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Accuracy Assessment of Terrestrial Laser Scanner in Heritage Documentation

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Abstract: Cultural heritage buildings play an important role in reflecting a country's identity. Recently, governments have directed their attention towards protecting cultural heritage buildings from war, natural disasters, and general wear and tear. In addition to individual countries, international organizations, such as the United Nations Organization of Education, Science and Culture (UNESCO), and its World Heritage Centre, are interested in documenting and preserving historical sites. Based on this increase demand, engineers have been seeking more efficient and cost effective methods to document these cultural heritage sites.

Rehabilitation and restoration of heritage buildings depend on being able to accurately record their measurements and details. In the last decade, the field of historic building documentation has developed competition among different surveying techniques systems, and devices for accuracy, cost effectiveness, and overall efficiency. Two of the main documentation techniques are: Digital Close-Range Photogrammetry (CRP) and Terrestrial Laser Scanner (TLS).

In this context, the terrestrial laser scanner is the adopted technique in this research, along with investigating all corresponding criteria that govern the final accuracy of the output 3D model. Some of these criteria are the resolution (the ability to detect small objects or object parts in the point cloud) and the quality (which affects the scanning time at fixed resolutions by applying additional noise expression).

The current research addresses the optimal recommended combinations of some tested criteria to reach at the most reasonable positional accuracy. Although these criteria are mostly dependent on each other, but certain conditions were set on the scanner for acquiring the best 3D model for any scanned detailed façade.

Index Terms: Heritage Documentation, Terrestrial Laser scanner, 3D Modelling

I. INTRODUCTION

The historical buildings are treasures that our ancient people left from many decades and should be frequently protected from damage or any disaster that may affect them. So, heritage documentation is a very necessary task to save the buildings, and always kept in a good shape. This will be done by acquiring drawings and 3D models of the buildings that can be easily implemented to bring them to the same shape before disaster [1].

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Heritage documentation is one of the official ways to give definition and recognition to cultural and historical infrastructure. Heritage documentation is used as an aid for protection, restoration, conservation, preservation, identification, monitoring, interpretation, and finally, management of historical buildings, sites, and cultural landscapes [2]. In the past, the heritage documentation mainly relied on human interpretation and record keeping, such as hand drawings, on-site measurement, and sculptures. Documentation tools have undergone a major improvement over the past 20 years. However, these tools provide an additional way to capture the materials, colors, texture, decorations, and so forth, in order to obtain more accurate results [3].

Surveying of the heritage buildings takes a lot of time due to the presence of Engravings, decorations, building breaks and artistic tabloids, when using a total station for surveying [4].

Actually, time consuming is not only the drawback but ground surveying techniques may expose the building to some dangers by its direct contact and touch. Accordingly, terrestrial laser scanners can be superior in this field of surveying due to many privilege factors that overcome the drawbacks. Such factors are producing a very dense number of points, used for non-accessible facades, and have less errors than non-prism total stations. As a principle, 3D laser scanners work by sending a laser beam to the reflective surface all over the field of view, and then the laser beam hits a reflective surface, it is reflected back into the direction of the scanner [5]. Hence, such technique helps in saving the architectural heritages and put them in the back form of the era in which they were built in. In additional, a software for preprocessing and exporting these output point cloud is usually supplied together with the scanning system [6].

II. DESCRIPTION OF TESTED AREA AND USED INSTRUMENT

The near description to the terrestrial laser scanner is to be an automatic motorized total station, but it differs in the surveyed points, that is a random points collected in a very dense state not selected by the user [7]. The only chosen issue is the area to be surveyed and the density of the collected points needed. Many criteria affect the density of the collected scanned points, which will be studied in this research as presented later in the next section. On the other hand, the selected tested area is the front façade of the faculty of Engineering, Ain Shams University, as shown in Figure 1. This tested area is scanned many times for the sake of reaching at the best combination of all inherit criteria govern the laser scanner final accuracy.

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In addition, the main building of Ain Shams University (El-Zaafrana palace) was selected as a heritage building for acquiring 3D models. The palace, as will be depicted later at the end of paper, is having a lot of details concerning decorations, trappings …etc.

Fig. 1. The Tested Façade

The used terrestrial laser scanner was Trimble TX5, which uses the technology of phase shift where constant waves of infrared light of varying length are projected outward from the scanner, as depicted in Figure 2. Without any contact with the object, waves are reflected back to the scanner. Each point coordinates (x, y, z) is calculated by measuring the angle encoders of the reflecting mirror and the horizontal angle of the rotating laser scanner. These angles are encoded simultaneously with the distance measurement. Distance, vertical angle and horizontal angle make up a polar coordinate (δ, α, β), which is then transformed to a Cartesian coordinate (x, y, z). The scanner can rotate and collect data for a field of view 360° HZ and 300° VL. The operator can only set the field of view that is needed to be surveyed, resolution and quality [8].

Fig. 2. The Used Terrestrial laser scanner Trimble Tx5

III. METHODOLOGY OF INVESTIGATION

Two control points were fixed in front of the façade where the E-axis was parallel to the façade, the N-axis was perpendicular to the façade and the H-axis is the vertical direction of the façade. Moreover, 49 well distributed paper prisms were placed on the façade, which gives different vertical and horizontal angles as illustrated in Figure 3.

The coordinates of points were surveyed and computed by a total station, In order to act as a base for comparison and then the assessment of the positional accuracy of the used laser scanner. The assessment will depend on the Root Mean Square Error (RMSE) of the computed discrepancy at each point, which is simply the difference in coordinates of both total station and laser scanner respectively.

Accordingly, georeferencing has been done between those both system taken three points out of the fifty ones using Scene 5.1 software. As stated before, different criteria are investigated to reach at the optimal conditions that give best positional accuracy, as presented separately in next section.

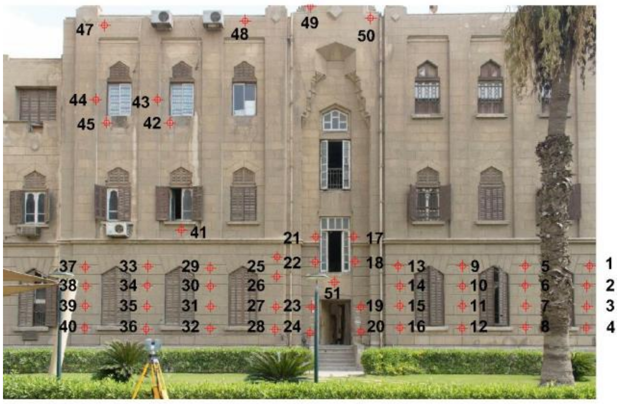

Fig. 3. The location of the Paper prisms on the Façade

The method of calculating the errors

$$RMSE\ \Delta E = \sqrt{\frac{\sum(E_{total\ station} - E_{laser\ scanner})^2}{n}}$$

$$RMSE\ \Delta N = \sqrt{\frac{\sum(N_{total\ station} - N_{laser\ scanner})^2}{n}}$$

$$RMSE\ \Delta H = \sqrt{\frac{\sum(H_{total\ station} - H_{laser\ scanner})^2}{n}}$$

$$RMSE\ \Delta HZ = \sqrt{\Delta E^2 + \Delta N^2}$$

$$RMSE\ \Delta P = \sqrt{\Delta E^2 + \Delta N^2 + \Delta Z^2}$$

IV. PRESENTATION OF RESULTS

This section is devoted to the presentation of the results, related to each scanning criterion.

A. Effect of Resolution

From a user's point of view, resolution describes the ability to detect small objects or object parts in the point cloud. Technically, the smallest possible increment of the angle between two successive points and the size of the laser spot itself on the object. Most scanners allow manual settings of the increment by the user. Since the combined effects of increments and spot size determine object resolution, a test object comprising small elements or small slots in front of a plane can serve to determine application related resolution information [9].

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A certain scanning distance of about 14.0 m away from the façade, which gives good configuration field of view, is selected and fixed within all scanning shots with different resolutions. This distance, which can be considered a preferable one as lies in the range from 10.0 m to 20.0 m [10], gives a field of view on a range of 90° horizontal angle and 55° vertical angle. It is worthwhile to mention here that, the best resolution does not depend only on the final reported accuracy, but the number of scanned points has also a significant effect.

This will yield to long processing and acquisition time, which conflicts with the main advantages of non-terrestrial data acquisition methods as laser scanner. Accordingly, Table 1 lists the number of scanned points, acquisition time and RMSE in each one of the three directions (E, N and H).

As quick glance on this table, it is quite evident that, the change in resolution has a great effect on the number of scanned points as well as the scanning time but with a slight fluctuation in the RMSE values in each direction. For example, decreasing the resolution to the half, as from 1/1 to 1/2 and/or from 1/2 to 1/4, has a change in accuracy in terms of millimeters in all directions whereas a reduction of about 75% in both scanned points and time. On the other hand, moving to the lower resolutions that give nearly an opposite results, in which there is a significant degradation in the accuracy in all directions with a small drop in the time.

Hence, it is more convenient to illustrate the general relationship between the resolution and the final positional accuracy, as shown in Figure 4. Merging both table and figure, the reasonable, but not the best, selected resolution is 1/4 or 1/5 since they give same positional accuracy with reasonable time, on contrary to the resolution of 1/2 which has the same accuracy but with too extra scanning time.

TABLE 1
The 3D accuracy within different scan resolutions

Resolution	No. of points (million)	Time (min)	RMSE (m)		
			ΔHz	ΔH	ΔP
1/1.	64.1	58.23	0.016	0.010	0.019
1/2.	16	15.28	0.021	0.016	0.026
1/4.	4	4.55	0.022	0.013	0.026
1/5.	2.6	3.25	0.021	0.015	0.026
1/6.	1	1.87	0.030	0.022	0.037
1/10.	0.6	1.53	0.041	0.028	0.049

It was also noticed that when using the terrestrial laser scanner with low resolution the time of the scanning needed has a negative effect on the final accuracy in the three main directions together. Generally, there is a direct relationship between both resolution and positional accuracy. Obviously, the accuracy at a resolution (1/1) was about 1.9 cm and decreased gradually till it reaches at a low resolution (1/10) to about 4.6 cm.

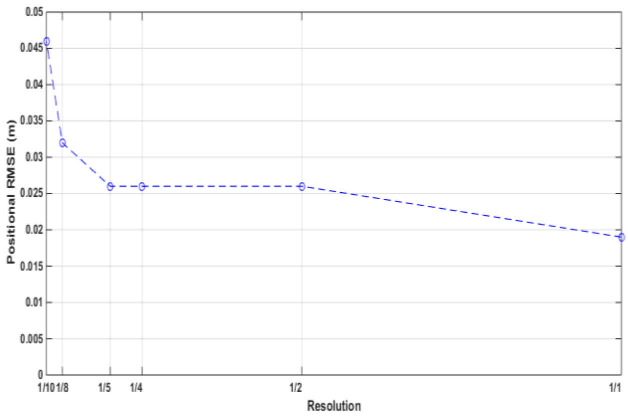

Fig. 4. The positional accuracy within different scan resolutions

B. Effect of Distance

In this practical experiment, the scanning distance is varied from 10.0 m to 28.0 m with a shift of 2.0 m in each study case, whereas the resolution was kept fixed at 1/4. In this terminology, the scanner set up first at 10.0 m away from the façade and frequently moved away in a perpendicular direction from the middle of the façade.

This configuration yields to an initial vertical field of view up to 75° and decreasing with 5° for each consequent scanning distance, whereas the horizontal field of view was about 115° with a reduction of 10° for each distance.

Again, table 2 lists the corresponding output results for each scanning distance. From this table, there is no abrupt drop in the number of scanned points and time with distance variation, as long as the resolution is fixed. In addition, there is no straightforward trend concerning the relationship between scanning distance and corresponding positional accuracy, as verified in Figure 5.

This means that there is a preferable range of scanning distance that gives nearly same positional accuracy, which was conducted in the current research to be from 14.0 m to 20.0 m. Distances less than this range gives the worst positional accuracy, probably due to the high vertical field of view, which is motivating the following subsection investigation. Similarly, distance above this range yields to a considerable degradation in the positional accuracy.

TABLE 2
The 3D accuracy within different scan distance from the façade

Distance (m)	No. of Points (million)	Time (min)	RMSE (m)		
			ΔHz	ΔH	ΔP
10	7.0	5.50	0.036	0.016	0.039
12	5.2	5.10	0.027	0.015	0.031
14	4.2	4.65	0.017	0.014	0.022
16	3.4	4.22	0.019	0.012	0.022
18	3.0	3.77	0.018	0.013	0.022
20	2.8	3.57	0.018	0.013	0.022
22	2.4	3.35	0.027	0.013	0.030
25	2.1	2.95	0.024	0.020	0.032

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Distance (m) VL. Angle (degree)	10	12	14	16	18	20
Point no. 50	58.00	53.82	49.88	45.80	41.86	38.66
Point no. 17	26.70	23.60	21.00	18.78	16.60	15.50
Point no. 18	21.07	18.50	16.53	14.77	13.03	11.85
Point no. 19	9.25	8.40	7.63	6.99	6.15	5.69
Point no. 20	2.70	2.72	2.74	2.81	2.52	2.38
28	1.9	2.55	0.030	0.014	0.033	

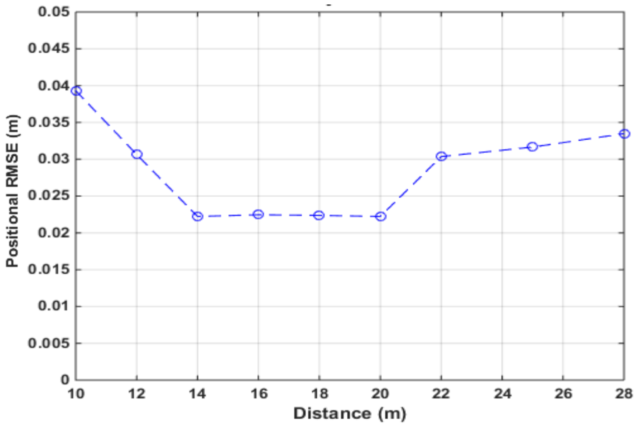

Fig. 5. The positional accuracy within different scan distance from the Façade

C. *Effect of Vertical angle*

The vertical angle is defined by the rotation angle of the reflecting mirror which deflects the laser beam on a circular track through the space. This angle is measured by a second angle encoder [11]. Five points were taken approximately on the same vertical line; the laser scanner were set on a distance of 16.0 m away from the façade, and the resolution were set to be 1/4. Figure 6 shows the position of these five points within the façade, at different height from the bottom and then of different vertical angles.

Fig. 6. The position of the paper prisms varying vertical angle

It was found that, the vertical angle has a high rate of change for point 50, in spite of the change in distance was 10.0m only, and the vertical angle changes from 58° to 38.66°. But for the point 20, the rate of change was small where the vertical angle changes from 2.70° to 2.38° within the same distance variation. The configuration of both vertical angles at each scanning distance, measured at each target point, is completely depicted in both Table 3 and Figure 7 respectively.

TABLE 3 The Actual vertical angles of all tested parts related to each scanned distance

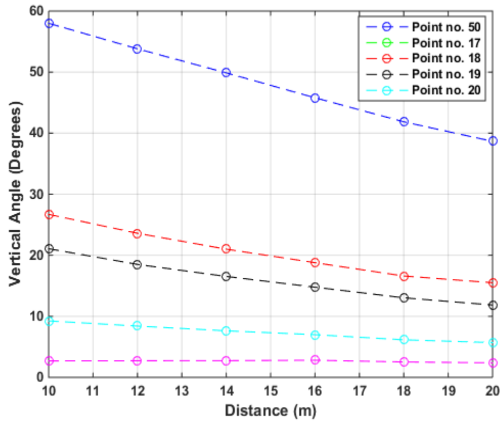

Fig. 7. The Actual vertical angles of all tested parts related to each scanned distance

Finally, Table 4 lists only the positional accuracy at each point, for all tested scanning distance and then its corresponding vertical angle. As a general finding, the smaller the vertical angle the better the positional accuracy, keeping in mind that both scanning distance and resolution are fixed with the vertical angle variation at each point, as depicted in Figure 8. This is hold true also when investigating the relationship between vertical angle and positional accuracy, expressed as a variation in the scanned distance, which is typically illustrated in Figure 8 too as an inverse proportional between both scanning distance and positional accuracy at each point separately. As a closing remark by considering the best scanning distance range, one can easily conclude from both Table 3 and 4 the suitable vertical angle is about 20°.

TABLE 4 The positional accuracy within different vertical angles and scanned distance

Distance (m) RMSE ΔP (m)	10	12	14	16	18	20
Point no. 50	0.064	0.057	0.053	0.043	0.037	0.030
Point no. 17	0.028	0.027	0.025	0.022	0.019	0.017
Point no. 18	0.025	0.020	0.018	0.017	0.015	0.013
Point no. 19	0.013	0.012	0.011	0.010	0.010	0.008
Point no. 20	0.010	0.009	0.009	0.009	0.008	0.008

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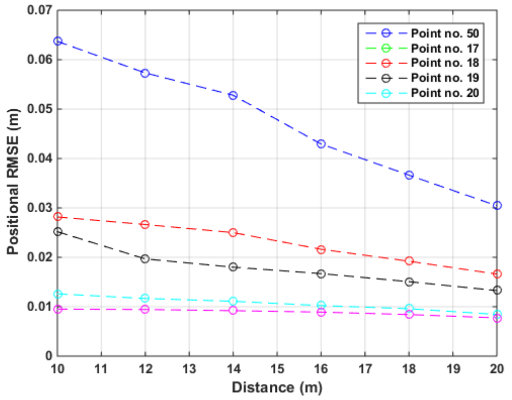

Fig. 8. The positional accuracy within different vertical angles and scanned distance

D. *Effect of Quality*

The term quality in the laser scanner affects mainly the time, since the change of quality changes the frequency of the laser beam. In this criterion, the laser scanner were set on a resolution of 1/4 and on a distance of 16.0 m away from the façade. Different scans have been done with all available quality of the used scanner.

It was found that, the change in quality has no effect on the final positional accuracy, as shown in Figure 9. In addition and although the number of points in the point cloud is the same in all different qualities, but there is a considerable change in the acquisition time with the variation of the quality of the laser beam. Figure 10, depicts this relationship, which indicates a very high rate of time change when transferring the quality from 8x to 6x, but still having a long and non-suitable time to be taken. Then, the rate becomes to somehow small for quality less than 6x, which gives best quality to be used as 4x.

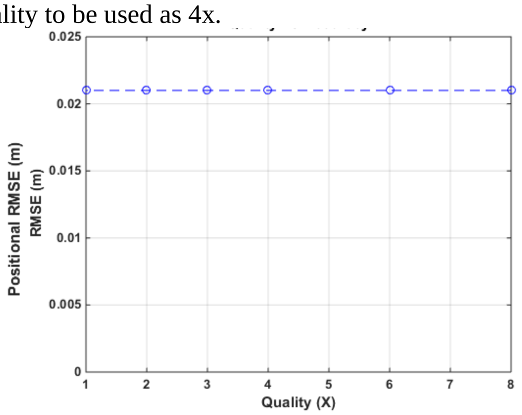

Fig. 9. The positional accuracy within different quality

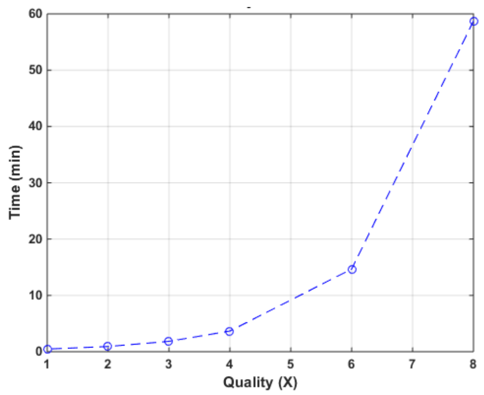

Fig. 10. The Actual time within different quality

V. 3D Modelling Production

All previous subsections were concerned with the final positional accuracy of the laser scanner, measured separately at some discrete individual selected points on the tested scanned façade. This positional accuracy is really a measure of the effeteness of laser scanner, but does not satisfy the main privilege of the terrestrial laser scanner in the full documentation and restoration of heritage buildings [12].

This is completely achieved by acquiring 3D models, to register all details, concerning engravings, decoration …etc. Here, this section is concerned with the acquisition of the 3D models of a certain façade, as mentioned before and illustrated here in figure 11. Moreover, nearly the whole façade was surveyed by a total station, in order to get some dimensions and shapes of some existing details, as depicted in Figure 12 and used as datum for evaluating the goodness of the produced 3D model.

Fig. 11. El-Zaafrana palace

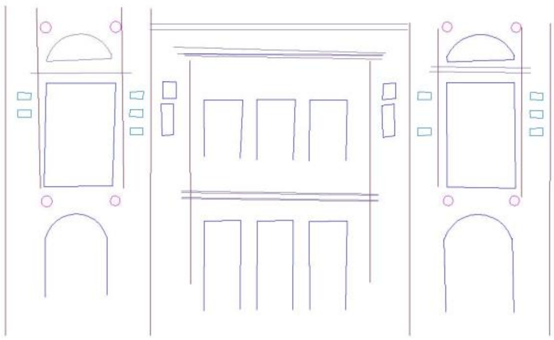

Fig. 12. The produced drawing from total station data

For acquiring the required 3D façade model, eight scans were done from different instrument locations within the surrounding area of the building. In order to have a fully detailed 3D model, another five scans were also done on the building roof, whose corresponding 3D modelling with the scanning locations are shown in Figure 13. All this scans are connected and registered together using some common natural targets in the building, to help in extracting an effective 3D model. This model is illustrated in Figure 14, and rotated to give nearly the same imaging shot of the building shown previously in Figure 11.

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Fig. 13. The roof of the produced 3D model of the palace

Fig. 14. The produced 3d model of El-Zaafrana palace

An automatic ortho photo for the façade has been generated from the scanned point cloud. This ortho photo was used to get some dimensions to assess the produced 3D model. This is simply carried out by corresponding digitizing on screen, to finally yield a drawing for the façade as typically shown in Figure 15. Also, Figure 16 shows a comparison between digitized engravings and the real shape captured from the original façade image. Obviously, a great percentage of matching has been developed and restored.

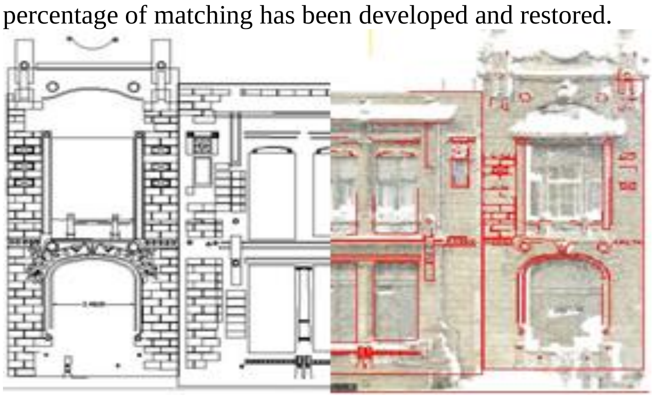

Fig. 15. The produced drawing from laser scanner data

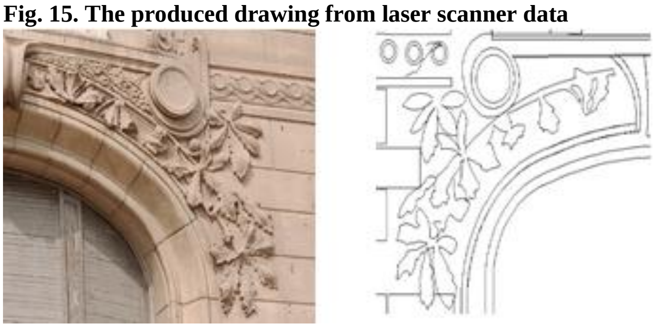

Fig. 16. The image and drawing of engravings on façade

For meaningful 3D model evaluation, some dimensions were taken for the features (windows, doors) from the collected data by the total station to be compared with the obtained ones of the laser scanner. Table 5 shows the difference in dimensions between the total station and the laser scanner at some selected features. Accuracy in terms of millimeters is achieved in all selected features, as a good and full assessment of the output 3D model.

TABLE 5 The dimensional accuracy of the features on the surveyed façade

Type	Total station (m)	Laser scanner (m)	Difference (m)
Window 1	3.520	3.506	0.014
	3.510	3.500	0.010
	3.500	3.505	0.005
	3.510	3.506	0.004
Window 2	1.440	1.416	0.024
	1.440	1.447	0.007
	1.440	1.447	0.001
	1.440	1.437	0.003
	1.440	1.452	0.012
	1.440	1.435	0.005
Door	1.600	1.608	0.008
	2.00	1.994	0.006

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VII. CONCLUSION

In this study, the terrestrial laser scanner technique was used for heritage site documentation in two different facades in Egypt: Faculty of Engineering, Ain Shams University and El-Zaafrana palace. Actually and to reach reasonable positional accuracy, all related criteria have been investigated. Since these criteria are dependent on each other, a perfect combination must be implemented and nearly maintained when using laser scanners. The most efficient practical condition must combine resolution, acquisition and processing time, scanned distance and field of view. In this context and according to the corresponding results, the Trimble TX5 has an optimal resolution as (1/4) within a preferable range of scanned distance lying between 14.0 m and 20.0 m away from the target. The scanned distance should preserve a vertical angle in the composed field of view up to 20°. Also, it is more convenient to avoid quality greater than 4x. All these criteria is combined with suitable time in both data acquisition and processing, in order to minimize the effort and cost. These considerations have a predicted positional accuracy as 2.0 cm, with an effective 3D model.

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