements from point cloud data.

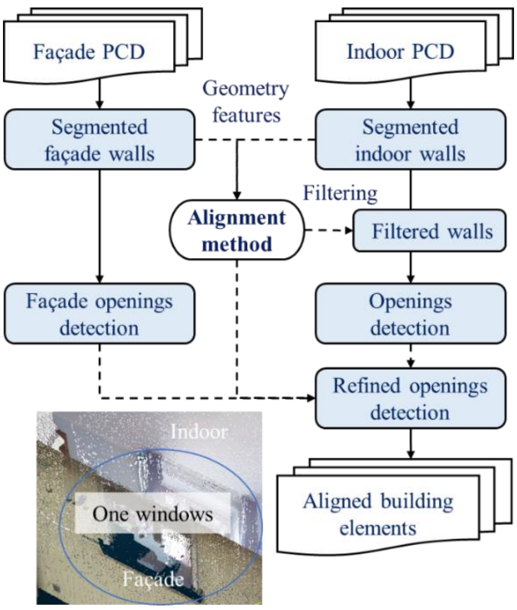


Figure 1. Pipeline of the proposed method

4 Experiments and Results

4.1 Case Background

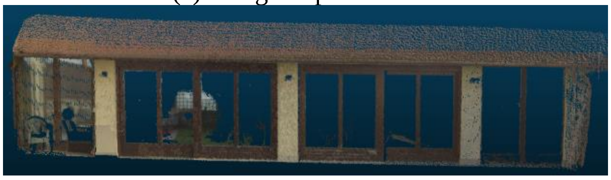
The data used in this research is the point cloud data of the house building in the European. The materials used to build the building constructed in 1980 are concrete for the structure and bricks for the facades combined with windows in aluminum. The retrofitting proposed for the building is aimed to provide renewable energy to cover all the energy requirements from a single family, to reduce the energy demand acting in the insulation of the envelope and improving the air quality/heating/cooling by including a new heating/cooling/ ventilation system in the facade. Improved air quality and comfort in the different spaces will be the main objectives of the proposed. The project will retrofit completely the envelope of the building. Apart from this, a new ventilation/heating/cooling system will be integrated in the façade and connected to the heat pumps with the possibility to heat/cool the building depending on the requirements. The first floor of the case is used for the experiments to validate the effectiveness of the proposed method.

The point cloud data is collected by using the Leica BLK360 imaging scanner [22]. The registration of point clouds collected from multiple stations was done with the Leica Cyclone REGISTER 360 PLUS [23].

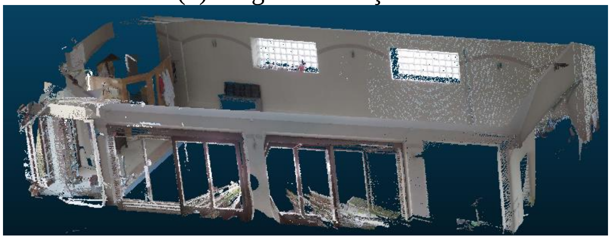
4.2 Indoor Wall Segmentation

After the region growing and RANSAC algorithms, the walls in the indoor environment PCD and façade PCD are segmented into individual and separate point clusters, which represent the walls of the building. The results of the segmented walls for the two PCD datasets are presented in the Figure 2. Figure 2a presents the original point cloud data of the ground floor. Figure 2b shows the segmentation results of the façade walls while Figure 2c shows the results of the indoor walls after segmentation. For the indoor environment PCD, there are more walls than the façade datasets. After the filtering process, the filtered walls that are connected to the façade are presented in Figure 2d.

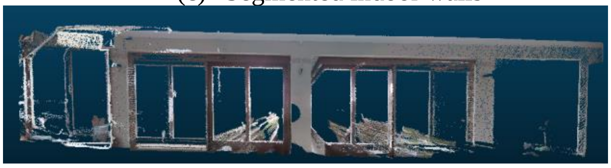
(a) Original point cloud data



(b) Segmented façade walls



(c) Segmented indoor walls



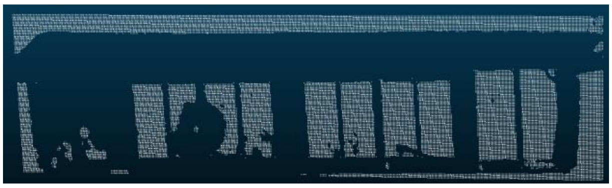
(d) Filtered indoor walls

Figure 2. Segmented walls. (a). Original point cloud data, (b). Segmented façade walls, (c) segmented indoor walls, (d) Filtered indoor walls.

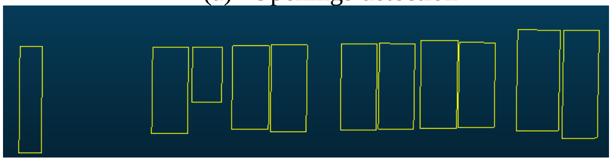
The results of the point cloud segmentation show that the indoor segmentation resulted in more walls as it has more rooms inside while the façade was an envelope of the building point cloud. By comparing the normal vectors of the wall clusters using RANSAC [24], the walls with similar normal vectors will be grouped as the same wall and will be remained. Therefore, the rest walls were filtered and removed. Only the walls that can match with the façade point cloud were further processed for the opening detection.

4.3 Façade Openings Detection

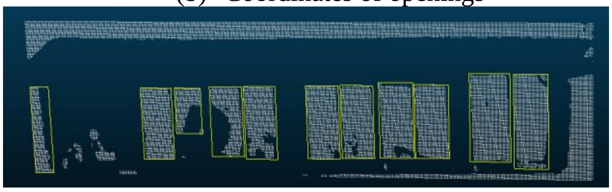
After the wall identification, the openings of the façade are detected using the opening detection method. The results of the opening detection of the façade are given in figure 3. Figure 3a presents the point cloud data for opening detection. Figure 3b shows the results of the detected openings. Figure 3c presents the geometry and the position of the openings. The results are obtained in the rectangle format, which contain the four corner coordinates of the openings. Therefore, the location and the geometry information can be computed with the rectangle information representing the openings.



(a) Openings detection



(b) Coordinates of openings

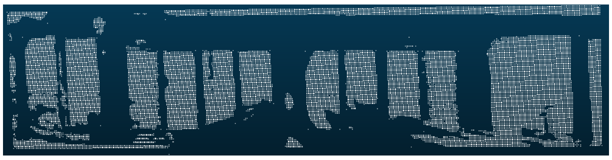


(c) Detected openings

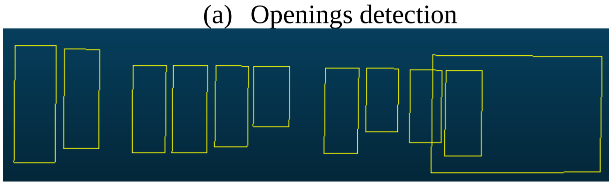
Figure 3. Façade openings detection

4.4 Indoor Openings Detection

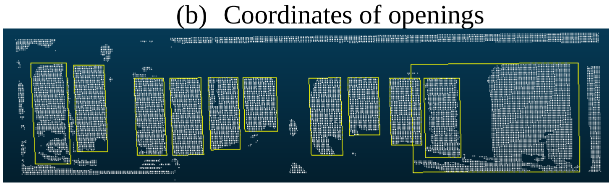
Similarly, the openings on the indoor point cloud can be obtained. The results of the opening detection of the façade are given in figure 4. Figure 4a presents the point cloud data for opening detection. Figure 4b shows the results of the detected openings. Figure 4c presents the geometry and the position of the openings.



(a) Openings detection



(b) Coordinates of openings



(c) Detected openings

Figure 4. Indoor openings detection

4.5 Aligned Building Elements

The last step is to align the results of the openings on the indoor openings detection with the detection results of façade point cloud. Figure 5 shows the alignment results of the openings on both point cloud. The detected openings are aligned based on their coordinates of the rectangles representing the openings. The red points represent openings detected in the façade point cloud, and white points correspond to openings identified in the indoor point cloud. The alignment is performed based on the similarity of detected openings, considering both the least distance between corresponding openings and their overall layout. By matching openings with minimal spatial deviation and maintaining consistency in their distribution, the method ensures accurate geometric integration of indoor and façade elements.

Figure 5. Aligned openings in indoor and façade point clouds

4.6 Discussions

The detection results presented in Figures 3 and 4 highlight key issues that contribute to errors and reduced accuracy. Notably, in Figure 4c, the largest rectangle detected is not a window. This error is attributed to occlusion in the point cloud, which occurred during data collection in the indoor environment. Occlusion is a common challenge in such settings, as furniture and other building elements obstruct the view of certain features, leading to incomplete or misinterpreted data [25].Improved noise filtering techniques, such as adaptive thresholding or advanced denoising algorithms, can help retain useful points while minimizing the impact of noise [26]. Additionally, data augmentation methods, including multi-view point cloud merging and the integration of photogrammetry with LiDAR, can enhance the reconstruction of occluded areas [27].

Another significant issue arises from the reflection points of glass in windows. These reflections create ambiguities in the data and are almost unavoidable when capturing point cloud data of windows. The reflective surfaces interfere with accurate feature extraction and increase detection errors. Machine learning-based segmentation methods could be trained to differentiate between real structural features and reflection artifacts in windows [28].

In addition, the inherent noise within the point cloud data further impacts detection accuracy. While algorithms designed to filter out noise can enhance overall data quality, they may inadvertently remove some useful points. This, in turn, affects the detection of openings and reduces the geometric accuracy of identified features. It is challenging to preserve essential data while removing noise.

Addressing these issues requires enhanced data preprocessing methods, improved algorithms for handling occlusions in point cloud data, and techniques to minimize the impact of reflective surfaces during data acquisition [29]. Deep learning techniques, such as convolutional neural networks and transformer-based segmentation models, have shown promising results in point cloud processing. Examples such as KPConv [30] and Point Net [31] have been widely used for point cloud segmentation and feature extraction.

The point cloud data used in this study were collected using a terrestrial laser scanner, which provides higher data quality and accuracy and is recommended for data collection when applying this method. However, while this study successfully demonstrates the feasibility of detecting openings using point cloud data, the façade surface area analyzed is relatively small and lacks significant geometric variations. Since the proposed method focuses on identifying the presence of openings rather than reconstructing their precise shape, it has the potential to be extended to a wider range of building structures. To ensure its generalizability, further validation across diverse building types, including those with complex façade geometries and irregular opening configurations, is necessary.

Although the case study validates the proposed method's feasibility, the lack of a quantitative comparison with existing point cloud alignment methods remains a limitation. A systematic performance evaluation would provide a more comprehensive assessment of the method's effectiveness. Future research will address this by incorporating quantitative evaluations, specifically assessing accuracy and computational efficiency, to strengthen the validation and facilitate comparisons with alternative approaches. Additionally, expanding the range of case studies will be essential to evaluate the method's scalability and reliability under different architectural and environmental conditions, further enhancing its applicability to real-world scenarios.

5 Conclusions

This research introduces a method for automatically aligning indoor building elements with façade features using point cloud data. The approach emphasizes the identification and integration of openings, such as windows and doors, to seamlessly connect indoor and outdoor geometries. The validation conducted through a real-world case study highlights the effectiveness of the proposed method.

The results demonstrate that façade point cloud data effectively improves indoor opening detection and achieves accurate alignment, significantly contributing to detailed 3D building reconstruction. This enhanced reconstruction not only improves the representation of building geometry but also supports advanced applications such as automated building energy analysis and retrofitting design.

However, there are still some limitations, including occlusions, noises, and reflective surfaces, which are common challenges in indoor point cloud data collection and processing. Future work will focus on refining the algorithms to better handle noise and occlusions, particularly in complex indoor environments, and further minimizing the impact of reflective surfaces during data acquisition. Additionally, integrating advanced preprocessing techniques could enhance detection accuracy and expand the applicability of the method to a wider range of building scenarios.

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