3D SCAN PLANNING OF OUTDOOR CONSTRUCTIONS BASED ON PHOTOGRAMMETRIC MODEL AND MATHEMATICAL OPTIMIZATION

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ABSTRACT: *A 3D scanner is capable of capturing surface shapes of the objects as a set of "point cloud" and is extending its applicability toward examining, re-designing and preserving the existing constructions as well as on-site information for BIM. One of the most difficult problems to collect complete surface data of outdoor constructions is to avoid self and mutual occlusions. If we want to collect complete data for covering whole surfaces of the constructions, then we have to measure them from multiple points usually. Moreover, multiple measurements require plenty of time and labor, and each measurement gives a data set consisting of hundreds of millions of 3D points to be processed for further computations. So it is very important to make an effective measurement plan a priori for avoiding redundancy for both labor and computational costs. In this research, therefore, we propose a method for 3D-scan planning of outdoor constructions based on photogrammetric models and mathematical optimization methods. In our proposed method, we first use photogrammetric techniques and make a rough 3D model of measurement scenery: we take photographs of the targets by a calibrated digital camera, and find corresponding characteristic points over the photographs, for example corners and intersection points of edge lines. Next, we triangulate the corresponding points by using 3D photo-modeling software. Finally, we obtain the rough 3D mesh model. After that, we make the optimal scan plan based on the rough 3D mesh model by using some mathematical methods: we examine the visibility and self/mutual occlusion property of each polygon of the 3D mesh, and calculate the minimum number of measurement points and their layout to scan all the surfaces of the targets. Moreover, our proposed method can calculate the optimal layout of the designated number of measurement points to maximize the obtainable data.*

KEYWORDS: *3D-Scan Planning, Photogrammetric Model, Mathematical Optimization.*

1. INTRODUCTION

A laser range scanner is a 3D surface imaging system which can obtain the surface data of target objects by performing a number of independent ranging, and a 3D image emerges by merging them. Laser scanners can be used for consistent and vast assessment of spatial conditions required by a variety kinds of construction applications such as investigation of management of construction processes (Shih et al. 2004, 2006), monitoring the as-built infrastructures (Miller et al. 2008), consequences of disasters (Watson et al. 2011) and so forth. Most of these applications require timely spatial information delivery. Collecting the needed information within limited time, therefore, is critical for many field applications on construction sites.

One of the most difficult problems to collect the complete surface data of target objects is to avoid occlusions. For collecting the complete data, we have to measure the objects from multiple viewpoints usually. However, examining multiple surface visibilities relative to variable multiple viewpoints is a complicated problem. Moreover, multiple measurements require plenty of time and labor, and each measurement gives a data set consisting of hundreds of millions of 3D points to be processed for further computations. Hence, it is very important to make an effective measurement plan a priori for avoiding redundancy for both labor and computational costs.

Since the advent of laser scanners, designing efficient and effective operation methods of a laser scanner has been developed as view planning. The existing view planning techniques are trial-based schemes, which segment

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scanned and unscanned regions in the target area to find the next best scanning viewpoint for minimizing the unscanned regions. This approach includes the methods for improving efficiency of sequential scanning (Asai et al. 2007, Pitto 1999, Pulli 1999) and three-dimensional environmental map generation by autonomous mobile robots (Blaer and Allen 2009, Grabowski et al. 2003, Surmann et al. 2003). These view planning techniques are designed for coping with a dilemma; the geometrical topology of the object is unknown until it is scanned. And thus the sequential scheme to estimate the next best viewpoint is based on the scanned data configuration. In other words, sequentially searching approaches do not meet the demands for outdoor scanning, where estimating the minimum time and cost for the whole scanning task before starting the survey process is important for practical operation.

For this problem, the authors proposed a method for making a measurement plan by using a ground plan of a target area as prior information (Dan et al. 2010). This method generates an optimized initial view plan prior to the on-site survey by using mathematical optimization. However, this method is based on a 2D plan, and hence, it is useful only for the cases where the height differences of the objects are not important comparatively. Therefore, in this paper, we propose an effective planning method for 3D geometry of the jobsite by calculating visibility and the amount of obtainable data based on simple photogrammetry techniques for preliminary survey. Since the view planning method itself follows the mathematical optimization framework, finding the least number of measurements needed to measure all the surfaces of the objects and the viewpoints' setup to maximize the total amount of scanned data within the limitation of the number of measurements.

2. GOAL AND APPROACH

The goal of this research is to propose a method for making a plan to scan the target outdoor constructions by using a 3D scanner. The scan plan must specify the scanning points from which we can scan all the surfaces of the target constructions.

To make a scan plan, we have to estimate the visibility of the faces of the target objects and the quality of the scan data. When we use a 3D scanner, it is the most important to consider the visibility of the target objects from the points we set a 3D scanner, and the visibility is determined by self and mutual occlusion. Self occlusion occurs when a part of the target object overlaps itself while seeing from a viewpoint. On the other hand, mutual occlusion occurs when the other target overlaps the target object. Self and mutual occlusion interferes scanning, and hence we must examine the occlusion property in the target area. Also, quality of the scan data highly depends on the scan density since the 3D shape information can be only read from the point set of the scan data. Higher and uniform scan density is preferable in general.

It is necessary for estimating the visibility and the scan quality to model the onsite condition, that is, the object and surroundings geometries. In this research, we employ photogrammetric techniques to model the target area. Also, we triangulate the obtained model. Triangulation of the surfaces of 3D objects is very common, and it is very advantageous to estimate the visibility and the scan density.

A scan plan should have good properties to meet the following requests:

[Request 1] We can scan all the surfaces of targets with avoiding self and mutual occlusion.

[Request 2] The number of times we scan should be minimized.

[Request 3] The amount of the obtainable data should be maximized with the limited number of scans.

To find the scan plan which has these properties, we employ mathematical optimization. First, we formulate and solve the optimization problem for [Request 1] and [Request 2]. The solution of this problem gives us the number of scans to respond to [Request 1] and [Request 2]. After that, we formulate another optimization problem for [Request 3] and this problem is solved with the minimum number of scans which is obtained from the previous problem. Moreover, the values of parameters used for formulating these problems can be determined from the photogrammetric model which we explained above.

In Section 3, we explain the photogrammetric modeling of the target area and its triangulation. In Section 4, we explain a method for examining the visibility and the scan density by using the photogrammetric model. And in Section 5, we consider the optimization models to find the optimal view plan.

3. PHOTOGRAMMETRIC MODELING FOR CONFIGURATION SETUP

In this research, photogrammetric models play a role to allow simulating the visibility of the target objects from candidate viewpoints of the scanner. To represent the 3D region occupied by the objects, its 3D model is prepared as a polygon model circumscribing the object volume. The 3D model of the objects consists of polygon meshes whose faces can be used for checking not only their visibilities but also their scan density from the viewpoints. The 3D model of the surrounding structures produces possible visual occlusion from a certain viewpoint to the surfaces of the objects.

To prepare this 3D model, photo-based modeling is suitable for scanning plan of many construction applications, since taking photos is common procedure for preliminary survey of the jobsite. In recent years, several stereo-vision types of digital cameras are available and make it easy to collect multiple-view photos. Furthermore, web-based application providing onsite photos from pedestrian’s point of view and aerial photos taken from multiple viewing angles are open to the public and can be used for the planning even at office nowadays. For example, Google Street-view and Google Earth provide us such photos.

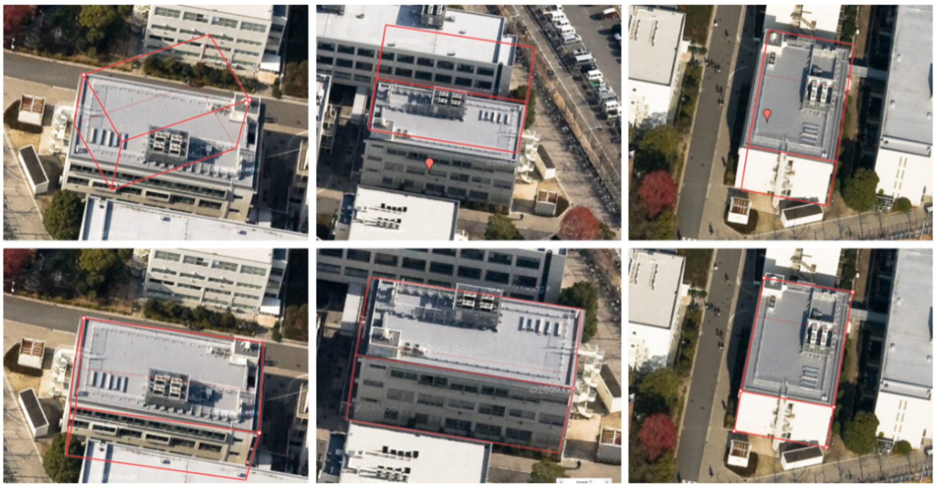

Fig. 1: Modeling process by Building Maker; Adjusting the size and positions of the bocks corners to that of building on the photos

Specifying corresponding points on the objects between multiple photos, visual triangulation can be performed to reconstruct 3D coordinate of the corresponding points e.g. corners of pillars, beams and sashes etc. of the buildings (Hartley et al. 2004). In addition, many kinds of commercial software for photogrammetry are also available, e.g. PhotoModeler, 2D3, Google SketchUp, Building Maker and so on (Figures 1, 2 and 3).

Fig. 2: Example of aerial photo set from multiple views; a building with a balloon is the target**.**

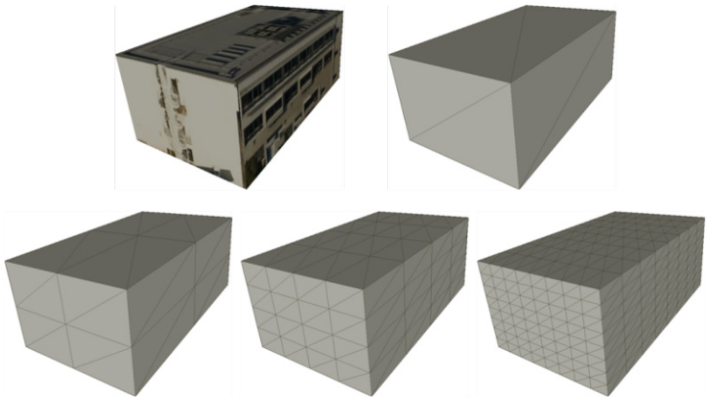

Fig. 3: Object model by Building Maker with and without texture (upper left and right), and recursively subdivided mesh models with mid-points method (lower).

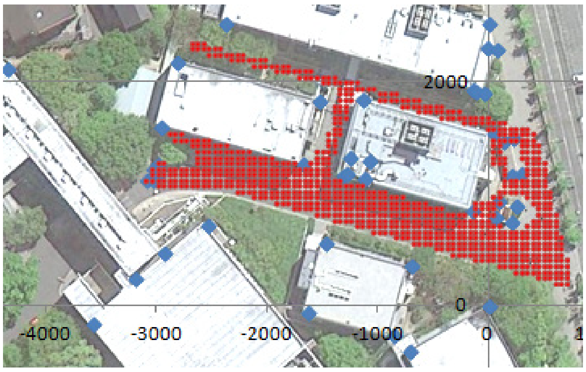

Fig. 4: Example of candidate viewpoints arrangement; Each red dot is a candidate viewpoint.

Moreover, we have to prepare candidate viewpoints, where the 3D scanner can be settled, in the obtained model (Figure 4).

4. VISIBILITY AND SOLID ANGLE OF TRIANGLE

As mentioned in the previous section, the surfaces of all the objects in the target area are approximated by triangles and a part of them are the target triangles, which have to be measured by a 3D scanner. For these triangles, we have to examine the visibility from the candidate viewpoints to make a scan plan. Moreover, the solid angles of the triangles viewing from the candidate viewpoints are also needed.

4.1 Visibility

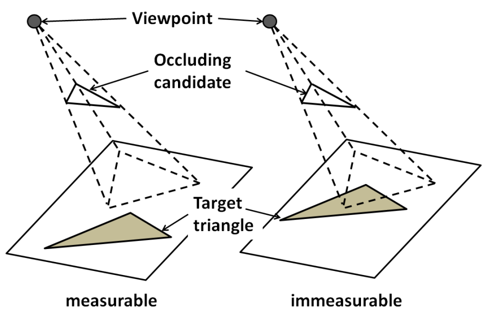

Fig. 5: Relationship between a viewpoint and a target triangle

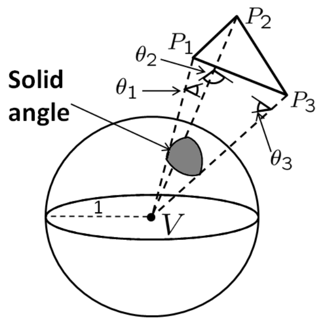

Fig. 6: Solid angle

Figure 5 shows the relationship between a viewpoint and a target triangle. If a triangular pyramid generated by a viewpoint and a target triangle intersects another occluding triangle, then the target cannot be scanned from the viewpoint; otherwise, it is measurable. To examine such relationship, we have to employ some mathematical methods. The authors have already proposed a method for this examination (Dan et al., 2011).

4.2 Solid Angle

For the case that $\Delta P_1P_2P_3$ is measurable from V, we have to calculate the amount of data which would be obtained by a 3D scanner. From the principle of a 3D scanner, the amount of obtainable data is proportionate to the solid angle of $\Delta P_1P_2P_3$ from V. A solid angle of $\Delta P_1P_2P_3$ from V is defined to be the area of the intersection of the cone generated by V and $\Delta P_1P_2P_3$ and a sphere of unit radius (Figure 6).

It is known that the solid angle of $\Delta P_1P_2P_3$ from V can be obtained by

$$s = \theta_1 + \theta_2 + \theta_3 - \pi,$$

where $\theta_i\,(i=1,2,3)$ are the three angles between three side faces of the triangular pyramid V - $P_1P_2P_3$ (Figure 6).

5. SCAN PLANNING BY MATHEMATICAL OPTMIZATION

In this section, we formulate two 0-1 integer optimization problems. As discussed above, these models have been proposed in the previous research (Dan et al., 2010). We use the same model in this paper.

We will use the following symbols in the mathematical optimization models in this paper:

[Sets and Indexes]

- $i \in I$: candidate points for measurement,
- $t \in T$: triangles on the surfaces of measurement objects.

[Variables]

$$x_i := \begin{cases} 0, & \text{a candidate point } i \text{ is unadopted as a viewpoint,} \\ 1, & \text{a candidate point } i \text{ is adopted as a viewpoint.} \end{cases}$$

[Parameters]

$$d_{it} := \begin{cases} 0, & \text{a triangle } t \text{ is unmeasurable from a candidate point } i, \\ 1, & \text{a triangle } t \text{ is measurable from a candidate point } i, \end{cases}$$

$$a_{it} := \begin{cases} 0, & d_{it} = 0, \\ \text{the amount of scanned data on a triangle } t \text{ from a candidate point } i, & d_{it} = 1, \end{cases}$$

$r :=$ the upper bound of the number of measurement.

Note that we can calculate the values of parameters, d_{ij} and a_{ij}, from the 3D model on the target area, as we explained in the previous section.

In this paper, we use these two mathematical optimization models (Dan et al, 2010):

$$\begin{aligned} \text{minimize} \quad & \sum_{i \in I} x_i \\ \text{subject to} \quad & \sum_{i \in I} d_{ij} x_i \geq 1 \quad (\forall j \in J), \\ & x_i \in \{0,1\}. \end{aligned} \tag{1}$$

$$\begin{aligned} \text{maximize} \quad & \sum_{i \in I, j \in J} a_{ij} x_i \\ \text{subject to} \quad & \sum_{i \in I} d_{ij} x_i \geq 1 \quad (\forall j \in J), \\ & \sum_{i \in I} x_i \leq r, \\ & x_i \in \{0,1\} \quad (\forall i \in I). \end{aligned} \tag{2}$$

The objective function of (1) is to minimize the number of viewpoints. Also, the term $d_{ij} x_i$ in the first constraint of (1) means as follows:

$$d_{ij} x_i := \begin{cases} 0, & \text{a candidate point } i \text{ is unadopted as a viewpoint } (x_i = 0) \\ & \text{or a triangle } j \text{ is unmeasurable from } i \ (d_{ij} = 0), \\ 1, & \text{a candidate point } i \text{ is adopted as a viewpoint } (x_i = 1) \\ & \text{and a triangle } j \text{ is measurable from } i \ (d_{ij} = 1). \end{cases}$$

Therefore, the first constraint of (1) means that all the triangles should be measured from one viewpoint at least. Consequently, we can find the least number of viewpoints to scan all the target triangles by solving (1).

The term $a_{ij} x_i$ of the objective function of (2) means as follows:

$$a_{ij} x_i := \begin{cases} 0, & \text{a candidate point } i \text{ is unadopted as a viewpoint } (x_i = 0) \\ & \text{or a triangle } j \text{ is unmeasurable from } i \ (a_{ij} = 0), \\ a_{ij}, & \text{a candidate point } i \text{ is adopted as a viewpoint } (x_i = 1) \\ & \text{and a triangle } j \text{ is measurable from } i \ (a_{ij} > 0). \end{cases}$$

Therefore, the objective function of (2) is to maximize the sum of the amount of scanned data. In addition, the second constraint of (2) is to restrict the number of measurements less than or equal to r. Here, r is normally equal to the optimal value of the problem (1), that is, the minimum number of viewpoints to scan all the surfaces of the targets. Consequently, by solving (2), we can obtain the optimal layout of r viewpoints to collect the scanned data as much as possible.

6. EXPERIMENTS AND DISCUSSIONS

In this section, we report some practical experiments by using our proposed method and discuss about the obtained result.

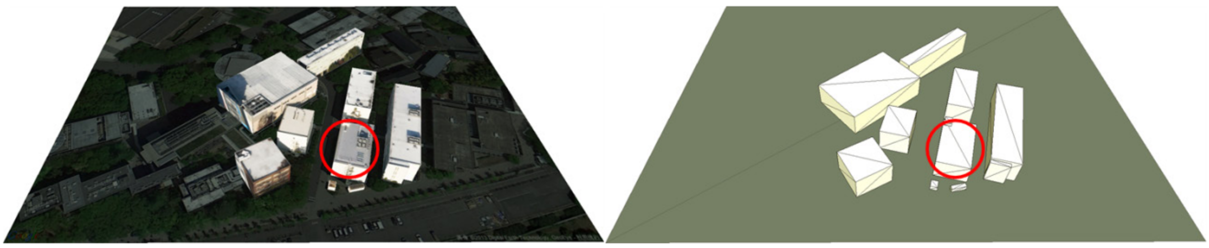

Fig. 7: The target building (left) and 3D mesh model around the target (right)

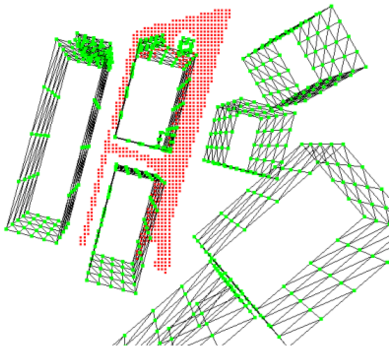

Fig. 8: 3D mesh model of the target scenery

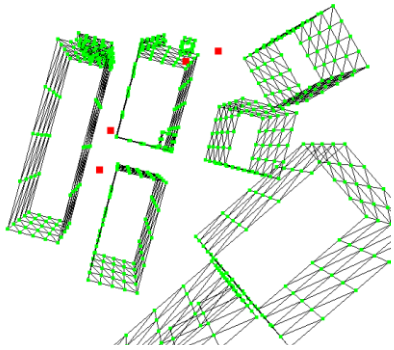

Fig. 9: The optimal layout of four viewpoints

(The building surrounded by candidate viewpoints in Figure 8 is the target.)

6.1 Scan Planning by Proposed Method

First, we have chosen one of buildings in the campus of Kansai University as a target building: we make a scan plan to measure the building and scan it practically in accordance with the obtained scan plan. Figure 7, left shows the target building. As you see, the target building is surrounded with other buildings and the area to set a scanner is comparatively narrow.

Second, we have made a rough 3D mesh model of the scenery around the target and set the candidate viewpoints by using Building Maker by Google. Figure 7, right shows the original mesh model, and we have subdivided the triangles on the surface of the mesh model. Consequently, we have obtained the mesh model of the target area and the candidate viewpoints (Figure 8). The detail of this model is in Table 1.

Table 1: Summary of the mesh model in Figure 8

	# vertices	# triangles
All	706	1124
Target	80	128

candidate viewpoints: 835

Next, we have examined the visibility of the target building and calculated the amount of obtainable data by using the method in Section 4. After that, we have calculated the smallest number of viewpoints to scan all the surfaces of the target building by solving (1): the smallest number of viewpoints to scan all the surfaces of target is equal to 4. Then, we have solved (2) to find the optimal layout of 4 viewpoints, that is, $r = 4$ holds, to maximize the amount obtainable data. The obtained optimal layout is Figure 9. Moreover, the experimental environment which we have used is shown in Table 2. The total calculation time is about 1 minute: the time for the visibility check and calculating the solid angle is 62.63 (sec.), and the times for solving the problem (1) and (2) are 0.01 (sec.) and 0.06 (sec.), respectively.

Table 2: Experimental environment

PC	Lenovo X230
OS	Windows 7 Professional SP1
CPU	Intel Core i7-3520M @ 2.90GHz
Memory	16.0 GB
Optimization Solver	CPLEX 12.5

6.2 On-site Scanning with the Obtained Plan

In accordance with the obtained scan plan, we have scanned the target building by using the 3D scanner LMS-Z420i manufactured by RIEGL.

Figure 10 shows the obtained data by the 3D scanner. This figure is made by merging the data sets which were scanned from the four viewpoints. We can confirm that all the walls of the target building have been scanned. However, there are some obstacles to scan the walls, for example, trees, roofs, circular staircases and so on (Figure 11). Consequently, a part of walls lacks in the data.

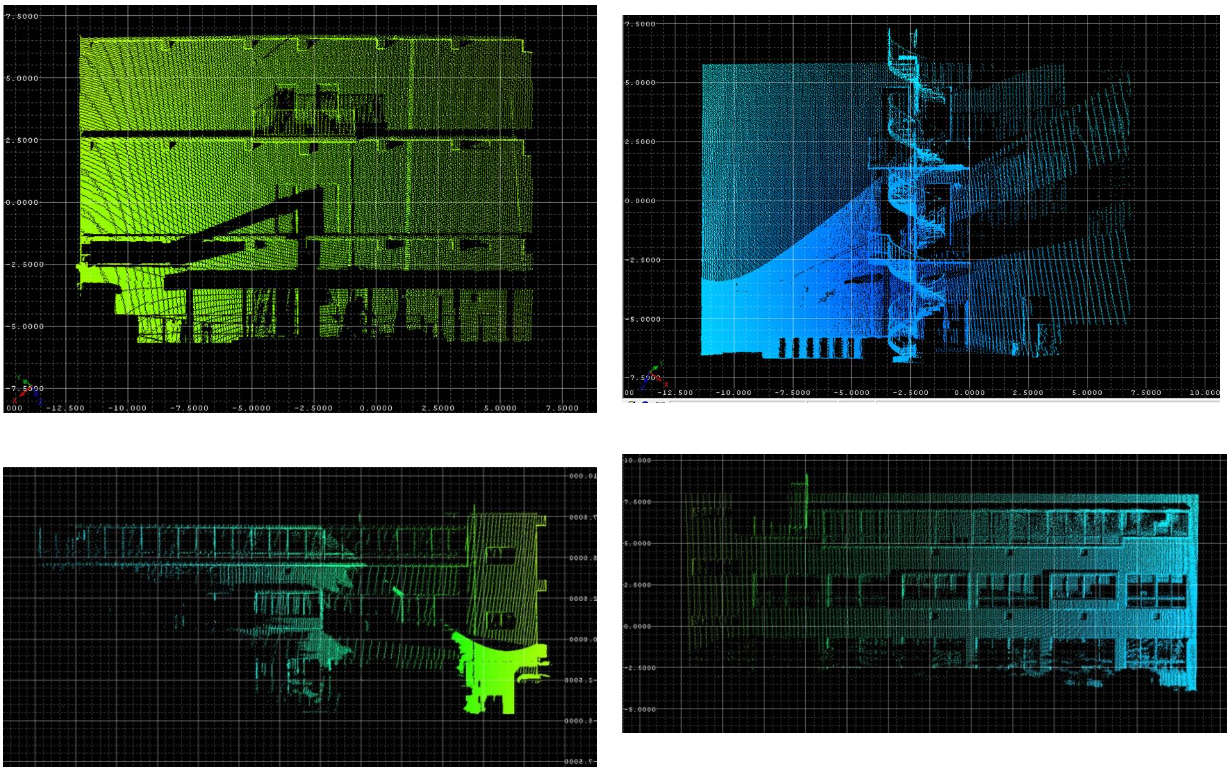

Fig. 10: The scanned data in accordance with the obtained scan plan

6.3 Discussions

Figure 12 shows that the shape of the building which is obtained by the scanned data roughly coincides with the shape of the mesh model. It ensures that the photogrammetric model is very advantageous for our proposed method.

However, as we can see in Figure 12, the height direction gap between the scanned data and the mesh model is comparatively large. This gap may occur from the height difference of the viewpoints. In this experiment, we have employed Building Maker by Google[2]. Building Maker assumes that the buildings are rectangular solid. Accordingly, it is assumed that the field is level implicitly. On the other hand, the area has some moderate slopes. This is the reason why the height direction gap occurred.

[2] Unfortunately, this sophisticated service is scheduled to be closed on 1 June, 2013.

Fig. 11: On-site photos; there are some obstacles for practical scanning

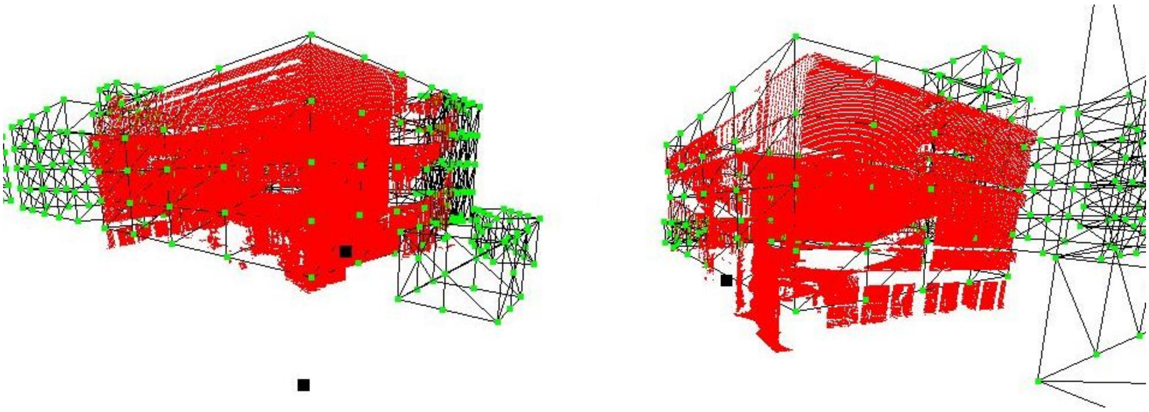

Fig. 12: The scanned data and the mesh model

As we explained above, the scanned data does not cover the target building completely because of obstacles, for example, trees, circular staircases and so on. A straightforward idea to avoid lacking the scanned data is to model the obstacles around the target objects on site. Also, for this purpose, we need some portable interface which can reflect the on-site condition in the rough 3D mesh model.

7. CONCLUSION

In this paper, we proposed a method for making a scan plan for outdoor constructions. Photogrammetric techniques give us a rough 3D model of the target area, and we can calculate the optimal viewpoints by using the model. The optimality of the obtained plan is based on minimization of the number of viewpoints and maximization of the amount of the obtainable data. Moreover, the practical experiment ensures the effectiveness of our proposed method.

8. ACKNOWLEDGEMENT

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