Planning for Scanning Using Building Information Models: A Novel Approach with Occlusion Handling

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ABSTRACT:

Terrestrial laser scanning is finding an increasing range of applications in the Architectural Engineering Construction and Facilities Management (AEC/FM) industry. While significant progress has been made in the performance of laser scanners and multi-scan registration, *planning for scanning* – i.e. the selection of locations for the scanner and registration targets – is still done quite subjectively by surveyors and is underpinned by little and basic scientific reasoning. This may lead to 3D point cloud data being incomplete or insufficiently accurate to deliver the completeness and accuracy expected from the subsequent measurement or modelling tasks.

In this paper, preliminary results are presented for a novel scientific approach for planning for scanning in the construction sector. The approach is designed to generate automatic laser scanning plans using as input: (1) the facility's 3D BIM model; (2) the scanner's characteristics; and (3) the scanning specifications in terms of individual point precision and surface area covered by the scanned data for each 3D BIM model object. The output is the smallest set of scanner locations required to achieve those requirements. The particular value of the proposed approach is its capacity to take model self-occlusions into account. The performance of this approach is assessed with a simple experiment simulating the scanning of a concrete structure.

Keywords -

Laser Scanning; BIM; 3D; Point clouds; Planning; Quality; Precision; Covered surface; Occlusion

1 Introduction

Terrestrial Laser Scanning (TLS) and Building Information Modelling (BIM) are two technologies with increasing impact on the Architectural Engineering Construction and Facilities Management Industry (AEC/FM). TLS enables conducting dense 3D surveys with millions of points acquired rapidly. The quality and density of the acquired point clouds enable valuable activities such as the creation as-built/ as-is 3D BIM models of existing facilities [1, 2], or the comparison the as-built/as-is 3D state of facilities with the as-designed 3D model for control purposes [3-5] . The work presented in this manuscript focuses on the latter context.

Geometric control constitutes an important part of all control activities during construction, with increasingly tight geometric tolerances [3]. Geometric control is also important to ensure facilities remain safe during the operational life.

These activities require that geometric features be measured with precision and accuracy. It is therefore critical that any laser scanning campaign delivers data of sufficient quality. TLS single point precision is typically at best ±2mm, but deteriorate as the surface is further away from the scanner or is at significant angle (incidence angle). With the industry setting increasingly tighter dimensional specifications, it is increasingly difficult to ensure than a laser scan will deliver points of sufficient precision and density.

An additional level of complexity arises from the fact that TLS is a line-of-sight technology. This implies that numerous scans typically have to be conducted from varying locations in order to acquire data from all surfaces of interest. And their subsequent co-registration in a common coordinate system further requires that targets be smartly located around the scanned environment.

This leads to the observation that a challenge of conducting TLS scanning campaign is to determine the number and locations of scans [6], taking into account the scanner's characteristic (e.g. field of view, single point precision), the characteristics of the scanning environment and objects to be scanned (level of clutter, surface properties), and the scanning specifications (minimum single point precision, and amount of surface required to be scanned for each object). This problem is referred to as *planning for scanning*.

It is observed that planning for scanning is commonly conducted by surveyors, in an ad-hoc manner, based on experience, and even sometimes once arrived on site [7-9]. This may however lead to:

- *Insufficiently precise and dense scans*;
- *Under-scanning* (incomplete data): e.g. to confidently and accurately model a pipe, data must be obtained all along its length and for a large portion of its curvature [5];
- *Over-scanning* (over-complete data): where an unnecessary number of scans are acquired resulting in an unnecessarily large datasets that has to be processed, which can take time (and significant computing resources). Over-scanning also means that other activities that need to occur in that environment must be delayed an unnecessarily long time [10].

Figure 1 shows two laser scanning plans as typically generated manually by a professional surveyor using Computer Aided Design (CAD), but yet based on basic information about the scanner's characteristics, the environment (in 2D) and experience (tacit knowledge). The typical approach, illustrated in Figure 1, is to use a compass and draw circles in a regular grid so that the circles cover the entire ground surface with (minimum) overlap; the radius of the circle being set based on the scanner's characteristic and the minimum point precision required. This approach not only discards critical factors that can impact data quality, such as incidence angle or surface materials, but it is also conducted in 2D, which may lead to additional aspects (e.g. 3D occlusions) being overlooked.

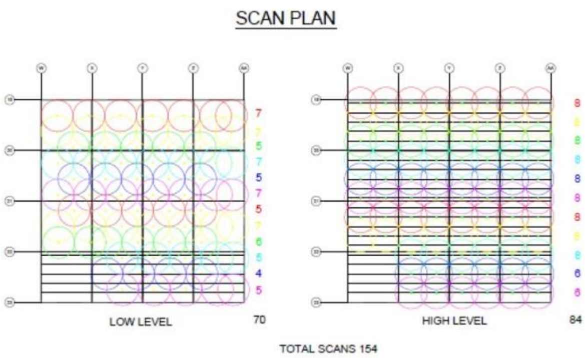


Figure 1. Low-level and high-level scanning plan

Figure 1 actually shows two generated plans, one with fewer scanning locations (low level) and one with denser scanning locations (high level). While the *high level* plan is more likely to provide the amount of data required, it will also result in a significantly larger amount of data that will have to be handled, albeit being possibly unnecessary.

There is thus a clear need for more scientific approaches to planning for scanning. In a perfect case, such an approach should recognize that scanning quality is a function of scanning incidence angle and range, the scanner's characteristics (field of view, and single point precision), clutter and the resulting occlusions, surface materials, weather conditions, etc. [11].

In this paper a novel scientific approach for automating planning for scanning is proposed that uses as input:

(1) the facility's 3D BIM model;
(2) the scanner's characteristics in terms of field of view and single point precision; and
(3) the scanning specifications in terms of individual point precision and surface area required to be scanned for each 3D BIM model object.

The particularity of the proposed method is its ability to take into account self-occlusions of the 3D BIM model.

The rest of the paper is structured as follows: Section 2 reviews existing methods for planning for scanning in the AEC/FM industry. Section 3 details the proposed approach in its current level of development. Preliminary experimental validations are reported in Section 4. Section 5 concludes this paper with a discussion on future work.

2 Background

This section focuses on existing works on the problem of scientifically planning for scanning in the construction industry. A short discussion is also provided on planning for scanning in robotics.

Argüelles-Fraga et al. [12] have proposed a scientific approach for planning for scanning tunnels with circular cross-sections (with a view to monitor the progress of works). The method aims to minimize scanning time (i.e. number of scans) while ensuring that the data will be of sufficient quality. Point density, point incidence angles and point footprints (which combines incidence angle and scanning range) are used as metrics for measuring data quality. Their approach only applies to tunnels with circular cross-sections and cannot be generalized to many other contexts.

Then, the main scientific work on planning for scanning in construction is that of Tang and Alaswad [9] who proposed a sensor-based model to generate scan plans. The approach aims to minimize data capture time while providing a minimum data quality expressed in terms of scan point density (or Level of Detail, LOD) and individual point precision (or Level of Accuracy, LOA). Note that the selection of these two data quality metrics is motivated by the fact they are those actually used by the General Services Administration (GSA) when they procure laser scanning works. In the work reported in Tang and Alaswad [9] assume an initial set of scan locations (e.g. provided by experts) and optimize these scanning locations in terms of angular resolution to be selected

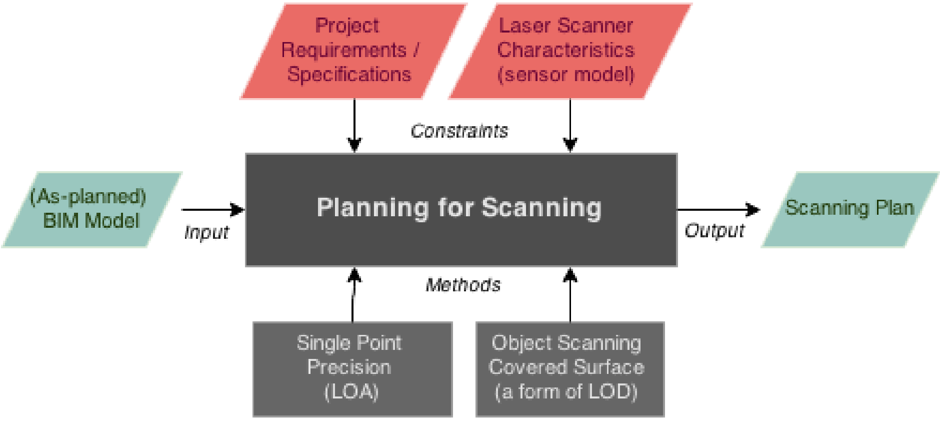


Figure 2. Planning for scanning framework

for each scan, and distance to key vertical surfaces. The main limitation with that approach is that it requires an initial set of scanning locations to be generated; the proposed approach is a solution to a local optimization problem, as opposed to the more general global optimization one considered here.

Subsequently, Song et al. [10] introduced algorithm utilizing the concept of "sensor configuration spaces" to automated laser scanning planning. The approach does not focus on surfaces (the focus in [9]), but small "point" features (e.g. window corners). Furthermore, the algorithm aims to achieve a global optimization that is finding the minimum number of scanning locations to be selected to achieve the scanning of those features with the specified LOD and LOA values. The locations are selected from a grid of potential locations sampled on the ground. The approach then defines a feasible space for each feature that is the area/volume where the scanner can be located to acquire the feature with the specified quality. The value of each potential scanning location is then assessed based on the number of feasible spaces it falls into; this is represented in the form of a heat map. The identification of the optimal set of scanning locations follows some *next-best-view* approach, where the location with the highest value (i.e. highest heat) is selected and the feasible spaces of the features covered by that scan are removed from the heat map, and this process is reiterated until all features have been covered. The method is well thought through and optimized, but, as acknowledged by the authors, the issue is that it only works for point features. Significant innovation is required to extend it to lines and surface features (for which "feasible spaces" would need to be defined efficiently).

Outside constructions, planning for scanning has been investigated in the robotics sector. However, most works focus on on-the-fly planning for scanning of unknown environments, i.e. for which no prior knowledge is available. A *next-best-view* approach is typically considered that uses scientific methods and heuristics to identify occluded areas and openings to optimize where the robot should be positioned for the next scan of the environment [13].

In this paper an alternative approach for planning for scanning is proposed. The approach achieves a global optimization of the scanning plan, it is not feature specific, and it fully handles occlusions using the project 3D (BIM) model. The approach is detailed in the following section.

3 Novel Approach for Planning for Scanning

The proposed planning for scanning approach, summarized in Figure 2, is designed to minimize the number of scanning locations. It assumes as input: (1) a 3D (BIM) model of the facility to be scanned; (2) the scanner's characteristics ("sensor model" in [9]), and (3) the scanning specifications/requirements defined in terms of minimum single point precision (LOA), and minimum surface covered by the scanned points for each object. LOD is not considered at this point, but could easily by added. Compared to previous work, we focus on covered surface, as we feel that this is an important laser scanning requirement since many activities (e.g. as-built modelling) not only require each point to have sufficient precision, but also require that data be acquired from as much of the surface of objects as possible. The approach follows three steps:

(1) Generating potential scanning locations (similarly to [10]).
(2) For each of the potential locations, calculate a virtual laser scan using the project 3D (BIM) model, and:
    a. Filter out the points that do not fulfil the specified individual point precision (LOA).
    b. Calculate the scanned surface area for each object in the BIM model.
(3) Identify the minimum set of scanning locations that fulfil the specific minimum covered surfaces for each object.

The methods employed to conduct those three steps are detailed in the following sub-sections.

3.1 Generation of Potential Scanning Locations

Assuming that the floor(s) on which the scanner can be positioned can be (automatically) identified in the 3D BIM model, a square grid is generated on top of it with a user-defined grid-size d_s (e.g. d_s = 1m). Each grid intersection is then considered as a potential scanning location. This is the same approach as in [10].

3.2 Calculation of Covered Surfaces for each BIM Object

For each potential scanning location, a virtual scan is conducted given the facility's 3D (BIM) model, taking into account the field of view and angular resolution of the scanner (sensor model). Each virtually scanned point is calculated as the closest intersection a ray coming from the scanner with a face of a 3D model object's mesh. This enables the calculation of the point's range and incidence angle.

As discussed in [9, 10, 14], individual point precision is a function of range, incidence angle, as well as several other factors. Therefore, given a specified single point precision (e.g. ±2mm) as well as pre-established relations between precision to range and incidence angle (e.g. see Figure 3), a maximum range ρ_{max} and incidence angle α_{max} can be defined for filtering out all the virtually scanned points (i.e. removing all points that would not fulfil the specified precision).

The challenge lies in pre-establishing the relations between precision, and range and incidence angle, [14] provides one such graph for a standard material, reproduced in Figure 3. In the figure, it can be seen that to ensure a precision of ±5mm at a maximum range of ρ_{max}=20m, then the incidence angle should not exceed α_{max}=70°. In the experiments reported later, we employ the graph in Figure 3 to define maximum range and incidence angle.

Once the insufficiently precise points have been filtered out of the virtual scans, the surface of each object covered by the scanned points is calculated. We use the approach described in [4, 15].

The surface covered by each scanned point j is calculated based on its range ρ_j and incidence angle(s) (φ_j, θ_j) as well as the scan's angular resolutions (φ_{res}, θ_{res}) using the equation:

$$s_j = \frac{\tan(\varphi_{res})\tan(\theta_{res})}{\cos(\varphi_j)\cos(\theta_j)}\rho_j^2$$

The point's covered surfaces are then added up for each face of each object's geometric mesh, providing the face's surface covered by the scan:

$$s_{o,f} = \sum_{j=1}^{J_{o,f}} s_j$$

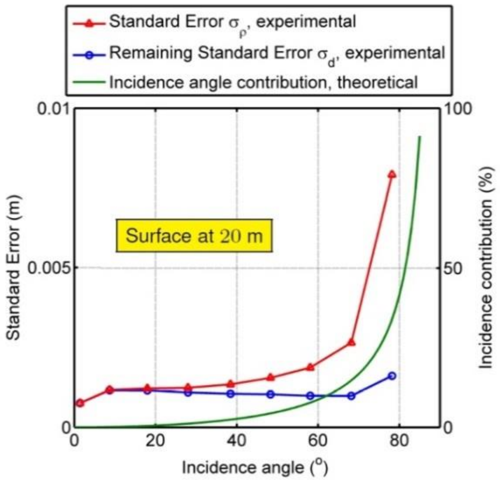


Figure 3. Example graph of single point precision (standard error) with respect to incidence angle at a range of 20m [14].

where $J_{o,f}$ is the number of points that were virtually scanned for the face f of the mesh of the object o.

Finally, all the covered surfaces for each face are added up to obtained the surface of each object covered by the scan:

$$s_o = \sum_{f=1}^{F_o} s_{o,f}$$

where F_O is the number of faces in the geometric mesh of object o. These calculations are conducted for each of the potential scanning locations.

3.3 Calculation of the Optimal Set of Scanning Locations

We formulate the planning for scanning optimization problem as an Integer (Binary) Programming problem as follows:

$$\text{Minimize: } c^T x$$
$$\text{Subject to: } Ax \geq b$$

where x is the $S\times 1$ vector of decision variables (binary variables), on whether to select each of the S scanning locations. c is the $1\times S$ coefficient vector of the objective function. c contains only 1's, so that $c^T x$ is the sum of selected scanning location (the objective function). A is the $O\times S$ matrix of scanning covered surfaces for all O objects from all S potential scanning location (as calculated in Section 3.2), so that Ax is the $O\times 1$ vector of covered surfaces areas for the selected scanning locations. b is the $O\times 1$ vector of minimum covered surfaces specified for each object. In our implementation these minimum surfaces are set as 50% of the overall object surfaces. But different values could be set for different types of objects, for example.

4 Experimental Validation

To validate the proposed approach, an experiment is conducted using a simple 3D BIM model of a concrete structure (see Figure 4) made of a concrete floor of size 12m x 8m, and 3x4 grid of cylindrical concrete columns spaced by 4m. The model also included footing foundations but these are not considered here (since they would be backfilled at the time one would need to scan the floor and columns). The BIM model was designed with Autodesk Revit and exported in IFC format for use in a software package that implements the proposed approach (developed by the authors). The experiment presented here establishes a set of potential locations using a square-grid of potential scanning locations with spacing d_s = 2m. Figure 5 shows the 6x4=24 scanning locations automatically generated by our system.

Next, the virtual scans are conducted within the environment defined by the 3D BIM model, from all 24 potential scanning locations, and given the scanner characteristic in terms of field of view and scanning angular resolution. Figure 6 shows two of the scans generated.

The acquired points are then filtered based on the maximum allowable scanning range and incidence angle, to ensure their meet the specified minimum single point precision. In the experiment reported here, a specified minimum single point precision of ±2mm is considered. Using the information in the graph in Figure 3, this precision is translated into a maximum range ρ_{max} = 20m and maximum incidence angle α_{max} = 60°.

The remaining points lead to the calculation of the covered surfaces for all objects from all 24 scanning locations.

Table 1 summarizes those covered surface areas. It clearly appears that some objects are hardly visible from some scanning locations, or their scanned surface (with adequate single point precision) would be smaller due to large scanning incidence angles or occlusions from other objects.

Finally, an Integer Programming algorithm is used to solve the optimization problem of finding the minimum set of scanning locations delivering the specified minimum covered surface for each of the objects of interest. In the experiment reported here, the specified minimum covered surface is simply set as 50% of the overall surface of each object.

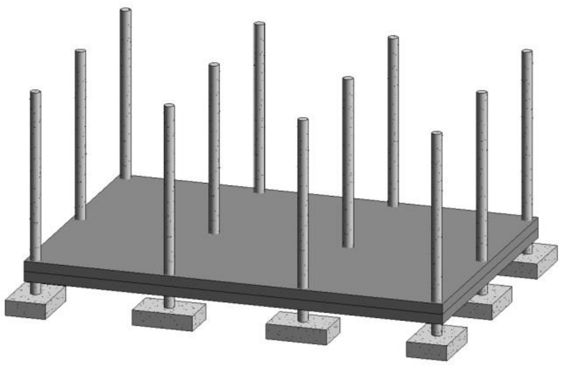


Figure 4. 3D BIM model of a simple concrete structure

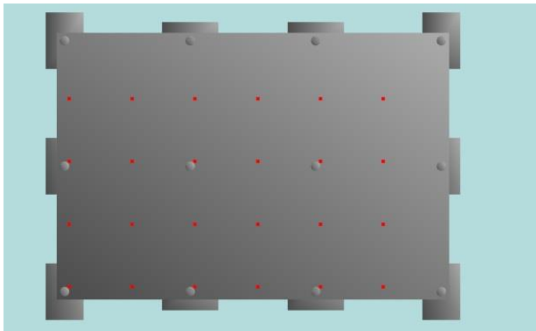
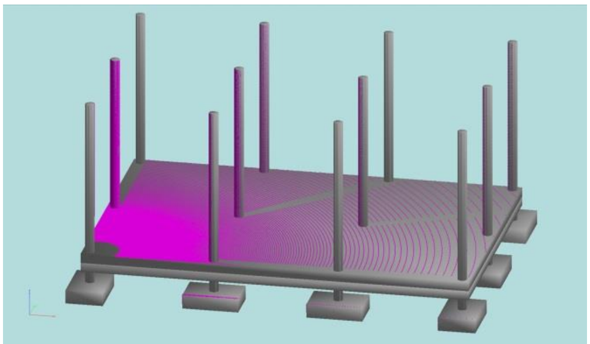
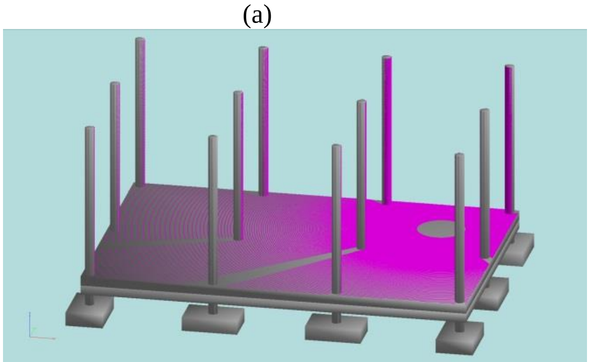


Figure 5. System generated 24 scanning locations



(a)



(b)

Figure 6. As planned scans from scanning location 1 (a) and 24 (b)

Table 1 Covered surface (in m^2) of given scanning objects. The covered surfaces are highlighted using color mapping over the range 0.00 (red) to 30% of the overall object surface.

Scanning Locations	Col. 0	Col. 1	Col. 2	Col. 3	Col. 4	Col. 5	Col. 6	Col. 7	Col. 8	Col. 9	Col. 10	Col. 11	Floor
SL1	1.51	1.58	0.03	1.61	1.59	1.58	0.00	1.60	0.00	1.55	1.25	0.00	8.62
SL2	1.60	1.34	1.51	1.53	1.60	1.56	1.41	1.58	1.48	0.00	1.50	1.52	14.39
SL3	1.52	0.03	0.00	1.60	1.68	1.55	1.39	0.00	1.62	1.25	0.00	1.62	14.07
SL4	1.68	1.51	0.00	1.60	1.61	1.60	1.47	1.58	1.62	1.50	1.52	0.74	14.08
SL5	1.51	1.56	1.52	1.72	1.59	1.34	1.61	1.53	0.00	1.26	1.48	0.00	14.39
SL6	1.60	1.66	1.63	1.58	1.59	1.66	0.00	1.60	1.64	1.72	1.65	1.48	25.40
SL7	1.24	1.52	1.64	1.58	1.34	1.59	1.59	0.00	1.56	1.48	0.00	1.59	25.22
SL8	0.99	1.63	1.57	1.56	1.66	1.72	1.64	1.47	0.65	1.65	1.48	1.73	24.50
SL9	1.60	1.55	0.00	0.00	1.58	0.03	1.61	1.59	1.58	0.00	1.60	0.00	14.07
SL10	1.64	1.59	1.57	0.00	1.34	1.52	1.53	1.60	1.56	1.33	1.58	1.58	25.22
SL11	1.65	0.00	0.00	1.68	0.03	0.00	1.60	1.68	1.55	1.60	0.00	1.59	19.52
SL12	0.60	1.57	1.48	1.34	1.51	0.00	1.60	1.61	1.60	1.58	1.58	1.65	24.46
SL13	1.59	1.60	0.00	1.58	1.56	1.51	1.72	1.59	1.34	1.62	1.53	0.00	14.54
SL14	1.63	1.72	1.55	1.47	1.66	1.63	1.58	1.59	1.66	0.00	1.60	1.47	25.69
SL15	1.66	0.00	1.64	1.61	1.52	1.57	1.58	1.34	1.59	1.53	0.00	1.57	25.44
SL16	1.66	1.55	0.00	1.66	1.63	1.55	1.56	1.66	1.72	1.60	1.47	0.67	24.79
SL17	1.64	1.41	0.00	1.59	1.55	0.00	0.00	1.58	0.03	1.60	0.71	1.68	14.07
SL18	1.60	1.49	1.53	1.57	1.59	1.64	0.00	1.34	1.52	1.67	1.60	1.61	25.23
SL19	1.55	0.00	0.00	1.59	0.00	0.00	1.68	0.03	0.00	1.59	1.68	1.59	19.52
SL20	1.56	1.53	1.61	1.50	1.57	1.64	1.34	1.51	0.00	1.60	1.61	1.71	24.46
SL21	1.60	1.52	0.00	1.65	1.60	0.00	1.58	1.56	1.51	0.19	1.59	1.34	13.89
SL22	0.68	1.54	1.55	0.67	1.72	1.57	1.47	1.66	1.63	1.50	0.71	1.66	23.16
SL23	1.25	0.00	1.60	1.71	0.00	1.48	1.61	1.52	1.57	1.59	1.34	0.00	23.97
SL24	1.67	1.55	1.53	1.55	1.55	0.00	1.66	1.63	1.55	1.59	1.66	1.55	23.58
Min. Surface	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	53.13

The results of the optimization are reported in Table 2. Only four of the scanning locations SL2, SL7, SL20 and SL24 should altogether suffice for acquiring sufficient data for each object and with the specified single point precision. Figure 7 shows those scanning locations and the resulting scans (before point filtering is applied).

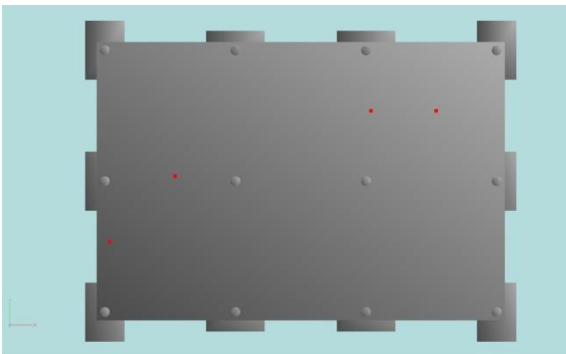


Figure 7. System generated 4 optimal scanning locations

Table 2 Covered surface areas for optimal scanning locations

Scanning Locations	Col. 0	Col. 1	Col. 2	Col. 3	Col. 4	Col. 5	Col. 6	Col. 7	Col. 8	Col. 9	Col. 10	Col. 11	Floor
SL2	1.60	1.34	1.51	1.53	1.60	1.56	1.41	1.58	1.48	0.00	1.50	1.52	14.39
SL7	1.24	1.52	1.64	1.58	1.34	1.59	1.59	0.00	1.56	1.48	0.00	1.59	25.22
SL20	1.56	1.53	1.61	1.50	1.57	1.64	1.34	1.51	0.00	1.60	1.61	1.71	24.46
SL24	1.67	1.55	1.53	1.55	1.55	0.00	1.66	1.63	1.55	1.59	1.66	1.55	23.58
Covered Surface	6.08	5.94	6.29	6.17	6.06	4.79	6.00	4.72	4.60	4.67	4.77	6.36	87.66
Surface	9	9	9	9	9	9	9	9	9	9	9	9	106.25
Bound	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	53.13

5 Conclusions and Future Research

This paper proposed a new automatic method for planning for scanning in construction. The method is not specific to any particular context, and could thus be applied in a wide range of contexts in the construction sector. This approach assumes as input: (1) a 3D BIM model of the environment to be scanned; (2) the scanner's characteristics in terms of angular resolution and field of view; and (3) scanning specifications in terms of single point precision and minimum covered surfaces for all objects of interest. The particular value of the proposed approach is that, while considering the most general case of surfaces, it is able to take into account individual point precision and occlusions of facilities components over other ones. It also uniquely considers the constraint of minimum covered surfaces. The problem of the selection of the optimal set of locations is currently formulated as an integer (binary) programming problem that can be solved with well-established algorithm. Preliminary experimental results using a simple example of a concrete structure demonstrate the performance of the approach.

However, some limitations can be identified. First of all, as currently formulated, the optimization problem actually does not address the issue that the surfaces covered from the selected scanning locations may actually overlap. This means that the currently estimated covered scanning surfaces may not be correct. Furthermore, experiments should be conducted in more complex contexts, with objects with varying surface properties. The resulting scan planned should also be comapred with those suggested by professional surveyors. Finally, this method, like previous ones, relies on the availability of tables relating individual point precision to scanning range, incidence angles, and likely other factors like surface reflectance. The establishment of such tables remains a subject requiring further research.

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