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Virtual Scanning Method Based on BIM and Ray Tracing for Occlusion Evaluation and Geometry Extraction

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Abstract

This paper presents a virtual scanning method based on Building Information Model (BIM) which can simulate the real scan process and occlusion condition. The method converts the geometry of BIM into triangular mesh and point cloud. The multi-level data encoding is performed for the triangular mesh and point cloud. An octree is created based on point cloud to accelerate query speed. Two stage intersection tests (ray-octree leaf node and ray-triangle intersection tests) are organized to minimize computational cost. The scanning process of the scanner is parameterized and returns the nearest point with a component label along the emitted ray. The virtual scanning method is validated on a steel structure with over 800,000 triangular meshes. The calculations of over 100 million rays are completed within 10 minutes with serial computation. The visibility ratio of every component is obtained by compare the number of points between virtual scan component and complete component with the same point cloud spacing. Furthermore, the method is validated by comparing the consistency between the virtual scan cross-sections and real scan cross-sections. The real component axis extracted by the registration between virtual scan cross-sections and real scan cross-sections demonstrates better stability.

1 Introduction

Laser scanning technology, with its high precision, high resolution, and efficiency, has been widely applied in geometric measurement and digital transformation (Wang and Kim 2019). In the field of civil engineering, compared to the single-point measurements performed by total stations, terrestrial laser scanning (TLS) can quickly acquire large amounts of high-precision point cloud data, making them more suitable for measurements in large-scale spaces and complex structures (Jiang et al. 2021). However, due to the complex arrangement of components and the terrain limitations of TLS, issues such as scanning occlusion and data loss are inevitable. The presence of occlusion significantly complicates object and state recognition, which are crucial for facility management and infrastructure maintenance (Agapaki and Brilakis 2020). Additionally, occlusion also impairs the accuracy of geometric extraction and model reconstruction (Yan and Hajjar 2022). Therefore, the degree evaluation of occlusion should be prioritized when performing scanning.

Previous studies have focused on scan planning to minimize the ratio of occlusion as much as possible (Chen et al. 2022; Li et al. 2022). However, visibility detection can be time-consuming and resource-intensive when dealing with large-scale or complex scenes (Noichl et al. 2024). Some simplified approaches often come at the cost of reduced accuracy in visibility detection. Virtual scanning technology simulates the process of a terrestrial laser scanner emitting laser rays and returning the coordinates of the nearest obstacles the laser reaches, which can maximally reflect the process of real-world scanning. Building Information Modeling (BIM) offers strong capabilities for 3D visualization and information integration in civil engineering sector (Liu et al. 2024). Combining virtual scanning technology with BIM makes it possible to simulate building laser scanning and occlusion assessment. This paper proposes a virtual scanning method based on BIM and ray tracing for large-scale scenes. The overall process of virtual scanning and applications are shown in Figure 1. The method converts the geometry of BIM to OBJ geometry and point cloud. Multi-level encoding of triangular meshes and point clouds is performed to support intersection detection and virtual scan point labeling. An octree is created to accelerate the query of ray-triangle intersections. Two-stage intersection detection: The intersection detection between rays and octree leaf nodes, as well as the intersection detection between rays and the triangles contained in the octree nodes, effectively reduces the query complexity. By setting virtual scanning parameters according to the scanner resolution and scanning process, the method can effectively simulate actual scans and multi-station scanning. In this paper, virtual scanning tests are conducted on a steel structure with over 800,000 triangular meshes. With serial computation of over 100 million rays, the calculations were completed within 10 minutes. Additionally, by analyzing the ratio of virtual scan point clouds to the full component point cloud, the occlusion degree of each component can be assessed. The paper compares the consistency between the virtual scan and real scan cross-sections, validating the correctness of the method. Furthermore, the component axis lines extracted from the registration of virtual scan cross-sections and real scan cross-sections demonstrate better stability.

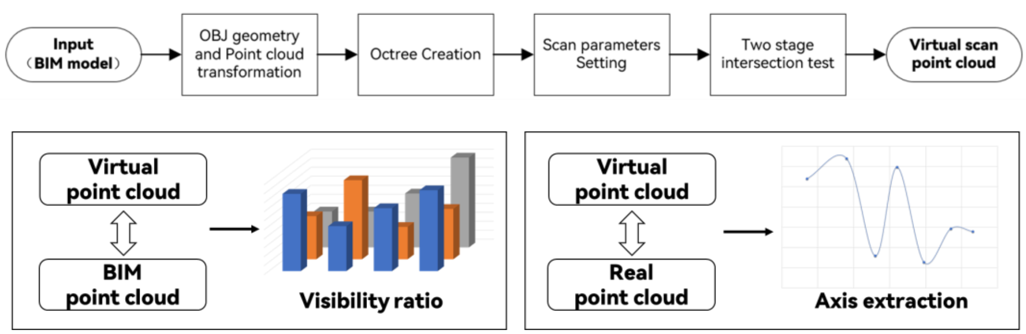

Figure 1: Virtual scan process and applications

The contributions of this method are as follows:

(1) An efficient virtual scanning method based on BIM models. The result of the virtual scan is a point cloud model with component labels and occlusion considerations, which can be used for the creation of deep learning datasets.

(2) An evaluation method for the occlusion degree based on the virtual scanning results.

(3) A more general method for applying occlusion-aware virtual scan cross-sections to the extraction of actual component geometric axis lines.

The rest of this paper is organized as follows. The method of virtual scanning is introduced in Section 2. In Section 3, the proposed approach is validated to compare the virtual scan with the real scan of a steel structure. In Section 4, some noteworthy remarks and limitations of the method are presented. The conclusions are summarized in section 5.

2 Method

2.1 Data Transformation and Encoding

The first step of the virtual scanning process is data transformation and encoding. First, the geometric information from the BIM model is extracted and converted into the OBJ triangular mesh format. Then, the triangular mesh geometry is transformed into point clouds. The purpose of this conversion is to: (1) enable the construction of the octree data structure, and (2) determine the intersection relationship between the triangular mesh patches and the octree leaf nodes (Park et al. 2021).

The density of the sparse point cloud generated from the triangular mesh should be set to at least half of the octree resolution. The encoding of each point cloud is the index of the triangular patches it belongs to, and the encoding of each triangular patches corresponds to the index of the components to which the patch belongs. The multilevel data encoding is shown in Figure 2.

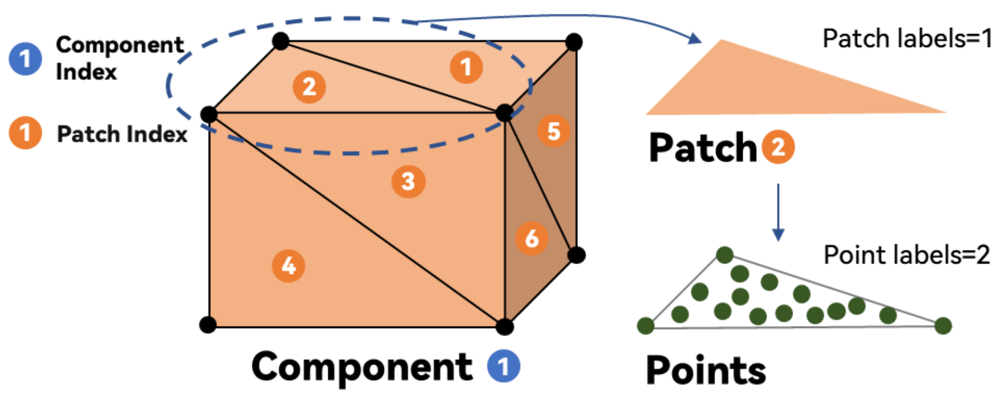

Figure 2: Multilevel Data Encoding

2.2 Octree Creation and Ray Intersection Tests

Due to the large-scale and extensive nature of many scanning tasks, the number of triangular patches in a structural BIM model often reaches hundreds of thousands or even millions. As a result, performing intersection detection through brute-force traversal is not practical. The octree, as a spatial partitioning data structure, recursively divides three-dimensional space into eight subspaces, which helps optimize both data storage and spatial query efficiency. The conversion of the sparse point cloud into the octree data structure is illustrated in Figure 3.

Simulated laser scanning primarily involves two types of intersection detection: one is the intersection detection between the ray and the octree leaf nodes (AABB bounding boxes) as shown in Figure 4, and the other is the intersection detection between the ray and the triangles. The intersection detection between the ray and the octree leaf nodes is performed using a top-bottom approach (Revelles et al. 2000). Once the intersection between the laser ray and the octree leaf node is detected, the point cloud contained in that leaf node can be queried. Based on the triangular patch encoding carried by the point cloud, further intersection detection between the ray and the triangular patches can be performed. The intersection detection between the ray and the triangular patches employs the Möller-Trumbore algorithm (Möller and Trumbore 1997). When $t>0$, $u>=0$, $v>=0$ and $u+v<=1$, the ray is determined to intersect with the triangular patch. The smallest t among all intersecting patches is selected, representing the point where the ray first strikes the BIM model.

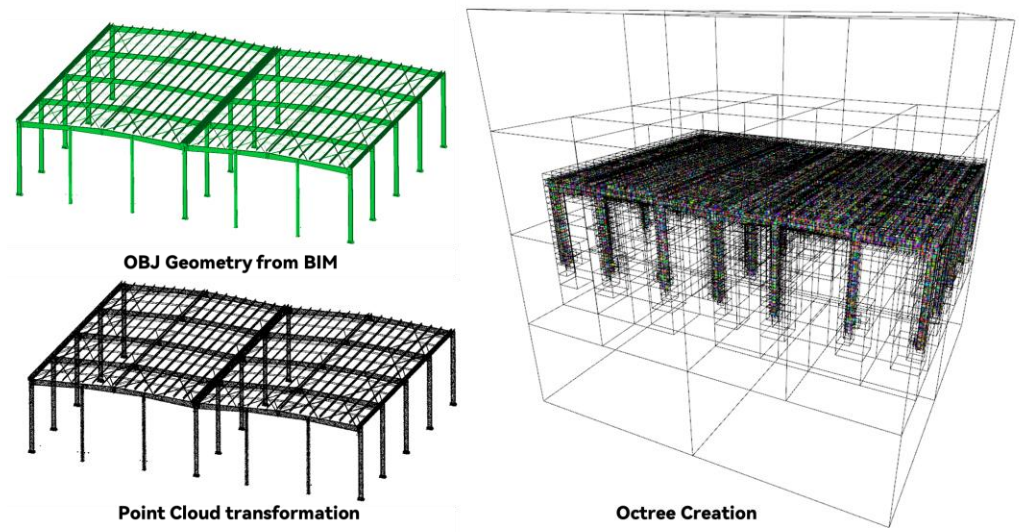

Figure 3: Data transformation and Octree creation

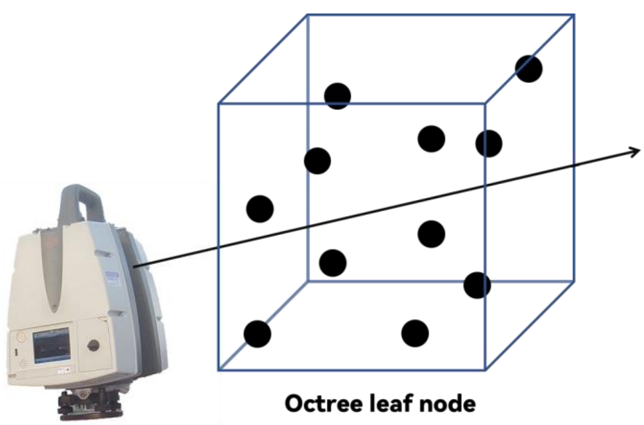

Figure 4: Ray and Octree Leaf Node Intersection Diagram

2.3 Virtual Scanning Simulation

The scanning process of a terrestrial laser scanner starts from a coordinate point in space, rotating 360° in the horizontal direction while rotating 360° in the vertical direction. Taking the Leica P40 as an example, the resolution needs to be set before scanning, such as 3.1mm@10m, which means the point cloud density is 3.1mm at a distance of 10 meters. Therefore, the angular change for each laser is determined by this resolution.

$$\alpha = \arctan(\frac{0.0031}{10})$$

Laser direction vector

$$\begin{cases} x = \cos(\theta)\cos(\varphi) \\ y = \sin(\theta)\cos(\varphi) \\ z = \sin(\varphi) \end{cases}$$

After calculating the intersection value t of the intersecting triangle, the scan point can be obtained by $O + t \cdot D$, where O is the origin of the ray and D is the direction vector. Additionally, based on the encoding of the component where the intersecting triangle is located, the corresponding label can be assigned to the scan point cloud.

3 Results

3.1 Virtual Scanning Results

The method proposed in this paper is validated on a two-span steel structure. The geometric model extracted from the BIM is shown in Figure 3, where the component, patch, and vertex count statistics can be found in Table 1. During the real scanning process, four scan stations were conducted and registered for the structure, with the real scan results and scanner positions shown in Figure 5. The specific scanner coordinates are provided in Table 2.

Num	Number
Components	3714
Patches	837146
Vertices	440200

Table 1: Number statistic

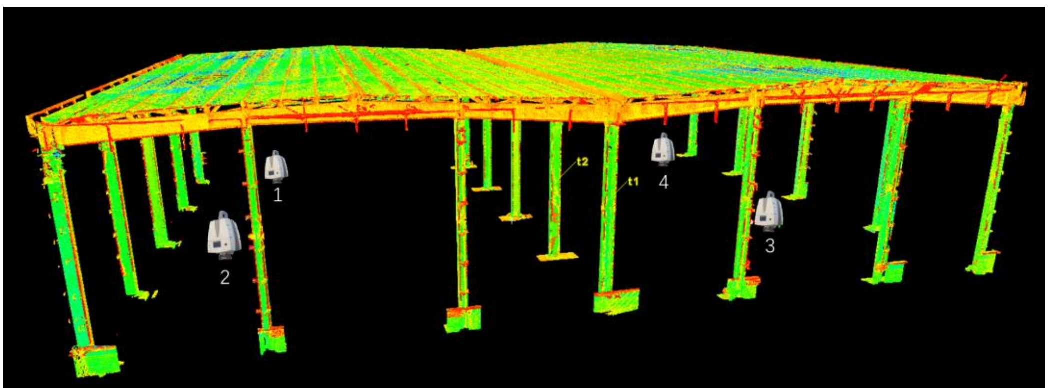

Figure 5: Real scan results and scanner positions

Virtual scanning was performed based on the coordinates of the scan stations using the method proposed in this paper. The calculations were implemented in C++ under serial computation and with a scanning resolution of 3.1mm@10m. The edge length of the octree leaf nodes is approximately 0.19m, and each scan station calculated over 100 million rays. The scanning time and point cloud quantity for each station are shown in Table 3. The scanning time for all stations is less than 10 minutes, and the point cloud of each station contained over 18 million points. The scan results are shown in Figure 6, where different colors represent different component labels. It can be observed that the scanning results vary across different stations, with significant differences in the visibility of columns between scan1 and scan4, where some columns are clearly occluded.

Origin	X/m	Y/m	Z/m
1	30.550564	41.752708	1.676277
2	13.477213	43.319534	1.571071
3	8.175106	10.082193	1.642238
4	29.850962	6.519911	1.704301

Table 2: Coordinate of scan stations

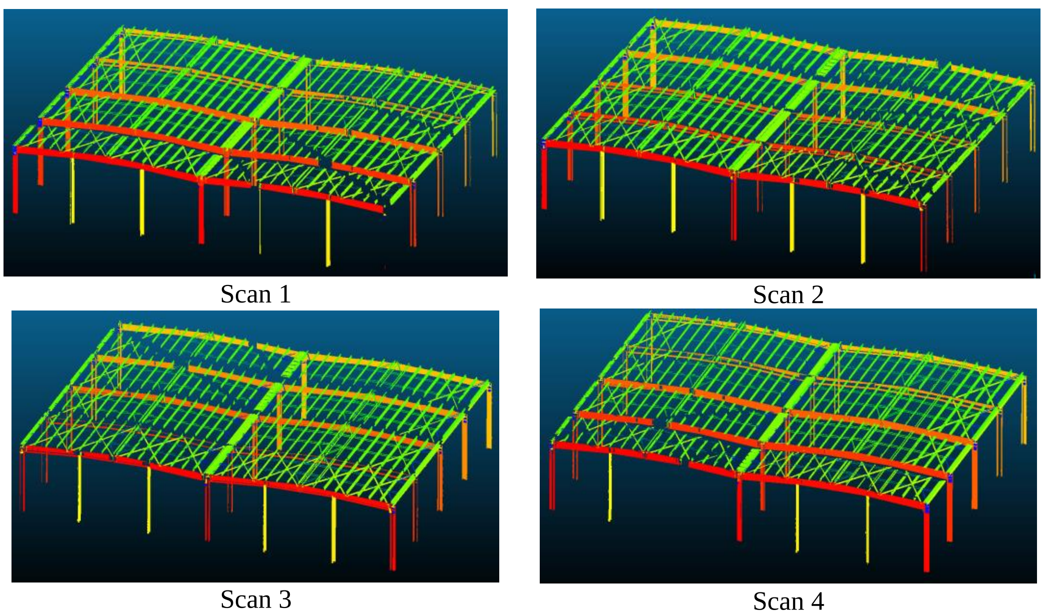

Figure 6: Virtual scanning results of different scan stations

Scan Station	Points Number	Time/s
1	18466676	414.303
2	21112038	475.774
3	23222200	526.679
4	18874496	430.148

Table 3: The scanning time and point cloud quantity of scan stations

The virtual scanning results from the four scan stations can be directly merged without the need for registration, as the point clouds from all four scans are in a unified coordinate system. After performing the point cloud merging, the point cloud was downsampled to a 5mm spacing. Based on the point cloud labels and the corresponding GUID numbers, the entire point cloud is segmented into different components. By comparing the number of virtual scanning component point clouds with the complete component point clouds at the same point cloud spacing, the visibility ratio of each component in the virtual scan can be assessed. The Figure 7 shows the visibility ratio of the main components of the steel structure. Some areas with relatively low visibility are highlighted in the image, and the reasons for their poor visibility vary.

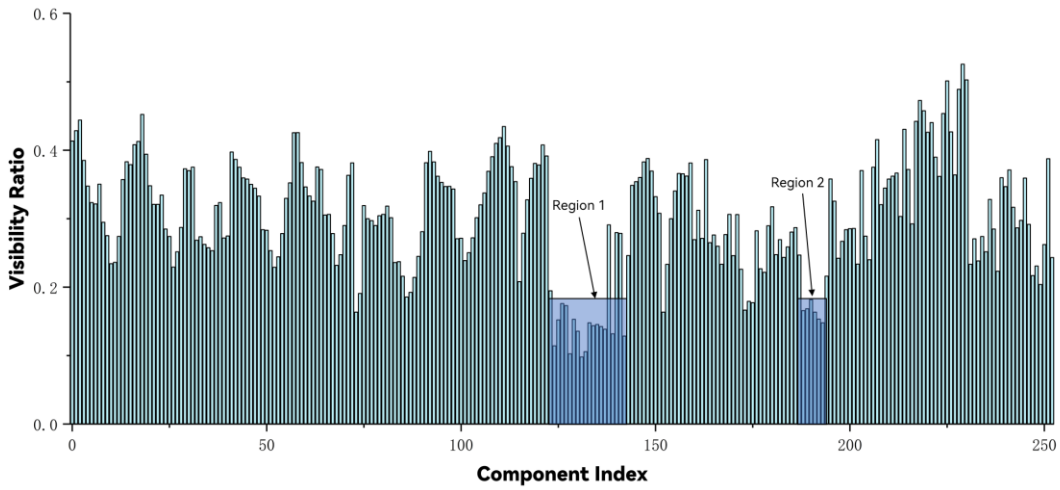

Figure 7: Visibility ratio of different components

Region 1 mainly consists of hat-shaped section components, whose low visibility is primarily due to their close proximity to adjacent channel steel components, resulting in significant occlusion, as shown in Figure 8. Region 2 mainly consists of circular tube components, and their poor visibility is due to the fact that the interior of the tubes is inherently not visible, leading to a lower overall visibility ratio.

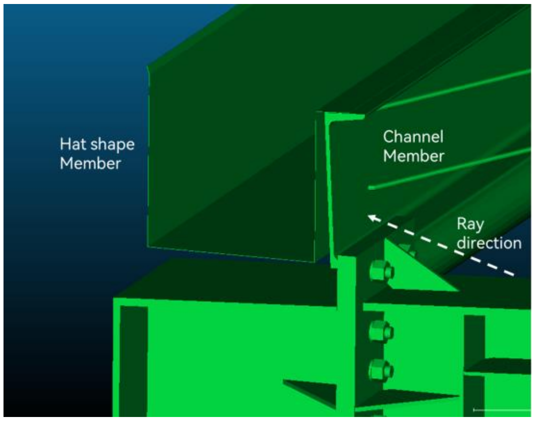

Figure 8: The layout of hat-shaped section components

3.2 Section Occlusion Comparison and Axis Extraction

The paper selects components with different cross-sections and compares the deviations between virtual scanning results and real scanning results, as shown in Figure 9. The figure shows the virtual and real scanning results of components with circular, channel, and I-beam cross-sections. It can be observed that the visibility of the virtual and real scanned cross-sections is generally consistent, further proving the accuracy of the virtual scanning method. Additionally, the registration between the virtual and real scanned cross-sections can facilitate the extraction of the component's axis.

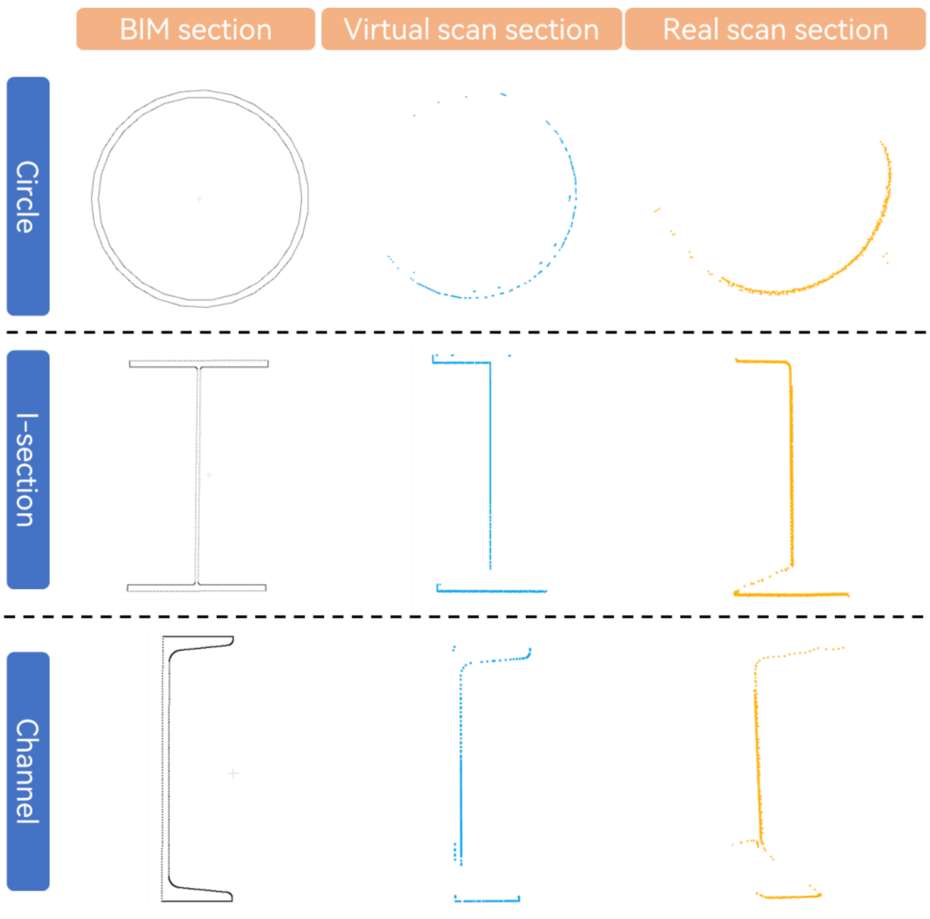

Figure 9: The comparison between virtual scan section and real scan section

Taking the I-beam component as an example, previous methods (Lin et al. 2025) involved slicing both the complete component and the real scanned component, and then aligning the full cross-section and the real scanned cross-section at corresponding positions to extract the axis. However, the extracted axis exhibits fluctuations in the plate thickness direction, as shown in Figure 10. This issue has been explained and addressed in previous work. In contrast, this paper presents a more general approach that applies to components with any cross-section by eliminating occluded point clouds through virtual scanning before performing the registration. By aligning the virtual scanned cross-section with the real scanned cross-section, the fluctuations in the extracted axis are significantly reduced, and the accuracy of the component axis extraction is improved.

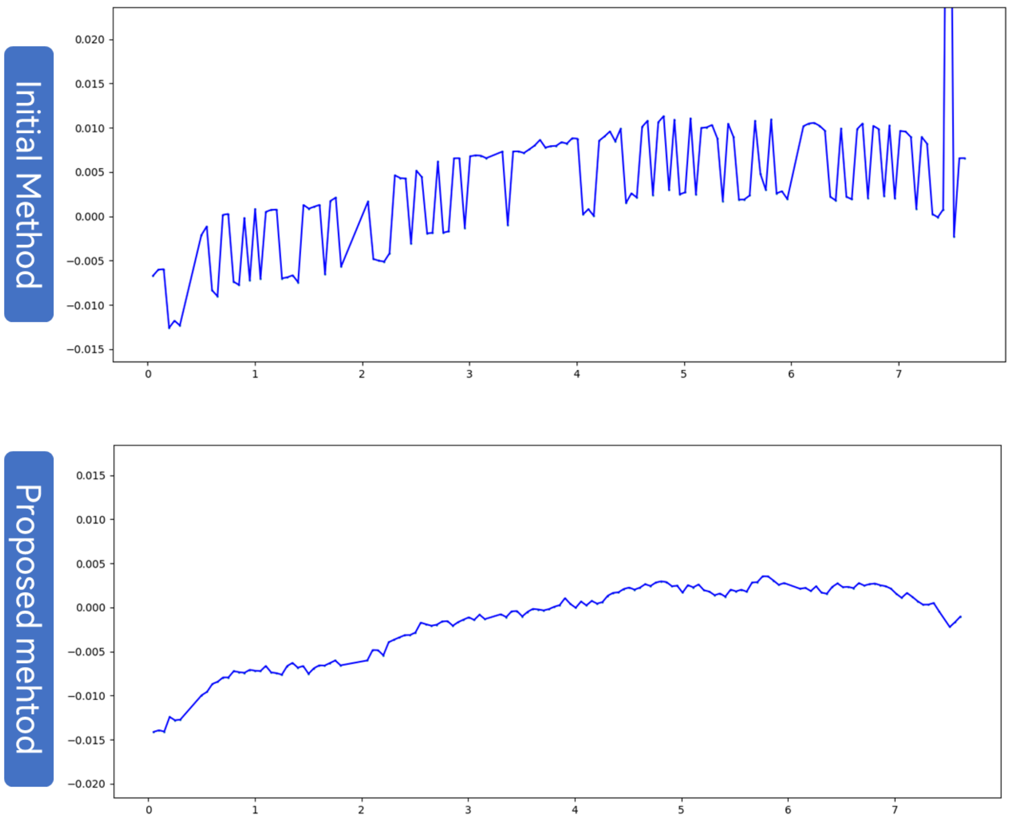

Figure 10: The comparison between initial method and proposed method considering occlusion

4 Discussion

The virtual scanning method proposed in this paper has the potential for broader applications based on the discussions presented. For instance, the point cloud model generated through virtual scanning is labeled and can be directly used as a dataset for deep learning. Additionally, the point cloud considering occlusion is more aligned with the actual situation compared to the complete BIM model point cloud. The deep learning model trained based on virtual scan point cloud is expected to perform better in practical applications.

Furthermore, since virtual scanning essentially simulates the actual scanning process, its visibility is also largely consistent with real-world scanning, making it a more effective evaluation metric for scan planning. However, the current computational efficiency remains one of the obstacles to using virtual scanning for optimizing scan planning. Future work could focus on parallel computing to further assess the simulation efficiency of the proposed virtual scanning method in large-scale BIM models.

5 Conclusions

This paper introduces a virtual scanning method based on BIM and ray tracing, designed to simulate the real-world scanning process and account for occlusion effects. The method first converts the BIM geometry into triangular meshes and point clouds and applies multilevel data encoding to the triangular meshes and point clouds. An octree structure is generated from the point cloud to accelerate query performance. To reduce computation cost, two-stage intersection tests are employed: ray-octree leaf node and ray-triangle intersection tests. The scanning process is parameterized to return the nearest point with a corresponding component label along the emitted ray. The effectiveness of the virtual scanning method is validated using a steel structure containing over 800,000 triangular meshes, with calculations for more than 100 million rays completed in under 10 minutes using serial computation. The visibility ratio of each component is determined by comparing the number of points in the virtual scan component to those in the complete component, both with the same point cloud spacing. Additionally, the method's correctness is further validated by comparing virtual scan cross-sections with real scan cross-sections. The real component axis, obtained through registration between virtual and real scan cross-sections, shows better stability.

The limitation of the method is still time-consuming for scan planning. The effectiveness of the virtual scanning will be further evaluated through parallel computing. The intersection tests between triangle patches and octree leaf nodes can be introduced to further improve the virtual scanning accuracy instead of converting the sparse point cloud. In the future, the component axis extracted can be applied to the BIM model update considering the cases of curves which can reflect a more realistic physical scenario.

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