A TIME EFFICIENT QUALITY CHECK METHOD BASED ON LASER SCANNING FOR INSTALLATION OF PREFABRICATED WALL PANELS

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ABSTRACT:

Verticality check of prefabricated elements is an essential part of prefabrication construction. Currently, it is mostly carried out by manual methods, which is slow and inefficient. Previous studies have used laser scanning for the quality check but mainly focused on surface defects, flatness, and the dimension of construction elements. Very few studies used laser scanning to evaluate the installation quality of prefabricated elements. Those, who adopted the laser scanning method, compared the as-built with the initial design version of BIM. Such approach requires an accurate design version of BIM with tedious manual tasks relying on human skills that involve errors. This on-going study investigates a verticality check method based on laser scanning for assessing the quality of wall panel installations without relying on previous drawings or BIM. The proposed method enables practitioners to confirm the quality of the wall panel installation and its vertical deviations based on the processed point cloud data. The region growing segmentation and random sample consensus are used to process the acquired data for computing the deviations. This method is validated in a real high-rise prefabrication residential building. Our method took about 9 min/100 m^2, versus the conventional method, which took 31 min/100 m^2. The experiments indicate that the proposed method is significantly more time-efficient compared to the conventional manual method. The contribution of this study includes suggesting suitable parameters for measuring the vertical dimensions of prefabricated wall panels and deviations that can be replicated in high-rise prefabricated residential projects.

1. BACKGROUND

Prefabricated wall panels (PWPs) have been widely utilized in building construction. Compared with traditional cast-in-site concrete, prefabricated panels provide higher quality, time-saving, and environmental benefits (Jin et al., 2020; Shahpari et al., 2020; Du et al., 2022). Despite these advantages, structural failure of prefabricated concrete systems can occur if the PWP is not installed conforming to design codes (Bataglin et al., 2020; Sun et al., 2022). Thus, it is significant to perform the quality assessment on PWPs after they are installed on the construction site. Verticality check of PWPs is an essential part of quality assessment. Currently it is mostly carried out by manual method by at least two inspectors. While one inspector makes the measurement of verticality using tapes, plumb bob, or 2 m rulers, the other inspector is in charge of data recording and analysis (Wang et al., 2021c; Tang et al., 2022). During the verticality quality check, the inspector must ensure that the ruler is perpendicular to the ground (Li et al., 2022). However, manual inspection has two major problems. Firstly, the results of manual inspection could be inaccurate and unreliable (Wang et al., 2021a; Wang et al., 2016a). As traditional acceptance testing adopts the sampling inspection, its results are usually difficult to be reproduced. Moreover, there is no requirement for measurement points specified in the current Chinese code (China Building Standards Design and Research Institute, 2014). Secondly, manual inspection is slow and inefficient, especially for large-size projects with a large number of prefabricated elements (Wang et al., 2019; Wang et al., 2021b). Therefore, there is a growing demand for an efficient and reliable method to provide verticality assessment of PWPs, especially for the high-rise prefabricated residential buildings or prefabricated projects with numerous similar floors.

In recent years, laser scanning technology is becoming more and more popular since it can acquire range measurement data at a high speed and high accuracy (Li et al., 2020a; Wang et al., 2020). It takes only a few minutes to capture the entire three-dimensional (3D) scene (Guo et al., 2020a). Due to these advantages, laser scanning has been used for quality check of prefabricated elements, including geometry quality assessment (Guo et al., 2020a; Wang et al., 2016a), and detection of surface defects and flatness (Wang et al., 2016b). Some studies have applied laser scanning to test the verticality of the concrete surfaces for indoor systems. Wang et al. (2015) proposed a house internal geometric quality check method using laser scanning, including the assessment of verticality of building rooms. Some studies used laser scanning for verticality check of building concrete structures, such as walls and columns (Li et al., 2022; Wang et al., 2015). Wang et al. (2021c) tested a proposed installation quality check method using laser scanning for PWPs of a prefabrication building construction site. Overall, onsite installation quality check using laser scanning is rare.

This study continues the research presented by Wang et al. (2021c). The method for verticality check has been improved significantly. More tests have been performed on a dataset with different types of prefabricated wall panels. The PWPs are identified from point cloud data based on region growing and plane fitting algorithms. This study intends to identify appropriate values for segmentation parameters based on trial analyses on a real project. The time efficiency of the proposed method is analyzed by comparing the time spent on checking

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PWPs for every 100 m^2 building floor between traditional manual measurement and using laser scanning method. The research illustrates suitable segmentation parameters can assist industry practitioners to speed up and improve the efficiency of verticality check of PWPs in high-rise prefabricated residential buildings or other similar prefabrication projects.

2. LITERATURE REVIEW

Laser scanning has been gradually adopted for quality check in construction projects. The collected laser scan data are used as the digital representation of the work-in progress projects. Some studies used design BIM model as a reference to detect variation in quality check. For example, Rausch et al. (2017) used laser scanning point cloud data and BIM to check the dimensional quality of prefabricated elements. Bosché and Guenet (2014) used scan-vs-BIM method to make a flatness assessment by matching each point from point cloud with the corresponding element in the BIM model. Li et al. (2020a) made alignment between point cloud data with an as-designed BIM model, and then check the deviations of the component surface. Li et al. (2020b) used BIM model and laser scanning data to detect installation deviation of modular removable floodwall installation. However, using design BIM model for quality check is not practical as it requires an accurate BIM model and skilled BIM engineers to process the data. In practice, designs may be frequently changed, and the updated BIM model is usually not available during construction process. Therefore, it is more practical to use a quality check method without using BIM model.

The geometry information of PWPs can be derived by processing point cloud without referencing a BIM model. Well-known segmentation and plane fitting algorithms can be adopted to obtain geometry information of PWPs and then compute their verticality deviations. Point cloud segmentation algorithms can divide point cloud into different clusters, such as region growing methods (Vo et al., 2015), clustering feature-based methods (Filin, 2002). However, adopting these algorithms needs to find the suitable parameters, which could also be time-consuming (Wang et al., 2021c). To reduce the time spent on testing and identifying the appropriate parameters, it is critical that the parameters are pre-determined for a particular type of prefabrication projects. Currently no research provides values or range of parameters used in practice for identifying PWPs from site laser scanning data.

The time efficiency of using laser scanning is a critical aspect of the proposed approach. Some studies quantitatively analyzed the potential time benefit of geometric quality check using laser scanning for construction projects. For example, Guo et al. (2020b) made time analysis of using laser scanning for geometric quality assessment on a typical residential building. It validated the time efficiency of using laser scanning is higher than manual measurement. Tang et al. (2022) analyzed the time benefit of using laser scanning for quality check, and concluded that using laser scanning method is more efficient due to reduced data collection time. Wang et al. (2021c) proposed an onsite installation quality check approach for PWPs using a common laser scanner, Leica BLK 360, to check the horizontal alignment and verticality in a real prefabricated building project. The proposed procedures and quality check methods have been validated. It estimated the efficiency of using laser scanner, while there is a lack of quantitative analysis of time efficiency.

In summary, there is a lack of practical and efficient method to make verticality check for PWPs without using BIM model, and the parameters for processing the point cloud data need to be identified for high-rise prefabricated residential building projects.

3. METHODOLOGY

This study aims to propose a time-efficient verticality check method for high-rise prefabrication residential buildings. There are two aspects in the research design. One aspect is the process of verticality check using laser scanning. As in practice, the quality check is usually carried out after the whole floor is completed, this study used a complete floor area as a typical case analysis. BLK 360 laser scanner is adopted as it is a commonly available and used laser scanner in China (Wang et al. (2021c). The specifications of the scanner are shown in Table 1.

3.1 Framework design

An important aspect of this study is to compare the time efficiency of the proposed laser scanning method with the traditional manual method. When the laser scanner is selected, the parameters in the point cloud data analysis can be pre-determined, so once the laser scan data is collected, it can be input to the software algorithm for immediate processing. In this study, the appropriate values of the parameters are determined using a use case. Determining the values of the parameters may be time-consuming as a few tests need to be carried out. However, once they are determined, the parameters can be used for similar projects and circumstances. Note, in the time comparison, the time for determining the values of the parameters is not included. The time of using predefined parameters for the laser scan data processing is compared with manual method for every 100 m^2 floor.

Scanning resolution	Every 10 mm in HZ and V (distance 10 m)
Ranging accuracy	4mm @ 10m / 7mm @ 20m
Speed of scanning	360, 000/s
Scanning range	60m
3D point accuracy	6mm @ 10m / 8mm @ 20m
Scanning time	Less than 3 minutes

Table 1. Technical specifications of Leica BLK 360.

The proposed laser scanning method for verticality check is presented in Figure 1. Based on the approach proposed by Wang et al. (2021c), this paper includes three new procedures, which are ground points removal, statistical outlier removal and filtering process. The computation efficiency is improved due to reduced number of unnecessary points.

Four major steps are required to compute the verticality of prefabricated elements. The first step is to collect point cloud data of construction site using laser scanning. After data collection, the second step is to pre-process the data in a commercial software CloudCompare (Girardeau-Montaut, 2011), including data registration and ground points removal. The third step is to identify individual PWP from the data, including noise removal, region growing segmentation, random sample consensus (RANSAC) plane fitting, and filtering process. The final step is verticality check, by computing the normal vector of each panel and calculating their vertical angles.

The proposed method is most beneficial for high-rise prefabrication residential building or projects with a large number of similar prefabricated elements and repetitive quality check tasks, because the pre-determined parameter values can be reused in each analysis.

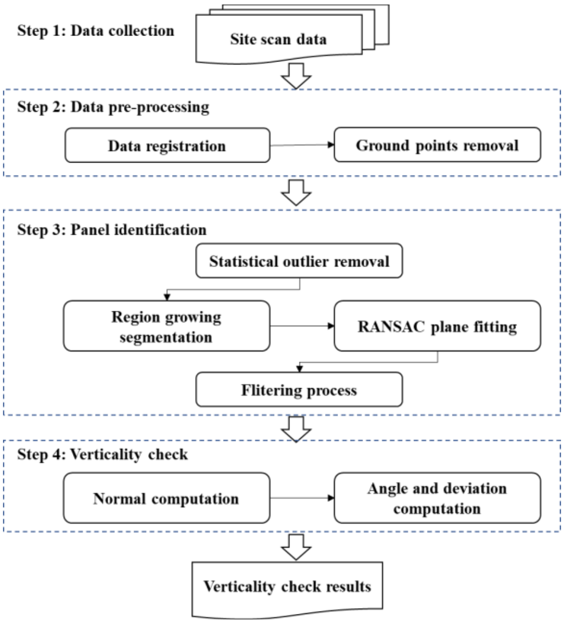

Figure 1. Framework of verticality check approach.

3.2 Data pre-processing

The pre-processing stage includes data registration and ground removal. Usually, one scan is not sufficient to obtain the 3D scene of one floor of prefabrication residential building. Therefore, different scans are performed and need to be registered in one dataset. Currently, commercial software could make data registration, such as Leica Cyclone 8.0, CloudCompare software (Girardeau-Montaut, 2011; Jung et al., 2014). After data registration, the data is cluttered with many unnecessary elements, such as crane tower, scaffold. The required data for verticality check are only the points containing PWPs. Therefore, the data is further cleaned by roughly removing background and ground points. These two processes are conducted manually using CloudCompare software.

3.3 Plane identification

The PWP identification from the pre-processed data includes four processes:

(1). Statistic outlier removal
The first process is outlier removal. Laser scan data usually contains noise that appears as fuzziness in the point cloud and they are generated due to the random error of laser scanners (Oskouie et al., 2016a). The data fluctuation features cannot be modelled with a specific distribution, however, they are quite close to normal in nature, thus they can be modelled with a normal distribution (Oskouie et al., 2016a). In this case, to reduce the influence of noise points, statistic outlier removal algorithm is adopted. This algorithm removes points that are further away from their neighbours compared to the average for the point cloud (Balta et al., 2018). The parameters used for statistic noise removal are set as 50 for the number of neighbours and 1 for the standard ratio as recommended in the study proposed by Oskouie et al. (2016a).

(2). Region growing segmentation
The second step is to separate PWPs by using a segmentation algorithm. As the proposed approach should be practical and efficient, the selected algorithm needs to be low computation cost and easy to use. Region growing is selected due to its simplicity and relatively low computational cost (Oskouie et al., 2016a; Wang et al., 2021c).

There are five parameters that need to be determined when using region growing for segmentation, which are K search (KS), number of neighbours (NN), minimum clusters (MC), smoothness threshold (ST), and curvature threshold (CT) (Dong et al., 2018; Xiao et al., 2013). Region growing method extracts 3D planes by progressively merging adjacent points with similar features (Dong et al., 2018). These features can be summarized as the proximity of the points and planarity or roughness of the surfaces (Vosselman et al., 2003). Points which are located at the vicinity of the seed region and have similar properties to those within the seed region are clustered into the same group. KS is the number of points used for the normal estimation of each point (Pauling et al., 2009). NN is the number of points neighbouring the seed points for region growing (Pauling et al., 2009). MC, ST, and CT are used as constraints to group points. ST limits the angle difference of normal vectors between seed points and their neighbouring points and CT is to test if a potential growing point can be added to a seed set (Shao et al., 2021). MC is used to set the minimum number of points for a valid plane.

In this study, segmentation parameters for a typical high-rise prefabrication residential building are determined. A few tests are carried out for the real case, to identify the parameters that could segment PWPs from point cloud data collected by BLK 360 scanner. The value of ST and CT were set as 5 and 1, respectively, as proposed by Wang et al. (2021c). The other parameters are KS and NN, which need to be determined for the real case covered in this study and can be adopted for similar circumstances.

(3). RANSAC plane fitting
The next process is to fit a plane for each segment, which is used to represent the wall panel. This process can be completed by using a plane fitting algorithm. The RANSAC algorithm is used to estimate the parameters of the best plane to the individual segments (Goebbels and Pohle-Fröhlich, 2020). It could filter the outliers of a fitted plane and obtain normal vector. After plane fitting, the plane equation and the containing points of each segment are computed. There are three parameters that need to be set for RANSAC fitting, including distance threshold, iteration and the number of minimum inliers for each plane (Fischler and Bolles, 1981). Distance threshold means the maximum distance of points to the fitted plane, so the points with distance less than the threshold are regarded as inliers (Duan et al., 2021). Iteration is the number of fitting cycles. The minimum number of inliers represents the minimum number of points for a fitted plane. These parameters adopted the same values as recommended by Wang et al. (2021c).

(4). Filtering process
After segmentation and plane fitting, points of some construction materials could still exist, such as supporting poles. In this case, further fliting process is developed to remove those unnecessary segments. The differences between PWP segments and other segments are their heights. The height of PWPs should be around 2.7 m. In this case, the segments with a height lower than 2 m could be removed. After the fliting process, the segments of PWPs are identified with computed plane equations, inliers, normal vectors, and heights. These factors will be used for verticality check.

3.4 Verticality check

After identification of the fitted plane PWPs, verticality check can be carried out. The deviation of verticality should be within tolerance of the verticality as required in construction specifications, which is 5 mm from the top to the bottom when the height of PWP is less than 5 m (China Building Standards Design and Research Institute, 2014).

The traditional manual measurement of verticality is shown in Figure 2 (left). The plumb bob is commonly used to check verticality on the construction site. The worker will put the plumb bob at one side of PWP and estimate the verticality deviation. Once the vertical line across the centre point of the tool, it means the wall panel is vertically installed.

The laser scanning approach is seen in Figure 2 (right). It captures the 3D point cloud data of the whole construction floor by placing the scanner at several places. The way to calculate the verticality follows the same principle as manual measurement (Figure 3). To compute the verticality deviation L_{12}, the height h of each PWP and its vertical angle are required. The equation to calculate L_{12} is shown in Equation (1). The height h of each PWP can be obtained by the range of z values of the containing points in each fitted plane. The vertical angle is computed as the angle between the normal vector of fitted plane v_2 and absolute vertical vector v_1. The normal vector of fitted plane v_2 is computed by RANSAC algorithm. The absolute vertical vector v_1 is (0, 0, 1) or (0, 0, -1). This approach computes the vertical angles of all PWPs, then identifies the verticality quality.

Figure 2. Verticality check of using traditional manual measurement (left) and using laser scanning approach (right).

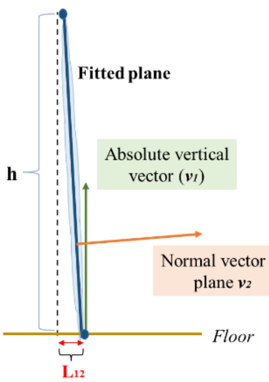

Figure 3. Verticality deviation computation.

$$L_{12} = h * \tan [90 - (\langle v_1, v_2 \rangle)] \quad (1)$$

where L_{12} = verticality deviation
h = height of each PWP
v_1 = absolute vertical vector
v_2 = normal vector of fitted plane

After computing the verticality deviation, the results are compared with limit of 5 mm, which is required in the construction specifications. Those planes that have verticality deviations larger than 5 mm are highlighted. Then the onsite worker has to make rectification on these identified PWPs only, instead of measuring all panels one by one manually.

4. EVALUATION IN THE PREFABRICATION BUILDIUNG CASE

4.1 Case background

The case study is undertaken on a typical high-rise prefabrication residential building project in Shanghai, China. It has 16 floors of the building. One typical floor of a building is selected, which has approximately 510 m^2 area with four residential units. There are 42 PWPs on the floor, 24 external PWPs and 18 internal PWPs. After installation of all PWPs, workers need to check the PWPs one by one. The Leica BLK 360 is adopted to scan the construction site. To collect the laser scan data, the operator should decide the scanning locations for the whole floor. Nine scans capture the 3D scene of the whole construction site. The co-registered point cloud is shown in Figure 4. CloudCompare software is used to remove the ground points and outliers. The following steps are conducted by the data processing algorithms and procedures designed in the Python environment.

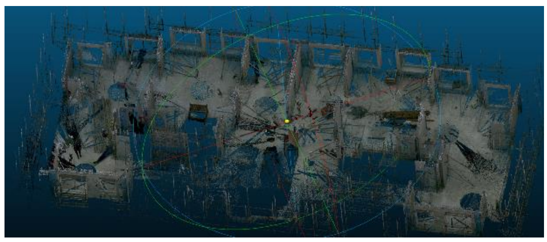

Figure 4. Collected point cloud data of the selected case using BLK 360.

4.2 Identification results

This study uses the same scanner, i.e. BLK 360, as proposed by Wang et al. (2021c). Therefore it adopted the same value set for KS that is 35. In this study, as the ground points and outliers are removed before segmentation, the value of NN is set by experiments. When NN is set as 75, it could obtain good segmentation results. In this case, 70 clusters are identified after segmentation, as seen in Figure 5. According to the range of segmentation parameters provided by Wang et al. (2021c), appropriate segmentation parameters can be determined relatively quickly, in about 20 minutes for this case. Following the RANSAC fitting algorithm and the filtering process, the final fitted planes of PWPs are obtained, as seen in Figure 6. The final clusters are 58. Ideally, 42 clusters should be identified. As PWP has four sides, some internal PWPs could have several surfaces identified from different sides. All the PWPs have corresponding fitted planes, which demonstrates the effectiveness of plane identification process in the proposed approach.

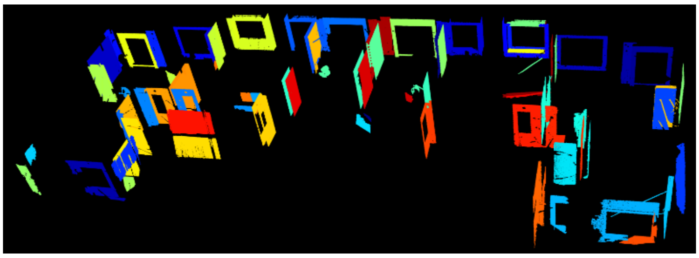

Figure 5. Region growing segmentation result (KS=35, NN=75).

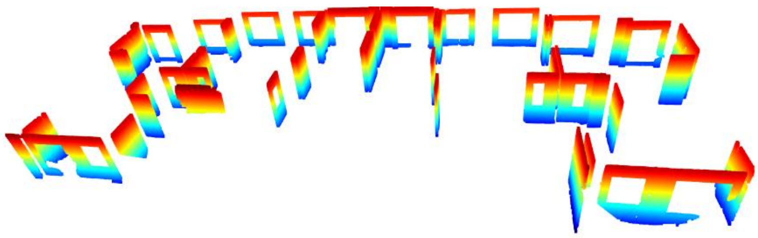

Figure 6. RANSAC fitting result.

4.3 Quality check results

The verticality check is conducted on all fitted planes. 11 planes are identified that have more than 5 mm verticality deviation. The identified planes are shown in Figure 7 (left). These planes are imported to CloudCompare software and compared with the original point cloud data, as seen in Figure 7 (right). The onsite workers could use these point cloud data to find the panels that need rectification directly .

The time efficiency of the laser scanning method is based on that the segmentation parameters are pre-determined, and these values can be adopted in other similar projects. Therefore, the time spent on testing parameters is not included in the final time comparison. The data pre-processing involves various tasks and not all of them are fully automated. Some tasks such as data registration and ground points removal are manually processed, therefore the associated time is also included. The plane identification and verticality check process are automated and streamlined, and the time given in Table 2 are computer processing time only. For both manual method and laser scanning data collection, time given in Table 2 are for an experienced person to conduct the task. The total time for both methods, and average time spent on each wall panel and the time efficiency of these two methods are compared in Table 2.

Based on the experiments, the total time for the two approaches are 160 min and 46.6 min respectively. The average time for checking a panel is around 3.8 min by using the traditional method and 1.1 min by using the laser scanning approach. The time efficiency T_e of each approach is calculated as the required quality check time (min) per 100 m^2. The results show that T_e value of the traditional manual measurement method is about 31.4 min/100 m^2. The T_e value of using the laser scanning approach is 9.1 min/100 m^2. The results show that the proposed laser scanning method is more time-efficient to make verticality quality checks than traditional manual method.

Traditional method		Laser scanning approach		
Item	Time	Item		Time
Data collection & Verticality check (Experience person average time)	160 min	Data collection	Using BLK360 by experienced person average time	33 min
		Data pre-processing	Data registration	9 min
			Ground points removal	1 min
		Plane identification & Verticality check (Streamline process)	Statistic outlier removal	0.6 min
			Segmentation	0.9 min
			Plane fitting	1.5 min
			Filtering process	0.1 min
			Verticality check	0.5 min
Total time	160 min	Total time	46.6 min	
Average time (per PWP)	3.8 min	Average time (per PWP)	1.1 min	
Time efficiency (T_e)	31.4 min/100 m^2	Time efficiency (T_e)	9.1 min/100 m^2	

Table 2. Comparison of time spent on verticality check using conventional method and laser scanning approach with predefined parameters

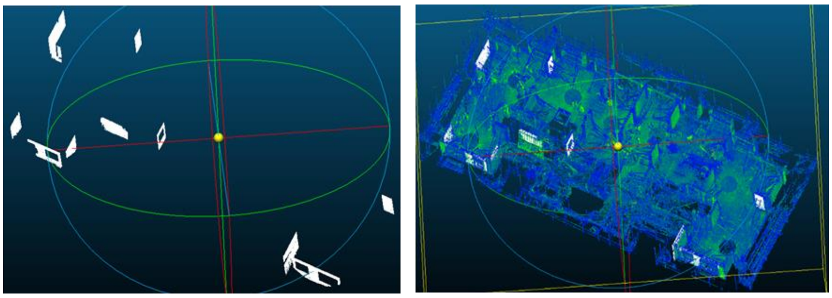

Figure 7. Identified faulty wall planes (left) and their locations in the floor (right).

5. DISCUSSIONS

The proposed laser scanning method for verticality check of PWPs has been adopted and tested in a real construction case, and appropriate value for the parameters in point cloud data processing has been determined. With the predetermined segmentation parameters, using laser scanning method for the quality check of the PWPs on 510 m^2 area of this project could save about 2 hours compared to the manual method. As the typical floors of the high-rise prefabrication residential building are usually identical, the proposed approach can be adopted for all floors of the building.

As parameters in laser scanning data analysis are determined, and the laser scanning locations on each floor can be the same, the time on the data collection and analysis could be even less for other floors as people become more experienced and skilful in repeating these tasks. In this case project, there are other 15 floors in the building, and the quality check time is around 46.6 min per floor. It can be estimated that the time for checking the whole building using laser scanning approach is 12.43 h. For the traditional method, checking one building could cost 42.67 h. The time saving for one building is about 30.24 h. Therefore, there is a great potential of time benefit by using laser scanning for high-rise prefabrication residential buildings, which have many identical floors. Although testing and determining segmentation parameters can be time-consuming and requires professional knowledge in point cloud processing, these parameters can be predetermined and provided to the construction practitioners beforehand. With these predefined parameters, automated and streamlined verticality quality check can be carried out very effectively and efficient.

The traditional manual measurement method of verticality could be error prone and hard to keep a systematic record. For example, some PWPs are not completely flat, so the measurement results could be inaccurate if the measurement tool is put on those uneven areas. To obtain accurate check result by using the manual method, the surfaces of PWPs must be flat and workers must operate the measuring process with great caution (Wang et al., 2018). The vertical deviations could vary if checking different parts of the surfaces for one panel. Moreover, manual measurement could only inspect limited areas of PWPs. In this case, the manual measurement result is not consistent. The benefit of using laser scanning is that it could capture the point cloud data of the entire PWP, and many point cloud data processing algorithms could be adopted to suit different circumstances to improve accuracy (Li et al., 2020a).

Using laser scanning could provide accurate and reliable geometry and position information of PWPs (Kim et al., 2014) and it is easy to keep in a digital record. The impact of using laser scanning method on the entire project is minimum as it can be done much more quickly than the manual checking method. The scanning processes can be conducted with the progress of installation tasks or during the break of installation tasks. With laser scanners are readily available in more and more construction projects, the proposed method could contribute significantly to time saving in comparison with the traditional manual method.

Compared with the study of using laser scanning for onsite quality check proposed by Wang et al. (2021c), it costs approximately 2.3 min to make segmentation process of 7 panels within one construction floor, this study used less than 1 min for segmentation with 42 panels, which is more time efficient. The improvement of the segmentation efficiency lies in the additional processes of ground points removal and outlier removal in this study. This is a further improvement in the laser scanning data processing based on the previous studies on installation quality check, and more elaborated tests of an entire building floor have been performed in this study (Wang et al., 2021c).

As mentioned above, some other previous studies made quality assessment based on the alignment of design BIM model with collected laser scan data (Li et al., 2021; Tang et al., 2022). However, the accuracy of using as-design BIM model for quality check depends on the accuracy of the BIM model, which usually is not frequently updated during construction, therefore cannot be relied on (Li et al., 2020a; Shirowzhan et al., 2017). In another aspect, using BIM-model for quality check needs to test the accuracy of model alignment and point matching process, which requires specialised skills and is not practical during daily construction process.

6. CONCLUSION

Verticality check is a critical part of quality control for prefabricated wall panels after they are installed onsite. To improve efficiency of PWPs verticality check for high-rise prefabrication residential building projects, this study proposed a practical and efficient approach using laser scanning. This approach could identify the individual wall panels in one building floor and compute the verticality of them.

The work presented in this paper distinguishes itself from similar studies by proposing a framework to identify PWPs from point clouds and computing verticality check without referencing the design BIM model. Compared with study presented by Wang et al. (2021c), the improvement of this research includes the ground removal process, which reduced the computational cost and improved the process efficiency. The region growing algorithm is used to obtain individual segments for wall panel.

This study made tests and experiments to suggest the segmentation parameters for a typical floor of a high-rise prefabrication residential building. The parameters KS and NN can be set as 35 and 75 respectively when using BLK 360 scanner to collect data. Using the predetermined parameters, this approach can be applied to the other floors in the building. The time used by the traditional manual measurement method is about 31.4 min /100 m^2, while the time used by the proposed laser scanning approach is 9.1 min/100 m^2. The dataset adopted in this research is an entire floor of prefabrication building, which is the scenario to use laser scanning in practice. The results indicate that the method is promising to improve efficiency of verticality check for the high-rise prefabrication residential building projects or projects with a large number of similar floors.

The limitations and future directions of this study are discussed as follows. The verticality check results are computed by the estimated normal vectors of each PWP. The reliability of verticality check depends on the accuracy of data quality, such as scanning procedure errors, scan registration inaccuracies, and environmental conditions (Oskouie et al., 2016b). More accurate scanners can be adopted to improve accuracy of point cloud data. There are other scanners that can be used for quality check of installing prefabrication elements, such as Faro focus X330 (Aryan et al., 2021), and Leica RTC360 (Tang et al., 2022). The time efficiency of using other scanners could be evaluated in future studies.

Overall, this research is a pilot study of using laser scanning to make verticality check without BIM model. The results of this research are most effective for high-rise prefabrication residential building, as most of the floors are the same or similar. The proposed approach can be adopted for other prefabrication projects with similar buildings.

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