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Registration-free 3D Point Cloud Data Acquisition Technique for as-is BIM Generation Using Rotating Flat Mirrors

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Abstract: Nowadays, as-is BIM generation has been popularly adopted in the architecture, engineering, construction and facility management (AEC/FM) industries. In order to generate a 3D as-is BIM of a structural component, current methods require a registration process that merges different sets of point cloud data obtained from multiple locations, which is time-consuming and registration error-prone. To tackle this limitation, this study proposes a registration-free 3D point cloud data acquisition technique for as-is BIM generation. In this study, small-size mirrors that rotate in both horizontal and vertical direction are used to enable the registration-free data acquisition technique. First, a geometric model that defines the relationship among the mirrors, the laser scanner and the target component is developed. Second, determinations of optimal laser scanner location and mirror location are performed based on the developed geometrical model. To validate the proposed registration-free as-is BIM generation technique, simulation tests are conducted on key construction components including a PC slab and a structural wall. The result demonstrates that the registration-free point cloud data acquisition technique can be applicable in various construction elements including PC elements and structural components for as-is BIM generation.

Key words: registration-free, 3d point cloud, data acquisition, laser scanning, as-is BIM generation

1. INTRODUCTION

As-is BIM model is defined as the as-is condition digital model involving 3D geometry information and 3D visualization of a construction project [1]. A project may not be constructed as its design, changes are required during sequence renovations, which points to the need for as-is BIM generation. On the other hand, it is also necessary to implement as-is BIM applications for an existing building in the O&M phase when the BIM model is missing or out-of-date. With the development of remote sensing technologies, point cloud data collection by laser scanner is an accurate and efficient way to create an as-is BIM model in the construction industry. This is because 3D laser scanning can rapidly and accurately measure the 3D shape of the target object [2]. Many researchers have studied and proposed diverse as-is BIM generation methodologies and approaches. There are two main trends of the research related to as-is BIM generation, namely as-is BIM generation with as-design model and as-is BIM generation without as-design model. As for the as-is BIM generation with as-design model, researches focused on different scales of construction components from a single structural component to an overall building structure. Bosché et al. [3] proposed a robust approach to perform as-built BIM generation for the column by integrating the as-designed model and 3D laser scanning data. Valero et al. [4] established the geometrical relationship among the interior objects to develop an accurate 3D semantic as-is BIM generation method for furnished office and home interiors based on as-is design model, which involved as-is BIM generation for both immobile structural element and mobile furniture. However, these studies showed that the performance of as-is BIM generation relied on the as-design model, which could not be applied to the project without the as-designed model in an accurate manner. Therefore, many researches have studied on as-is BIM generation without the aid of as-is design model to address this limitation. For example, Wang et al. [5] and Sanchez et al. [6] proposed automatic as-built BIM creation methods for planar building interiors and building envelops based on prior knowledge respectively, which was capable of generating simple models in terms of ceilings and floors without the as-design model.

However, in order to generate as-is model of a structure or component, those prior works require a registration process that merges different data sets obtained from multiple positions, which may be time-consuming and cost demanding. In addition, registration errors are inevitable due to the imperfectness of the merge process based on targets or common features from different scans. To tackle these problems, this study proposes a novel registration-free as-is BIM generation technique. The proposed technique uses flat mirrors to scan the hidden surfaces of a target component from the view of laser scanner so that the entire surfaces (both visible and invisible surfaces) can be scanned without a registration process. In this way, scanning time can be reduced and registration error can be prevented. The rest of paper is organized as follows: First, section 2 reviews the current research about the data acquisition quality determination and scan planning. Then, the development of a registration-free data acquisition technique is illustrated in section 3, which includes the overall scheme and procedure of the proposed technique. Next, the proposed method is simulated on PC slab and a structural component respectively in section 4. Lastly, section 5 presented the conclusion and the contribution of the study.

2. LITERATURE REVIEW

It is important to ensure that point cloud data are acquired in the required quality in order to guarantee good performance of as-is BIM generation. So far, many studies on 3D data acquisition methods and scan planning have been conducted to achieve effective as-is BIM generation. Therefore, the sections below present the recent literature related to data acquisition quality and scan planning.

2.1. Data acquisition quality

There have been many criteria or guidance for data quality determination for as-is BIM generation. U.S. General Services Administration (GSA) [7] presented data quality requirements reflected by allowable dimensional deviation and the smallest recognizable features according to different applications of as-is BIM creation. In addition, the parameters evaluating the point cloud data quality have been discussed in previous research. Dai et al. [8] evaluated 3D point cloud data quality based on the three parameters including data density, tolerance and coverage completeness. As the most popular parameters for point cloud data quality evaluation, spatial density and tolerance are mainly influenced by the collecting parameters including angular resolution, incident angle and scanning range. Coverage measures the proportion of the target object covered by the point cloud data, which is important when occlusion among building components exist [9,10]. Besides the three parameters mentioned above, Wang et al. [10] proposed a scan-to-BIM framework with the consideration of the RGB color. In order to capture such properties, the scanning locations are required to be carefully located to ensure a line of sight from the laser scanner to the target component.

2.2. Scan planning

After determining the required data acquisition quality, scan planning is considered to use efficient 3D point cloud data acquisition. Soudarissanane et al. [11] proposed a method to determine optimal laser scanner locations by projecting the scene into a 2D map in order to simplify the process and reduce the computation workload. Tang et al. [12] developed a mathematical model between the collecting parameters and data quality to determine optimal parameters for 3D point cloud generation. The validation results showed all data points could satisfy the data acquisition quality requirement up to GSA level 3 within the data collection time of 6 minutes 40 seconds for each scan. Biswas et al. [9] presented a method to select the smallest set of scanner locations by an integer programming algorithm to achieve accuracy and coverage requirements. The proposed method was validated by conducting a scan planning on a concrete floor with a satisfaction precision of less than 2 mm and expected scan coverage of more than 50%. Ahn et al. [13] reported an interactive scan planning position decision approach for heritage building with both analytic computation and heuristic decision. The experiment results showed that the proposed method cloud achieve optimal scanning location determination with required scanning range and incident angle. Argüelles-Fraga et al. [14] conducted the determinization of scanning locations for circular cross-section tunnels based on tunnel dimensions, scan density and footprint size. A validation test conducted on a tunnel (105m long) indicated that the interval distance among the different scanning locations should be properly selected because point cloud data quality was decreased as the scanning range increased.

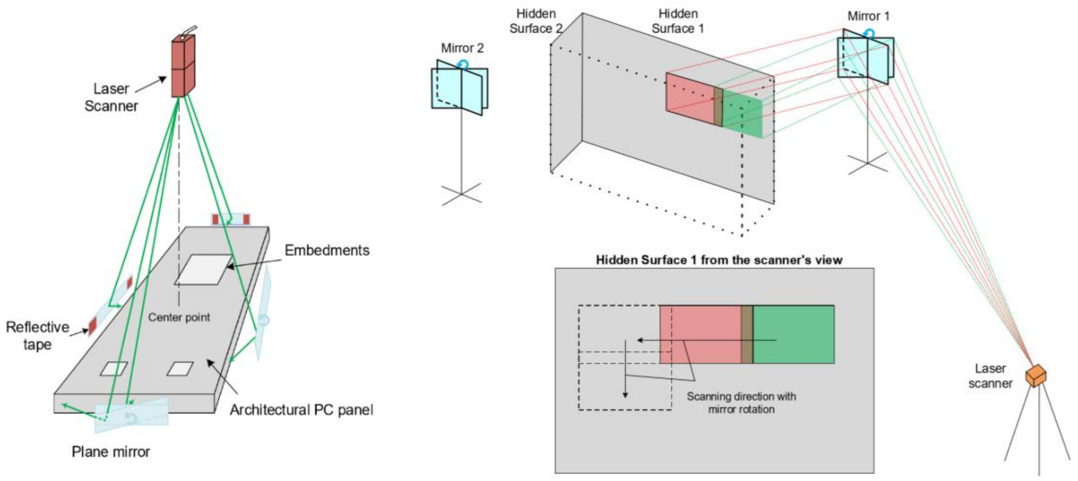
Despite previous scan planning studies, these studies are mainly assumed that a complete 3D scanning is achieved with multiple scans at different locations. For this reason, a registration process is needed for merging multiple scans. However, scanning parameter determination is ignored for the registration-free technique. Hence, through the development of registration-free data acquisition technique proposed in this study, the collecting parameters determination including laser scanner location and mirror location decision is investigated for a comprehensive scan planning consideration.

In this study, registration-free data acquisition technique for as-is BIM generation using rotating flat mirrors and laser scanning is investigated firstly. Then, data acquisition for as-is BIM generation of the PC slab and a structural component are simulated based on the proposed technique.

3. TECHNIQUE DEVELOPMENT

3.1. Overall scheme of the registration-free 3D data acquisition technique

Figure 1 shows the overall scheme of registration-free data acquisition technique for as-is BIM generation using rotating flat mirrors and laser scanning. In this study, two components including precast concrete units and structural walls are targeted for investigation. First, for the PC slab as shown in Figure 1(a), 4 flat mirrors are positioned next to the side surfaces to reflect the hidden side surface from the laser scanner and achieve a registration-free point cloud generation of the entire surface of the PC unit. Here, the mirrors are aided by a goniometer to achieve rotation in horizontal and vertical direction in order to cover the end part of the side surfaces. Here, the mirrors rotate in the horizontal and vertical direction to cover the end part of the side surfaces. On the other hand, as for the structural element as-is 3D point cloud data acquisition, the proposed technique uses two flat mirrors to simultaneously scan a portion of the two hidden surfaces using the stationary flat mirrors as shown in Figure 1(b). Note that laser scanner beam has the same property with nature light that they can be reflected by the flat mirror. In addition, small sizes of flat mirrors are employed in the proposed technique based on the reasons that large-size mirror is easily broken and hard to be used in real off-site and on-site environment. Note that with these two scan configurations, there is no need for change in the laser scanner and mirror location during the scanning process, resulting in a registration-free approach without changes in the laser scanner position.



(a) (b)

Figure 1. Overall scheme of registration-free data acquisition technique using rotating flat mirrors and laser scanner on: (a) PC element and (b) construction components (e.g. structural or internal wall)

3.2. Procedure of the registration-free data acquisition technique

Figure 2 shows the detailed procedure for the registration-free data acquisition technique. There are five primary steps that are 1) mathematical relationship model development, 2) scanning route planning, 3) laser scanner location determination, 4) mirror location determination, and 5) data acquisition execution for as-is BIM generation.

First, a mathematical model that represents the geometrical relationship among the laser scanner, mirrors and target object is developed. Then, scan route planning is performed to determine the direction and technical details of scanning using the flat mirrors that reflect laser beams on the hidden surface. Once the two key basic steps are conducted, an optimal laser scanner location is selected based on the evaluation of data quality on visible surfaces. Next, mirror location is then determined by finding the location which allows for minimum scanning time. Finally, a set of point cloud data on the entire surface of the target object is collected for as-is BIM generation

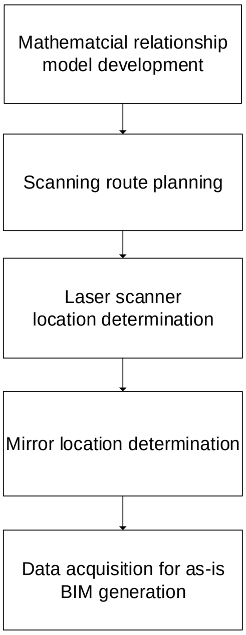


Figure 2. Primary steps of registration-free point cloud data acquisition technique for as-is BIM generation

3.2.1 Mathematical relationship model development

This step aims to understand and develop a geometrical relationship model that represents the relationship among the laser scanner, mirrors and hidden surfaces of the target object. Figure 3 illustrates the input-output diagram of the mathematical relationship model. The input parameters of the model are the laser scanner location, mirror plane and hidden surface plane of the target object. To be specific, the parameters of the mirror plane include 1) the mirror plane normal vector, 2) the centre point of the mirror and 3) four mirror corner points. Meanwhile, the parameters of hidden surfaces are 1) the hidden surface normal vectors and 2) the centre point of the hidden surfaces. The output of the relationship model includes 1) the four points reflected by the four mirror corner points and falling on the hidden surfaces and 2) the scanning area generated by the four output corner points. Note that the four corner points are calculated according to the mirror reflection principle. The details are shown as following: The laser beam emitted from the laser scanner is reflected by the mirror corner point and reaches the point on the hidden side surface of the target object. However, the laser scanner generates the coordinates of the virtual scan point on virtual side surface based on the assumption that the laser beam travels in a straight line. The 3D coordinates of the corner points on hidden surface is then calculated according to the geometrical relationship that virtual scan point and the corner point on hidden surface is symmetric with respect to the mirror. Note that the scan route planning, that is the next process, can be conducted using the output information of the mathematical relationship model.

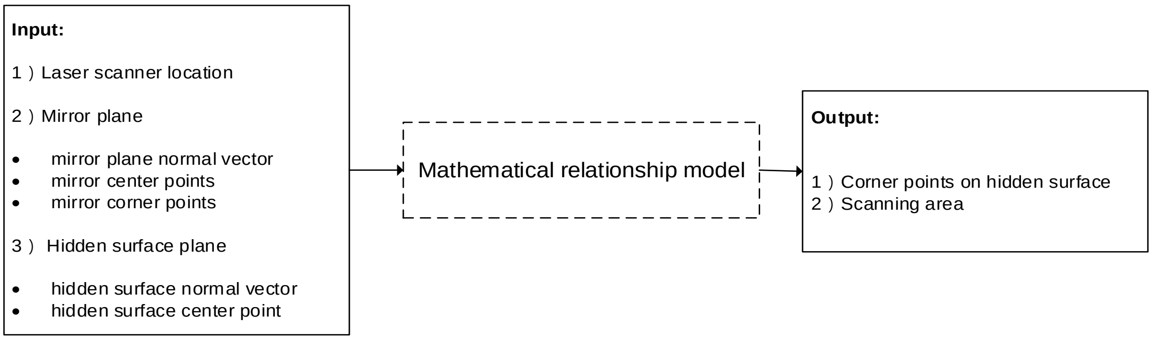


Figure 3. Input-and-output diagram of the mathematical relationship model

3.2.2 Scanning route planning

This step aims to plan the scanning route to be scanned by the rotating mirror on the hidden surface in order to achieve a complete scan on the hidden surface. Figure 4 shows the proposed scan route planning on a hidden surface. This study assumes that scanning is conducted from the bottom to the top of the hidden surface. First, the scanning route named '1st' horizontal route' is conducted along the bottom line of the hidden surface by changing the mirror angle. To do this, there are two constraints used in this study. First, two side boundaries and the bottom boundary of the hidden surface should be covered in the '1st' horizontal route. Second, there should be a certain amount of overlap between any two adjacent scans with different mirror angles. Once the bottom horizontal route is completed, a new boundary for vertical route and a new horizontal route is updated. The updated bottom boundary is parallel to the previous bottom boundary and covers the lowest scan point generated from the previous scanning route ('1st horizontal route'). Then, a new scan covering the update bottom boundary and the side boundary near the last scan of the previous horizontal route is generated, resulting a vertical route in order to increase the scanning level. Next, a new horizontal route ('2st horizontal route') is generated with the consideration of the two constraints mentioned before. Finally, the scanning level is increased until full hidden surface scan is achieved through the horizontal route and vertical route scan. It is noted that this step only provides scanning route and the number of scans will be determined once the locations of the laser scanner and the mirror are selected. Also, the number of scans is affected by the other parameters including mirror size and the overlap threshold.

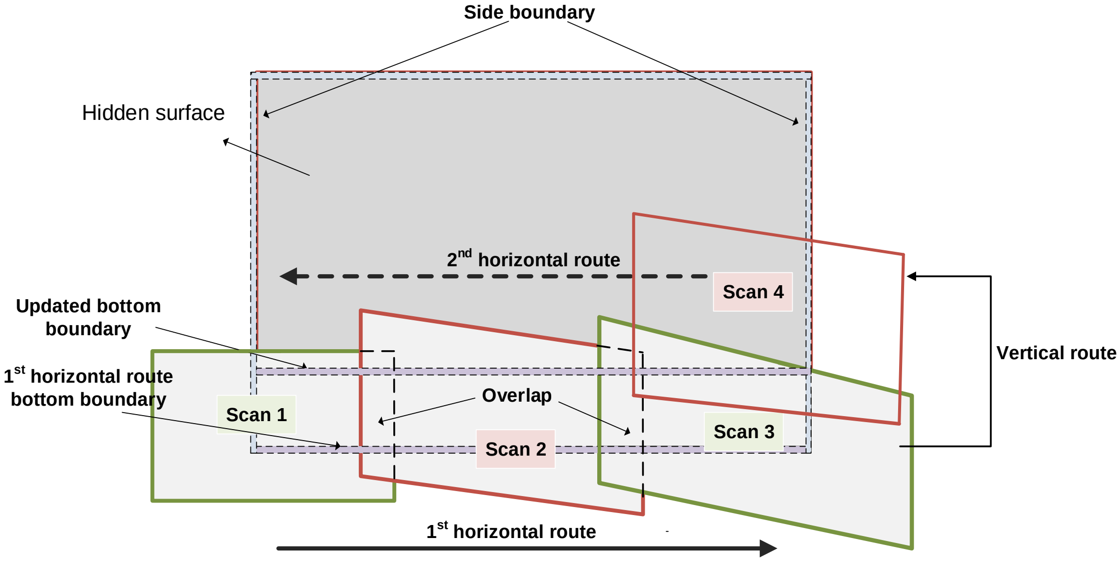


Figure 4. Scanning route planning

3.2.3 Laser scanner location determination

This step aims to select an optimal laser scanner location by finding the location where the best scan data quality on the visible surfaces of a target object is achieved. In terms of scan data quality, three criteria related to 1) visible surfaces, 2) feature points and 3) point-to-point distance, are used. First, visible surfaces of the laser scanner should be maximized. For example, there are one and two visible surfaces for the cases of Figure 1(a) and 1(b), respectively. Second, feature points defined as the key geometric features of the target objects should be captured. For instance, corner points of the top surface of Figure 1(a) are the feature points that should be captured. Third, the optimal scan location should meet the requirement for point-to-point distance defined as the distance between two adjacent scan points. Table 1 shows the requirements of point-to-point distance with varying target objects set by the GSA [7] for as-is BIM generation. For example, a large point-to-point distance of 25 mm (sparse scan data) is required for the data acquisition of building exteriors while a low point-to-point distance of 13 mm (dense data) needed for building interior components (e.g. floor level, room and artifact) [7,14].

Table 1. Data Quality and Requirements Standardized by GSA [7]

GSA Level	Area of Interest	Point-to-Point Distance
1	Total project area	152 mm
2	Subsection of Level 1 (e.g building)	25 mm
3	Subsection of Level 2 (e.g floor level)	13 mm
4	Subsection of Level 3 (e.g room or artifact)	13 mm

The process of selecting the optimal laser scanner is presented as follows. First, potential scanning locations are generated in 2D grid with a user-defined grid distance. Note that small grid size will generate more potential scanning locations for determination but increases the computation workload, so the gird size should be properly decided according to the two considerations above. Here, the intersections of the grids are regarded as potential scanning locations for the laser scanner position. Second, potential scanning positions that meet the two criteria 1) feature points and 2) point-to-point distance are determined. Note that feature points may have multiple point-to-point distances because they can be the intersection points of surface edge lines with different directions. In this case, it is required that all point-to-point distances should meet the requirement set by the GSA. If there is a featured point of a potential scanning location fails to satisfy the point-to-point distance condition, the potential scanning location is eliminated and not considered as the optimal location. Third, calculation of the degree of meeting the point-to-point distance requirement is performed for the remaining possible scanning locations. To do this, a scoring metric named '***FP Score***' is used to compute the degree of suitability. The '***FP Score***' of each feature point (P_i) is defined as:

$$\boldsymbol{FP\ Score}(P_i) = \sum_{j=1}^{m} \frac{D_{required} - D_{measure}(j)}{D_{required}} \tag{1}$$

Where $D_{measured}\ and\ D_{required}$ refer to the point-to-point distance measured, and the maximum point-to-point distance required, respectively. Also, m stands for the number of point-to-point distance that a feature point has. Next, the suitability of each remaining scanning location is computed. Here, the location suitability score named '$\boldsymbol{SP\ score}$' of each potential scanning location (L_i) is calculated as:

$$\boldsymbol{SP\ score}(L_i) = \sum_{k=1}^{n} \boldsymbol{FP\ Score}(p_k) \tag{2}$$

Where n refers to the number of featured points. Finally, the optimal scanning location with the highest $\boldsymbol{SP\ score}$ is determined as the laser scanner location.

3.2.4 Mirror location determination

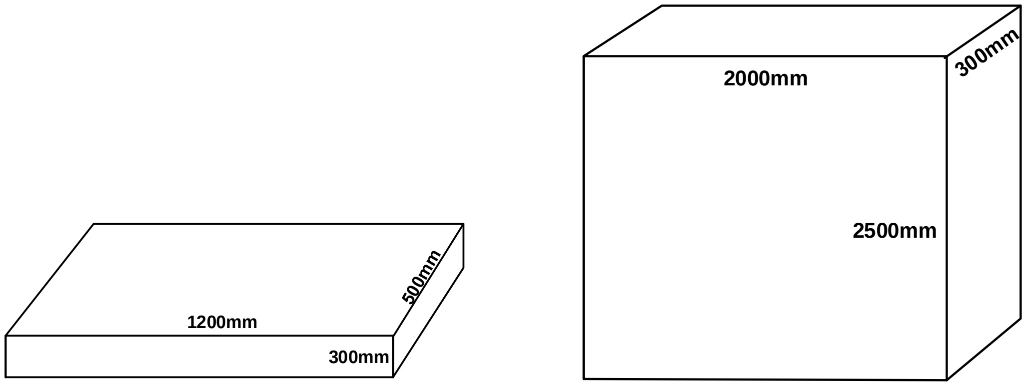
First, mirror size is determined by considering scanning site physical constraints. Second, 3D grids with a user-defined resolution are generated behind the hidden surface of the PC element within the available scanning area, and the intersection points are set as potential mirror centre locations. Third, similar to the laser scanner location selection process, the removal of mirror locations based on the two conditions that are 1) mirror locations are invisible from the laser scanner; and 2) mirror locations have not enough space for mirror rotation. Fourth, for the remaining potential mirror locations, the number of scanning along the planned scanning route mentioned in Section 3.2.2 is computed for each potential mirror location. As the final step, the optimal mirror location is selected as the location having the minimum number of scanning.

3.2.5 Data acquisition for as-is BIM generation

Once the laser scanner location and mirror location are determined, 3D point cloud data of the target component is collected along the planned scanning route. In this way, the laser scanner consecutively scans a portion of the hidden surfaces to cover both the visible and invisible surfaces surface of the target component without changing the scanner location, resulting in a registration-free scan data acquisition for as-is BIM generation.

4. VALIDATION

In order to validate the proposed registration-free scan data acquisition for as-is BIM generation, a series of simulation were conducted. Figure 5 shows the size of a PC slab and an interior wall used for the simulation. The PC slab and the interior wall have the dimensions of 1200 mm (length) × 500 mm (width) × 300 mm (height) and 2000 mm × 300 mm × 2500 mm, respectively. According to Table 1, the target objects, PC slab and interior wall, are under the GSA level 4 so that the required point-to-point distance (***D-required***) is less than 13 mm. Also, the angular resolution of 0.036° was used for calculating the measured point-to-point distance (***D-measure***).



(a) (b)

Figure 5. Dimensions of target components for simulation: (a) PC slab and (b) Interior wall

4.1. Simulation on PC element

For the simulation of the PC slab, the laser scanner height was selected as 1.2 m which is higher than the PC element in order to cover the three visible surfaces. A user-defined size of grid 0.1 m × 0.1 m was used for generating potential laser scanning locations, resulting in the creation of 496 potential scanning locations. Based on the two criteria related to feature point and point-to-point distance, 372 potential locations which fail to meet the two criteria were filtered out. Next, the performance of the remaining 124 laser scanner locations was computed based on Eq. (5) and the location of (1.7m, -1.1m,1.2m) respect to the left-bottom corner point of the PC slab was selected as the optimal scanning position. Figure 6 shows the result of the determination of the optimal laser scanner location. Note that the points in gray color refer to the scanning locations filtered out and the remaining scanning locations are provided with different colors. In the figure, warmer color point refers to higher suitability for laser scanner location.

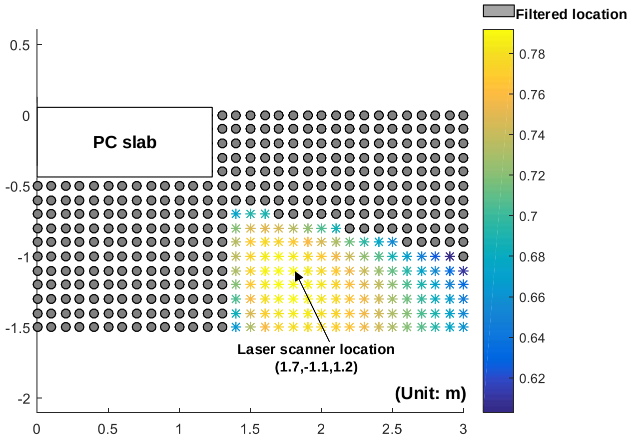
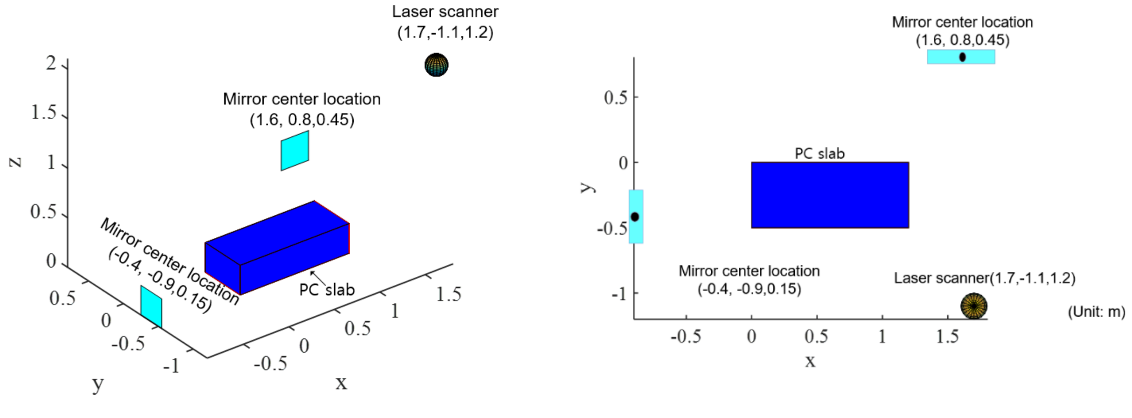


Figure 6. Result of laser scanner location determination. Here, warmer color point refers to higher suitability for laser scanner location

After the selection of the laser scanner location, the mirror location decision was conducted by finding the location with the least scanning time in 3D grid. For the PC slab with two hidden surfaces, two mirror locations are required to be used. Based on the consideration of scanning site physical constraints, the mirror size was set as 0.3m × 0.3m. As for the longitudinal hidden side surface, a 3D grid with a size of 0.4 m (length) ×0.4 m (width) ×0.15 m (height) is first generated on behind of the longitudinal hidden surface of PC slab for potential mirror centre locations, resulting in 72 potential mirror locations. Then, 30 mirror locations were filtered out according to the criteria and 42 potential mirror centre locations are used to calculate the number of scans to achieve a complete scanning on the hidden surface. From the computation, the location of (1.6 m, 0.8 m, 0.45 m) was selected as the optimal mirror location having the least scanning time. The mirror location for transversal side surface was then determined in the same method. The mirror size was set as dimensions of 0.3m×0.3m and 3D grid size was set as 0.4m×0.4m×0.15m, which were same as the setting for longitudinal side surface. There were 72 mirror locations generated and 17 mirror locations were filtered out according to the two criteria. For the remaining 55 mirror locations, the optimal mirror center location was selected as the location with the least scanning time for hidden transversal side surface scanning, which is at the coordinate of (-0.4m, -0.9m,0.15m). Figure 7 shows the determined laser scanner location and mirror location for PC slab.

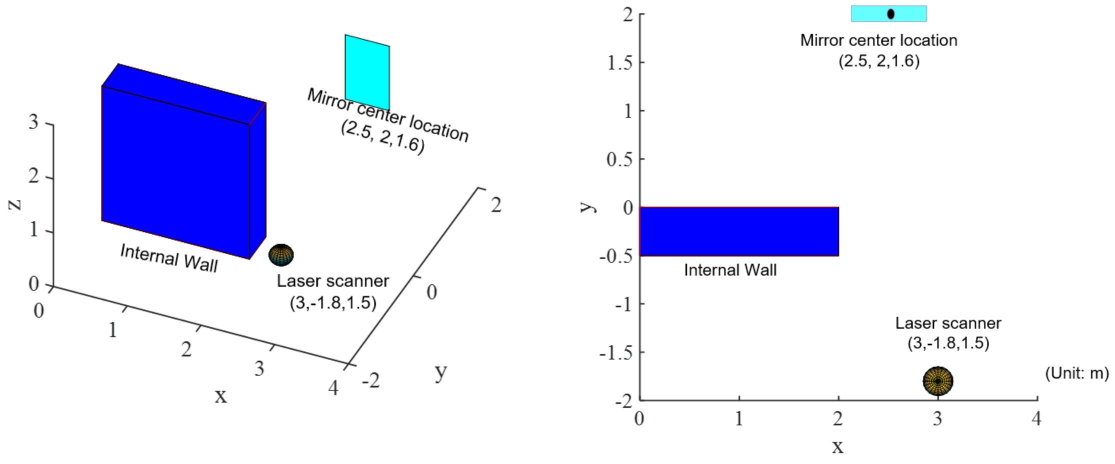


(a) (b)

Figure 7. Determined laser scanner location and mirror location for PC slab:(a) 3D view and (b) 2D view.

4.2. Simulation on wall

This section simulates the proposed registration-free data acquisition on wall for as-is BIM generation. First, the user-defined laser scanner height was set to be 1.5m which was lower than the wall. Then, the gird generated in 2D for finding the optimal laser scanner location was defined as the size of 0.1m×0.1m. 961 potential locations were generated in this way and 807 scanning locations were filtered out according to the conditions defined in section 3.2.3. After evaluating the performance of the remaining 154 scanning locations, the optimal lasers scanner location was selected as the location with the best performance, which was at the coordinate of (3m, -1.8m,1.5m). After deciding the laser scanner location, mirror center location for hidden surface scanning was defined as follows. It was assumed that one transversal side surface of the wall was connected to the other structural components (e.g. another wall that is perpendicular to this transversal side surface) of the building. Therefore, only one longitudinal side surface was required to be scanned. First, the mirror size was set as a size of 0.6m×1.2m and 3D grid size was set as 0.25m×0.5m×0.2m. Then, 153 mirror center locations were generated in 3D grid. After the filtering, 36 potential mirror center locations were filtered out. The optimal mirror center location was selected as the location with the least scanning time for hidden transversal side surface scanning, which was at the coordinate of (2.5m, 2m,1.6m). Figure 8 shows the determined laser scanner location and mirror location for the wall.



(a) (b)

Figure 8. Determined laser scanner location and mirror location for wall: (a) 2D view and (b)3D view.

4.3. Discussion

In this study, the potential locations for both laser scanning location determination and mirror location determination are generated with a user-defined gird size. The selection of small size grid is likely to generate more potential locations with low resolution but increase the computation load. In this way, the grid size should be properly selected according to the two considerations. In addition, the mirror size is also determined with a user-defined value according to the physical site constraints in this study. However, the selection of the mirror size has influence on the performance of the complete hidden surface scan, which requires more comprehensive investigation in future study.

5. CONCLUSION

This paper presented a registration-free 3D point cloud data acquisition technique for as-is BIM generation. The proposed technique uses flat mirror which can rotate in both horizontal and vertical way to scan the side surfaces of target components. In this way, the entire surfaces of target components are scanned without registration process. which prevents registration-error and reduce scanning time. To develop the proposed method, five key steps are introduced in this study, which are mathematical relationship development, scan route planning, laser scanner location determination, mirror location determination and data acquisition. Though the simulation tests based on the data acquisition technique, it is concluded that the proposed technique has potential to be applied to various construction elements including PC elements and structural components onsite. This research improves the effectiveness of data acquisition technique by developing a registration-free method, which contributes the as-is BIM generation of various construction components. However, the mirror size selection and gird generation for optimal scanning location and mirror location in this study relies on a manual way. Therefore, future work will focus on the automatic system creation for mirror size and location determination.

REFERENCES

[1] Tang, P., Huber, D., Akinci, B., Lipman, R., & Lytle, A. (2010). Automatic reconstruction of as-built building information models from laser-scanned point clouds: A review of related techniques. *Automation in construction*, *19*(7), 829-843.

[2] Ma, Z., & Liu, S. (2018). A review of 3D reconstruction techniques in civil engineering and their 2applications. *Advanced Engineering Informatics*, *37,* 163-174.

[3] Bosche, F., Haas, C. T., & Akinci, B. (2009). Automated recognition of 3D CAD objects in site laser scans for project 3D status visualization and performance control. *Journal of Computing in Civil Engineering*, *23*(6), 311-318.

[4] Valero, E., Adán, A., & Bosché, F. (2015). Semantic 3D reconstruction of furnished interiors using laser scanning and RFID technology. *Journal of Computing in Civil Engineering, 30*(4), 04015053.

[5] Wang, C., Cho, Y. K., & Kim, C. (2015). Automatic BIM component extraction from point clouds of existing buildings for sustainability applications. *Automation in Construction, 56,* 1-13.

[6] Sanchez, V., & Zakhor, A. (2012, September). Planar 3D modeling of building interiors from point cloud data. In *2012 19th IEEE International Conference on Image Processing* (pp. 1777-1780). IEEE.

[7] GSA. GSA BIM Guide for 3D Imaging. 2009. Available online: https://www.gsa.gov/cdnstatic/GSA_BIM_ Guide_Series_03.pdf.

[8] Dai, F., Rashidi, A., Brilakis, I., & Vela, P. (2012). Comparison of image-based and time-of-flight-based technologies for three-dimensional reconstruction of infrastructure. *Journal of construction engineering and management*, *139*(1), 69-79.

[9] Wang, Q., & Kim, M. K. (2019). Applications of 3D point cloud data in the construction industry: A fifteen-year review from 2004 to 2018. *Advanced Engineering Informatics*, *39,* 306-319.

[10] Wang, Q., Guo, J., & Kim, M. K. (2019). An Application Oriented Scan-to-BIM Framework. *Remote Sensing*, *11*(3), 365.

[11] Soudarissanane, S. S., & Lindenbergh, R. C. (2011). Optimizing terrestrial laser scanning measurement set-up. In *ISPRS Workshop Laser Scanning 2011, Calgary, Canada, 29-31 August 2011; IAPRS, XXXVIII (5/W12), 2011*. International Society for Photogrammetry and Remote Sensing (ISPRS).

[12] Tang, P., & Alaswad, F. S. (2012). Sensor modeling of laser scanners for automated scan planning on construction jobsites. In *Construction Research Congress 2012: Construction Challenges in a Flat World* (pp. 1021-1031).

[13] Ahn, J., & Wohn, K. (2016). Interactive scan planning for heritage recording. *Multimedia Tools and Applications*, *75*(7), 3655-3675.

[14] Argüelles-Fraga, R., Ordóñez, C., García-Cortés, S., & Roca-Pardiñas, J. (2013). Measurement planning for circular cross-section tunnels using terrestrial laser scanning. *Automation in construction*, *31*, 1-9.