Journal of Mining and Earth Sciences

Website: http://jmes.humg.edu.vn

Displacement monitoring of high-rise buildings by using terrestrial laser scanners: Faro Focus^{3D} X130

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ARTICLE INFO

Article history:
Received 07th July 2021
Revised 03rd Oct. 2021
Accepted 02nd Nov. 2021

Keywords:
Cloud - to - Cloud distance,
Faro Focus3^{D} X130,
High-rise buildings,
TLS.

ABSTRACT

Monitoring the displacement of high-rise buildings using a terrestrial laser scanner (TLS) is an active research topic in the field of engineering surveying. The Faro Focus^{3D} X130 is one of the most suitable scanners which is widely used in different industries, such as architecture, archaeology, shipbuilding, and construction. However, in engineering surveying, the potential use of this scanner is not investigated for displacement monitoring yet. This paper's goal is to evaluate the accuracy of this scanner in the displacement monitoring of high-rise buildings. In the fieldwork experiment, the high-rise-rise building's displacement is simulated by a movement of the board installed on this building. In addition, the surface material, scanning geometry, and point density of data that influenced the scan quality are investigated. The cloud - to - cloud method in CloudCompare software is applied to measure the distance between point clouds in two epochs. The distance between two point clouds allows determining the displacement of the board in two epochs. The results show the deviation between displacement analyzed from point clouds and the actual displacement is smaller than 2 mm in all experiments. TLS completely fulfills the required accuracy in the displacement monitoring according to the Vietnam construction standard. This study indicates that Faro Focus^{3D} X130 is suitable to use in the displacement monitoring of high-rise buildings in practical engineering surveying.

1. Introduction

Monitoring displacement is one of the major concerns when dealing with high-rise buildings. The removal of the building is caused by several reasons, such as the types of structures and the

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DOI: 10.46326/JMES.2021.62(6).05

load's unpredictable and changing nature. It is critical to monitor the high-rise buildings' displacement for safety purposes. Generally, GPS and other conventional techniques (e.g., leveling and total station) are famous for solving this issue. However, the main disadvantage of these techniques is the limitation of measured points, which may lead to misinterpreted information about the displacement of constructions.

By contrast, TLS allows collecting massive points known as a point cloud of an object. The TLS was widely applied in deformation monitoring in surveying engineering. The assessment of the accuracy of TLS for deformation monitoring can be found in Lindenbergh and Pfeifer (2005), which presented an investigation on the accuracy of Leica HDS2500 on the tracking of a locked door. Schneider (2006) used Riegl LMS - Z420i, a pulse scanner with 8 mm of accuracy to determine the bending line of a television tower. González - Aguilera et al. (2008) used TLS to monitor a large dam. In that study, a novel methodology is developed by incorporating different statistical and modeling approaches. In tunnel monitoring, Van Gosliga et al. (2006) presented the first investigation of using TLS to monitor the bored tunnel deformation. An artificial deformation is generated and then determined through a point cloud obtained by TLS. The result of that study shows that TLS is appropriate for this purpose. Aligning with static deformation, TLS can also be used for dynamic deformation. Jatmiko and Psimoulis (2017) used TLS to monitor the displacement of a steel structure.

In Vietnam, there are no investigations and a standard procedure of TLS in monitoring displacement of high-rise buildings. Hence, the paper aims to develop a method for monitoring the removal of high-rise buildings and evaluate the accuracy of TLS on this application.

The paper icontains five sections, introduction and conclusion are inclusive. Section 2 describes in detail the comparison method. Section 3 presents the experiment. The influence of some potential factors on scan quality is investigated in section 4. The final section is conclusions, limitations, and future works of TLS for monitoring displacement of high - rise buildings.

2. Analysis of displacement from point clouds

In TLS, the object's displacement can be computed by the change of point clouds measured at two epochs. The removal can be determined by hypothesis test (Wujanz et al., 2013, Wujanz 2016). This method can show the object's displacement, but its quantitive measurement cannot be determined.

By contrast, the displacement can be determined by comparing methods, such as point - to - point, cloud - to - cloud, and cloud - to - mesh. Some existing methods for computation distance for two different point clouds can be found in (Lague et al., 2013). The point-to-point approach is widely used for displacement monitoring when the number of measured points is limited. This approach is also called the point-wise comparison, and it is applied for monitoring in mining excavation (Little, 2006).

Since TLS can acquire a high point density, the C2C distance should be applied (Jafari et al., 2017). This approach is a fast and straightforward direct comparison of point clouds because it does not require data meshing. The C2C method applies an octree structure to divide 3D spaces, and then the closest point is found between two already registered point clouds.

The principle of nearest neighbor distance is used to compute the distance between two points by a norm (e.g., Euclidean). In this computation, one point is in the compared Cloud and another is searched in the reference cloud. To approximate the actual distance from the reference surface, a local surface model is introduced. Figure 1 shows the local model surface using for C2C method.

The local model surface is a mathematical primitive fitting by the least square method. In CloudCompare (CC) software, a local surface model is a plane of triangles generated by three points. The distance between two clouds is computed by Hausdorff distance. The Hausdorff distance, a max-min distance, is used to calculate the distance between two point clouds. Given two finite point sets $A = \{a_1 \quad \cdots \quad a_p\}$ and $B = \{b_1 \quad \ldots \quad b_p\}$, the Hausdorff distance is defined as (Huttenlocher et al., 1993):

$$H(A,B) = max\big(h(A,B), h(B,A)\big) \qquad (1)$$

Where:

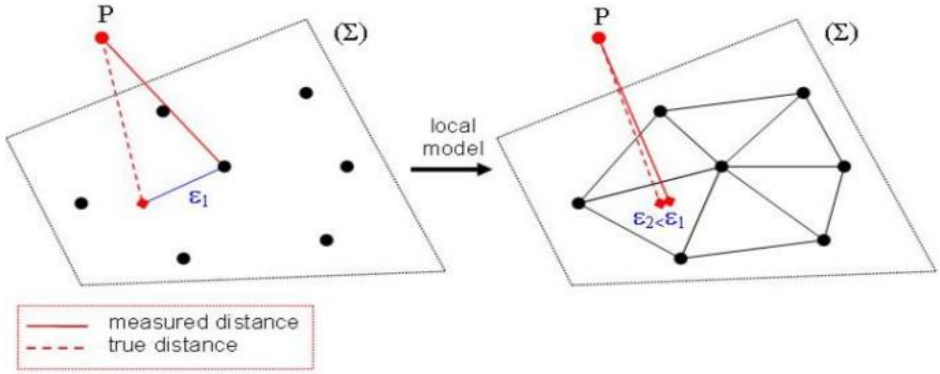

Figure 1. The concept of local surface model of C2C method. (https://www.cloudcompare.org/doc/wiki/index.php?title=Distances_Computation#Local_modeling).

$$h(A,B) = \max_{a \in A} \min_{b \in B} \|a - b\| \qquad (2)$$

And $\|\cdot\|$ is a norm on the points of A and B (e.g., the Euclidean norm).

Function h(A,B) is called the directed Hausdorff distance from A to B. This approach is also used in cloud matching techniques, such as ICP (Iterative closest points) defined by (Besl and McKay, 1992).

The C2C method applied in CC software estimates the distance between two point clouds in which one of them is the reference or model cloud and the other one is compared Cloud. CC will compute the distances of each point in the compared Cloud relative to the reference one. Hausdorff estimates the distance between two clouds.

Apart from C2C, the distance between two clouds can be computed by the Cloud - to - mesh distance (C2M) (Oniga and Chirila, 2013) that is also one of the common techniques in inspection software. However, creating a surface mesh is complex for point clouds when a surface is not flat or missing data due to occlusion (Lague et al., 2013). Hence, the C2M method is not discussed in the limitation of this study.

3. Experiments

This section investigates the impact of scanning geometry, surface material, and point density on scan quality. In the experiment, the scanner used is the Faro Focus^{3D} X130, and artificial displacement is a movable board. A brief introduction of the experiment is presented in the following:

Scanner

The phase-based scanner used in the experiment and described here is the Faro Focus^{3D} X130 (see Figure 2). This type of scanner allows us to collect the data with a very high point density quickly, but the range from the scanner to the scanned object is limited (about less than 120 m). The specification of this scanner is listed in Table 1. The experiment is carried out in a high-rise building on the Hanoi University of Mining and Geology campus for three days (from 20th to 22nd February 2021).

Artificial displacement

To assess the capability of TLS in displacement monitoring, artificial displacement is generated by using a movable board. The experimental board with a size of 60 cm x 60 cm is mounted on the steel monument. The steel monument can be moved on two parallel raids, and its displacement can be measured by a steel ruler with an accuracy of 0.1 mm (see Figure 2 (b)).

In the first epoch, the experimental board is scanned when it is fixed at a certain position. The experimental board is scanned in the second and third epochs after moving back 10 and 20 mm.

Scanning geometry

The change of scanning geometry is due to the measured distance and the incidence angle. The incidence angle is defined as the angle between the laser beam vector and the normal vector of the scanned surface (Soudarissanane et al., 2009). In the first experiment, the

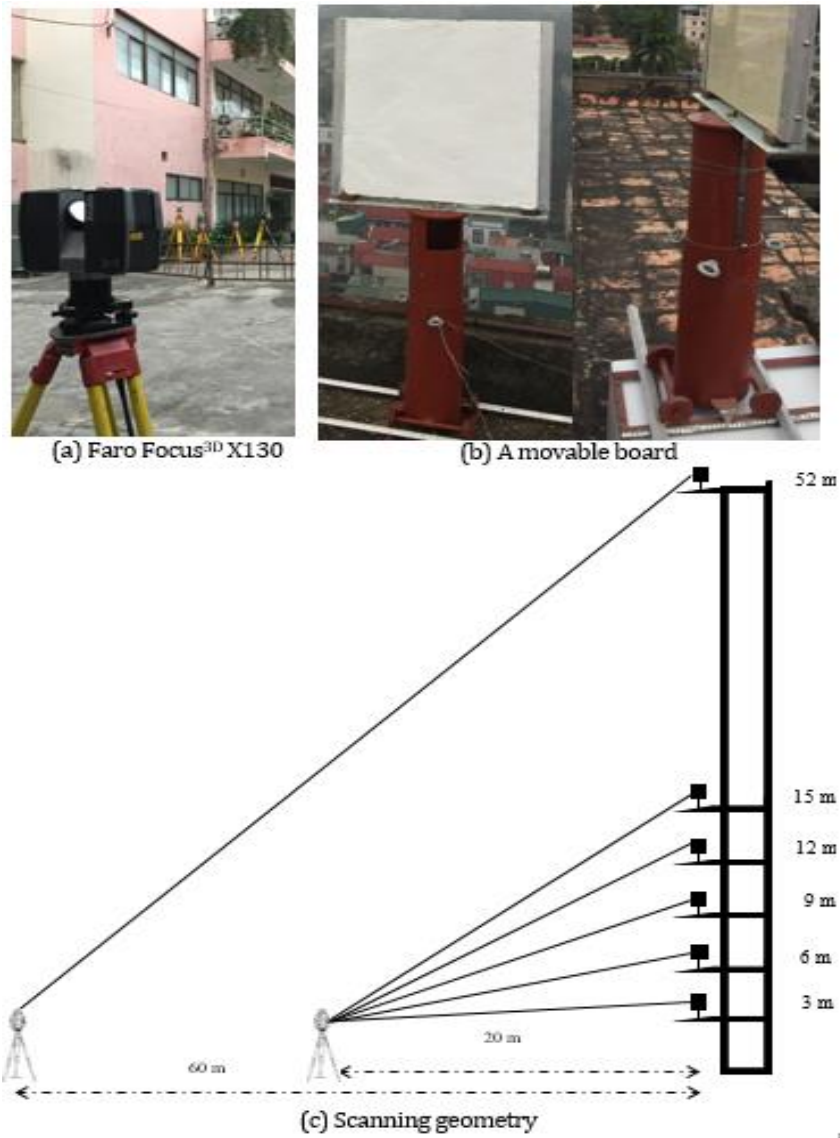

Figure 2. The experimental area and scanned board.

experimental board is located on different floors. The height of the board is in six levels of 3, 6, 9, 12, 15, and 52 m. The corresponding incidence angles increases by 9, 17, 24, 31, 37, and 46^0. The scanner is set up at two positions that the distance from the scanner to the scanned object is about 20 and 60 m, respectively (see Figure 2 (c)).

Surface materials

In the second experiment, the influence of surface materials of the scanned object on the scan quality is investigated. The reflectivity property of surface material is defined by the amount of light scattered relating to the wavelength of the laser light in use (Soudarissanane, 2016). The surface materials of the scanned object are conducted by granite and concrete that are standard materials of high-rise building structures in Vietnam recently. The surface of granite is smoother than that of concrete, as depicted in Figure 2. In this study, the evaluation is carried out by two surface materials of granite and concrete at six independent times. Each material is scanned from the same position. Other factors related to the surface of a scanned object like the clour are not discussed in the restriction of this study. This issue can be found in (Reshetyuk, 2006; Voegtle et al., 2008; Berenyi et al., 2010).

Point density

The point density is an critical factor influencing the scan quality. It is clear that the scan quality increases with higher point density, but the amount of increase depends on each case. In the experiment, the point density changed in four different levels which are set up by the resolution parameter before scanning.

Table 1: Manufacter's Specifications of Faro Focus^{3D} X 130.

Items	Characters
Measure Technology	Phase shift
Vertical field of view	$- 60\div 90^0$
Horizontal field of view	$0\div 360^0$
Max. Range	$0.6\div 130$ m
Single point accuracy	±2 mm
Angular accuracy	0.005^0
Max. Scan rate	976000 (pts/sec)
Max. resolution	1.5 x 1.5 mm at 10 m

4. Results and discussion

This section will present results about the influence of scanning geometry and surface material on the scan quality in the context of displacement monitoring for high-rise building constructions. In the following analysis results, the difference value is compared between the real displacement and the distance estimated by the C2C method. It is reminded that the real displacements in the 2nd and 3rd epochs are 10 and 20 mm, respectively (see more details in section 3). It is noting that the displacements between two epochs are computed by the C2C method using CloudCompare (CC) software in version 2.11.3.

4.1. Influence of the scanning geometry on the scan quality

The influence of the scanning geometry on the scan quality is shown in Figure 3. In this evaluation, the experimental board's displacements obtained by C2C are compared to their real ones in the 2nd and 3rd epochs, which are 10 mm and 20 mm, respectively.

In 20 m of distance from the scanner to the board, this influence is not essential when the incidence angle increases from 9^0 to 37^0. The standard deviation of the measurement is smaller than approximately 1.2 mm. There is no increased tendency of both different values and standard deviation with the increasing incidence angle. In 60 m of distance, the other values are 1.2 and 1.7 mm in the 2nd and 3rd epochs, respectively. The corresponding standard deviations are 2.6 and 4.1 mm, respectively.

The above results can be explained by the change of the incidence angle (from 10^0 to 37^0) does not influence the scan quality because the distance from the scanner to the board is small. In this case, the quality of measurement is quite similar. This result agrees with the investigation in (Soudarissanane et al., 2009). The scan quality is not affected by the incidence angle between 0^0 to 40^0 with 20 m of the measured distance.

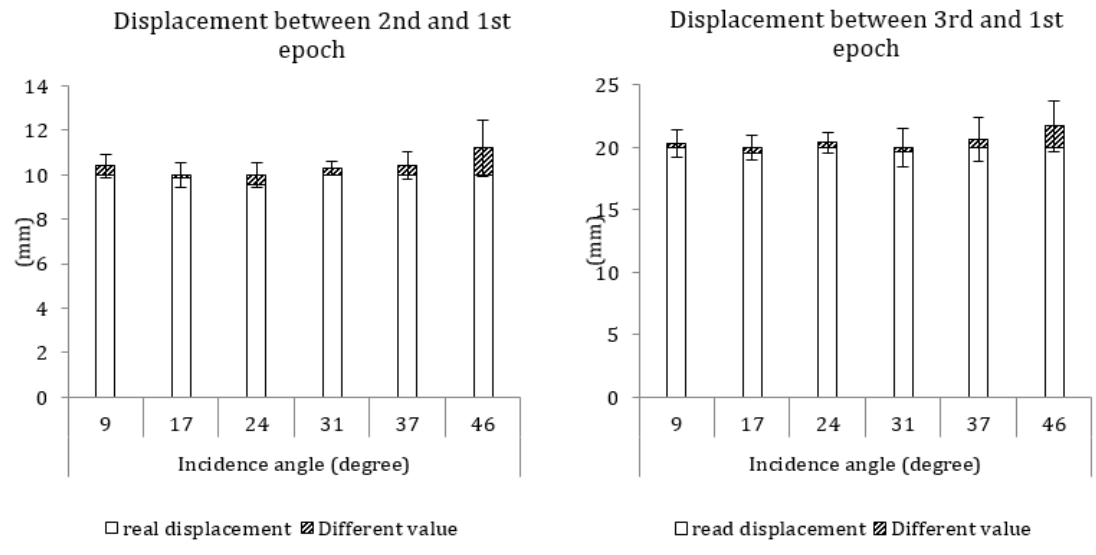

Figure 3. Displacement monitoring vs. scanning geometry.

In contrast, when the incidence angle is 46^0, and the distance from the scanner to the board is 60 m, the difference and the standard deviation are more considerable.

The poor scanning geometry is the leading cause of this issue. These results agree with the theory that the received signal level influences the precision of the distance determination. The received signal level of measurements increases with decreasing incidence angles. However, this influence behavior of the incidence angle on scan quality is not considered in the scope of the study.

4.2. Influence of surface materials of scanned objects on the scan quality

Figure 4 (left) shows the influence of surface material on scan quality pointed out by the displacement's mean and standard deviation values. The displacement of the scanned object conducts the data at the 3rd epoch compared to the 1st one. Granite is the better material for reflectivity in this experiment. The determination of displacement using the granite material is approximately from 1.5 to 3.0 times more accurate than the concrete one concerning the different values. This result is proper because the granite surface is smoother in this experiment (see Figure 2). The standard deviation values in changing materials are not different but cannot be explained here.

4.3. Influence of point density on the scan quality

The point density set up by the resolution parameter significantly influences the scan quality, as shown in Figure 4 (right). The scan quality is pointed out by the different values increasing with a higher point density. This different value increases from 0.1 to 3.3 mm when the point density reduces from 10000 to 750. Similarly, the standard deviation also increases quickly from 1 to 3.2 mm, decreasing the density to 750 points.

However, some limitations in the study should be shown here. First, the height of the experimental board is approximately 50 m that is not satisfactory for very high-rise buildings in Vietnam. Second, the influence of incidence angle on the scan quality is evaluated on the range of [9^0, 46^0]. This range does not adequately reflect the influence of the incident angle on the scan quality. Third, the paper only discussed the relative displacement of a building by comparing the distance between point clouds at two corresponding epochs. Last, since the relative displacement of the building is measured at a single scanning station in the experiments, the registration and georeferencing errors are not concerned here.

5. Conclusions

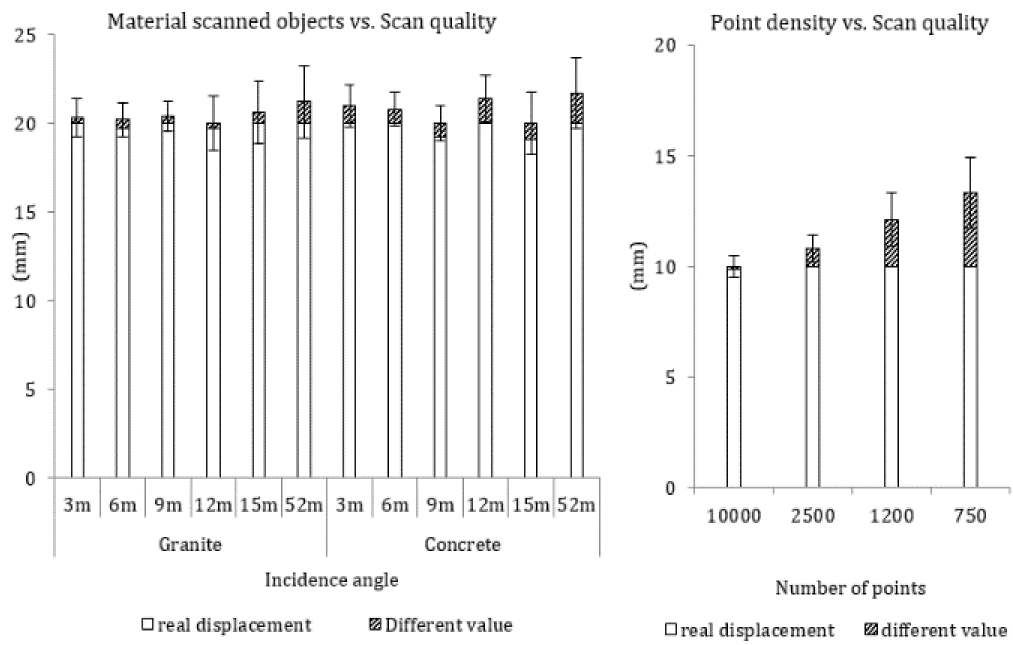

Figure 4. Influence of surface material (left) and point density (right) on the scan quality.

The accuracy of Faro Focus^{3D} X130 is sufficient for monitoring the displacement of high-rise buildings according to the Vietnam construction standard. The displacement accuracy is smaller than 2 mm for a scanned object that is lower than 50 m in height. The proposed method can be used for monitoring the relative displacement by TLS.

The surface material and scanning geometry are essential characteristics in the displacement monitoring of high-rise buildings. However, if the distance from the scanner to the monitoring object is short, the influence of these above-mentioned characteristics is not significant. Additionally, the point density is another reason that highly impacts the scan quality. The author suggests that the resolution and quality parameters of the scanner should be set up at a considerably high level in the monitoring displacement.

The C2C method is a good choice for the computation of the distance between two-point clouds. The advantage of this method is that it is not necessary to generate a mesh and can be applied to any surface to use the C2C for displacement monitoring of complex buildings.

Several potential limitations should be noted in this study. Since the scanned object in this experiment is limited to about 50 m and the incidence angle is on the range of [9^o, 46^o], its impact behavior on scan quality is not researched. In addition, the proposed method is only to determine the relative displacement but not for the absolute displacement.

Other methods for estimating the distance between two-point clouds (e.g., C2M) are worth investing in future work. The weather conditions, such as humidity, wind, and temperature should be analyzed in monitoring the displacement of high-rise building constructions.

Acknowledgements

This paper has been funded under the research program T21/20 of Hanoi University of Mining and Geology.

Author contribution

Trung Dung Pham contributes to the idea, data acquisition, analysis, and writes the manuscript. Cuong Xuan Cao, Duc Tinh Le, Cuong Sy Ngo and Dinh Van Le contribute to collecting the data.

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