Automatic Planning for Scanning: Optimizing 3D Laser Scanning Operations Using BIM and TLS

Humayun Kabir Biswas

***Abstract*—Application of Terrestrial Laser Scanning (TLS) technology in the Architectural Engineering and Construction (AEC) industry is gaining popularity because the technology uniquely offers the means to create as-built three dimensional (3D) models of existing facilities, and conduct construction project progress and dimensional quality measurements. An open challenge with regard to the use TLS for such applications is to efficiently generate effective scanning plans that satisfy pre-defined point cloud quality specifications. Two such specifications are currently commonly used: Level of Accuracy (LOA) that focuses on individual point precision, and Level of Detail (LOD) that focuses on point density. Given such specifications, current practice sees professionals manually prepare scanning plans using existing 2D CAD drawings, some ad-hoc rules (of thumb), and their experience. However, LOA and LOD are point-based specifications, and do not ensure that a sufficient amount of the surface of each object is covered by the acquired data, despite this being important to many of the applications for which TLS is employed (e.g. modelling existing facilities). Therefore, this research uniquely proposes a novel planning for scanning specification, called Level of Surface Completeness (LOC) that assesses point cloud quality in terms of surface acquisition completeness. In addition, an approach is proposed for automatic planning for scanning in the AEC industry that takes both LOA and LOC specifications into account. The approach is 'generic' in the sense that it can be employed for any type of project. It 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 LOA and LOC specifications. The output is the smallest (optimal) set of scanning locations necessary to achieve those requirements. The results are evaluated in terms of effectiveness, efficiency and sensitivity analysis. However, the experimental results also highlight a significant issue of the approach which is that it does not take into account the overlapping of surfaces covered from different scanning locations.**

***Index Terms*— Planning for Scanning, Terrestrial Laser Scanning, Construction Industry, BIM, 3D Point Clouds**

I. INTRODUCTION

NOVEL technologies are transforming the way activities, such as surveying, progress measurement process and creating as-built three dimensional (3D) Models, are conducted in the Architectural Engineering and Construction (AEC) industry. Among those is 3D Terrestrial Laser Scanning (TLS) that is a surveying technology that uses laser to measure the 3D surfaces of objects automatically and efficiently. TLS thus enables the rapid and accurate acquisition of the as-is (as-built) state of projects, and is particularly advantageous in the cases of inaccessible or hazardous environments [1]. For all these reasons, TLS has been rapidly gaining popularity [2-8]. The quality and density of the acquired point clouds enable valuable activities such as the creation as-is 3D BIM models of existing facilities [9, 10], or the comparison the as-built/as-is 3D state of facilities with the as-designed 3D model for control purposes [11-13]. The work presented in this manuscript focuses on the latter context. Geometric control constitutes an important part of all control activities during construction, with gradually tight geometric tolerances [11]. Geometric control is also significant to ensure facilities remain safe during the operational life-cycle. 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 level of surface 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.

In addition level of complexity arises from the fact that TLS is a line-of-sight technology. This infers that several scans typically have to be conducted from varying locations in order to acquire data from all surfaces need to be scanned. 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 [14], taking into account the scanner's characteristic (e.g. field of view, angular resolution, single point precision), the characteristics of the scanning environment and objects to be scanned (level of clutter, surface properties), and the scanning specifications (level of scanning accuracy, and level of surface completeness required to be scanned for each object). This problem is stated to as planning for scanning.

It is noticed that planning for scanning is frequently conducted by surveyors, in an ad-hoc manner, based on experience, and even sometimes once arrived on site [15-17]. This may however lead to; (i) insufficiently precise and dense scans; (ii) 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 [13]; (iii) over-scanning (over-complete data): where an unnecessary number of scans are acquired

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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 [5].

Figure 1 represents 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. 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. This approach not only discards critical factors that can effect data quality, such as incidence angle or surface materials, but it is also conducted in 2D, which may lead to additional aspects being overlooked.

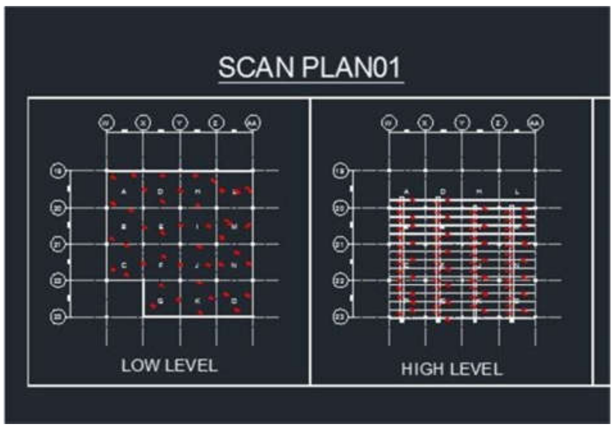

Figure 1. Low-level and high-level scanning plan generated manually by a professional surveyor

Figure 1 actually represents 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 generate the amount of data required, it will also result in a significantly larger amount of data that will have to be filtered, 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. [18]. In this paper a scientific approach for automating planning for scanning in terms of satisfying level of accuracy and level of surface completeness is introduced that uses as input:

(1) the facility's as-planned 3D BIM model;
(2) the scanner's characteristics in terms of field of view, angular resolution and height of scanner; and;
(3) the scanning specifications in terms of Level of Accuracy (LOA) and Level of Surface Completeness (LOC) to be scanned for each 3D BIM model object;

In particular, the proposed method is its ability to take into account self-occlusions of the as-planned 3D BIM models.

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 an approach for automatic planning for scanning in terms of LOA and LOC. Section 4 explained experiments and results. To evaluate the proposed approach, experimental results in terms of effectiveness, efficiency and robustness are illustrated in Section 5. Section 6 concludes this paper with a discussion on future work and limitations.

II. REVIEW of LITERATURE

This section reviews technologies recently introduced to the AEC and Facilities Management (AEC&FM) industry to increase the efficiency and quality control of construction projects. Building Information Modelling (BIM) is reviewed in Section II (A). Section II (B) initially discusses Terrestrial Laser Scanning (TLS) and its application, particularly in relation to BIM. It then reviews point cloud quality specifications typically considered in the AEC&FM sector, and conducts an analysis of the factors impacting TLS point cloud quality.

A. Building Information Modelling

Building Information Modelling (BIM) is a rapidly growing procedural and technological change in the AEC&FM industry [19]. It appeared in the 1970 with the development of information technologies for construction project management. BIM is an approach to digitally and collaboratively model and manage a construction project over its entire life cycle from briefing through to design, construction, operation and maintenance and finally repurposing or demolition [20, 21]. BIM aims to provide all stakeholders with a unique set of information that is interoperable among various technology platforms. There is no unilaterally agreed definition of BIM, but some organizations that have been playing crucial roles in its development do provide well-informed definitions. In particular, the British Standards Institution (BSI) defines BIM as "a suite of technologies and processes that integrate to form the system which is a component-based three dimensional (3D) representation of each building element" [22], while the international BuildingSMART organization defines it as a "business process for exchanging building data and information to design, construct and operate the building during its lifecycle" [23]. BIM can assist in the development of a more integrated design and construction process that delivers better quality with predictable (even lower) cost and time. The benefits of BIM are expected to be so significant that it has gained world-wide interest from both public and private organizations. In the UK, the government has mandated that all public projects be delivered with BIM Level 2 by 2016 [24].

BIM is aimed to support a wide range of tasks over a building's life cycle. Some tasks commonly mentioned include quantity take-off, cost estimating and conducting energy consumption simulations. With BIM, these tasks can be efficiently (sometimes automatically) updated/repeated when changes are made to the BIM model. Such feature is not available to designers working with two-dimension (2D) or three-dimension (3D) CAD tools that produce drawings or other documents that are merely disintegrated hand-offs lacking semantic information [25]. BIM also helps avoiding, or detecting and correcting, design conflicts, thereby helping project team members coordinate their discipline-specific models throughout the project [26-29].

The BIM model is a digital representation (a file, set of files or database) of a building that gathers all life-cycle information or data about it. The BIM model contains "all kinds of information, from spaces and geometry, to costs, programming, specifications and other information types" [30]. This includes geometry and other semantic information on performance, planning, construction and operation. Each building component is created from a product library and has embedded semantic information about it. BIM models significantly differ from CAD models as they are object-based with the particular implication that each of the objects has a type (e.g. wall, door, floor). In contrast, CAD models only contain geometric information, lacking any semantic information such as the type of each 3D object.

Despite the great progresses made by present BIM technologies to enhance data management and communication in the AEC&FM sector, one important remaining challenge is the limited interoperability among data models produced by the numerous software packages that are used over the life cycle of projects and even within each one of its stages. To address this issue, the industry is looking to develop open data standards for data exchange and BIM modelling. The Industry Foundation Classes (IFC) is the most significant BIM open data standard (actually a set of standards) which is developed and promoted by BuildingSMART. Automatic progress tracking systems have been investigated by numerous researchers [31-33]. It is noted in [32] that, for effective project performance tracking, dynamic and reliable survey information is needed to enable effective comparison of the as-built state of projects against their as-planned (or as-designed) state [31, 34]. The 3D BIM model is increasingly used as representing the as-design state. Accurate TLS data is also required in the case a 3D (BIM) model has to be generated from scratch from a TLS point cloud of a given site. The following section reviews about the current TLS technologies are used in AEC industry.

B. Terrestrial Laser Scanning

TLS is a recent 3D surveying technology that is based on the latest laser technologies for distance measurement, and is increasingly used in the AEC industry since the beginning of the 21st century [35]. TLS is valuable for its rapid acquisition of dense and accurate 3D point cloud data that can be used for measurement as well as accurate object modelling [36, 37].

C. TLS principles

There are different types of terrestrial laser scanners that differ by their distance measurement principles. Currently, three popular technologies are used: time-of-flight measurement, phase-based measurement (strictly speaking a form of time-of-flight technology), and optical triangulation. Laser scanners used on construction sites employ either time-of-flight or phase-based principles. Phased-based technology measures the phase shift between the emitted and return signal to establish the time of flight and therefore the distance travelled. In contrast, time-of-flight technology measures the time taken for an emitted pulse to return to the scanner, and infers the distance travelled from that time. The different measurement principles used means that phase-based technology enables faster scanning but at limited range (under 100m). In contrast, time-of-flight technology allows scanning at distances of a kilometre and more, but has typically shown to be slower [36].

A terrestrial laser scanner is made up of two significant components, a laser probe and a two-axis pan-and-tilt mechanism device. As a result, a laser scanner natively acquires the position of each 3D point in spherical coordinates, i.e. with an azimuthal (horizontal) angle φ, a polar (vertical) angle θ and a range distance ρ. Trigonometric functions are then used to transform the point's spherical coordinates (φ,θ,ρ) into Cartesian coordinates (x,y,z). All those coordinates are provided in the inner coordinate system of the laser scanner.

D. TLS Point Cloud

A laser scanner generates a collection of 3D points collectively called a point cloud [37]. A point cloud may be in the form of unorganized (or unstructured) 3D points, it may also be in the form of organized 3D points (within a 2D matrix), in which case it is often called a range image; in a 2D range image, each 'pixel' corresponds to one 3D points, with the pixel location in the image corresponding to a unique scanning direction defined by a pair of azimuthal and polar angles, and the pixel value is the range. Laser scanned 3D points are described at least by three coordinates (x, y, z) defining their location in space, but may also contain other parameters such as colour (R, G, B) and intensity (I). As discussed earlier, point clouds may be used as-is or as an intermediary representation for object recognition and reconstruction [38].

E. Point Cloud Quality Specifications

The quality of point cloud data can be assessed using various criteria [17]. However, two main criteria are commonly used in practice in the AEC sector:

LOA (Level of Accuracy): point cloud specification that specifies the tolerance of positioning accuracy of each individual point in 3D point cloud data; this ultimately specifies the positioning accuracy of the scanned objects. LOA is typically defined in millimeter.

LOD (Level of Density): point cloud specification that defines the minimum object size that can be extracted from the point clouds. It relates to how dense the scanned points are on object surfaces. LOD is thus typically defined as a distance in millimetre specifying the maximum allowable distance between neighbouring scanned points.

While the two criteria above are widely used (e.g. LOD and LOA data quality metrics are employed by the US General Services Administration (GSA) when they procure laser scanning works), the author notes that the following criterion could also be additionally considered:

LOC (Level of Surface Completeness): point cloud specification that requires that a minimum amount of the surface of an object of interest has been scanned. LOC should specify the minimum amount of the object surface, and possibly even which parts of that surface, that need to be acquired. This criterion is important as it is often difficult to acquire the entire surface of an object; but a sufficient amount of this surface could suffice for the intended purpose. For example, Kim et al. [39] proposed a method to automatically model pipes from 3D as-built point. The local surface curvature information is used to identify each pipeline's location and size.

III. PLANNING SCANNING APPROACH

Effective Scan-to-BIM and Scan-vs-BIM applications, in particular dimensional quality control, require that the point clouds associated to the different objects under analysis be acquired with sufficient precision and cover the surface of those objects as completely as possible. Without adequate planning for scanning, scanned point clouds can have insufficient accuracy and incomplete 3D geometric information. This can lead to discarding the acquired data and re-scanning, which is time consuming and constitutes a clear financial loss [40].

In the context of the construction industry, a few works have already been published on automated planning for TLS that use ideas suggested by works in the manufacturing context, adapting them to the specificities of the construction context. In this paper, the prior works are reviewed in detail in the following sub-sections that group those methods according to their main specificity. This review particular considers the very recent state-of-the-art works by Dr. Pingbo Tang and his colleagues [5, 17, 41].

A. Planning for Scanning for Specific Case

Argüelles-Fraga et al. [4] investigated planning for scanning for the specific case of straight tunnels with cylindrical shapes with the aim of acquiring data enabling robust comparison of the as-built and as-designed conditions (Scan-vs-BIM). They propose an algorithm generating scanning locations by taking several factors into account, such as tunnel dimensions and incidence angle. The laser scanner's height and incremental distance between scanning stations are found to be the two most important parameters influencing scanning results. Point density and footprint are considered as LOD metrics, and incidence angle is considered as LOA metric. Using the naming in Figure 2, the coordinates (xi, yi, zi) of each scanned point i are defined as:

$$(x_i, y_i, z_i) = (t + r_i \sin V_i \sin H_i , r_i \sin V_i \cos H_i , h + r_i \cos V_i) \qquad (i)$$

where, h is the height of laser scanner, t is the orthogonal distance to the tunnel's centerline (i.e. cylinder's main axis), and (Hi, Vi, ri) are the spherical coordinates of the point as measured by the scanner. The vector normal to the surface at the scanned point's location is $n_i = (-x_i, 0, -z_i)$, the incidence angle α (LOA) can be easily calculated from the formula:

$$\cos \alpha_i = \frac{-n_i \cdot r_i}{\|n_i\| \|r_i\|} \qquad (ii)$$

The size of the laser footprint at each point (LOD) has a roughly elliptical shape, and its major and minor axes have lengths that can be calculated using the formulas:

$$F_i = \frac{r_i \tan\frac{\varphi}{2}}{\cos \alpha_i} \qquad (iii)$$

$$f_i = r_i \tan\frac{\varphi}{2} \qquad (iv)$$

where φ is the scanner's laser beam divergence angle (provided by the scanner's manufacturer).

Argüelles-Fraga et al. then define the planning for scanning problem as the problem of minimizing scanning time with three variables and point density (LOD), footprint (LOD), and incidence angle (LOA) specifications. The total time required to perform a full scan of the tunnel is calculated as:

$$T_{total} = N_S T_S + (N_S - 1)\Delta T \qquad (v)$$

where, ΔT represents the time required to change position, T_S is the time needed for each scan and N_S is the number of scans calculated as:

$$N_S = ceil\left(\frac{L - pD_R}{(2-p)D_R}\right) \qquad (vi)$$

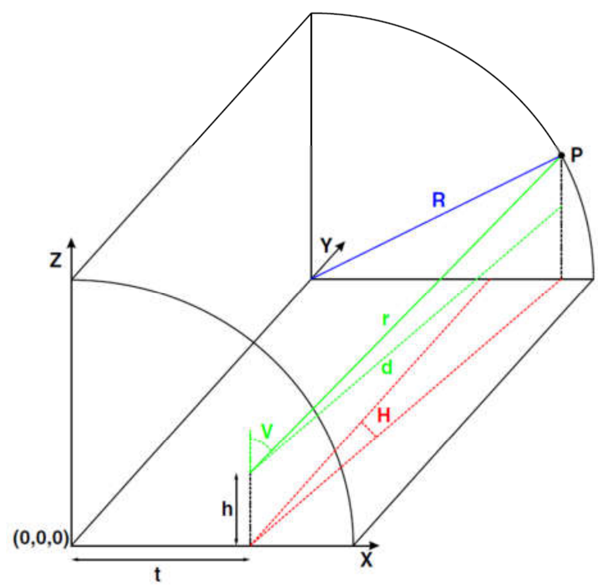

Figure 2. Diagram depicting measurement of a circular tunnel using TLS

where, $ceil(x)$ returns the integer larger than x, L is the length of the tunnel, DR is the incremental distance, and p is the user-defined overlap between scans. Note that increasing the spherical angular resolution of scans (i.e. acquiring denser measurements) improves the distance from the scanner at which the point density LOD specification will be met, but increases the time required to conduct each scan. Unfortunately, Argüelles-Fraga et al. do not detail the method employed to solve the optimisation problem they define.

B. Planning for Scanning as Local Optimization of Preselected Locations

In this approach [17] the positioning error, e, of scanned points is considered for measuring LOA. e represents the difference of the coordinates of a scanned 3D point from its actual physical position. The value of e is argued to mainly depend on the point range and incidence angle:

$$e = f_e(D, \alpha) \qquad (vii)$$

where, $\cos\alpha = \frac{d}{D}$. Note that this formulation only works for vertical or horizontal surfaces. The LOD is calculated using two metrics:

(1) Surface sampling S (i.e. point density), that is the distance of a given point from its nearest neighbour (see Equation (viii) below); and
(2) Laser beam width on surface B_w' (i.e. footprint). The laser beam width depends on the point range and incidence angle, as well as the beam divergence angle (φ) and laser beam width calibration distance, D_0 (see Equation (*ix*) below).

$$S = \frac{D\Delta}{\cos\alpha} = \frac{D\Delta}{\frac{d}{D}} = \frac{D^2\Delta}{d} \qquad (viii)$$

$$B_w' = \frac{B_w' + (D - D_0)\varphi}{\cos\alpha} \qquad (ix)$$

Finally, the authors employ what can be seen as a LOC metric that is the vertical surface scanned, captured by the parameter r that relates to D and d with the formula:

$$r^2 = D^2 - d^2 \qquad (x)$$

Equations (vii) to (x) are set for each vertical planar surface of interest. Using those equations, the Optimisation model is then formulated as a time minimisation model, where the overall scanning time is the time to acquire each of the surfaces of interest, and each of those times is calculated as:

$$t = \frac{\left(\frac{2\alpha}{\Delta}\right)^2}{C} = \frac{4\alpha^2}{C\Delta^2} = \frac{4\times\left(\cos^{-1}\frac{d}{D}\right)^2}{C\Delta^2} \qquad (xi)$$

where, $\left(\frac{2\alpha}{\Delta}\right)^2$ is the number of points within the surface of interest and C is the scanner's data collection rate. The LOA, LOD and time constraints to this Optimisation model are then:

$$\begin{cases} e \leq e_{limit} \\ S \leq S_{limit} \\ t \leq t_{limit} \end{cases}$$

Integrating equations (vii) to (xi) in the Optimisation model above, leads to the reformulation of the objective function for each of the surfaces of interest as the maximisation of:

$$P = \frac{\pi r^2}{t} = \frac{\frac{Sd}{\Delta}d^2}{\frac{4\times\left(\cos^{-1}\frac{d}{D}\right)^2}{C\Delta^2}} = \frac{(Sd\Delta - d^2)C\Delta}{4\times\left(\cos^{-1}\frac{d}{D}\right)^2} \qquad (xii)$$

It should be noted that Tang and Alaswad do not explain how r is integrated in this model. It is assumed that r is likely considered as a fourth constraint of the form:

$$r = h$$

where, h is the height (above the scanner) up to which scanned points are expected to be acquired. Assuming the vertical surface is a wall, *h* could thus be defined as the height of the wall.

It however aims to work in somewhat more general contexts, as the built environment indeed presents numerous vertical (and horizontal) surfaces. Furthermore, the approach appears to consider some LOC specification, although the authors themselves do not seem to recognize this. Nonetheless, despite these interesting advancements, the approach of Tang and Alaswad still presents two main limitations:

(1) It requires an initial set of scanning locations; it is thus a solution to a local Optimisation problem, as opposed to the more general global optimization problem that would consider no initial scanning locations.
(2) The approach actually makes an important simplification (not stated by the authors) that all points at the same height on a vertical surface have the same incidence angle.

C. Planning for Scanning as Global Optimization

In contrast with the earlier work in [17], this approach aims to optimize the scanning of 'point' features (e.g. window corners) as opposed to planar surfaces. For each point feature on the given object surface, a feasible space, from within which that point can be scanned, is defined for the given LOD specifications. The approach considers the surface sampling S as LOD metric, calculated the same way as in their previous work in [17] and the authors find that the resulting LOD feasible space is a sphere that is tangent to the surface at the point location and has a radius of $\frac{S'}{2\Delta}$, where S' is the LOD specification and Δ is the scan resolution ($\Delta = \Delta_\theta = \Delta_\varphi$).

The minimum set of scanning locations required to acquire all the point features with the required LOD specification, i.e. the optimal plan, is then searched using a progressive algorithm similar to Next Best View (NBV) approaches. In this approach, scanning location are incrementally added by selecting in the heat map the location with the highest temperature. The heat map is then updated by removing the feasible spaces of the features captured by that location, and the process repeated until all point features are captured by the selected set of scanning locations. This method represents a significant improvement over prior works. The approach however still has two limitations:

(1) It does not consider LOA specifications. While the authors do not discuss this, it can nonetheless be assumed that their approach could be extended by calculating LOA feasible spaces and infer LOA+LOD feasible spaces for all point features by intersecting the LOA and LOD feasible spaces.

(2) It does not consider LOC specifications. In fact, because this approach focuses on point features as opposed to surfaces, this approach simply cannot accommodate any LOC-type specification.

Significant works, essentially all by Dr. Tang et al., have been published on the problem of planning for scanning in construction. Table 1 summarizes the strengths and limitations of the various works of Tang et al. with respect to six performance criteria and represents the comparison in between the proposed planning for scanning approach and previous planning for scanning systems.

Table 1. Comparing proposed approach with existing methods

Criteria	Tang and Alaswad (2012) [17]	Song et al. (2014) [5]	Zhang and Tang (2015) [41]
LOA	*Yes*	*No*	*No*
LOD	*Yes*	*Yes*	*Yes*
LOC	*Partially*	*No*	*No*
Occlusions	*Yes*	*Yes*	*Yes*
Optimization	*Local*	*Global*	*Global*
Generalization	*Yes*	*Yes*	*Yes*

The analysis of Table 1 leads to the identification of a clear knowledge gap that there is currently no automated method for planning for scanning in construction (using 3D BIM models) that is 'general' for any context, that achieves a global Optimization, and that takes into account not just LOD but also LOA and LOC specifications. The lack of support for LOC specifications is particularly noted because the only two global approaches that have been published focus on 'point' features and so cannot accommodate at all LOC-type specifications.

IV. EXPERIMENTS AND RESULTS

In order to evaluate the proposed approach for planning scanning, experiments are conducted using the Simple and complex Structural Models of a typical structural 3D BIM model of a building storey that is made up of columns and a floor, and the Structural+MEP Model of a section of the structural model extended with Mechanical, Electrical and Plumbing (MEP) components. While the simple and complex models are considered for the planning of the scanning of structural works, the Structural+MEP model is used to more specifically consider the planning for scanning of MEP components. Table 2 summarizes the number of objects in each model.

Table 2. List of experimental as-planned 3D BIM models

As-planned 3D BIM Models	Plan size	Number of Objects
Simple Structural Model	12m x 8m	**25**
Complex Structural Model	66m x 54m	**64**
Structural+MEP Model	33m x 6m	**118**

A. Simple Structural Model

The Simple Structural Model can be considered as simulated data because it is designed by the author. This model was mainly used to check that the proposed planning for scanning method is working as expected and identify any necessary correction prior to testing at larger scales. As shown in Figure 3, this model is made up of one floor, twelve columns and footings. However, footing foundations are not considered within the Optimization as they would be backfilled at the time one would need to scan the floor and columns.

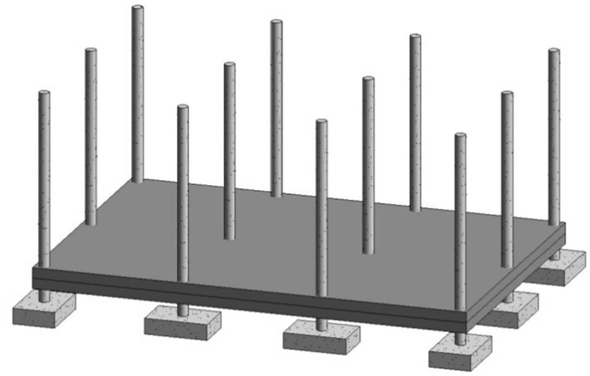

Figure 3. 3D view of the Simple Structural Model

The working of the proposed planning for scanning system is illustrated using the Simple Structural Model. For the experiment, the necessary input parameters are set as summarized in Table 3.

Table 3. Scanner characteristics, scanning specifications and other parameters set for the illustrative experiment

Parameter	Value
Scanner Characteristics	
Angular Resolution	0.17° x 0.17°
Scanner Height (h)	2m
Field of View	360° x 152°
Scanning Specifications	
LOA	±2mm
LOC	50% of the object's overall surface (same for all objects)
Other Parameters	
Grid density (β)	4m

The defined grid density leads to the generation of 24 potential scanning locations as shown in Figure 4.

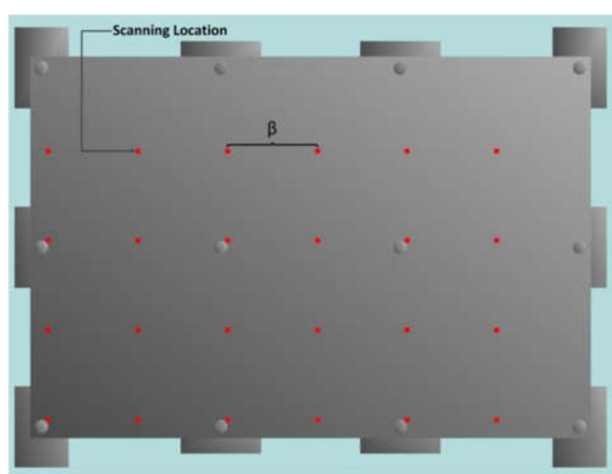

Figure 4. 24 potential scanning locations are generated for the example of the simple structure of Figure 4, using β=2m

The covered surface areas calculated by the system for all 13 objects and for all of the 24 potential scanning locations. The virtual scan from the potential scanning 24 is demonstrated in Figure 5. The Optimization stage finds a minimum solution demonstrated in Figure 6. The results indicate that the minimum set of scanning locations necessary to fulfill the LOC (and LOA) specifications for all 13 objects contains four locations (Table 4). Set reported by the system includes the scanning locations *SL6, SL8, SL13* and *SL14* (see Figure 6), but other sets of 4 scanning locations may solve the problem. However, there is no solution that contains 3 or fewer locations.

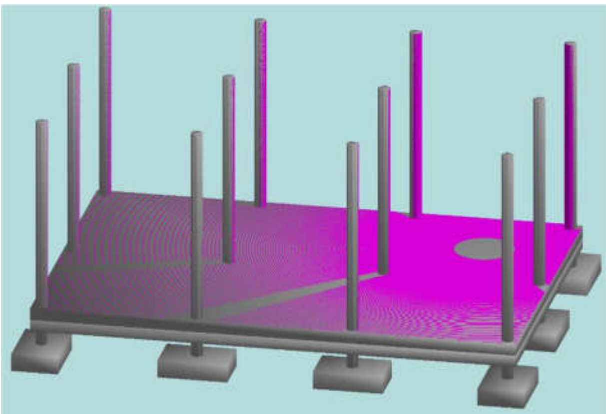

Figure 5. Generating virtual scan from scanning location 24

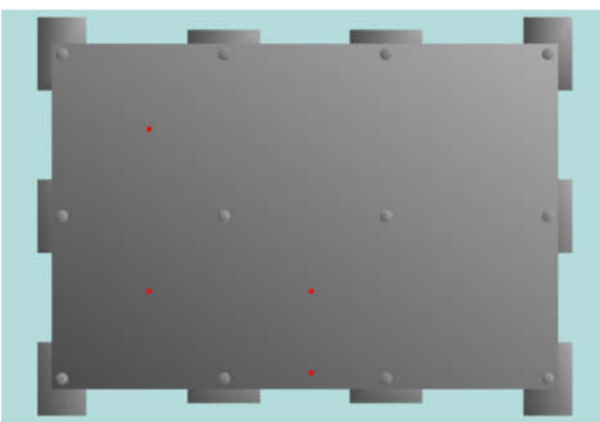

Figure 6. Top view of the Simple Structural Model showing the optimal set of scanning locations (four locations) obtained for the illustrative example

B. *Complex Structural Model*

The Structural Model, shown in Figure 7, is the ground storey of a sample Structural 3D BIM model provided by Autodesk. The Structural Model (of the ground storey) is composed of 63 cylindrical concrete columns and one large floor slab.

C. *Structural+MEP Model*

A section of the Structural Model above is also considered extended with Mechanical, Electrical and plumbing (MEP) components (also provided by Autodesk). This model, shown in Figure 8, is composed of 118 objects: 10 structural columns, one floor and 107 MEP objects (including rectangular duct, duct elbow, pipes, etc.). This model is used to assess the value of the proposed P4S method for planning the scanning of MEP systems, as opposed to structural ones.

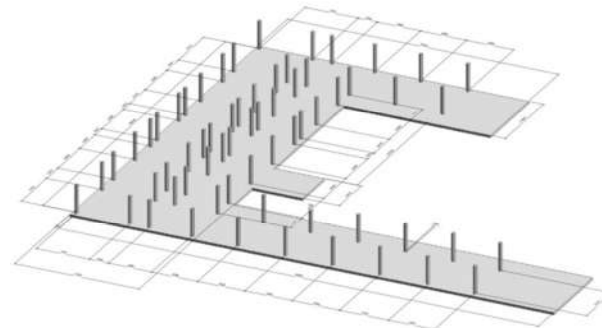

Figure 7. 3D view of the Structural Model is composed of 63 cylindrical concrete columns and one large floor slab.

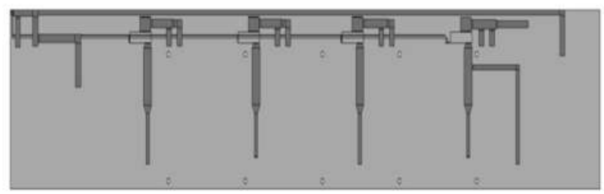

Figure 8. Top view and 3D view of the Structural+MEP Model

V. CONCLUSION

This research proposed a new automatic approach 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 for Planning for Scanning (P4S) in the context of the construction industry is developed that takes as input a 3D BIM model of the facility to be scanned, and generates an optimal scanning plan that satisfies constraints related to the characteristics of the scanner, and LOA and LOC scanning specifications. The P4S algorithm follows five steps:

Step1: Semi-automatically select the floor in the given input 3D BIM model on which the scanner shall be located, and then automatically generate a grid on the top face of the floor. Each grid intersection is then considered as a potential scanning location.

Step2: Given the scanner characteristics, automatically calculate virtual laser scans from all potential scanning locations.

Step3: Filter each virtually scanned 3D point according to the LOA specification. This is achieved indirectly by filtering points according to specified maximum range (ρmax) and maximum incidence angle (σmax) that should altogether ensure fulfillment of the LOA specification.

Step4: Automatically calculate the covered surface areas for each object of interest for each potential scanning location.

Step5: Automatically calculate the optimal set of scanning locations (i.e. minimum set of scanning locations) that satisfy the LOC specification expressed in terms of minimum covered surface for each object of interest. This is achieved by formulating the optimization problem as a BIP

Table 4. Covered surface areas for the optimal solution of four scanning locations found by the system

SLs	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
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
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
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
Covered Surface	5.81	6.60	4.75	6.19	6.48	6.51	4.94	6.25	5.29	4.98	6.26	4.68	90.14
Total Surface	9	9	9	9	9	9	9	9	9	9	9	9	106
LOC specification	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

problem and solving it using a Branch-and-Cut algorithm.

A prototype system has been developed that implements the above approach. The system also provides a user-friendly Graphical User interface (GUI) that enables easy data input and visualization of the results. Then, three different 3D BIM models have been used to conduct illustrative and performance assessment experiments.

A simulated simple structural model was first used to demonstrate the working of the approach. Then, a real (medium-size) Structural Model and a portion of it augmented with MEP components were used to evaluate the performance of the proposed approach in terms of effectiveness, efficiency, and sensitivity to the selected grid size.

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. The problem of the selection of the optimal set of locations is currently formulated as an integer (binary) programming problem that solved with well-established CBC algorithm.

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