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The capability of terrestrial laser scanning for monitoring the displacement of high-rise buildings

PHAM Trung Dung[1], PHAM Quoc Khanh[1*], CAO Xuan Cuong[1], NGUYEN Viet Hung[2], NGO Sy Cuong[3]

[1] Hanoi University of Mining and Geology, Department of Engineering Surveying, Hanoi, Vietnam
[2] University of Transport and Communications, Faculty of Information Technology, Hanoi, Vietnam
[3] Vietnam Natural Resources and Environment Company

Corresponding author: phamquockhanh@humg.edu.vn

Abstract. Recently, terrestrial laser scanner (TLS) has been increasingly used to monitor of displacement of high-rise buildings. The main advantages of this technique are time-saving, higher point density, and higher accuracy in comparison with GPS and conventional methods. While TLS is ordinary worldwide, there has been no study of the capability of TLS in monitoring the displacement of high-rise buildings yet in Vietnam. The paper's goal is to build a procedure for displacement monitoring of high-rise buildings and assess the accuracy of TLS in this application. In the experiments, a scanned board with a 60 cm x 60 cm mounted on a moveable monument system is scanned by Faro Focus^{3D} X130. A monitoring procedure using TLS is proposed, including three main stages: site investigation, data acquisition and processing, and displacement determination by the Cloud-to-Cloud method (C2C). As a result, the displacement of the scanned object between epochs is computed. In order to evaluate the accuracy, the estimated displacement using TLS is compared with the real displacement. The accuracy depends on scanning geometry, surface property, and point density conditions. Our results show that the accuracy of the estimated displacement is within ± 2 mm for buildings lower than 50 m of height. Thus, TLS completely meets the accuracy requirements of monitoring displacement in the Vietnam Standards of Engineering Surveying. With such outstanding performance, our workflow of using TLS could be applied to monitor the displacement of high-rise buildings in the reality of geodetic production in Vietnam.

Keywords: Terrestrial laser scanner, monitoring of displacement, the accuracy of displacement, high-rise buildings

1. Introduction

Monitoring the displacement of high-rise buildings has been a topic of great relevance. The displacement of these constructions is caused by the types of structure and the load's unpredictable and changing nature. Hence, monitoring of the high-rise buildings is needed to secure and preserve the safety of these constructions. In Vietnam, GPS and other conventional methods (e.g., levelling, theodolite, and total station) are widely used for monitoring displacement of the high-rise buildings. These methods can only monitor a specific number of points, restricting the estimation of the displacement of constructions. By contrast, TLS allows collecting massive points known as a point cloud from the monitoring object. A key element of monitoring displacement is transforming several epochs into one standard coordinate system. Typically, the standard coordinate system is a geodetic coordinate system that is determined by some reference points. At reference points, artificial targets like check boards or spheres are fixed on these points. The stable points are to detect an absolute displacement of the object that occurred in among epochs. In displacement monitoring by using TLS, the same monitoring object at different epochs is compared. Two basic algorithms normally used for identifying the displacement are test and comparison [1]. While the test method does not allow measuring the displacement quantitatively, the compare method enables us to solve this issue. The displacement of the monitoring object is measured by the distance between two-point clouds of different epochs.

TLS was widely applied in the field of deformation monitoring, such as structural monitoring [2], tunnel deformation monitoring [3], dam and tower monitoring [4], and deformation monitoring of a steel structure [5]. The deformation monitoring using TLS can also find in related studies [6, 7, 8, 9]. However, in this field, both a standard rule and a comprehensive evaluation of the accuracy of TLS is lack. Few published works applied TLS for monitoring displacement and deformation of construction based on conventional geodetic methods. That procedure includes site investigation, data acquisition, data processing, and data analysis. A procedure of the three-stage process model [10] is developed to compute the deformation of a dam by block to point estimation and fine registration Iterative Closest Point (ICP). This procedure, then, is developed to become multiscale-model-to-model cloud comparison (M3C2), piecewise alignment, and block to point methods [8].

To evaluate the accuracy of TLS, Lindenbergh and Pfeifer [7] presented an investigation on the accuracy of Leica HDS2500 on the monitoring of a locked door. This issue can find in other evaluations of the accuracy of TLS for the health monitoring of structure [8, 11, 12]. The scanning geometry, materials, colour and roughness of properties, weather conditions such as wind, temperature, and humidity are important factors influencing the scan quality [13, 14, 15]. In the displacement monitoring of high-rise buildings, building characteristics that could affect scan quality should be considered, such as scanning geometry and the structure's surface material. This paper aims to develop a procedure for monitoring the displacement of high-rise buildings and evaluate the accuracy of TLS considering these influencing factors.

The paper presents the following structure and organization: after this introduction, Section 2 describes the methodology developed for displacement analysis and procedure for monitoring displacement of high-rise buildings. 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. Methodology

2.1. Displacement analysis

The displacement of an object can be computed directly by comparing the location of this scanned object at different epochs. Computation distance for two point-clouds can find in Lague, Brodu [16]. The point-to-point approach is widely used for displacement monitoring when the number of measured points is limited. This approach is called the point-wise comparison (see [17]) and is applied for monitoring mining excavation. Since a high point density can be acquired by TLS, the cloud-to-cloud (C2C) distance should be used [18]. This approach is the fast and straightforward direct comparison of point cloud because it does not require any data meshing. The C2C (Fig. 1) method applied in CC software estimates the distance between two-point clouds in which one of them is the reference or model cloud, and another is the compared cloud. Apart from C2C, the distance between two clouds can be computed by the cloud-to-mesh distance (C2M) [19], which is also a 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 [16]. Hence, the C2M method is not discussed in the limitation of this study.

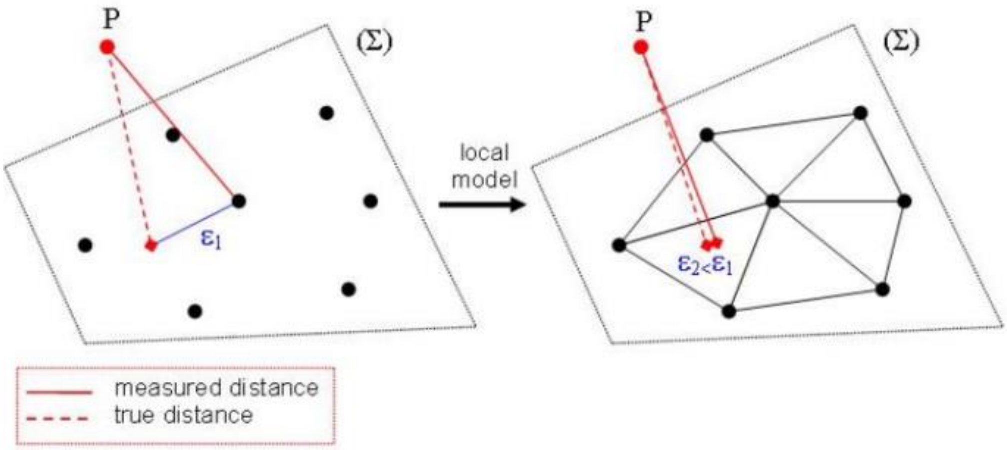

Fig. 1. The concept of local surface model of C2C method. The local surface allow us to better approximate measured distance ($\varepsilon_2 < \varepsilon_1$) [20].

The C2C approach applies the Hausdorff distance, which is defined by a max-min distance. The brief introduction of this distance can be described as follows. Given two finite point sets $A = \{a_1 \quad \cdots \quad a_p\}$ and $B = \{b_1 \quad \cdots \quad b_p\}$, the Hausdorff distance is defined as [21]:

$$H(A,B) = max\big(h(A,B), h(B,A)\big), \tag{1}$$

where

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

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) [22].

2.2 Procedure of displacement monitoring

In displacement monitoring of high-rise buildings, the survey procedure is still an open question in TLS, and there have been no standard rules have in Vietnam yet. However, like any type of geodetic survey (e.g., theodolites, total station), initial planning is fundamental for deriving all necessary information on the objects scanned. Currently, to the author's best knowledge, a procedure for monitoring displacement of high-rise buildings includes the main stages as follows:

First, in the investigation stage, the information about the surveyed object needs to be collected. Large-scale maps and existing reference points are helpful in this respect. A preliminary scan with a low resolution is useful for further planning tasks if the surveyed area is large.

In the second stage, to acquire the expected resolution and accuracy of the point cloud, the parameters of resolution and quality should be set up [23]. The required accuracy in the determination of displacement depends on the types of constructions. According to the Vietnam construction standard (TCVN-9399), the accuracy for monitoring the displacement of high-rise buildings is 1/10.000 building's height (e.g., the accuracy of 10 mm with corresponding 100 m in high). Hence, the resolution and quality are set up at a considerable high level to meet the corresponding high accuracy requirement. Besides, the artificial targets (e.g., checkboard or sphere) are used to reduce errors in the registration and alignment. The types of targets and places for their locations to guarantee a good geometric configuration have to address. In the monitoring displacement of high-rise buildings (e.g., towers), the ground floor is assumed to be a stable area used to compute the displacement of unstable parts in higher floors. Because the displacement of a high-rise building is relative movement, a local coordinate system can be used instead of a geodetic reference coordinate system. Hence, we can be neglected georeferencing approach as well as its error.

The third stage of this procedure is to compute the displacement between two registered point clouds. The alignment between two point clouds is done by using pair points. At least three pairs are chosen at the stable area on the ground floor or by artificial targets centring on benchmarks. The alignment is to transform all epochs into a common coordinate system of the first epoch. Two different point clouds then are compared in which the point cloud at the first epoch is the reference cloud, and another one is compared cloud. In practice, the whole object is scanned, but only some parts of constructions are actual displacement. Some other parts are not actual displacement (e.g., setting up new equipment). Hence, segmentation that allows the automatical segmenting of several pieces from the point cloud is applied to solve this issue. The principle of segmentation is based on the same feature of objects. (e.g., properties, colour) [24]. This procedure is to extract the compared object that often planes, cylinders, etc. The segmentation had to be done in a similar procedure for all epochs. Then, segmented point clouds at corresponding epochs are compared using the C2C distance method described in section 2. Finally, the statistical parameters, including the mean of displacement and standard deviation of residuals, are estimated.

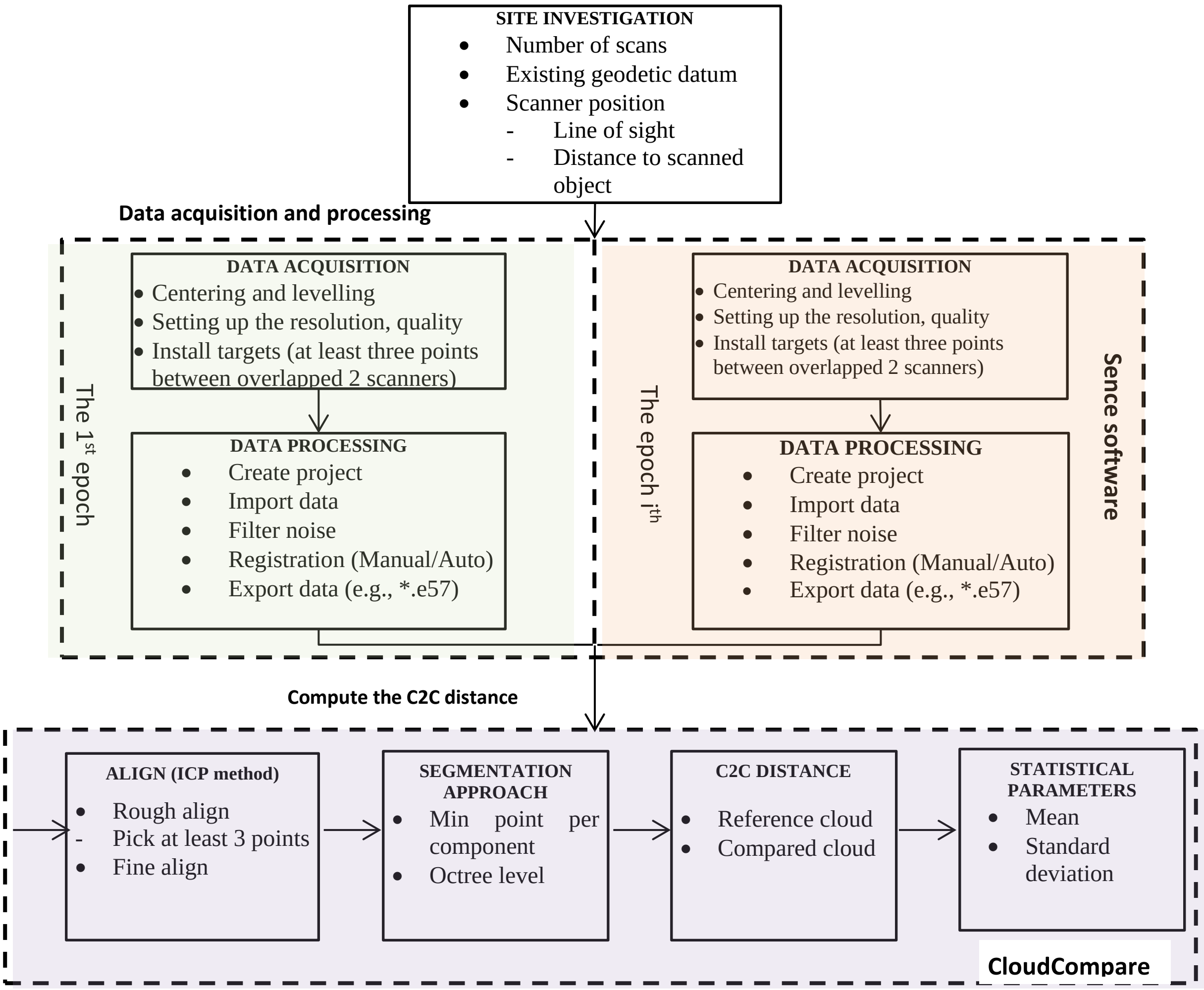

Fig. 2. The procedure for monitoring displacement of high-rise buildings using TLS.

3. Experiments

The displacement of an object can be determined by comparing its position at different times (epochs). In this study, the experimental data is collected by the Faro Focus^{3D} X130, that its specifications are listed in Tab. 1.

Tab. 1. Manufacters' Specifications of Faro Focus^{3D} X 130.

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

The experimental measurements are carried out in three epochs at a high-rise building on the Hanoi University of Mining and Geology (HUMG) campus for three days (from 20th to 22nd February 2021). The artificial displacement is generated by using a movable broad. This experimental board with a size of 60 cm x 60 cm is mounted on the steel monument. The steel monument can move on two parallel raids, and its displacement can be measured by a steel ruler with an accuracy of 0.2 mm (see Fig. 3). In the first epoch, the experimental measurement is scanned when scanned broad is fixed at a certain position. In the second and third epochs, the experimental broad is scanned after this moved back along the incident direction of the laser beam 10 and 20 mm, respectively. These artificial displacements are considered real displacements since errors in the determination of these displacements are sufficiently small.

TLS is a novel technique for monitoring of displacement of high-rise buildings in Vietnam. A reflectorless method is applied in TLS in which the reflectance that is defined as the ratio between reflected and incident laser power is the main factor influencing the scan quality. The potential factors that can impact the reflectance in the context of scanning high-rise buildings consist of the height of a scanned object, the incidence angle of the laser beam, the surface material of a scanned object. Thus, the experiment aims to investigate the influence of these factors on the scan quality. In addition, a sampling resolution strongly influencing the scan quality is evaluated in this experiment. The set of experiments and analysis results are presented in section 4. It is noting that the displacements between two epochs are computed by the C2C method using CloudCompare (CC) software in version 2.11.3.

Fig. 3. The experimental area and scanned board.

These experiments are to access the influence of some factors on the scan quality as follows:

The first experiment investigates the scanning geometry contribution due to the difference in the high of the scanned object on the scan quality. In the monitoring displacement of high-rise buildings, all construction parts in different high levels must be scanned to analyze the displacement and the bending line (e.g., a tower). In this study, an artificial displacement is created using the experimental board (more detail see in section 3), which is located at a distance of 20 m to the scanner. The board is placed on several floors with high levels of approximately 3 m, 6 m, 9 m, 12 m, 15 m, 52 m, as depicted in Fig. 5. It is worth noting that on the 14th floor, the distance from the scanner to the board is about 50 m. The high levels in this experiment are irregular due to the existing condition of HUMG's campus. Scanning geometry investigation could be helpful if object's scans have a complex shape or the difference in high, such as high-rise building structures like buildings and towers.

In the second experiment, the effect of the scanning geometry on the scanning quality is investigated by the incidence angle. The incidence angle is defined as the angle between the laser beam vector and the normal vector of the scanned surface [25]. This experiment simulates the case of a shortage of space for setting up scanning stations. High-rise buildings are usually built in an urban area where it is difficult or even impossible to find a suitable position to set up the scanner. Hence, the scanning geometries in monitoring high-rise buildings are bad in many cases. In this experiment, the experimental board is fixed at a certain position, while the scanner is changed in the range of 15 m and 20 m, respectively (Fig. **4**).

The third experiment investigates the influence of surface materials of the scanned object on the scan quality. The reflectivity property of surface material is defined by the amount of light scattered relating to the wavelength of the laser light in use [15]. 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 surface of concrete, as depicted in Fig. 1. 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 find in [13, 26, 27].

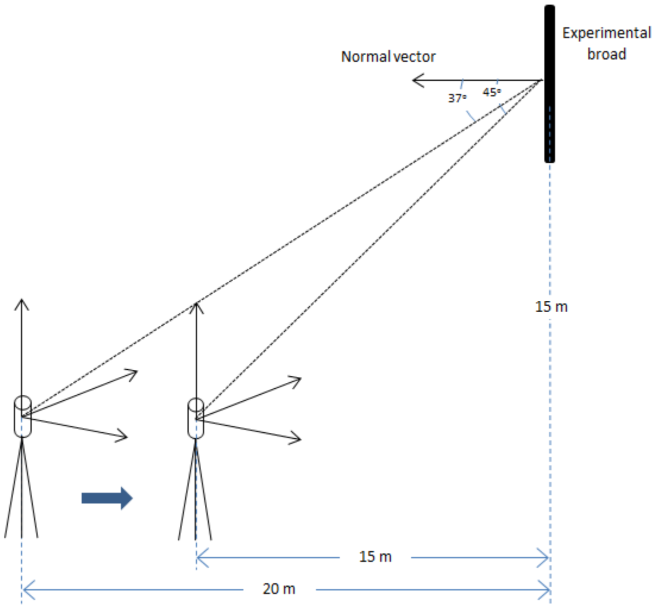

Fig. 4. Scanning geometry due to the incidence angle.

Lastly, the sampling resolution (or point density), another factor influencing scan quality, is investigated in this study. The higher the sampling resolution is set up, the more details of the scanned object can be acquired, but the scanning time also increases. Thus, the resolution parameter should be set for suitable to certain applications. This parameter can be set in the scanner before scanning, and it depends on manufacturers' specifications and scanned range. In general, the scanning resolution of phase-based scanners can provide a higher resolution than that of time-of-flight types. In this experiment, the resolution is examined in four different levels using Faro Focus^{3D} X130, which is a phase-based scanner. In Vietnam, other experiments of TLS for different applications (e.g., mining application) can find in [28,29].

4. Results

This section presents the influence of four potential factors as described in section 3 on the scan quality in the context of displacement monitoring for high-rise buildings. 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).

4.1 Influence of height of scanned objects on the scan quality

In this section, the influence of the scanning geometry is analyzed. The scanning geometry is investigated due to the difference in the height of the scanned object. Fig. 5 shows the displacement's mean and standard deviation values and the different values at the 2nd and 3rd epochs. The different value is small (between 0.2 and 0.6 mm) for both epochs. There is no significant different value when the height of the scanned object is less than 15 m (below 6th floors). The reason for this result is that the measured distances are not much different. In addition, the varying incidence angle (from 10^{o} to 37^{o}) in a short-range is insignificantly influenced by the scan quality. This result agrees with the investigation in [25]. The scan quality is not affected by the incidence angle between 0^{o} to 40^{o} with a 20 m measured distance. By contrast, on the 14th floor, the different value increases to approximately 2 mm in both epochs (2nd and 3rd epochs) due to poor scanning geometry. In this case, the distance from the scanner to the scanned object is about 50 m, and the incidence angle is 46^{o}, leading to poor scanning geometry.

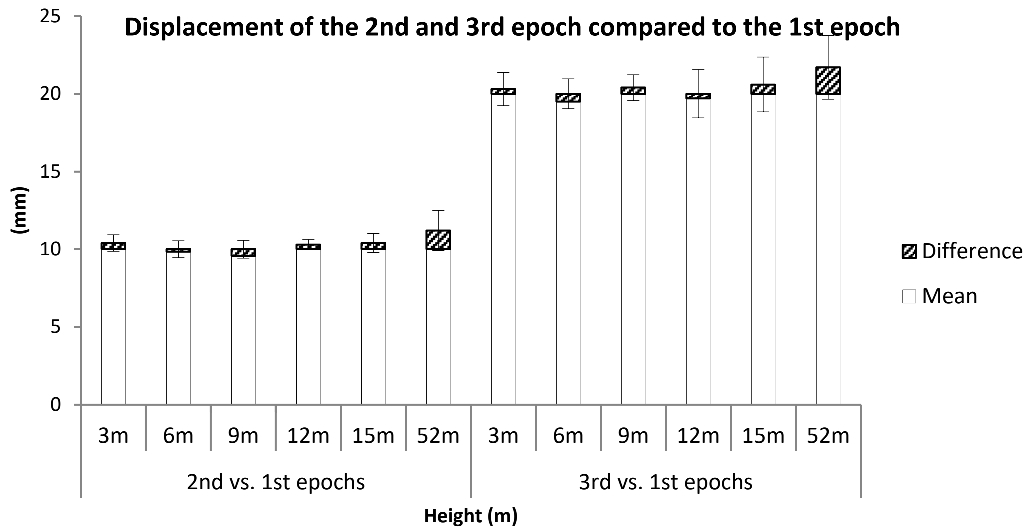

Fig. 5. The displacement measured by TLS with varying the height of a scanned object.

4.2 Influence of the incidence angle on the scan quality

Fig. 6 shows the influence of the incidence angle on the scan quality in two cases of 37° to 45° of the incidence angle. If the incidence angle is higher, the scan quality becomes worse. The different value in the displacement increases from approximately 0.5 to 1 mm. Similarly, an increased tendency of the standard deviation value can be seen in Fig. 6. These corresponding values increase from approximately 1 to 2 mm. These results agree with the theory that the received signal level influences the precision of the distance determination. Since the received signal level of measurements increases with decreasing incidence angles. However, this influence behaviour of the incidence angle on scan quality doesn't investigate in the scope of this study.

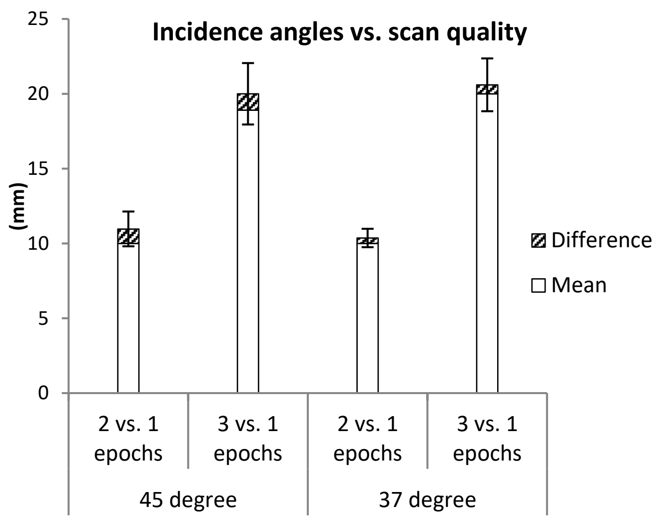

Fig. 6. Influence of incidence angle on scan quality.

4.3 Influence of surface materials of scanned objects on the scan quality

The influence of surface material on scan quality is pointed out by the displacement's mean and standard deviation values (Fig. 7). The displacement of the scanned object is compared between the 3rd epoch and the 1st one. Since the granite surface is smoother than the concrete surface (see Fig. 3), the reflectivity of the granite is better than the reflectivity of concrete. Thus, the determination of displacement using the granite material is approximately 1.5 to 3.0 times more accurate than that of concrete in this study.

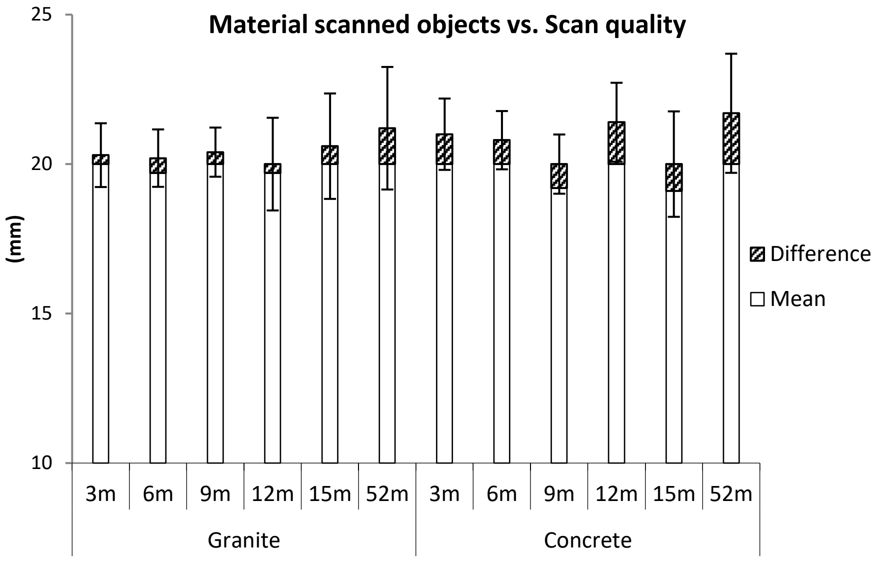

Fig. 7. Influence of surface material on scan quality.

4.4 Influence of Sampling resolution on the scan quality

The point density has a significant influence on the scan quality (Fig. 8). The difference in mean value between displacement calculated by the C2C method and the real one increases dramatically with decreasing the point density. This value increases from 0.1 to 3.3 mm when the point density reduces from 10000 to 750 points. Similarly, the STD also increases quickly from 1 to 3.2 mm by decreasing the density to 750 points.

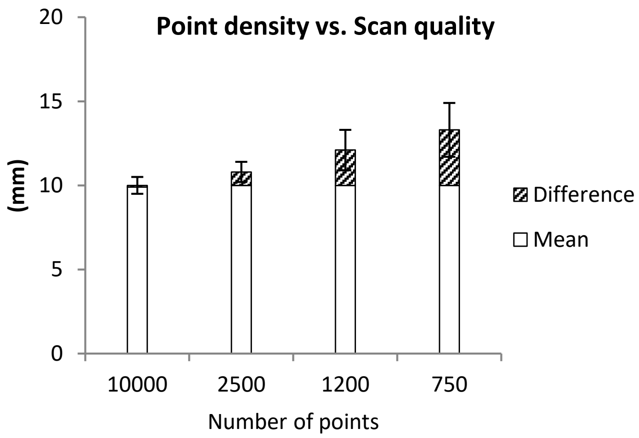

Fig. 8. The influence of sampling resolution on the scan quality.

5. Conclusions

The main goal of this paper is to assess the capacity of TLS on the displacement monitoring of high-rise buildings. This issue has been an initial stage in surveying engineering in Vietnam. In this paper, the main contributions are building a procedure for displacement monitoring of high-rise buildings using TLS and evaluating its accuracy for displacement monitoring.

First, the procedure for monitoring the displacement of high-rise buildings is proposed, including three main steps of site investigation, data acquisition, and processing, and compute the displacement through the distance between two-point clouds. In this procedure, a free coordinate system is used to avoid the error of georeferencing. Moreover, the artificial target is also utilized to improve the accuracy of both registration and alignment procedures.

Second, the accuracy of TLS 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. Although it takes a longer time to collect the data with high point density, the author suggests that a moderately high resolution need to be used to meet the high requirement of accuracy in monitoring displacement. In addition, the paper indicates that the surface material and scanning geometry due to the distance and incidence angle are the main factors that influence the scan quality of TLS for a building higher than 20 m.

Several potential limitations of this study should be noted. First, the influence of error of registration and alignment procedures on displacement accuracy is not considered. Second, the scanned object in this experiment is limited to about 50 m in high. The behaviour impact of the incidence angle on scan quality is not studied in this paper.

In future work, other methods for estimating the distance between two different point clouds (e.g., mesh to cloud method) are worth investigating. The weather conditions, such as humidity, wind, and temperature, should be analyzed to monitor high-rise buildings' displacement.

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