Mesh Models as Enhancements to Point Cloud-Based Surveying and Mapping

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Abstract: *Point cloud, known for the ability to describe real-world scenes, have been widely used to obtain high-precision spatial information. However, surveying and mapping tasks from point cloud are often challenging due to noise, occlusion, sparsity, density changes, etc. which usually reduce efficiency and leave so many hard tests. At the same time, the 3D mesh model is a kind of data structure generated from the point cloud and consists of interconnected triangles or other polygonal elements. Compared with discrete point cloud, mesh models provide a more refined geometric and topological description, but the simplification and smoothing of data during generation may lead to the disappearance of target features. Although both point cloud and mesh models can be utilized in surveying and mapping tasks, each has its own advantages and disadvantages. To enhance the efficiency, accuracy, and completeness of spatial information extraction, this research introduces mesh models into the point cloud as references for visual quality, particularly relying on the geometric representation provided by meshes. It aims to analyze how the data between the point cloud and the mesh models correspond to and complement each other's disadvantages for different targets and scenarios. Eventually, through these analyses, the potential development opportunities and concerns of point cloud and mesh models were identified, further enhancing the accuracy and efficiency of surveying and mapping work.*

Keywords: *Photogrammetric point cloud, Mesh models, Surveying and mapping*

Introduction

Three-dimensional spatial information, represented by fundamental vector features such as points, lines, and surfaces, is used to describe the geometric shape of real-world objects and environments. This information has been widely applied in fields such as architecture, surveying, and geographic information systems (GIS). With the advancement of technology, in addition to traditional stereophotogrammetry methods, point cloud and mesh models have also been extensively utilized to more accurately capture, analyze, and visualize the 3D structure and content of objects, scenes, or terrains. These methods offer new pathways for acquiring spatial information and have become essential tools in modern surveying tasks.

Point cloud is a 3D data representation that uses a large number of unstructured points with coordinates to reconstruct the surface of an object or scene. Point cloud data can be further processed to generate mesh models, which consist of interconnected polygons, usually triangles.

Mesh models provide more detailed geometric information (i.e., surface normals) and topological data (i.e., the mesh connectivity and the relations between the faces). In recent years, during the execution of numerous surveying and mapping tasks by the National Land Surveying and Mapping Center (NLSC) in Taiwan, both point cloud and mesh models have frequently served as the foundation for reconstructing the 3D structure of buildings, particularly for capturing detailed features of roofs and walls (NLSC, 2019; NLSC, 2023). Additionally, they are commonly used for the visual presentation of modeling results (NLSC, 2023).

However, both point cloud and mesh models have their own distinct characteristics and challenges. Point cloud, in addition to representing 3D coordinates, can integrate color or intensity data through photogrammetry, providing a more realistic representation of scenes and object features, with a high degree of flexibility in application. The redundancy or imperfections in point cloud data, such as the lack of clear boundaries, can lead to visual fatigue, reducing the efficiency of spatial information extraction and potentially affecting the accuracy of the model. In contrast, mesh models simplify and structure point cloud data, offering a smooth and continuous representation that is well-suited for large-scale modeling. Nevertheless, some details may be lost during the mesh generation process, especially during smoothing, which can result in the loss of important geometric information. Moreover, mesh models are often large in data size, requiring more computational resources and storage space. (Yang & Jaw, 2023)

In practice, point cloud and mesh models are frequently used alternately, but each has its advantages and disadvantages, and there is no definitive answer as to which is superior. Currently, there is a lack of in-depth research on how these two models affect surveying outcomes. Therefore, this study will explore whether, during the process of mesh model generation, the simplification of point cloud data results in the loss of critical features. In addition, this research will also examine the integration of mesh models into point cloud-based surveying practices and analyze the complementarity of both data types in different scenarios and tasks. Ultimately, we aim to propose a set of reference guidelines to improve the efficiency and accuracy of spatial information extraction and further promote the automation of surveying tasks.

Although the development of automated technologies has made significant progress in enhancing surveying efficiency, current automation systems remain incomplete and still require substantial manual intervention for inspection and revision. Therefore, the focus of this research is to explore how to integrate mesh models into existing photogrammetric point cloud-based surveying techniques and fully utilize the data characteristics of both models.

Literature Review

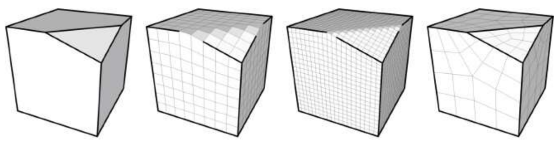
a. Spatial information extraction by using point cloud and mesh models

In spatial information extraction tasks, the traditional approach often involves directly processing large amounts of unstructured point cloud data for feature classification, as demonstrated by the PointNet (Qi, et al., 2017) and PointNet++ (Qi, et al., 2017) network models. However, in recent years, the use of mesh models for 3D shape classification has also gained traction (Bassier et al., 2020; Gao et al., 2022). Compared to the unstructured nature of point cloud data, mesh models' structured geometric information reduces the influence of noise and sparsity, providing an advantage for machine learning-based feature classification and enhancing the effectiveness of topological structure analysis.

Nevertheless, as highlighted by Park and Lee (2019) in Comparison between Point Cloud and Mesh Models Using Images from an Unmanned Aerial Vehicle, the precision of point cloud and mesh models for object measurement based on UAV imagery has been compared. The study showed that while mesh models provide more structured surface representations, point cloud outperform mesh models by approximately 2% in measurement accuracy for individual objects. This suggests that point cloud has a clear advantage in high-precision surveying tasks, whereas mesh models offer more detailed geometric and topological information when handling large-scale scenes.

b. Evaluation of mesh quality and feature retention

In fact, the results of mesh model generation are not without imperfections. Noise, irregularities in point cloud data, or the choice of algorithms can often lead to incomplete topologies and surface defects in mesh models, which can affect practical applications. Various research efforts have focused on addressing these challenges. For instance, multiple algorithms have been developed for noise reduction, hole filling, and triangulation to generate smoother meshes (Remondino, 2003). To address these typical defects, numerous mesh repair methods also have been proposed over the past two decades (Attene et al., 2013). Additionally, systematic research has been conducted on the evaluation of mesh quality, with a particular focus on feature retention (Sorgente et al., 2023). One key aspect of this evaluation is whether the edges of the mesh model accurately represent the target object's edge lines, shown in Figure 1.



Source: (Sorgente et al., 2023)

Figure 1: The impact of different algorithms on the representation of structure lines

Comprehensive studies comparing the characteristics, strengths, and weaknesses of point cloud and mesh models in surveying tasks remain lacking. This study, therefore, approaches the topic from the perspective of spatial information acquisition, exploring the development potential of both data types and further investigating their complementary applications.

Methodology

In this study, we focused on generating a photogrammetric point cloud from aerial imagery, which served as the basis for producing two mesh models using different software. The point cloud and two mesh models were generated from the same dataset: one mesh model was created in Metashape, and the other in Cloud Compare. All models were then uniformly imported into Cloud Compare for analysis, ensuring that the same measurement tools and rendering methods were applied consistently across comparisons. For quality assessment, repeated measurements were conducted on specific target features, such as corner points and line segments of the objects. The measurement scene, coordinates, and measurements of each feature were carefully recorded for further analysis. Finally, the collected data was categorized and analyzed to compare the impact of different models on model reconstruction completeness and accuracy, summarizing the strengths and limitations of each model in spatial information extraction.

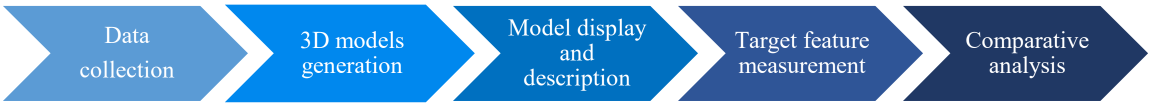


Figure 2: Workflow

a. Data collection

The study area is located at the Zonghe Lecture Building of National Taiwan University, covering an approximate area of 80 square meters. This site offers a variety of features, including a building height exceeding 60 meters, uniquely curved exterior walls, and diverse objects of different sizes and materials, such as electrical boxes, wooden benches, and irregularly shaped windows. These characteristics provide ideal conditions for conducting the analysis in this study.

Table 1 presents all the relevant information regarding the aerial images used in this study.

Table 1: Image information

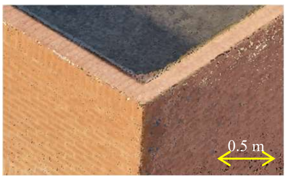
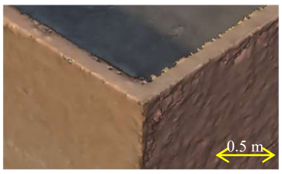
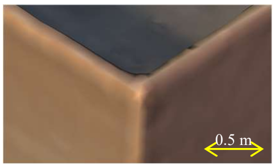
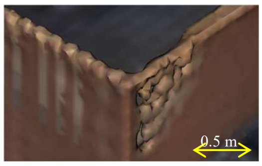
Camera Model	DJI Mavic 2 pro
Flight altitude	59 m
Image resolution	5472 X 3648
Actual focal length	10 mm
Sensor size	13.2 X 8.8 mm

Pixel size	0.00241228 X 0.00241228 mm
GSD	1.4 cm/pixel (ground level); 0.7 cm/pixel (roof level)
Image overlap	85% forward overlap; 80% side overlap
Flight path	11 flight lines
Number of vertical images	147
Number of oblique images	70
Ground control points	7 points
Control point error	0.040976(m) / 0.408(pix)

b. 3D models generation

Based on the images collected from the aforementioned flight plan, Metashape was used to process and generate point cloud, followed by the creation of mesh models from the same point cloud data. Since parameter settings influence the level of detail in mesh models, the highest quality models supported by the software were used for analysis in this study. However, it was observed in Cloud Compare that when the model quality reaches a certain level, significant distortions occur in the mesh models, shown in Table 2. To ensure the accuracy of the analysis, mesh models that most closely resemble the original point cloud in appearance were specifically selected for further examination.

Table 2: The different level of detail in models

Point cloud	**Mesh model (Metashape) (highest)**	**Mesh model (Cloud Compare) (Level 10)**	**Mesh model (Cloud Compare) (Level 12)**
			

c. Model display and appearance description

A total of seven target corner points were selected for the analysis, including building corners (concrete, metal sheet) and objects (sharp-edged, slender iron rods). Additionally, four target lines were chosen, consisting of straight lines (flowerbed edges, road markings) and curves (complex piping, building edges). These targets were specifically selected for their varying colors and shapes to enable a more comprehensive comparison and analysis.

In Figure 3 and 4, both a top view and an oblique angle provide perspectives showing that each target is evenly distributed across the study area, whether on the upper or lower parts of the building, or along the edges or in the center.

Figure 3: Distribution of target objects within the entire study area

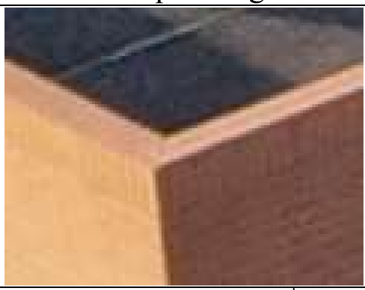
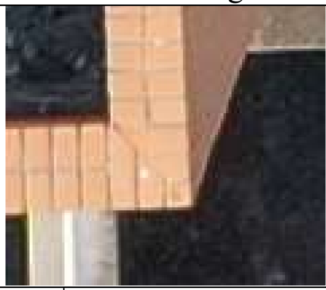
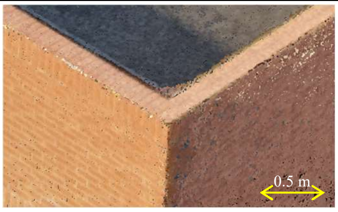
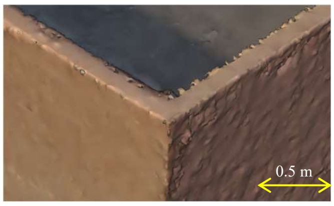
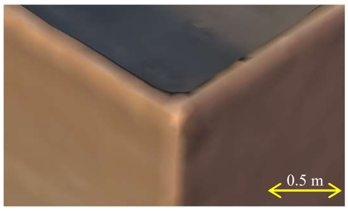
Figure 4: Spatial distribution of target locations

Corner points are critical for building models, as much of the spatial information obtained during surveying is derived from these points. Therefore, the representation of corner points across different models becomes a key focus of analysis.

In this study, the building in the research area has a height of approximately 60 meters. Given this height, the difference in Ground Sampling Distance (GSD) in aerial images can introduce notable variations. Thus, the quality of corner point representations at different heights is observed to assess their impact on model accuracy.

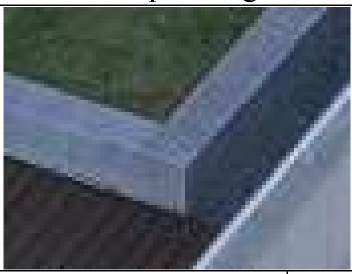
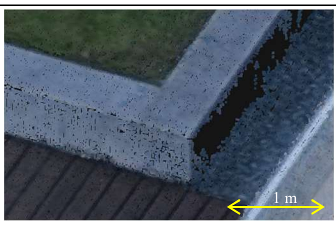
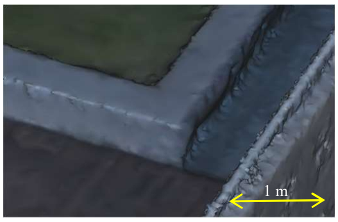
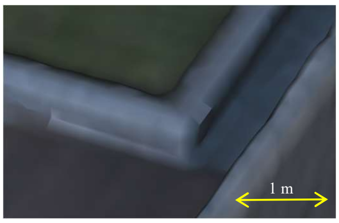
P1 (upper corner point) (Table 3) is located at the highest point of the building. Due to lighting conditions, the surrounding area in the image has blurred edges, leading to noise along the building's edge in the point cloud. In the mesh model generated by Metashape, dense matching resulted in noticeable undulations in the point positions, causing excessive surface fluctuations on what should be a flat plane. In contrast, the mesh calculation in Cloud Compare successfully removed the noise in this area. However, it also smoothed out the vertical transitions of the parapet, leading to a loss of sharp detail.

Table 3: Display of P1 (upper corner point) in different models

<table>
<tr><th colspan="3">P1 (Upper corner point)</th></tr>
<tr><td>Oblique image</td><td colspan="2">Vertical image</td></tr>
<tr><td></td><td colspan="2"></td></tr>
<tr><td>Point cloud</td><td>Mesh (Metashape)</td><td>Mesh (Cloud Compare)</td></tr>
<tr><td></td><td></td><td></td></tr>
</table>

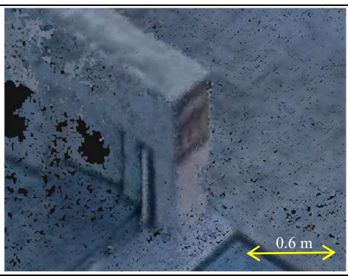
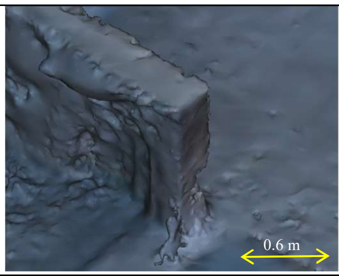
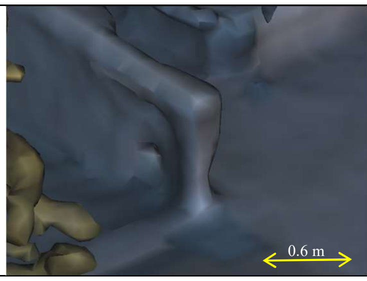
P2 (middle corner point) (Table 4) is notable for being positioned away from the building's edge, located instead at a central point. In the point cloud, a portion on the right side shows incomplete matching. However, in the mesh models, the missing areas were filled in using interpolation. Similar to previous observations, the mesh model generated in Cloud Compare also exhibited rounding of the corner edges.

Table 4: Display of P2 (middle corner point) in different models

<table>
<tr><th colspan="3">P2 (Middle corner point)</th></tr>
<tr><td>Oblique image</td><td colspan="2">Vertical image</td></tr>
<tr><td></td><td colspan="2"></td></tr>
<tr><td>Point cloud</td><td>Mesh (Metashape)</td><td>Mesh (Cloud Compare)</td></tr>
<tr><td></td><td></td><td></td></tr>
</table>

P3 (lower corner point) (Table 5) is primarily characterized by a significantly lower point density after dense matching compared to the previous two points, making the geometric differences between the models more pronounced. As shown in the Table 5, the mesh model generated by Metashape exhibits more pronounced edge undulations, while the smoothing effect in the Mesh model from Cloud Compare is even more exaggerated.

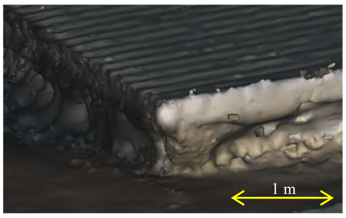
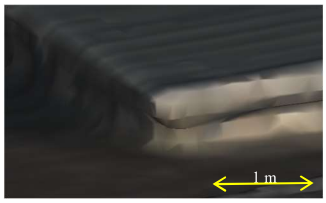
Table 5: Display of P3 (lower corner point) in different models

<table>
<tr><th colspan="6">P3 (Lower corner point)</th></tr>
<tr><td colspan="3">Oblique image</td><td colspan="3">Vertical image</td></tr>
<tr><td colspan="3"></td><td colspan="3"></td></tr>
<tr><td colspan="2">Point cloud</td><td colspan="2">Mesh (Metashape)</td><td colspan="2">Mesh (Cloud Compare)</td></tr>
<tr><td colspan="2"></td><td colspan="2"></td><td colspan="2"></td></tr>
</table>

P4, a building corner (tin-sheeted roof) (Table 6), differs from the intersection of clear structural lines found in concrete walls. The thinness of the metal roof, coupled with limited angles for capturing images, affects the results of dense matching in the point cloud. This article explores the impact of these factors on measurement outcomes.

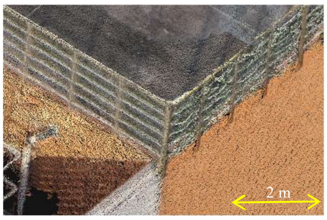
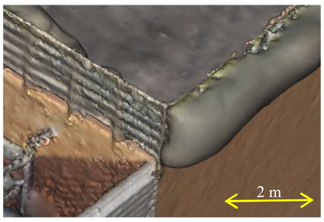
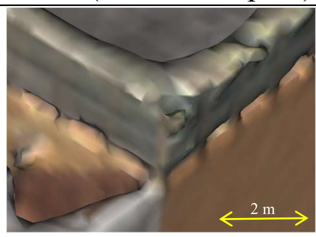
Table 6: Display of P4 (tin-sheeted roof) in different models

<table>
<tr><th colspan="2">P4 (Tin-sheeted roof)</th></tr>
<tr><td>Oblique image</td><td>Vertical image</td></tr>
<tr><td></td><td></td></tr>
</table>

Point cloud	Mesh (Metashape)	Mesh (Cloud Compare)
		

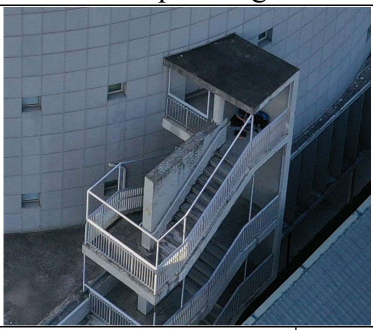
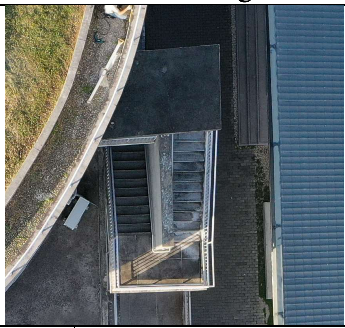
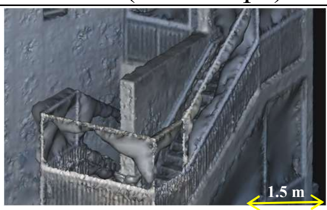
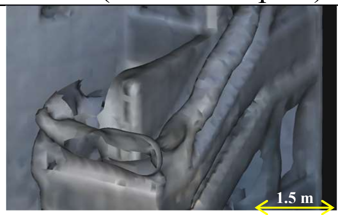
P5, the rooftop fence (Table 7), is located at the highest point of the target building and has the smallest GSD. It was captured in numerous images, including many oblique ones. However, as shown in the Table, the model produced exhibits relatively more erroneous corner points and unusual protrusions, likely due to the influence of background elements and shadows in the images.

Table 7: Display of P5 (rooftop fence) in different models

<table>
<tr><th colspan="6">P5 (Rooftop fence)</th></tr>
<tr><td colspan="3">Oblique image</td><td colspan="3">Vertical image</td></tr>
<tr><td colspan="3"></td><td colspan="3"></td></tr>
<tr><td colspan="2">Point cloud</td><td colspan="2">Mesh (Metashape)</td><td colspan="2">Mesh (Cloud Compare)</td></tr>
<tr><td colspan="2"></td><td colspan="2"></td><td colspan="2"></td></tr>
</table>

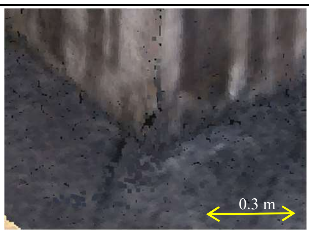
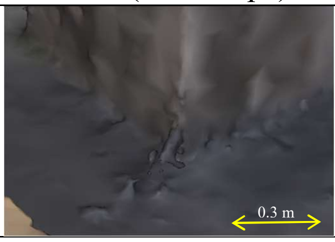
P6, the staircase railing (Table 8), is one of the most complex target structures in the entire study area. If the model can fully reconstruct this structure in three-dimensional space, it would significantly enhance the detail and precision of spatial information extraction. Therefore, the reconstruction of this model is a key focus of this study.

Table 8: Display of P6 (staircase railing) in different models

<table>
<tr><th colspan="6">P6 (Staircase railing)</th></tr>
<tr><td colspan="3">Oblique image</td><td colspan="3">Vertical image</td></tr>
<tr><td colspan="3"></td><td colspan="3"></td></tr>
<tr><td colspan="2">Point cloud</td><td colspan="2">Mesh (Metashape)</td><td colspan="2">Mesh (Cloud Compare)</td></tr>
<tr><td colspan="2"></td><td colspan="2"></td><td colspan="2"></td></tr>
</table>

P7, a rooftop object (Table 9), has a color similar to the ground, which led to numerous mismatched points during dense matching of the corner point below the target. However, after generating the mesh models, the noise from the mismatched points was partially eliminated.

Table 9: Display of P7 (rooftop object) in different models

<table>
<tr><th colspan="6">P7 (Rooftop object)</th></tr>
<tr><td colspan="3">Oblique image</td><td colspan="3">Vertical image</td></tr>
<tr><td colspan="3"></td><td colspan="3"></td></tr>
<tr><td colspan="2">Point cloud</td><td colspan="2">Mesh (Metashape)</td><td colspan="2">Mesh (Cloud Compare)</td></tr>
<tr><td colspan="2"></td><td colspan="2"></td><td colspan="2"></td></tr>
</table>

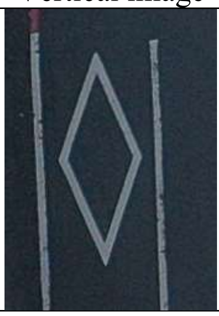
The flowerbed (Table 10) is located on the side of the building, where shading and the blending of edge structure lines with the background contributed to a certain degree of geometric distortion in the model.

Table 10: Display of L1 (flowerbed edge) in different models

<table>
<tr><th colspan="6">L1 (Flowerbed edge)</th></tr>
<tr><td colspan="3">Oblique image</td><td colspan="3">Vertical image</td></tr>
<tr><td colspan="3"></td><td colspan="3"></td></tr>
<tr><td colspan="2">Point cloud</td><td colspan="2">Mesh (Metashape)</td><td colspan="2">Mesh (Cloud Compare)</td></tr>
<tr><td colspan="2"></td><td colspan="2"></td><td colspan="2"></td></tr>
</table>

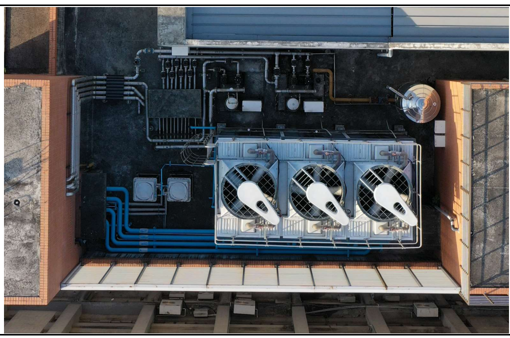
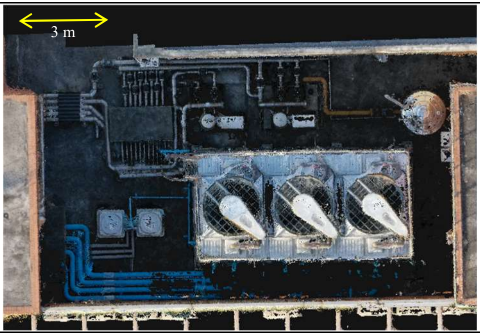
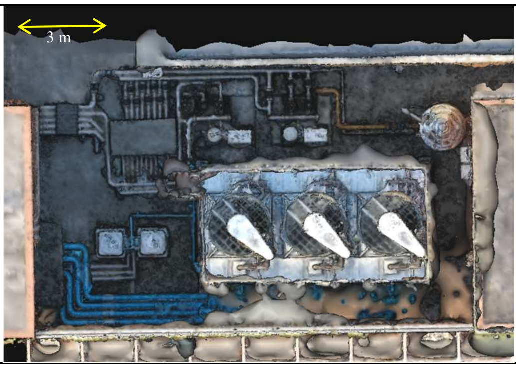
In the current practical applications of high-definition map production, extracting road sign information from point cloud has become a widely discussed area. As a result, whether mesh models can assist in this task has also become a focus. As shown in the Table 11, it can be observed to some extent that mesh models tend to cause the color of road markings to blend with their surroundings.

Table 11: Display of L2 (Road marking) in different models

<table>
<tr><th colspan="4">L2 (Road marking)</th></tr>
<tr><td>Vertical image</td><td>Point cloud</td><td>Mesh (Metashape)</td><td>Mesh (Cloud Compare)</td></tr>
<tr><td></td><td></td><td></td><td></td></tr>
</table>

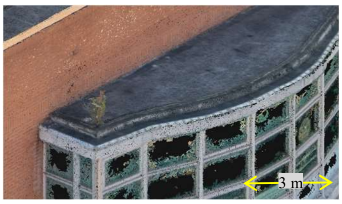
L3, shown in Table 12, the complex piping system, possesses many unique features that are not present in the other targets. The inclusion of this target in the analysis aims to understand the differences between various models in extracting spatial information in small, complex areas. Based on initial visual observations, no significant differences between the models have been detected thus far.

Table 12: Display of L3 (piping system) in different models

L3 (Piping system)	
Vertical image	Point cloud
	
Mesh (Metashape)	Mesh (Cloud Compare)
	

Compared to straight lines, curves are more challenging to represent in model structures (Table 13). If a 3D model can improve the reconstruction completeness of curved building edges, it would result in more accurate reconstruction of the building's structural lines.

Table 13: Display of L4 (curved building edge) in different models

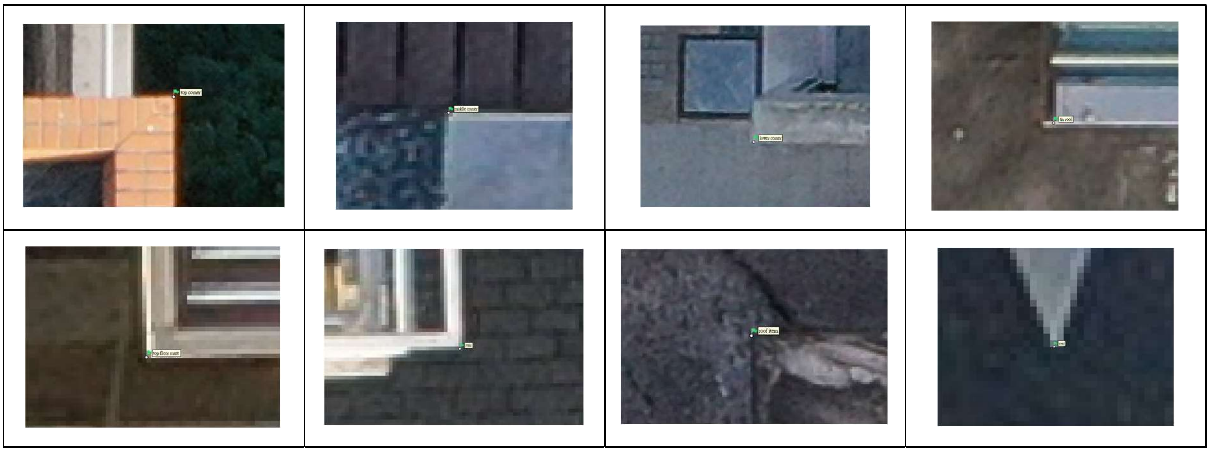
L4 (Curved building edge)		
Oblique image	Vertical image	
		
Point cloud	Mesh (Metashape)	Mesh (Cloud Compare)
		

d. Target feature measurement and comparative analysis

- **Reference values**

In this study, Metashape was used to process the same set of image parameters and select target points within the images. A specific target point was selected from one of the images, as shown in Table 14. And its coordinates were calculated using multi-ray photogrammetric intersection, serving as a relative reference value. This reference value will be used to compare the differences between the measured points in various models and the reference point.

Table 14: Target measure in image



For target L1 and L2, we conducted to measure in situ for their lengths, as shown in Figure 5.

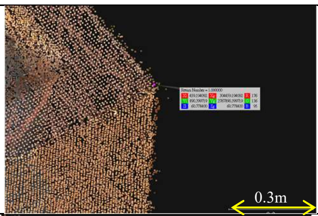
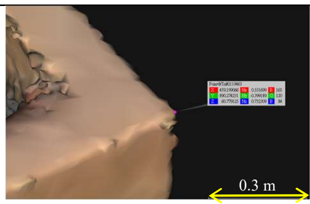
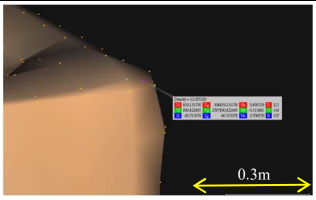
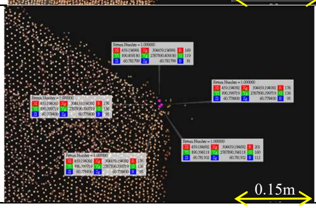
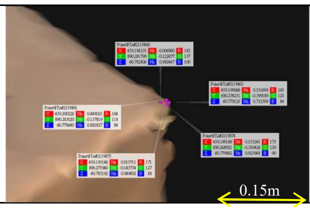
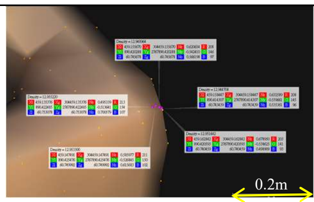
Figure 5: Measurement in situ (L1 and L2)

- **Measured scenarios and data metric comparison**

The following section presents real-world measurements across different models. Differences in color, geometric shape, and even background can influence the selection of measurement points. Therefore, analyzing the impact of these factors on the measurement results is one of the main focuses of this study. To ensure consistency, we used the measurement tools in Cloud Compare, performing 5 repeated measurements at the same point and recording the data for each instance.

Subsequently, all measurement data were compared with the reference values, and a vector diagram of the measurement deviations was plotted. By analyzing these deviation vectors, we can determine whether systematic bias exists or observe the direction of the deviations, allowing us to further quantify the impact of different models on the measurement results.

Table 15: The actual scene of measuring point (P1)

	Point cloud	Mesh (Metashape)	Mesh (Cloud Compare)
P1			
			

As shown in Figure 6, there is a notably outlying observation in the mesh model (Metashape). Since similar phenomena were not observed in other measurements, it is presumed to be a random error. Meanwhile, in the mesh model (Cloud Compare), a collective shift of approximately 5 cm in the x-direction is clearly noticeable.

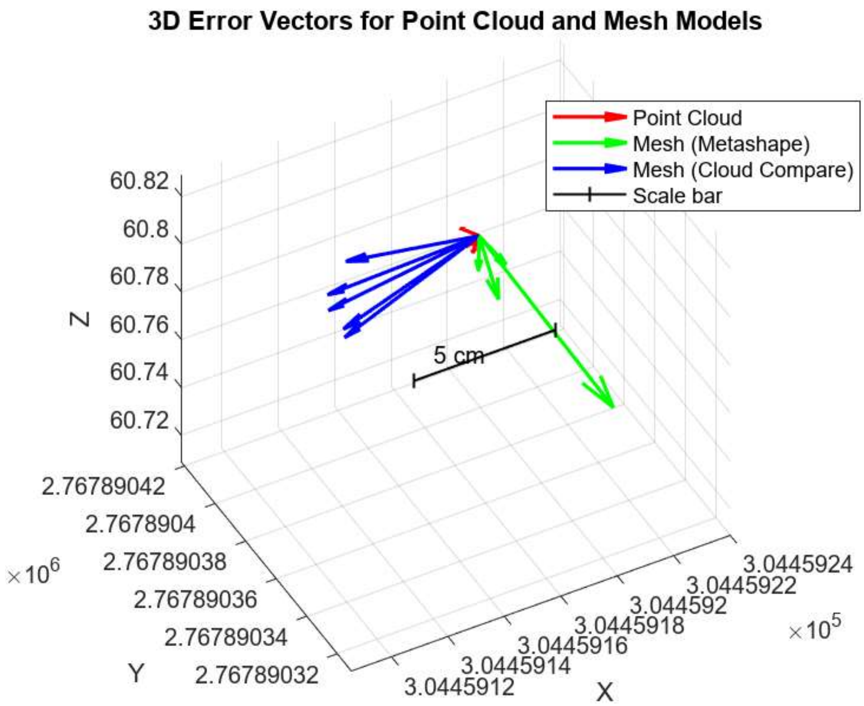


Figure 6: Error vectors plot (P1)

Based on Figure 7, this shift is likely caused by the simplification of surrounding points during mesh computation, resulting in an inward contraction of the model.

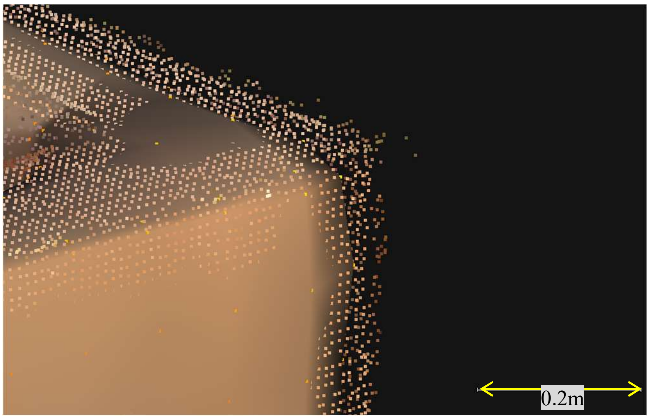
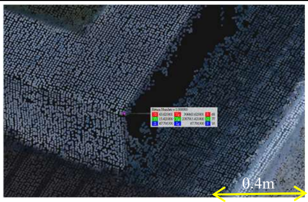
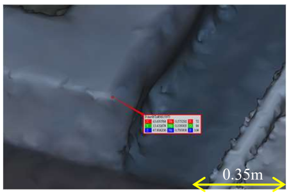
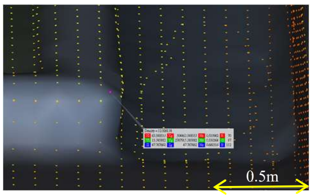
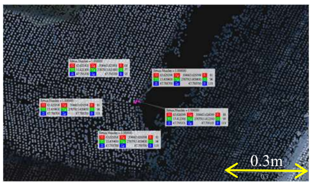
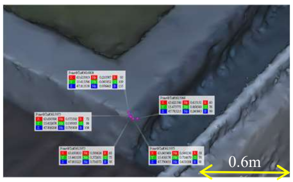
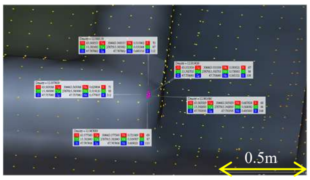


Figure 7: Overlap point cloud and mesh model (Cloud Compare)

Table 16: The actual scene of measuring point (P2)

	Point cloud	Mesh (Metashape)	Mesh (Cloud Compare)
P2			
			

From Figure 8, it can be observed that both mesh models exhibit errors ranging from 2 to 6 centimeters.

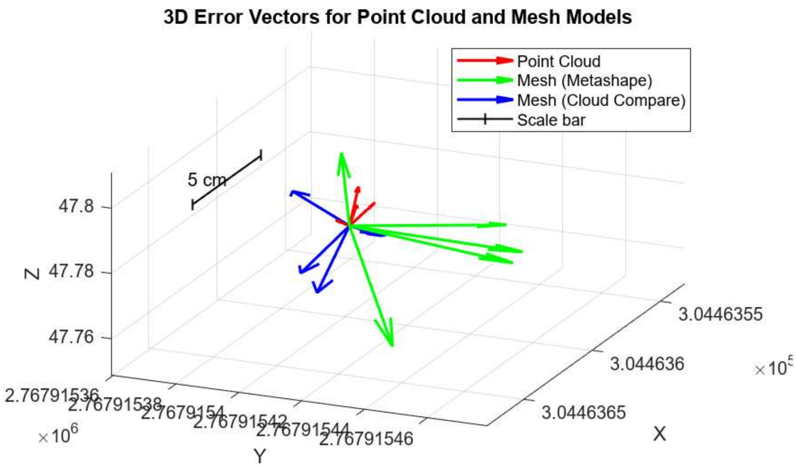


Figure 8: Error vectors plot (P2)

When overlaying the mesh models with the point cloud to investigate the reason, as shown in Table 17, the edges of the mesh model (Metashape) protrude beyond the point cloud, while the mesh model (Cloud Compare) shows inward shrinkage at the corners. These geometric differences further impact the collection of observational data.

Table 17: Overlay of point cloud and mesh models (point cloud shown in white)

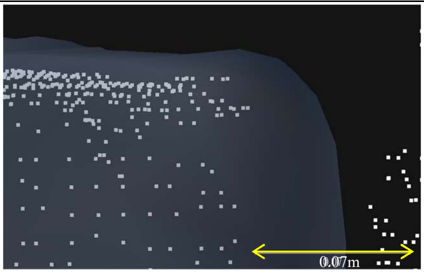
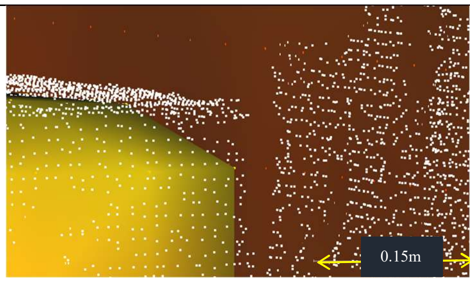
	
Mesh model (Metashape)	Mesh model (Cloud Compare)

Table 18: The actual scene of measuring point (P3)

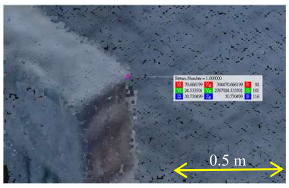
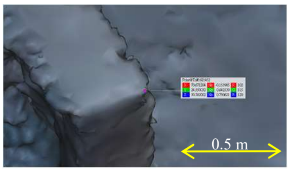
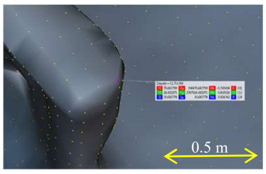
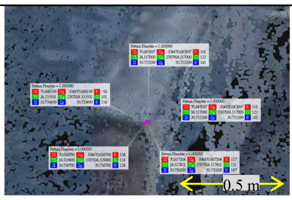
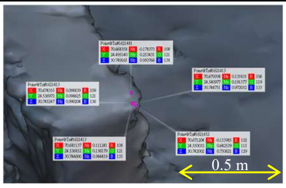
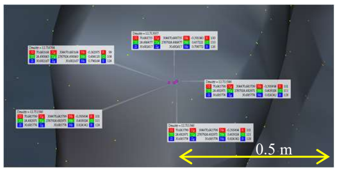
	Point cloud	Mesh (Metashape)	Mesh (Cloud compare)
P3			
			

Figure 9 shows that the Mesh model (Metashape) has an error exceeding 10 cm.

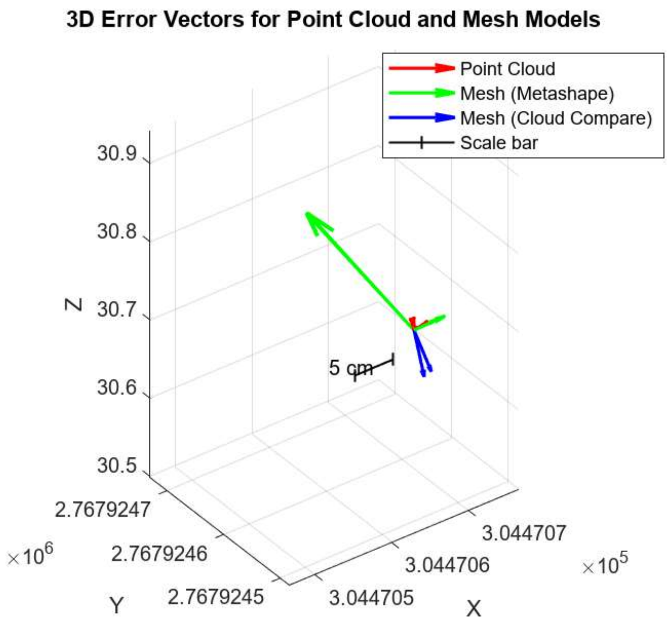


Figure 9: Error vectors plot (P3)

When displaying the selected point on the model (Figure 10), it can be observed that one point is located significantly farther from the other observations, thus it is currently regarded as a random error. Similarly, the Mesh model (Cloud Compare) exhibits a similar error trend as with the previous target, which is likely related to the inward shrinkage of the corner points (Figure 11).

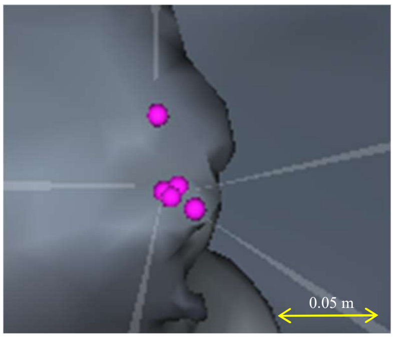


Figure 10: Zoom in on the mesh model (Metashape)

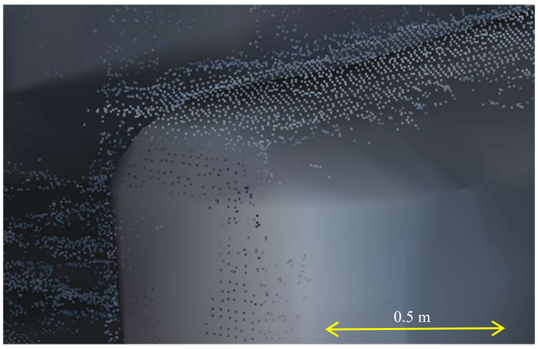
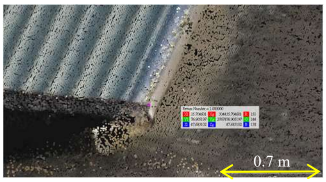
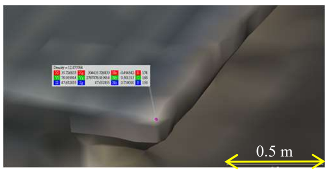
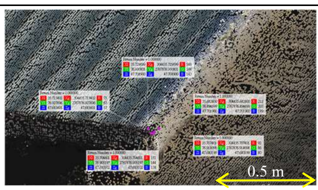
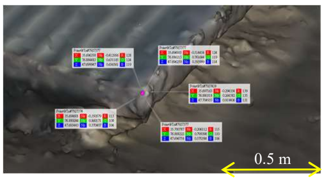
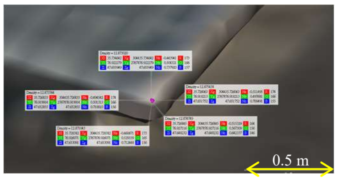


Figure 11: Overlay of point cloud and mesh model (Cloud Compare)

Table 19: The actual scene of measuring point (P4)

	Point cloud	Mesh (Metashape)	Mesh (Cloud Compare)
P4			
			

From Figure 12, it is evident that the measurement results across the three models exhibit similar average error amounts.

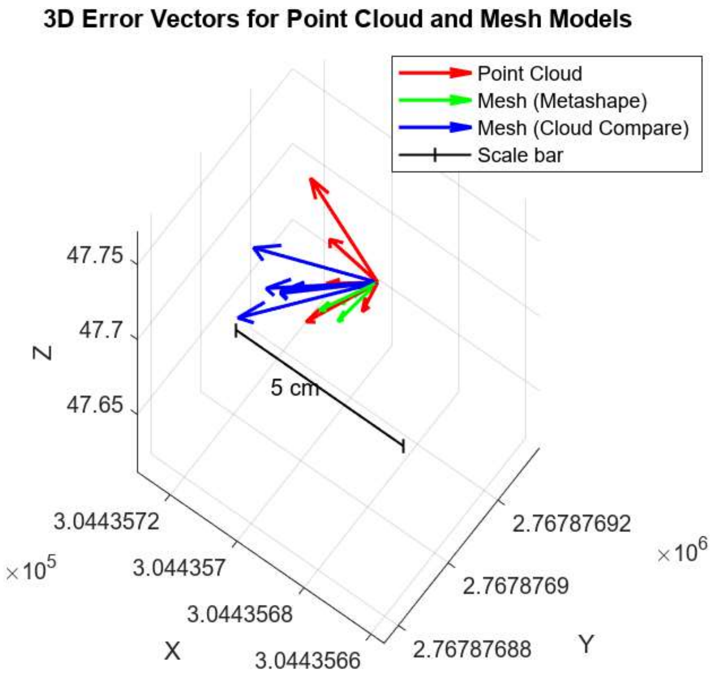


Figure 12: Error vectors plot (P4)

As shown in Figure 13, it can be further observed that this target initially contained numerous noise points during the point cloud generation, leading to slight difference in each point cloud measurement.

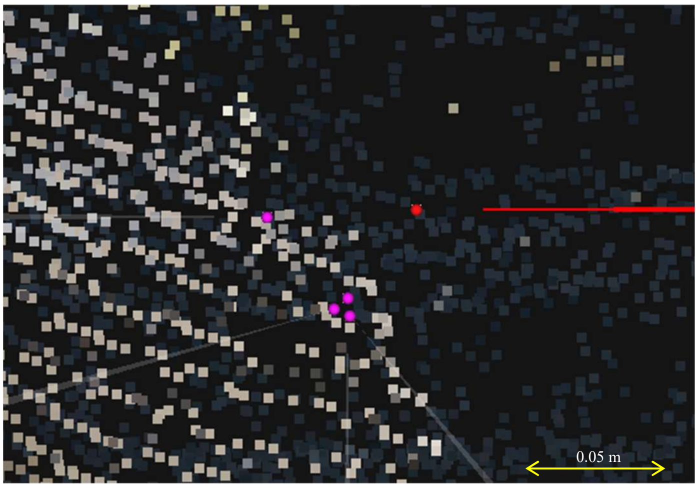


Figure 13: Zoom in on point cloud

In Table 20, the differences between the models can be observed. Whether it is the mesh model (Metashape), which incorporates noise points as part of the edges, or the mesh model (Cloud Compare), which exhibits inward shrinkage at the corner points.

Table 20: Overlay of point cloud and mesh models (point cloud shown in white)

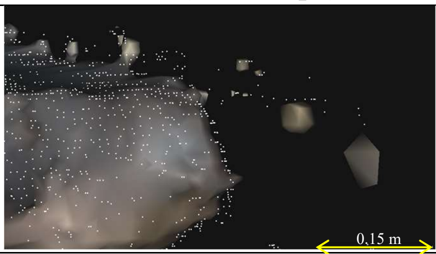
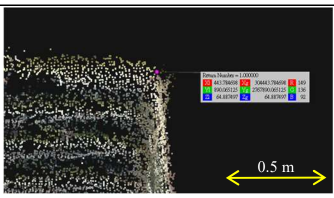
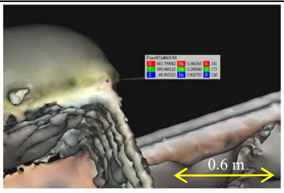
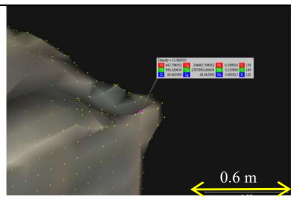
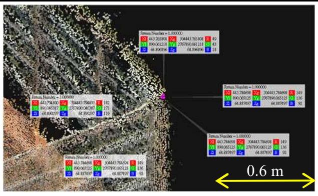
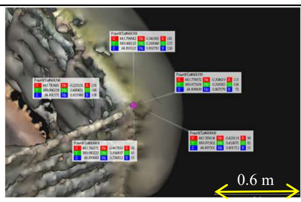
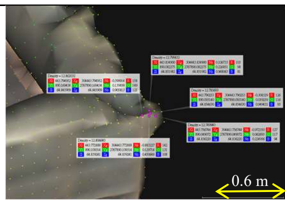
Mesh (Metashape)	Mesh (Cloud Compare)
	

Table 21: The actual scene of measuring point (P5)

	Point cloud	Mesh (Metashape)	Mesh (Cloud Compare)
P5			
			

As shown in Figure 14, compared to the previously discussed targets, P5 exhibits significantly larger measurement errors in the mesh models.

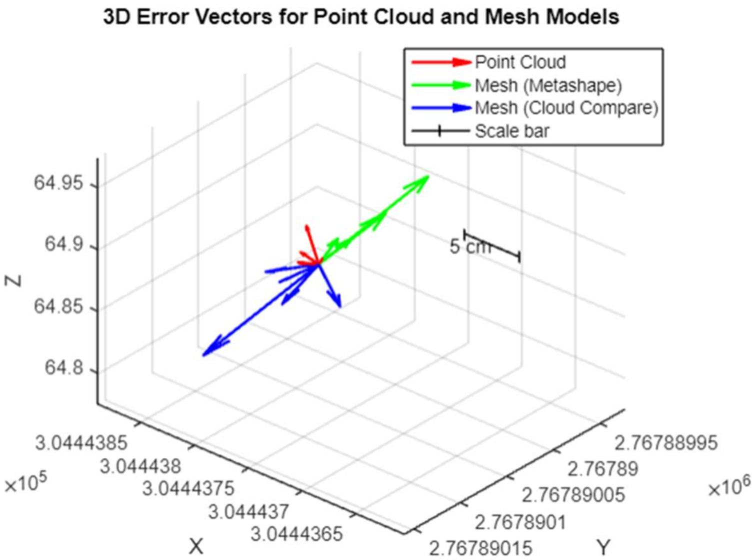


Figure 14: Error vectors plot (P5)

As seen in Table 22, we can better understand the cause of this error. This target, in the mesh model (Metashape), is affected by noise points, resulting in unreasonable protrusions along the edges, which in turn affect the position of the corner point. Meanwhile, the mesh model (Cloud Compare) still has the issue of inward shrinkage.

Table 22: Overlay of point cloud and mesh models (point cloud shown in white)

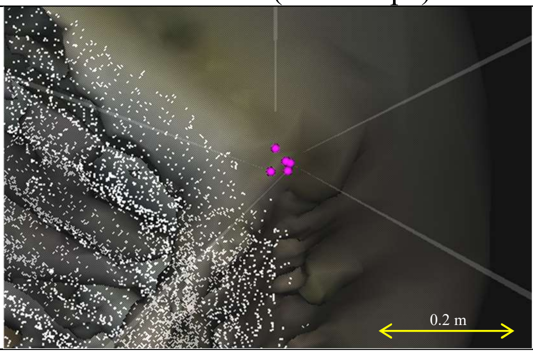
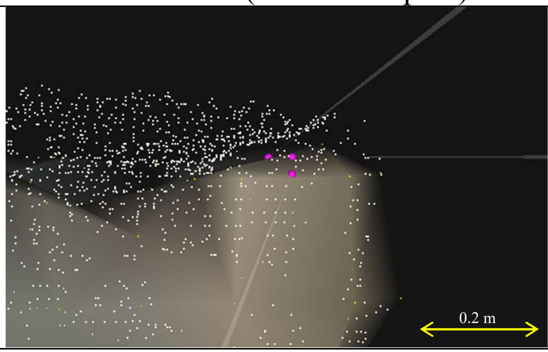
Mesh model (Metashape)	Mesh model (Cloud Compare)
	

Table 23: The actual scene of measuring point (P6)

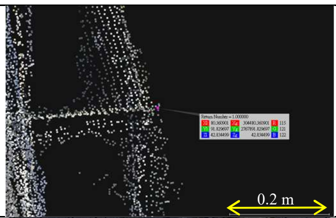
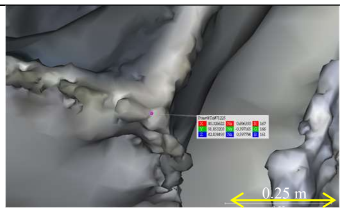
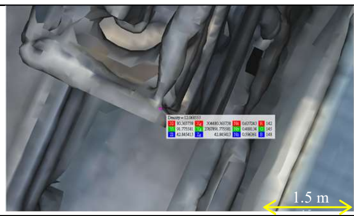
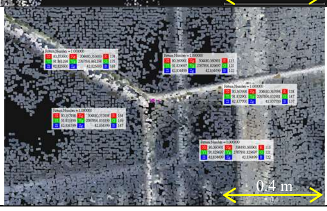
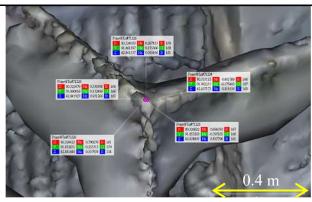
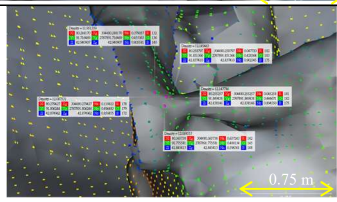
	Point cloud	Mesh (Metashape)	Mesh (Cloud compare)
P6			
			

Figure 15 shows a comparison of the model results for P6, where the corner points in the mesh model generated by Metashape shift inward, while in the Cloud Compare mesh model, the corner points extend outward.

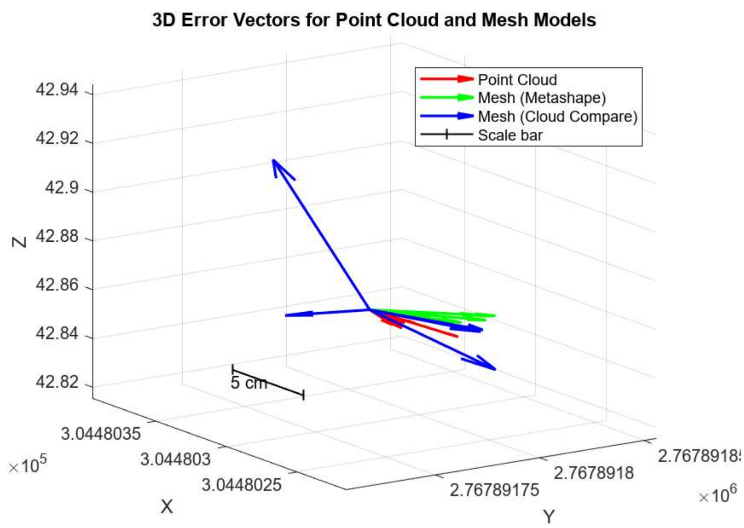


Figure 15: Error vectors plot (P6)

As indicated in Table 24, due to errors in mesh calculation, the corner points in the Metashape mesh model were excessively reduced, causing the model to shrink inward. In contrast, in the Cloud Compare mesh model, the color representation has a greater influence on the measurement results than the geometric structure, which is the main reason for the significant variations in each measurement within the Cloud Compare mesh model.

Table 24: Overlay of point cloud and mesh models (point cloud shown in white)

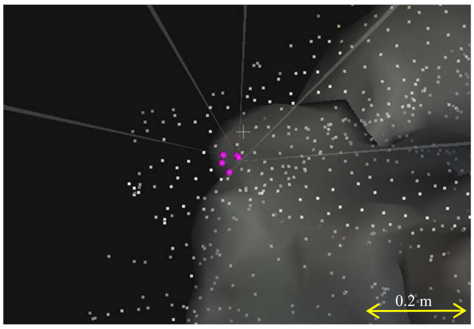
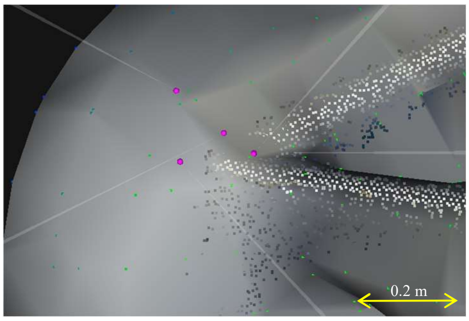
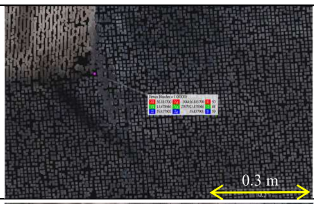
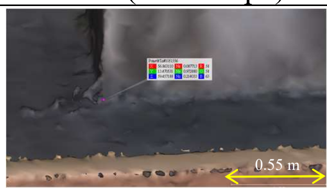
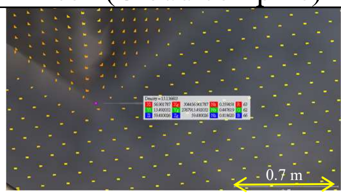
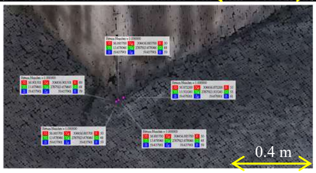
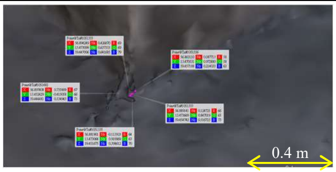
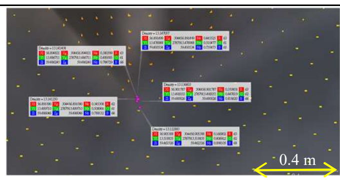
Mesh (Metashape)	Mesh (Cloud Compare)
	

Table 25: The actual scene of measuring point (P7)

	Point cloud	Mesh (Metashape)	Mesh (Cloud compare)
P7			
			

From Figure 16, we can observe that both the point cloud and mesh models have an error of 2 to 5 cm compared to the reference value.

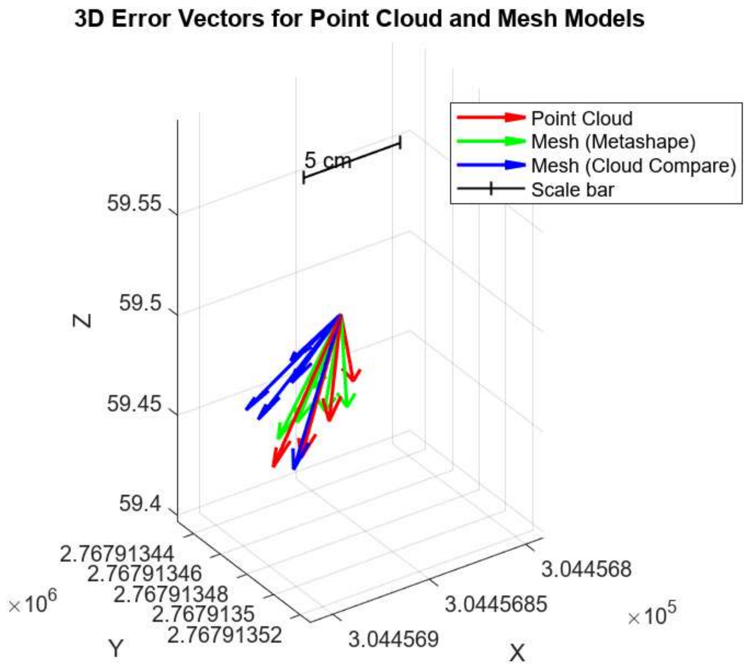


Figure 16: Error vectors plot (P7)

Looking back at the aerial imagery (Table 26), it becomes clear that P7 has a similar color to the surrounding scene, and due to limited angles, only a few images captured this corner point. As a result, the corner point identified in the images contains some deviation.

However, as shown in Figure 16, when measuring in three-dimensional space, P7 becomes easier to measure, and the results across different models are highly consistent. This outcome demonstrates the advantages of conducting measurements in a 3D space.

Table 26: Screenshot of the aerial image captured on the P7

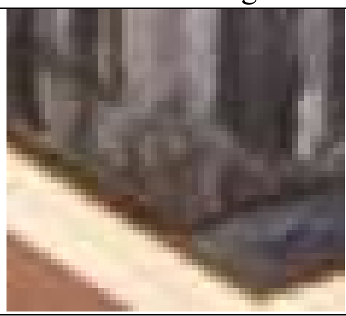
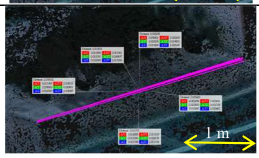
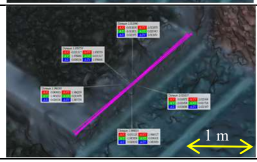
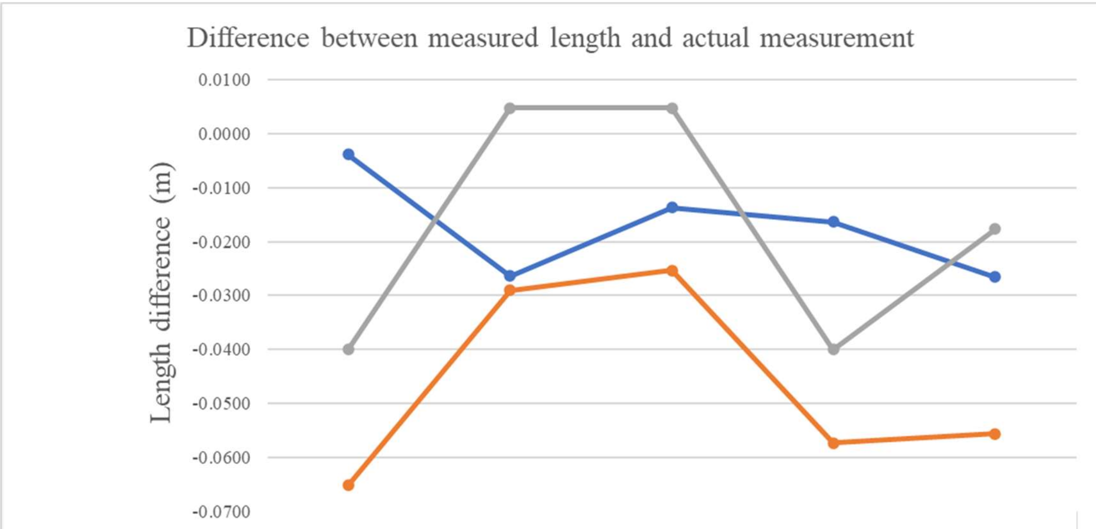
Oblique image	Vertical image
	

Table 27 presents the actual scene of measuring the flower bed surface. The recorded values are then compared with the in-site measurements, as shown in Table 27 above. The horizontal axis represents the number of measurements.

Table 27: The actual scene of measuring line (L1)

	Point cloud	Mesh (Metashape)	Mesh (Cloud compare)
L1			
			

From Figure 17, it can be seen that most of the length differences are negative, indicating that the measured segment lengths on the model are shorter than the reference values. Additionally, since this target is located at the lower part of the building, its corner points may not have been successfully matched during the point cloud generation phase, leading to the incomplete reconstruction of the flower bed's corners. The variations in mesh model data are also greater than those in the point cloud, suggesting that while the simplification of mesh models may accelerate measurement decisions, it can result in significantly different outcomes that affect the measurement results.



Measure times	1st	2nd	3rd	4th	5th
Point cloud	-0.0039	-0.0264	-0.0137	-0.0163	-0.0266
Mesh(Metashape)	-0.0653	-0.0290	-0.0254	-0.0574	-0.0556
Mesh(Cloud compare)	-0.0401	0.0048	0.0048	-0.0401	-0.0176

Figure 17: Length difference graph (L1)

Due to the low point density in the area where L2 is located, the features in the mesh model (Cloud Compare) were overly simplified (Table 28), resulting in very blurred texture information. In Table 29, the yellow line represents the point cloud, the blue line represents the mesh model (Metashape), and the orange line represents the mesh model (Cloud Compare). It can be observed that the excessive simplification caused the drawing results of the mesh model (Cloud Compare) to differ significantly from the other two.

Table 28: The actual scene of measuring line (L2)

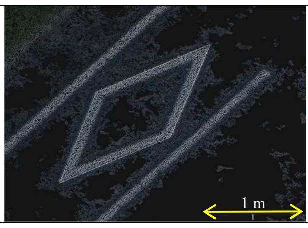
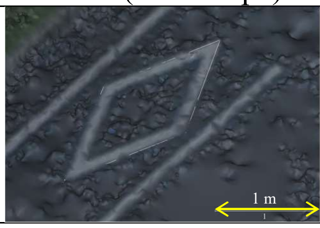
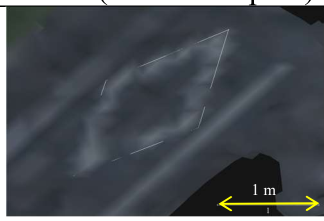
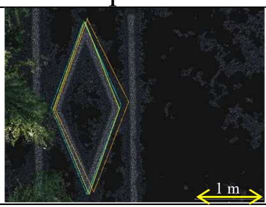
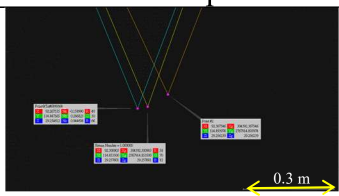
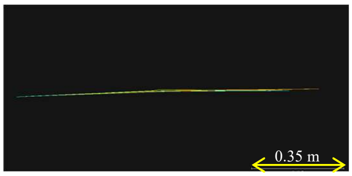
	Point cloud	Mesh (Metashape)	Mesh (Cloud compare)
L2			

Table 29: Presentation of the measurement results for the line segments

Top view	Measured point	Side view
		

On flat surfaces, fewer mesh wireframes are needed to represent the complete plane, and the spacing between mesh wireframes is much larger compared to point clouds. As a result, when color is applied to each mesh wireframes, the line cannot be as finely detailed as those in point clouds. Instead, a stepped or jagged edge appears rather than a smooth, continuous geometric boundary, as shown in Table 30.

Table 30: Different 3D models representation of radial feature line

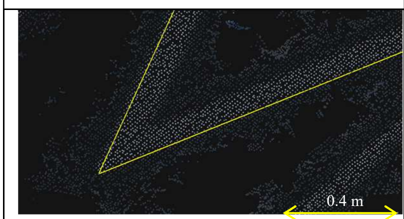
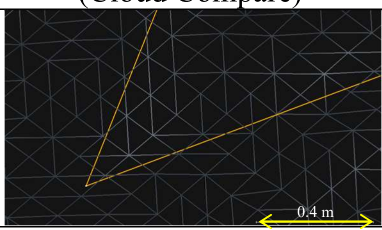
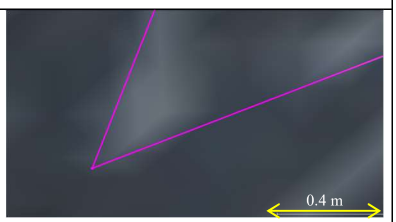
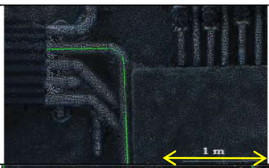
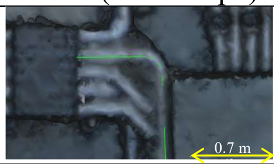
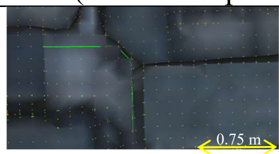
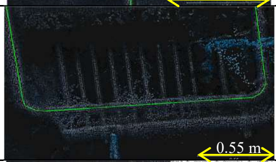
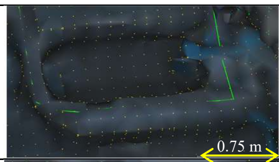
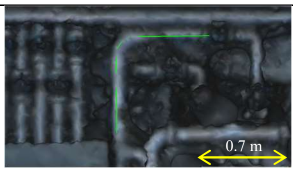
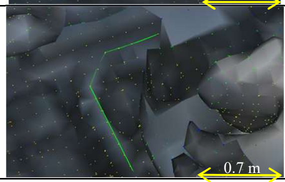
Point cloud	Mesh Wireframe (Cloud Compare)	Mesh (Cloud Compare)
		

Table 31 shows the actual scene of drawing line segments in different sections of L3 (Piping system) for each model.

Table 31: The actual scene of measuring line (L3)

	Point cloud	Mesh (Metashape)	Mesh (Cloud compare)
L3			
			
			

We then overlaid the line measurement results and presented them in Table 32. The yellow line represents the point cloud, the blue line represents the mesh model (Metashape), and the red line represents the mesh model (Cloud Compare). It can be observed that there is not much difference in the measurements of this target across the different models. However, a notable observation is that when drawing lines on the mesh models, the lines can be obscured by the color-filled mesh, making it more difficult to verify the accuracy of the drawn lines.

Table 32: Presentation of the measurement results for the line segments

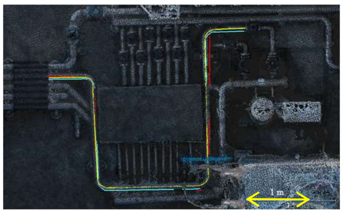
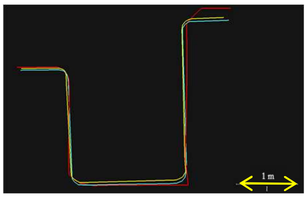
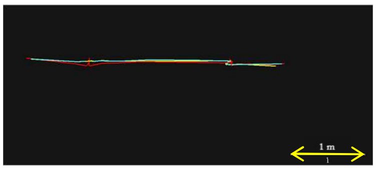
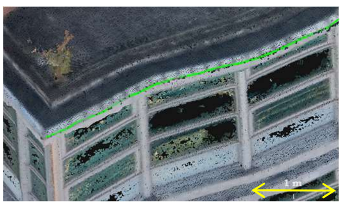
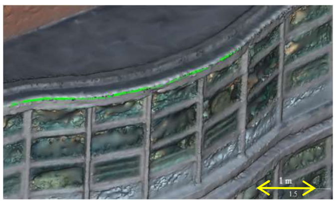
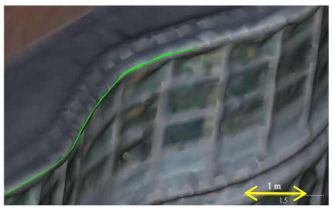
Top view		Side view
		

Table 33: The actual scene of measuring line (L3)

	Point cloud	Mesh (Metashape)	Mesh (Cloud Compare)
L3			
	top view		
			

In Figure 18 and 19, the yellow line represents the point cloud, the blue represents the mesh model (Metashape), and the orange represents the mesh model (Cloud Compare). It can be observed that the Mesh generated in Cloud Compare is more stable in rendering the curve edges compared to the other two, but it also clearly exhibits inward shrinkage. In Figure 19, the red line represents the vertical distance between the point cloud and the mesh model (Metashape), with a difference of approximately 1-2 cm. The pink line indicates the vertical distance between the point cloud and the mesh model (Cloud Compare), with a difference of around 10 cm.

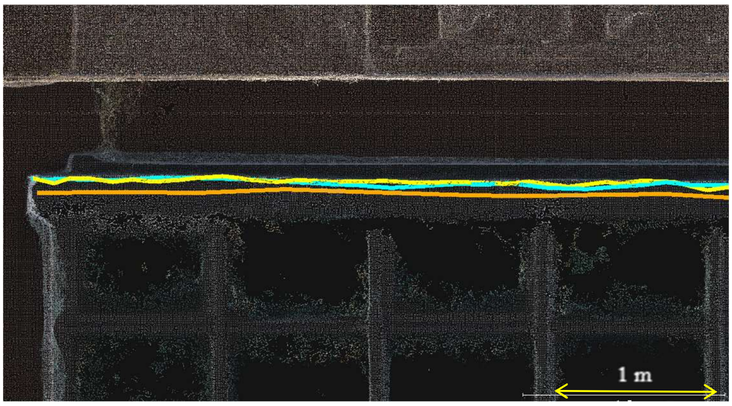


Figure 18: Side view of the curve

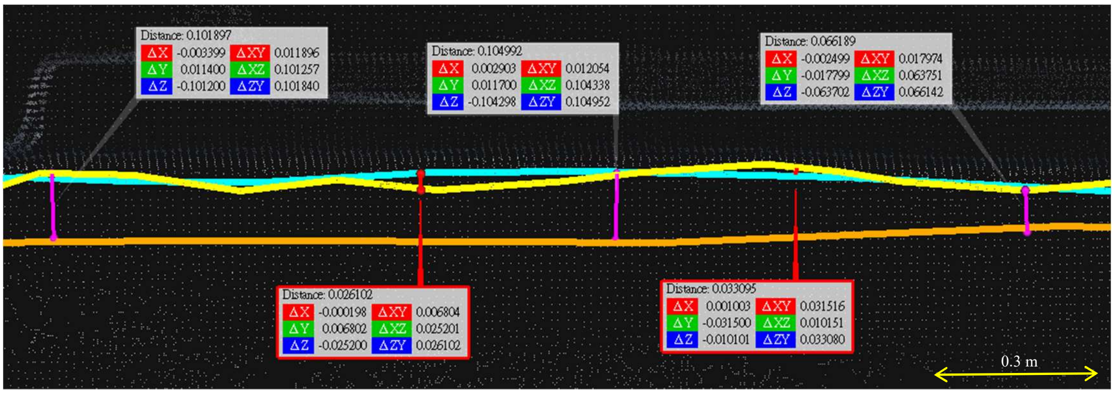


Figure 19: Vertical distance between curves

Overall evaluation

a. Model distortion level

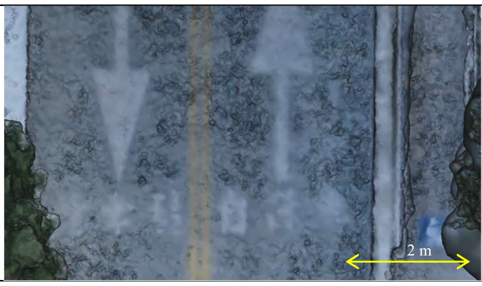
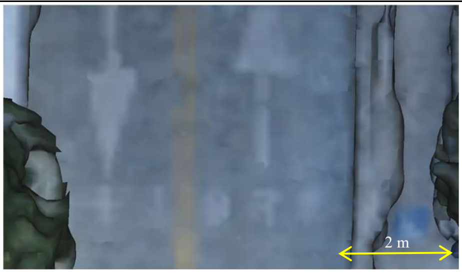
The representation of the model directly influences the efficiency of spatial information acquisition and the quality of the resulting data. Therefore, observing the geometric and radiometric performance of the model under different conditions is essential.

- **Radiometric distortion**

(1) The clarity of road markings

When the observed target consists of only a single plane, as shown in Table 34, the color display of individual points in the point cloud helps distinguish the boundary between the road markings and the concrete surface. However, in the mesh model, due to its smoothness, the boundary colors become blurred, making them difficult to recognize. This highlights that mesh models are not well-suited for extracting features of this category.

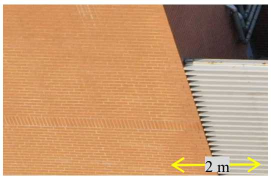
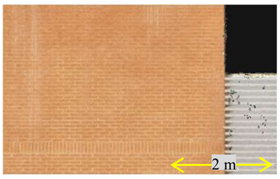
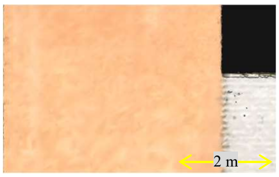
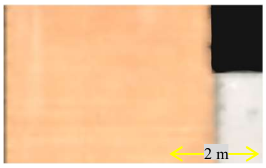
Table 34: Road markings display in different models

Image	Point Cloud
	
Mesh (Metashape)	**Mesh (Cloud Compare)**
	

(2) Wall texture

Similar results can be observed in the reconstruction of wall textures, where the mesh models tend to weaken the color lines and surface details of the target. Additionally, in the Table 35, the model's colors are easily influenced by the rendering platform and viewing angle. In contrast, the color representation in point cloud is much more stable.

Table 35: Wall texture in different models

Image	Point Cloud	Mesh (Metashape)	Mesh (Cloud Compare)
			

- **Geometric distortion**

(1) Reconstruction accuracy of elongated objects

Elongated objects typically exhibit sparse or unevenly distributed points during dense matching of point cloud, which can significantly affect the outcome of model generation (Table 36).

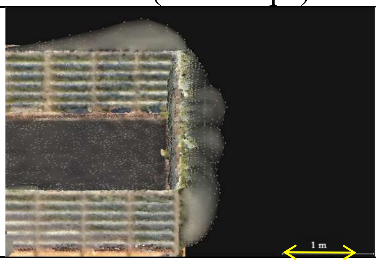
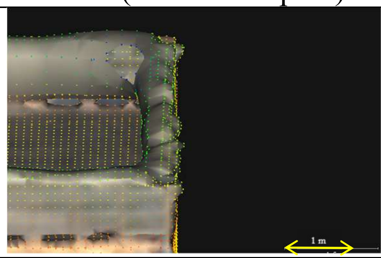
Table 36: The performance of elongated objects in different models

Image	Point Cloud	Mesh (Metashape)	Mesh (Cloud Compare)
			

(2) Generation of new points during mesh computation

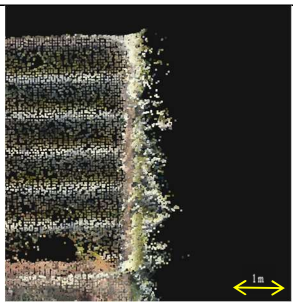
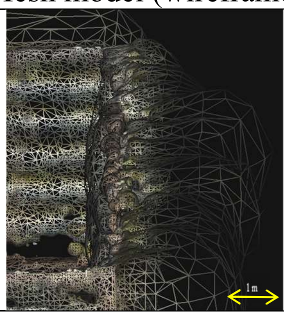
In Table 37, it can be observed that the mesh models exhibit significant deformation around target P5.

Table 37: The model performance around target P5

Point cloud	Mesh (Metashape)	Mesh (Cloud Compare)
		

In some areas, mesh grids are generated in the mesh model despite the absence of original point cloud data. Table 38 provides a notable example. If similar occurrences are found in other regions, they could potentially affect the accuracy of the surveying results.

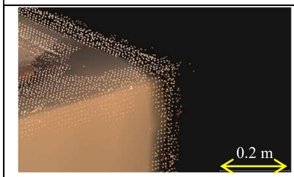
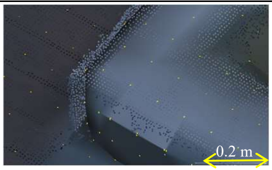
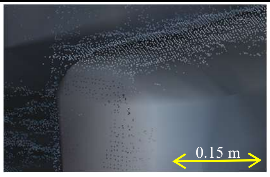
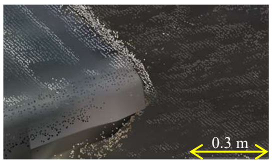
Table 38: Observation using a wireframe view

Point cloud	Mesh model (wireframe)
	

(3) Disappearance of edges in mesh models (Cloud Compare)

When overlapping the point cloud with the mesh model (Cloud Compare), it becomes evident that most targets exhibit inward shrinkage, shown in Table 39, indicating a significant systematic bias in the mesh models generated by Cloud Compare. The primary cause of this phenomenon is the algorithm used for mesh calculation. However, if both the point cloud and the mesh model are displayed simultaneously during measurements, the issue of disappearing edges can be quickly identified.

Table 39: The overlapping scene of two models across different targets

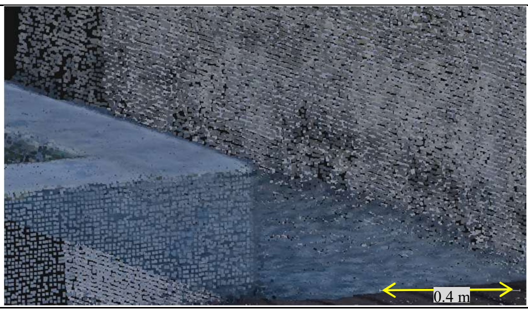
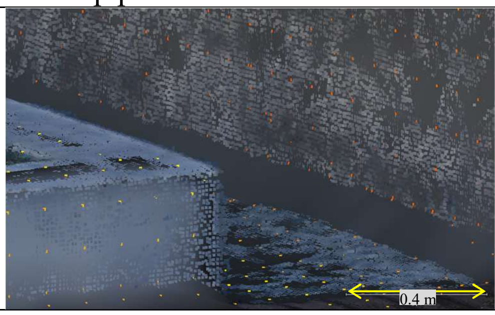
P1	P2	P3	P4
			

b. Discussion on model complementarity

(1) The issue of foreground and background overlap

In point cloud surveying tasks, foreground and background overlap frequently occurs, significantly reducing surveying efficiency (Table 40, left). However, by incorporating mesh models with complete color rendering, this issue can be resolved (Table 40, right). The visual relationships between targets in the scene are more clearly displayed, allowing for a better understanding of the foreground and background separation.

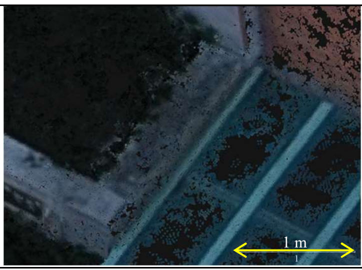
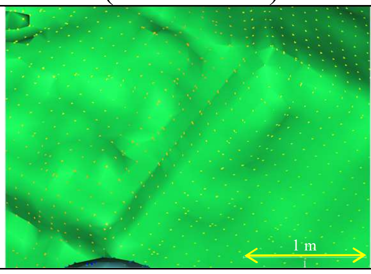
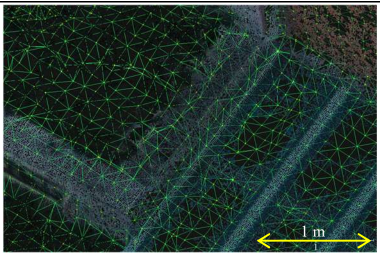
Table 40: Scene changes before and after the overlay of P2 models

Point cloud	Overlap point cloud and mesh models
	

(2) Clearer geometric structure

For example, in the point cloud, one of the edges of the flower bed is very unclear (Table 41, left). By utilizing the advantage of the continuous geometric structure of mesh models, the edge can be quickly identified (Table 41, middle), improving the efficiency of spatial information acquisition tasks. Additionally, overlaying the wireframe data from the mesh model with the point cloud (Table 41, right) allows for the combined use of the point cloud's color advantage and the mesh model's geometric structure. This approach can facilitate edge identification and accelerate the measurement process.

Table 41: Display of L1 in different models

Point cloud	Mesh (Cloud Compare) (None colors)	Overlap both
		

Conclusion

This study compared point cloud and mesh models generated using different software, focusing on their geometric accuracy and color representation when applied to various target features. The distinct characteristics and limitations of point cloud and mesh models, and how they influence the outcomes in surveying tasks, were central to the analysis in this study. Additionally, this research highlights that without a clear comprehension of their characteristics, accurate and reliable results cannot be achieved, underscoring the need for careful consideration when utilizing these emerging technologies in practice.

a. Differences between point cloud and mesh models

Point cloud and mesh models exhibit notable differences in surveying applications, particularly in terms of geometric accuracy and color representation. Point cloud offer higher precision in capturing fine details, such as object edges and textures, making them suitable for tasks requiring detailed geometric descriptions. In contrast, mesh models are better suited for visualizing the overall structure of objects, providing a more continuous and complete representation of the geometric shape. However, the presence of geometric distortions and color reproduction issues in mesh models, commonly observed during this study, highlights the potential risks these models pose to surveying accuracy.

In Figure 20, the white points represent the point cloud, while the green wireframe represents the mesh model. The figure demonstrates that even under the same conditions, the results produced by these two models can vary significantly. While both data types have the potential to enhance surveying tasks, improper application or interpretation of mesh models can lead to negative effects on the accuracy and reliability of the results.

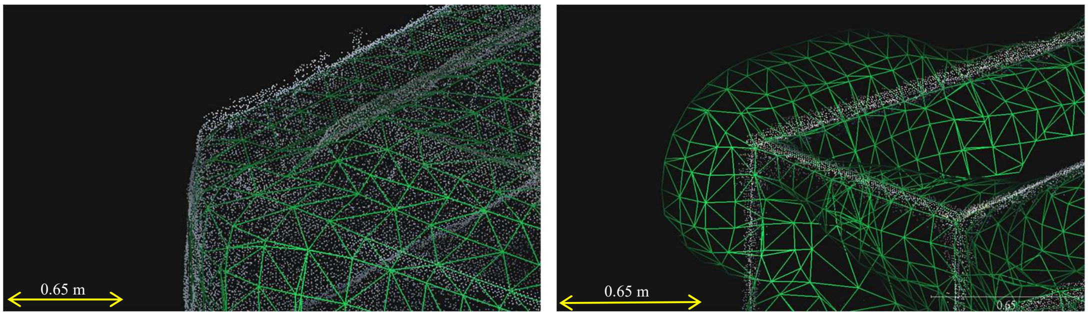


Figure 20: Differences in model performance across different sections

b. Factors affecting measurement results

The main factors affecting measurement results include noise points, excessive smoothing or protrusions in the mesh models, and the influence of color representation. These elements were shown to impact the geometric accuracy of the models in different ways, depending on the software and parameters used. For instance, the distribution of noise points and the overall density of the point cloud can significantly influence the inward or outward distortion of the mesh models. When fewer points are present, the mesh model tends to undergo greater simplification, leading to more pronounced deformations in the outer contours.

Additionally, the study found that mesh models can be susceptible to color variations, which may subjectively affect judgment during manual measurements. This variation in color can cause measurement discrepancies, particularly when relying on visual clues beyond the model's geometric edges.

c. Complementarity and application scenarios

The findings of this study suggest that, with current technology, neither point cloud nor mesh models alone are sufficient to meet the higher accuracy requirements of modern surveying tasks. However, the two data types have the potential to complement each other, addressing their respective limitations. Point cloud is good at accurately describing color boundaries and textures, as well as providing detailed geometric information. Mesh models, on the other hand, are more suitable for visualizing the overall geometric structure of the target, offering a more comprehensive representation for visualization and presentation.

The integration of both point cloud and mesh models, based on the specific needs of the task, can significantly enhance the effectiveness of surveying operations. However, a major limitation is that only Cloud Compare currently supports the overlay of both data types, while most other software platforms support only one type of format. Therefore, to fully realize the potential of combining point cloud and mesh model data, it is essential to develop a platform capable of simultaneously visualizing and processing both types of models. This would enable more accurate and efficient surveying, addressing the limitations observed in current workflows.

d. Future improvements and research directions

This study explored the application of point cloud and mesh models in spatial information acquisition tasks. However, with the continued advancement of technology and the increasing demand for applications, many unresolved issues and challenges remain. Future research could focus on the following directions:

- **Comparison of mesh model processing on different platforms**

Different software platforms use varying algorithms and parameter settings in generating mesh models, which significantly impacts the final model results, as indicated in Table 42. Future research could explore more methods of mesh model production, helping to generate the most suitable mesh models for specific surveying needs while avoiding biased conclusions based on a single model.

Table 42: Mesh models at different depths with varying parameter settings.

Level 8	
Level 10	

- **Impact of different file formats on geometric accuracy**

File formats (i.e., obj., ply.) have different effects on the geometric representation of mesh models. Future research could delve into analyzing the advantages and disadvantages of these formats in surveying applications, particularly regarding their impact on model accuracy.

- **Enhancing the integration of automated processing and manual editing**

While current automated technologies are not yet fully developed and still require manual involvement for model drafting and correction, future improvements in software functionalities could help detect objects or features within models and allow for manual edits after automated processing. This approach could effectively reduce the amount of manual correction work and improve overall surveying efficiency.

- **Balancing measurement efficiency and accuracy**

Future research should focus on finding the optimal balance between measurement efficiency and accuracy. This not only involves choosing the appropriate file formats and software tools but also optimizing model processing workflows and software resource management. The goal is to ensure that large-scale surveying projects can maintain efficient operation while achieving the required accuracy standards.

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