

A SERVER-CLIENT SYSTEM FOR OPTIMIZED PLANNING OF OUTDOOR 3D LASER SCANNING

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ABSTRACT: Effective and practical planning for laser scanning of outdoor construction is a challenging task. The selection of scanner positions according to on-site conditions within a limited time typically depends on ad-hoc procedures based on an operator's personal experiences. By using mathematical programming, the authors have been developing a planning technique to obtain minimum scan positions and their best configuration as an optimized solution. This technique takes into account the visibilities of the target object from every candidate scan position, based on precedent information such as 2D plans of the jobsite or primitive 3D models based on photogrammetry before starting the on-site scanning. Because existing applications cannot handle replanning and additional jobsite conditions, adhering to a prepared plan is often difficult. This paper proposes a mobile application to deal with the replanning functionality. Using a server-client system implementation, the proposed method transfers the high computational capability of the server to a mobile client at a jobsite.

KEYWORDS: Laser Scanner, Optimized Planning, On-site Work, Server-client System

1. INTRODUCTION

A laser range scanner is a 3D surface imaging system that can obtain the surface data of target objects. Laser scanners can consistently assess the vast spatial conditions present in various construction applications, including managing construction processes (Shih et al. 2004, 2006), monitoring as-built infrastructures (Miller et al. 2008), evaluating the consequences of disasters (Watson et al. 2011), and so forth. Most of these applications require timely spatial information as input. Collecting the needed information within a limited time, therefore, is critical for many field applications on construction sites.

For collecting a set of complete surface data of an object, repeated scanning of an object from multiple viewpoints is needed. However, examining the

visibilities of the object surfaces from different viewpoints is a complicated problem. Furthermore, as the number of measurements increases, the time and labor increase. Hence, effective scanning plans are necessary beforehand. A scanning plan or view planning with a laser scanner has been developed in trial-based schemes. In such schemes, segments in scanned and unscanned regions in a target area are used to find the next best scanning viewpoint for minimizing the number of unscanned regions (Pitto 1999, Pulli 1999, Asai et al. 2007). In addition, 3D environmental map generation by autonomous mobile robots (Blaer and Allen 2009, Grabowski et al. 2003, Surmann et al. 2003) has been investigated. However, the trial-based method is not able to preplan the total scanning procedure. Therefore, Dan et al. (2010) proposed a basic planning

method by using the ground plan of a target area before on-site scanning. This method generates an optimized scanning plan by mathematical programming. Estimating the minimum scale and the complexity of the whole scanning task is possible by examining the visibility of wall segments of the target object from the candidate scanner positions. This framework can be extended to a 3D version of the visibility check as reported in Dan et al. (2011) Dan et al. (2012) also designed an interactive graphical user interface (GUI) to reflect the on-site conditions by allowing the user to edit the 2D diagram intuitively. This interactive editing could potentially enable field-oriented feedback to acquire a newly optimized view plan. This paper describes a practical implementation scheme to realize a total system that combines the high computational capability for an optimal scanning plan and a lightweight mobile GUI system to flexibly deal with on-site conditions.

2. METHODOLOGY

2.1 Overview

This paper uses an optimization scheme with mathematical programming and a 3D version of a visibility check by using photogrammetry to obtain simple 3D modeling. Photogrammetry allows the arrangement of primitive 3D models of the target site without visiting the jobsite. By using a set of multiple photos of the target site, the buildings can be modeled as a set of 3D primitive shape models based on the visual triangulation technique (Hartley and Zisserman 2004). The primitive models can then be used as a visibility check of the target walls from candidate viewpoints. At this point, the optimization scheme selects the minimum combination for the best scanning plan.

Therefore, this paper focuses on bringing this approach to an on-site work application, which allows users to perform trial-and-error tasks while op-

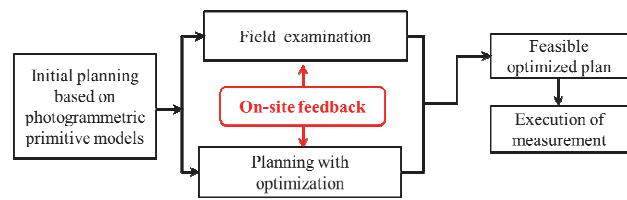


Figure 2.1: Schematic flow of scanning work

erating 3D models according to the conditions and on-site examination. Figure 2.1 shows the measurement work flow proposed in this paper. To enable this work flow, we provide a mobile device with an interactive GUI to reflect the on-site conditions. Figure 2.2 shows the functionality of the mobile system that we are going to realize in the objective work flow. This framework enables field-oriented feedback to acquire a practical view plan by taking into account the information that is impossible to know in advance. The GUI allows the user to edit and update the 3D models intuitively and then interpret the 3D geometry into the parameters of the mathematical programming models to find the newly optimized scanning plan. We can expect that this GUI will help users who are non-professional mathematical programmers to make a view plan that reflects the on-site conditions.

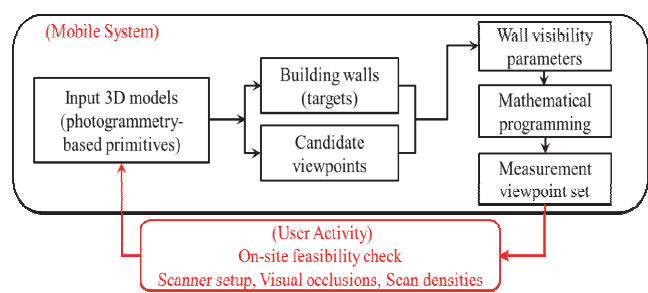


Figure 2.2: Proposed work flow with on-site feedback

2.2 Scan planning by mathematical programming

Formulation

Dan et al. (2010) proposed the formulation of two 0-1 integer optimization problems for the scan-

ning plan. We use the same formulation in this paper. The following symbols are used 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 of the target area.

In this paper, we use the following two mathematical optimization models, presented in (2.1) and (2.2):

$$\begin{aligned} & \text{minimize} && \sum_{i \in I} x_i \\ & \text{subject to} && \sum_{i \in I} d_{ij} x_i \geq 1 \quad (\forall j \in J), \\ & && x_i \in \{0,1\}. \end{aligned} \quad (2.1)$$

$$\begin{aligned} & \text{maximize} && \sum_{i \in I, j \in J} a_{ij} x_i \\ & \text{subject to} && \sum_{i \in I} d_{ij} x_i \geq 1 \quad (\forall j \in J), \\ & && \sum_{i \in I} x_i \leq r, \\ & && x_i \in \{0,1\} \quad (\forall i \in I). \end{aligned} \quad (2.2)$$

The objective function of (2.1) is to minimize the number of viewpoints. The term $d_{ij}x_i$ in the first constraint of (2.1) has the following meaning:

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

Therefore, the first constraint of (2.1) means that all the triangles should be measured from at least one viewpoint. Consequently, we can find the least number of viewpoints to scan all the target triangles by solving (2.1).

The term $a_{ij}x_i$ of the objective function of (2.2) has the following meaning:

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

Therefore, the objective function of (2.2) is to maximize the sum of the amount of scanned data. In addition, the second constraint of (2.2) is to restrict the number of measurements less than or equal to r . Here, r is typically equal to the optimal value of the problem (2.1), that is, the minimum number of viewpoints to scan all the surfaces of the targets. Consequently, by solving (2.2), we can obtain the optimal layout of r viewpoints to collect as much scanned data for the target surfaces as possible.

Visibility check for optimization conditions

Using 3D primitive shaped models, 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 the 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 viewed from the candidate viewpoints are also needed.

Figure 2.3 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 a relationship, we employ some mathematical methods. The authors already proposed a method for this examination

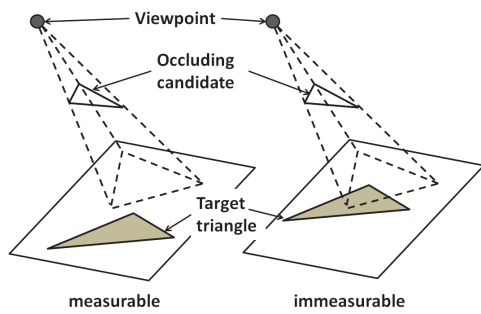


Figure 2.3: Relationship between a viewpoint and a target triangle

based on Dan et al. (2011).

2.3 Initial planning

In this research, 3D models of the target scene allow the simulation of the visibility of target objects from the candidate viewpoints of a scanner. To represent the 3D region occupied by the objects, a 3D model is prepared as a polygonal model circumscribing the object volume. The 3D model of the objects consists of polygonal 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 can verify possible visual occlusion of the object surfaces from a certain viewpoint.



Figure 2.4: Photogrammetry-based modeling process with multiple photos; Building Maker allows adjusting the size and positions of the blocks corners to that of building on the photos.

To prepare this 3D model, photogrammetry-based modeling is a suitable scanning plan of many construction applications, since taking photos is a common procedure for preliminary surveys of a jobsite. In recent years, several stereo-vision types of digital cameras have become available and make it easy to collect multiple-view photos. Furthermore, web-based applications providing on-site photos from a pedestrian's point of view and aerial photos taken from multiple viewing angles are available to the public and can be used for planning, even from an off-site office. For example, Streetview (Gogle Street Viwe) and GoogleEarth (Google Earth) provide us such photos. As shown in Figure 2.4, we used Building Maker by Google Inc. for preparing 3D models of the buildings in the target scene¹ (Figures 2.4, 2.5).

2.4 On-site plan refinement

By using the photos taken from a limited number of view directions for photogrammetry, the generated primitive 3D models are rather simple and approximate. To make a more realistic scanning plan, on-site investigation must be taken into account in preparing the 3D models, which greatly affect the visibility check in optimization planning. Some trees

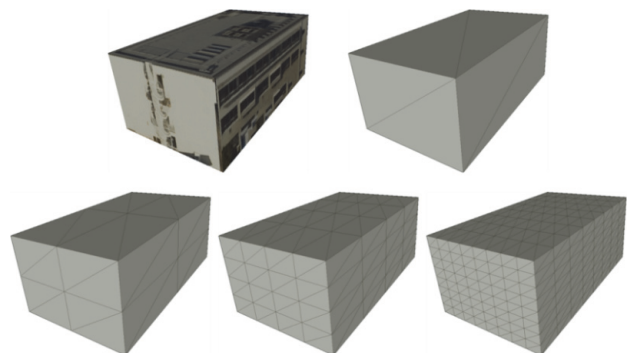


Figure 2.5: Object model by Building Maker with and without texture (upper left and right), and recursively subdivided meshes with mid-point method (lower).

¹ Unfortunately, this service closed on 1 June 2013.

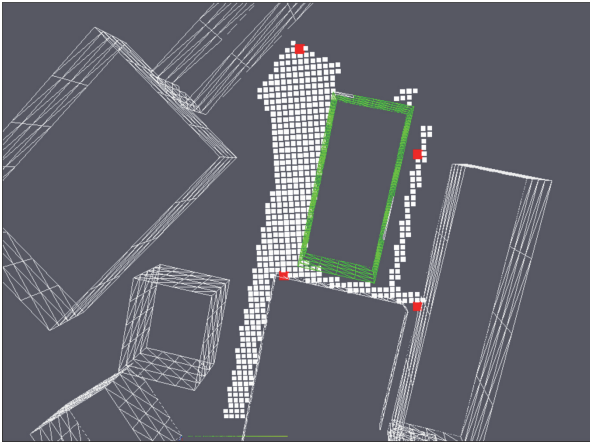


Figure 2.6: An example of an optimal scan plan; four viewpoints (red points) are selected as the minimum set of scanner positions for the target building (green lines) from candidate scanner positions (white dots).

nearby and outdoor installations may obscure a wall surface of the target building from some candidate scanner positions. These kinds of obstacles are easily found by on-site observation and are desirably modeled and added to the planning conditions. On the other hand, the scanning target may also have to be altered. When some parts of the building surface have a scanning priority, deselecting low-priority parts from the scanning target surface relaxes the optimization conditions to acquire a realistic scanning plan. Otherwise, feasible scanning plans would not be found by the solver for tough cases, in which the number of obstacle objects is many and the number of candidate scanner positions is small, for example.

On-site investigation requires a worker to move around and check the planimetric features around the target building, in contrast with a prepared scanning plan. A highly mobile device is preferable for bringing the scan-planning capability to the worker. The input information of our optimizing solver module requires vertex lists in triangle meshes of the 3D models. Since this list can be easily transmitted via Internet connection, we apply a server-client frame-

work, in which a lightweight mobile device is the user interface for manipulating an on-site planning task, while the server supports the optimal computation process with a powerful solver module.

3. IMPLEMENTATION FOR SERVER-CLIENT SYSTEM

3.1 System overview

Figure 3.1 shows the proposed configuration of the schematic server-client system. The key method is to introduce the HTML5 standard for compatible implementation of both the graphical view capability on the client side and a standard messaging interface for interactive communications. WebGL is an implementation of the JavaScript version of OpenGL ES (embedded system) package which follows the HTML5 standard. HTML5 resources are basically web pages running on web browsers, but are also capable of handling local graphics hardware resources for sophisticated 3D representation. As for the server side, the core functionality for computing an optimal scanning plan is realized by the native C++ solver library of CPLEX, which can be wrapped by Java Native Access (JNA) for access by Java codes. Thus, a consistent system implementation with Java provides a Java Servlet interface to communicate with the client side. From

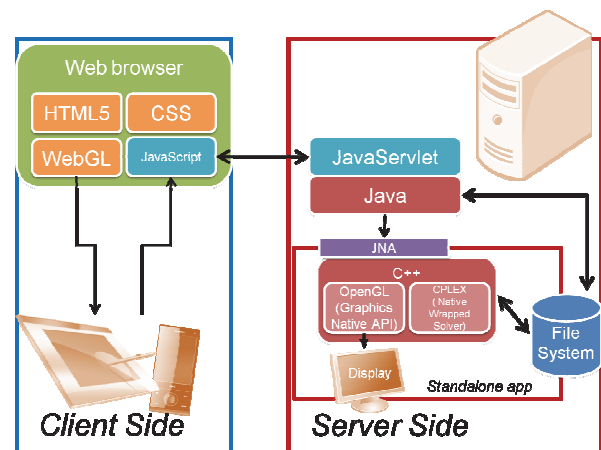


Figure 3.1: The proposed system configuration

a web browser on the tablet, the server access can be easily established by specifying the IP address, the port and the html location by asynchronous communication. The server can trigger the planning calculation by messaging from the client, and then the computation of the optimized planning runs as a standalone application (Figure 3.1). The result is saved in the file system of the server, so that the client can fetch it for visual feedback to the user.

Between the client and the server, a data file of 3D models is transmitted. This data contains 3D model information, including the vertex coordinates of polygonal vertices and mesh connections, as well as a candidate viewpoint list and their coordinates. Polygon models have ID tags for distinguishing the scanning target. The data context is designed in our project, but the format is based on JavaScript Object Notation (JSON), a subset of the JavaScript programming language. JSON is a lightweight data-interchange format and is easy for machines to parse and generate. In addition, the text style of the file description is easy for humans to read and write, as shown in Figure 3.2. A client device uses the data file to display the existing scanning plan to the user with 3D CG by WebGL. The client device also allows the user to directly access the scanning plan and modify the planning conditions. The server side

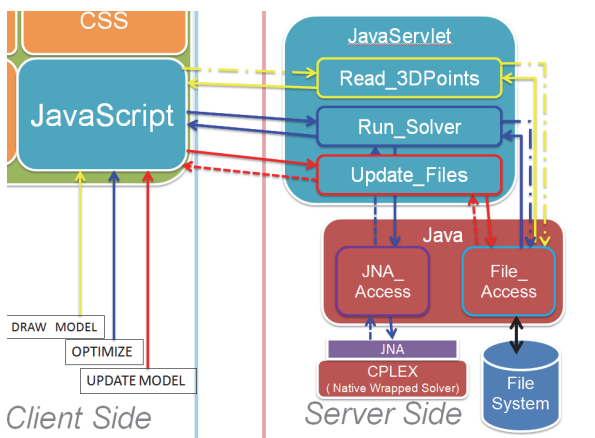


Figure 3.2: Flow of data between the client and the server for updating the conditions and recalculating the new solution of a scanning plan

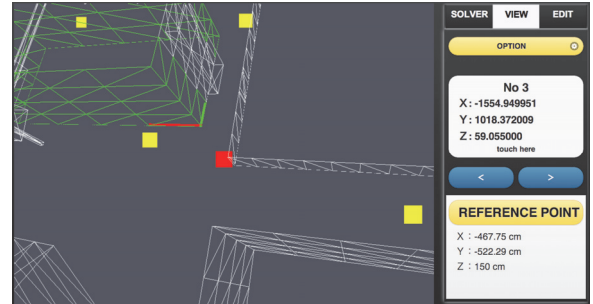
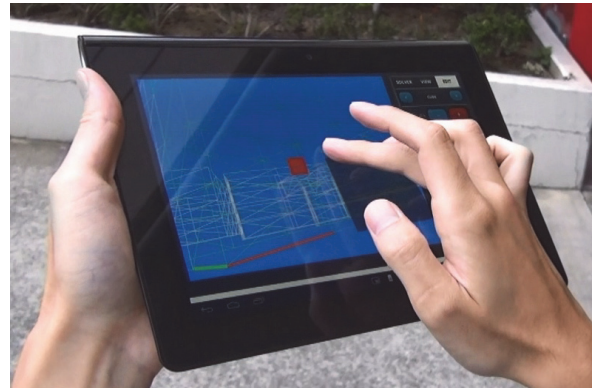


Figure 3.3: Implemented mobile client on a tablet (upper) and view details of the plan (green highlighted mesh is the target building) (lower)

uses the 3D model data for computing the visibility check to solve the mathematical programming along with the formulation described in Section 2.2.

3.2 Implemented functionality

For the client side device, we designed the user interface to manipulate and modify the 3D models by direct manipulation without specifying numerical properties, such as ID numbers of the objects, the coordinates of the vertices or viewpoints, as shown in Figure 3.3. The user is supposed to place and arrange the 3D object in the virtual 3D space for planning as a counterpart of the physical space in sight. Possible obstacles, such as trees and other objects, can be added to the planning space, while considering relative size and positions from the target building based on observation and simple range measurement on the spot. The objects are simple polygonal meshes or box-type primitives, which are deformable and easily chained to their positions and

sizes on the tablet display by the user. Once the 3D models are added to the space, the client system lists the coordinates of the 3D geometry and uploads the data to the server.

Arbitrary surface meshes in 3D models can be selected by controlling a bounding volume to include the meshes within it. The user can select the existing model(s) in various scales from a single triangle mesh to whole meshes of multiple 3D objects. This allows the user to select or deselect the surface(s) of the wall(s) for editing a scanning target list as well as for deleting objects. The lists of the total meshes and the scanning target meshes are managed by the mesh ID numbers in the JSON file. The JSON file is used for highlighting target meshes in the view on a client device while transmitting updated scanning plan conditions to the server.

The client device does not always require network communication with the server. On-site work of editing the 3D models can be conducted in a standalone application without a network connection. Updating the 3D model conditions and recalculation of the optimal planning require connection with the server. After information of the newly computed scanning plan is returned from the server, again the client works as a standalone application to display the plan and conduct further edits in the off-line status. By the implemented functions described above and by refining the model of the visibility conditions in a trial-and-error manner, based on the in-situ observation, it is possible to acquire a realistic and effective plan.

4. Experiment

We implemented the proposed system with a desktop PC (Core2 Quad, 2 GHz, 2 GB RAM) for the server side and a tablet PC (Sony XPERIA, NVIDIA Tegra2 1 GHz, 1 GB RAM) as a client device. The target location is a four-story building on



Figure 4.1: Scanning target building

the campus of Kansai University, Japan. Based on photogrammetry models using the set of photos in Figure 2.4, trees and outdoor installations (stairs) were not modeled in the planning conditions. As shown in Figure 4.1, the target building is surrounded by other buildings, constructions and trees. The initial plan for 3D scanning is shown in Figure 2.6.

The two photos on the top row in Figure 4.2



Figure 4.2: The actual conditions (top row), 3D target surfaces are highlighted in green in the initial plan (middle and bottom row) and obstacle primitive models are added (gray surfaces in bottom row).

show the target building in this experiment. The pictures on the second row show the 3D model used in the initial planning from the viewpoint of selected scanner positions in the optimized scanning plan. The existence of a small warehouse, arcade sidewalk, staircase and some trees are observed as differences between the initial model and the physical scene and apparent visual obstacles from the scanner positions. As shown in the third row in Figure 4.2, we created and added the primitive models to the 3D scene on the client device based on on-site investigation.

Due to the obstacles, one of the four major walls contains an invisible part from the ground level, occluded by the obstacles of the warehouse and the arcade sidewalk. Then we deselected invisible parts of the wall surfaces on the client tablet device and updated the planning conditions on the server PC. The result of the optimized scanning plan is shown in Figure 4.3. Wireframes with blue lines are the added primitive models of obstacles. Candidate scanner positions are the same as in the initial planning. The seven red points are the updated optimal scanning positions.

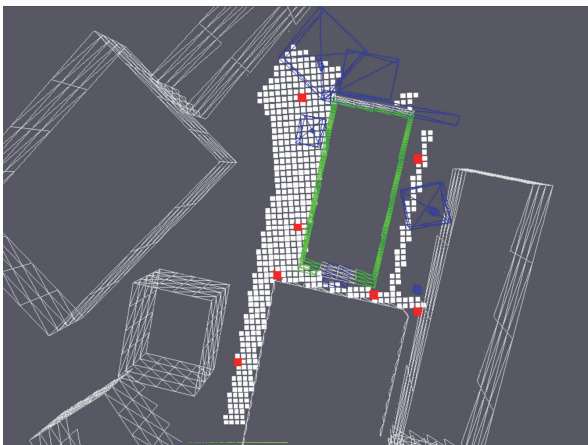


Figure 4.3: The updated optimal scanning plan. Green lines are the target surfaces. Blue lines are the added obstacle models, and white points are the candidate scanner positions, out of which red points are the optimal scanner positions.

For a definitive comparison, we conducted laser scanning by using the 3D scanner LMS-Z420i manufactured by RIEGL, according to both the initial and the updated plans. In the upper picture in Figure 4.4, blue dots show the acquired scanned point cloud data based on the initial plan with four scanner positions. In the lower picture, red dots show the point cloud data by the updated plan with seven scanner positions. In the result of the initial plan, corners and large wall surfaces are incorrectly scanned by the occluded obstacles. As for the updated plan, not only the minimum number of necessary scans but also the scan positions are changed from the initial plan. Consequently, the wall surfaces are well-scanned.

5. Discussion and Conclusion

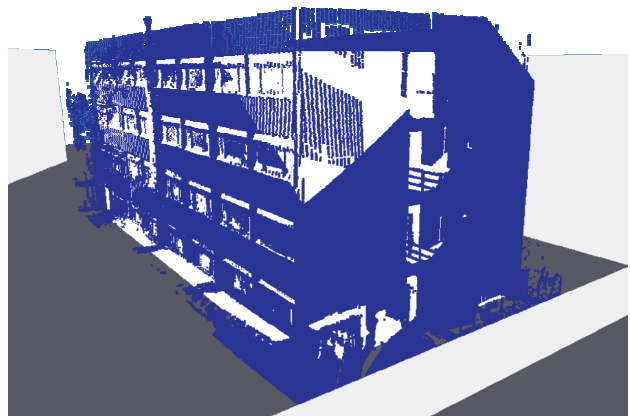


Figure 4.4: Comparison of scan results based on the plan

Prior to conducting laser scanning, selecting scanner positions is important to complete the scanning of the target surfaces. The optimization process can be a good tool for deriving a good scanning plan as a solution. Our server-client system delivers a powerful computation scheme into the lightweight mobile tool at the worksite. On the other hand, a native optimization process may be able to derive a solution and easily meet infeasible conditions. The proposed mobile system allows the user not only to take in-situ conditions into account but also to relax the conditions to acquire a realistic scanning plan by prioritizing the target meshes based on the on-site observations.

Our future work includes preparing a greater variety of primitive types and developing an evaluation method to estimate the scanning quality distribution in terms of point cloud density.

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