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Novel method to determine laser scanner accuracy for applications in civil engineering

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One of the most important aspects of controlling the condition of civil engineering structures is the deformation monitoring. 3D laser scanners show some advantages related to the controlling of unexpected deformations which cannot be monitored with total stations or levels. Technical datasheets provided by laser manufacturers give the accuracy of single point measurements, although these figures can be improved using fitting algorithms. This paper depicts a novel technical procedure used to detect real accuracy that can be achieved using surface fitting techniques. This technique is based on the displacement of an aluminum plate by means of a precision actuator. Shift produced in the plate is measured by a laser scanner and a total station. Accuracy is evaluated as the difference between the values given by the actuator and those provided for the geodetic instruments.

The procedure has been tested using a laser scanner RIEGL LMS Z390i and a total station Leica TCR 1102. The results obtained are very close in both cases and depict values of accuracy less than 1 mm. These results confirm the possibilities of the RIEGL system to detect small deformations. It can be concluded that this system can be used in the monitoring of civil engineering structures.

On the other hand, the single point measurement exhibits an accuracy around 6 mm and confirms the data provided by the manufacturer of the laser scanner.

Keywords: laser scanning, deformation monitoring, accuracy, surveying, civil engineering.

1. Introduction

The number and complexity of the current civil engineering infrastructures makes it necessary to use accurate, fast and reliable monitoring systems to ensure the safety both during construction and operation. One of the most important aspects is controlling the deformations in tunnels, bridges, dams, *etc*. Convergence processes in tunnels depend of the re-arrangement of stresses just after the excavation, and hence describes the deformation of the surrounding rockmass and of support, independently of any stress-focusing models and measurements. Convergence values are typically from 0.1 mm to 5 mm /day until the tunnel stabilization [1, 2]. Deformation in bridges is important in load tests to evaluate the fatigue resistance and assess the load carrying capacity. Values around 20 mm are common in these tests [3–6]. Deformation monitoring in dams is also a topic of interest. The actual behavior may differ from the initial values computed at the design stage for differences between the proposed design and built structure, assumptions in structural modeling and analysis, material fatigue, earthquakes, *etc*. Deformation values around 20 mm can be measured. These deformations correlate with the water level height of the dam [7, 8]. Other engineering structures with important requirements in deformation monitoring are the slopes of the roads [9, 10].

Geodetic instrumentation such as precise levels, total stations, global positioning systems and terrestrial laser scanners can be used for these inspection works. These techniques have become especially useful as inspection tools in civil engineering applications, where physical access to the structure is not possible or usually involves high risk to operators. The classical topographic methods based on angles and distances are very common and include instrumentation such as levels and total stations with accuracies around 0.5–2 mm. The accuracy depends on the working distance and the technical specifications of the instruments. Contact sensors comprising inclinometers, dial gauges, extensometers, reflectors and precision bar codes complete the measurement unit. Global Navigation Satellite Systems (GNSS) are used in some applications such as the monitoring of large dams [11, 12]. However, this technique has two main limitations: accuracy is a changeable magnitude which depends on the number of satellites, geomorphology, density and distribution of vegetation and it cannot be used indoors (tunnel applications). On the other hand, the precision limits of GNSS are around 1 cm horizontally and 2 cm vertically. The classical topographic methods operate at a relatively small number of single points. This situation causes that the resulting models used for geometric analysis have to be strongly simplified. Consequently, full area coverage cannot be provided.

Non-contact techniques for surveying and documenting built-up structures have evolved significantly in the last decade. 3D laser scanning and close range photogrammetry are the main exponents of this evolution: both provide point clouds of thousands or millions of coordinates with millimeter accuracy. These techniques overcome some of the disadvantages of traditional geodetic methods in surveying civil structures. In this sense, terrestrial laser scanners show simplicity of usage and high speed of data acquisition [13]. They allow a complete geometrical model of the structure to be obtained and it is not necessary to discretize the object by reference points [14, 15]. This fact enables the detection of unexpected deformations.

Single shot accuracy laser scanning is poorer than that obtained with the total stations. Values around 5–10 mm can be achieved [16]. They are usually considered as inadequate for the monitoring of structural deformations due to the subtle nature of some deformations. However, it should be noted that the average of the precision from the object surface improces the results. Some authors report that modeled terrestrial laser scanner data could achieve accuracy up to 20 times as high as that of the single point coordinate precision [17]. This result is close to those obtained for the classical topographic methods and makes the system reliable to be used in the inspection of deformations in civil engineering structures. In this situation, technical specifications of the systems typically include accuracy data that cannot be easily extrapolated to the accuracy required for measuring a real deformation. The data of the technical specifications include single point accuracy. However, deformations must be obtained from the fitting data from the surface. In this work, a laboratory procedure based on the displacement of a precision electromechanical actuator is proposed to evaluate the accuracy of deformation measurement, prior to the field data acquisition. The aim of this procedure is to contribute to the evaluation of the instrumentation before the final selection. Another application of the procedure is to detect a potential need of recalibration in the systems. This procedure was applied to the accuracy detection of terrestrial laser scanning system RIEGL LMS Z390i and it was compared with the results provided by the Leica TCR 1102 total station.

2. Materials and methods

The experimental procedure designed to evaluate the accuracy of laser scanning systems is based on the three main pillars: a device, data acquisition and processing. A laser scanner and a total station are the instruments used to perform the geometric acquisition. An actuator device causes a precise displacement of a plate to simulate small deformations. Measurements are performed at different ranges. Figure 1 shows a scheme of the system.

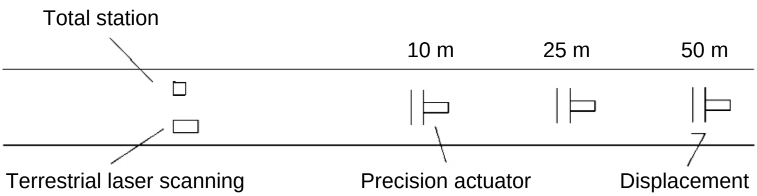


Fig. 1. Experimental arrangement.

The device mainly consists of an electromechanical actuator which produces a precise shift of a target plane. The precision actuator is a linear stage PLS-85 (Micos) which is mainly intended for precision applications. Cross-roller bearings guarantee very high guiding stiffness. It is driven by a recirculating ball screw and equipped with a DC stepper motor. Two hall sensors limit the travel range to 52 mm. The straightness of the system is 2 μm, pitch 90 μrd, yaw 90 μrd, weight 1.3 kg, and point repeatability 1 μm. The system is computer controlled using a Matlab program specifically developed for this purpose. A right angle precision mounting from Thorlabs is used to fix the plane target (aluminum plate) to the actuator. The aluminum plate can be easily measured by the laser scanning system and the total station. The dimensions of the aluminum plate are 100 mm×100 mm×2 mm. The whole system is mounted on a topographic tripod.

Data acquisition and processing must reproduce the measuring conditions of the system during real inspection of deformations in a bridge, tunnel, dam, slope, *etc*. Metrological parameters (laser scanner resolution, range or processing algorithms) must be kept constant to produce comparable results. The test performed in our laboratory uses a laser scanning system RIEGL LMS Z-390i and a total station Leica TCR 1102. Temperature and relative humidity are monitored and introduced into the control software of the laser scanner to establish the correction related with the Edlén equation, and the relationship between the refractive index of air and the speed of light [18]. The control software of the laser scanner makes it possible to introduce temperature and relative humidity data to correct the range measurement. The only way to introduce it is by the human operator. The procedure we adopt here uses an environmental sensing unit located in the neighbourhood of the laser scanner. After each displacement of the actuator and the corresponding measurement with the laser scanner, the environmental conditions are checked and reintroduced in the RIEGL software to guarantee the quality of measurements. The ranges of measurement of the geodetic equipment evaluated are: 10, 25 and 50 m. These displacements make it possible to measure lengths of 0.1, 0.3, 0.6, 1.0, 3.0, 6.0, 10.0, 20.0 and 30.0 mm. These displacements make it possible to measure displacements of 0.1 mm (from 0 to 1 mm), 1 mm (from 1 to 10 mm) and different intervals (from 10 to 30 mm), as well as repeated measurements calculated from different combinations of absolute positions. Finally, the total number of combinations between these established positions gives 42 displacements. This procedure was repeated for the three ranges of measurement. Maximum displacement is limited to 30.0 mm. It is clear that larger deformations can be perfectly detected with the RIEGL LMS Z-390i. It appears most important to determine the measurement limit for small deformations.

Angular differences between the measurements are very small. If we take into account the distances of 10, 25 and 50 m and the size of the aluminum plate (100 mm×100 mm), the maximum angles of ray incidence are 2.86°, 1.14° and 0.57°, respectively.

The terrestrial laser scanner used in this work, RIEGL LMS Z-390i, classified as time of flight (TOF), is composed of a collimated laser source that emits infrared laser beam pulses. Part of the signal reflected by the object surface re-enters the laser system and is collected by the detector diode which generates an electric signal. The period of time between the emission and reception of the pulsed beam is measured by a quartz clock. The TOF allows the distance between the object and the laser equipment to be measured. The velocity of light propagation in air is known for a certain temperature, relative humidity and pressure. The system for distance measurement is combined with a ray deflector which points the beam towards the object surface. The RIEGL configuration consists of a rotary mirror which allows vertical scanning and a servomotor that makes the mechanism rotate about the optical axis for the horizontal scanning. At the same time, the intensity of the reflected signal is stored as an attribute of the intensity for each measured point. It collects information about the reflectivity of an object, and consequently, information about the spectral characteristics of the surface of the object. The RIEGL LMS Z-390i is a long range terrestrial laser scanner, with a range of measurement from 1.5 m to 400 m. The nominal accuracy is 6 mm at 50 m range (standard illumination conditions). Beam wavelength is 1540 nm, with an acquisition rate between 8000 and 11000 points per second. The field of view of this instrument covers 360 degrees horizontally and 80 degrees vertically. The minimum stepwidth is 0.002 degrees horizontally and vertically.

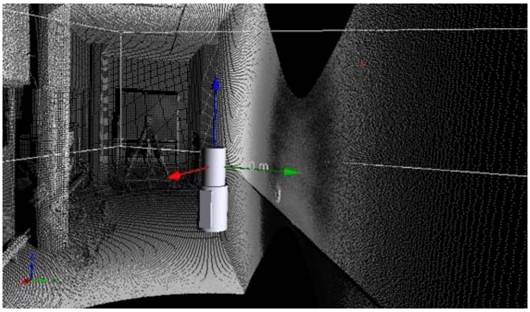
The Leica TCR 1102 total station was used for the purpose of comparison with the data obtained from the laser scanning system. Each position of the actuator is also monitored by means of 16 points taken with the total station. Technical specifications give an angular accuracy (horizontal and vertical) of 2" and maximum range of measurement from 3500 m to 80 m, depending on whether the measurement is performed using a prism or in a reflectorless mode. The accuracy of distance measurement according to ISO 17123-4 [19] is 2 mm + 2 ppm (standard measurement mode). Red laser (633 nm wavelength) is used in phase measurement configuration. These instruments modulate the laser beam and measure the phase difference between the emitted and collected signals which is proportional to the range measurements.

3. Results and discussion

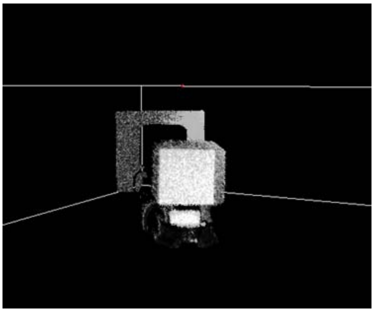
3.1. Data acquisition

Three scanner stations were selected. A panoramic point cloud of the laser environment was collected. This option only pretends to establish the position of the target object in space. It takes 713261 points during 89 s, with a step-width of 0.2° for vertical and horizontal angles and covering all the scanner angular ranges (360° horizontal and 80° vertical). Figure 2 shows a scan made with the RIEGL LMS Z390i in “overview” mode (full field of view).

Subsequently, the data acquisition continues with a detailed point cloud from the actuator and aluminum plate (Fig. 3). A step-width of 0.004° is selected in all the cases. The acquisition time and the number of points change from 74 s and around 223000 points at 10 m to 29 s and around 38000 points at 50 m.



▲ Fig. 2. Full field point cloud.



▲ Fig. 3. High resolution point cloud (actuator and aluminum plate).

Simultaneously, the total station was positioned sided with the laser scanner. For each position, all the shifts of the actuator were registered by means of the measurement of 16 points all over the plate surface.

3.2. Data processing

The data from aluminum plate are segmented from the raw point cloud to be used in further calculations (Fig. 4**a**). Octree (Fig. 4**b**) and raster 2.5D (Fig. 4**c**) filters are also applied to the images. All this data processing is performed using RiSCAN PRO software provided by RIEGL.

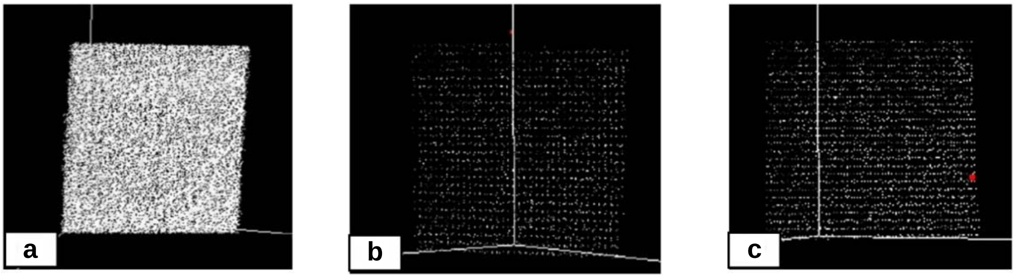


Fig. 4. Point cloud segmented from the aluminum plate. Raw data (**a**), octree filter (**b**) and raster 2.5 D filter (**c**).

Octree filter is based on an octree structure where a cube is divided into 8 equally sized cubes. These cubes are again divided until cubes with minimum size are obtained. The extension of the base cube can be entered by the user. The division into sub-cubes is done on demand by filling the points into the octree, and stopped as soon as a given minimum cube size is reached. After generation of the octree, the cube contains one point which is the center of gravity of the averaged points representing, in general, a larger number of points.

Raster 2.5D filter divides the point cloud in cells whose size is defined by the user. The filter forces each cell to contain only one point. One cell containing more than one point inside is forced to select from among the higher value, the lower value or the value given by the gravity center of them. The entire filtering process is developed using a resolution of 5 mm.

The shift of the actuator is evaluated using two different approaches: first, the distance between planes is determined, and on the other hand, the distance between a single point and a plane. Matlab algorithms are used for this purpose:

– The raw point cloud of aluminum plate (Fig. 4**a**) is fitted to a plane using a least square fitting algorithm. The same procedure is applied to the point cloud filtered using the Octree (Fig. 4**b**) and 2.5D raster (Fig. 4**c**) filters and to the total station data. Displacement L_S is evaluated in all the cases as a distance between the parallel planes obtained from the different steps of the actuator. Figure 5**a** shows the results for

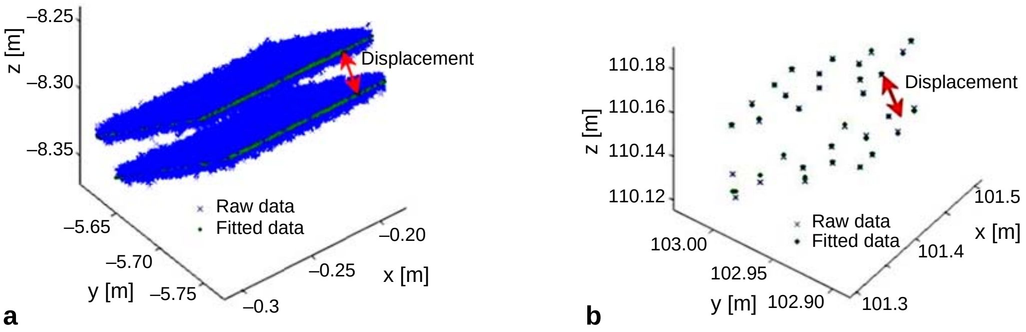


Fig. 5. Distance between planes. Laser scanner (**a**) and total station (**b**).

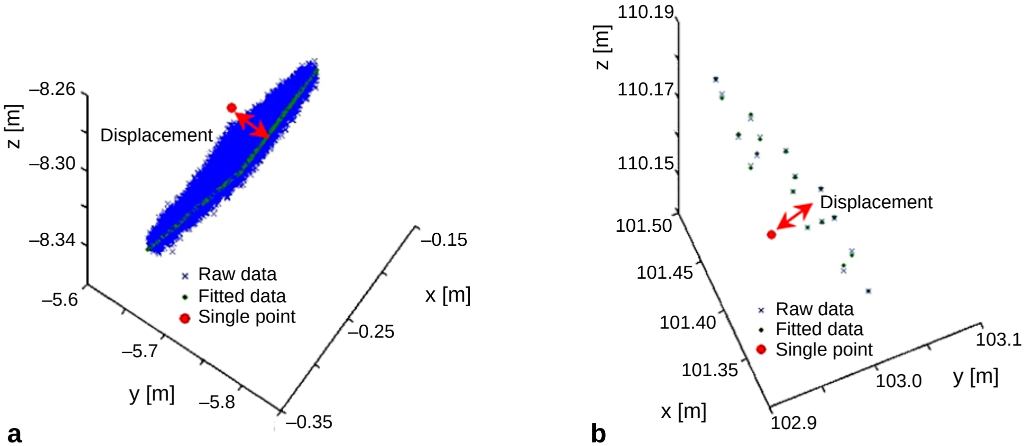


Fig. 6. Distance between a single point and a plane. Laser scanner (**a**) and total station (**b**).

the laser scanner (30 mm displacement) and Fig. 5**b** for the total station (30 mm displacement).

– Single point accuracy. A random point from the laser scanning data located around the center area of the plate, as well as another random point of the point cloud measured by the total station, is used to calculate the displacement of the actuator. That displacement L_S is considered to be a distance between the single point and a plane fitted to the point cloud captured from the initial position of the actuator. Figure 6 shows the results for a 20 mm displacement.

The results depicted in Fig. 7 for the accuracy ΔL are obtained as the difference between the values provided by the shift of the actuator L_A (standard values) and those provided by the geodetic instruments L_S, using the Matlab algorithms shown previously:

$$\Delta L = L_A - L_S \tag{1}$$

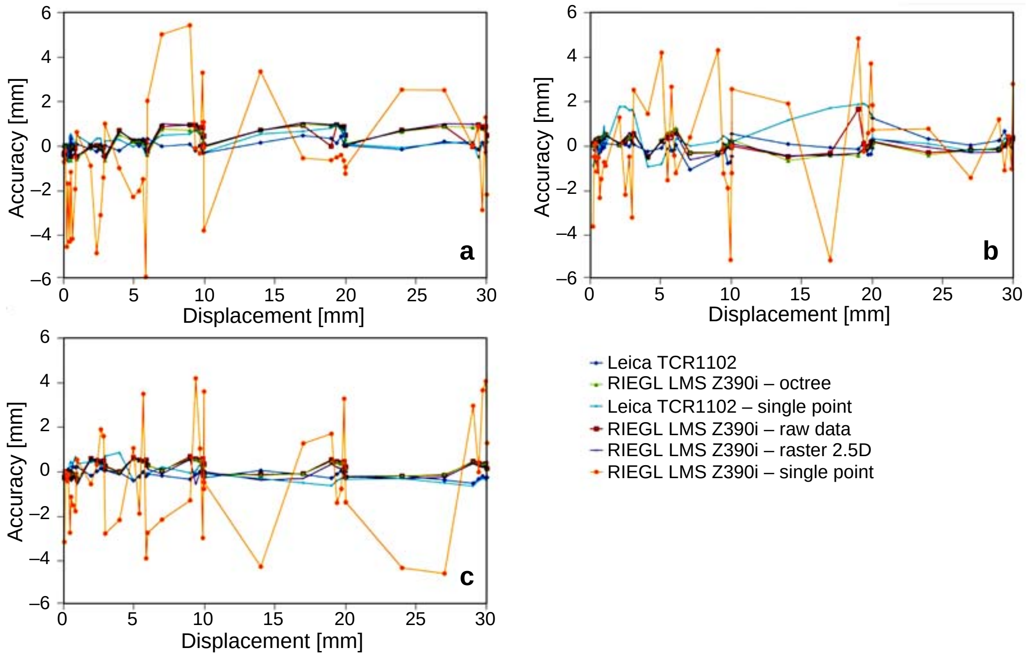


Fig. 7. Accuracy. Ranges of 10 m (**a**), 25 m (**b**) and 50 m (**c**).

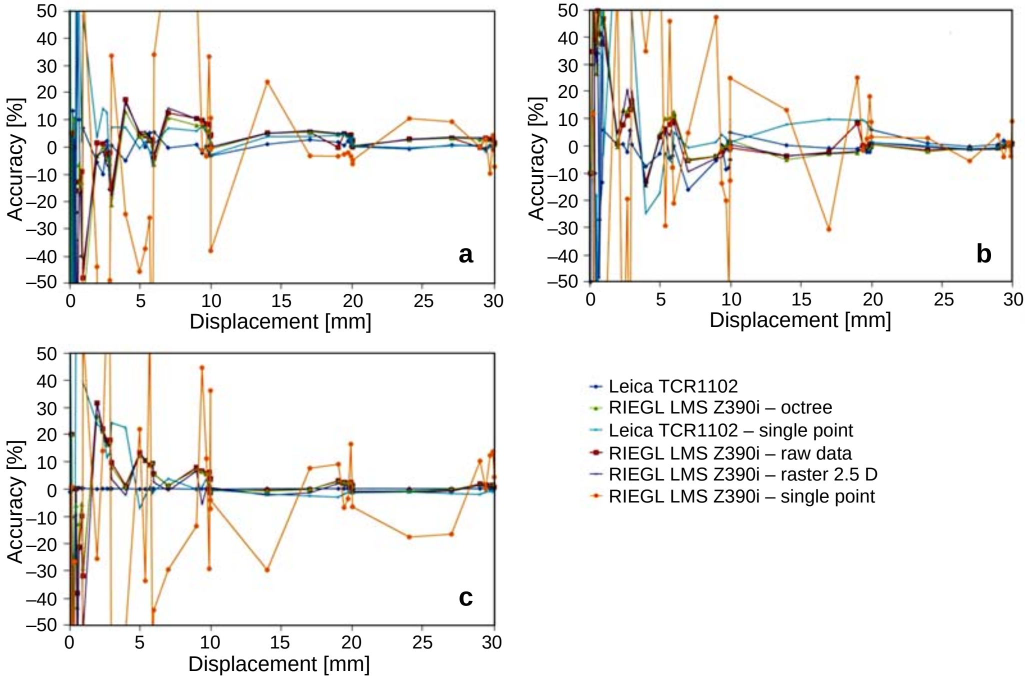


Fig. 8. Accuracy per unit of length. Ranges of 10 m (**a**), 25 m (**b**) and 50 m (**c**).

Displacement data obtained from the single point approximation with the laser scanner show a variability of accuracy achieved to be 4–5 mm in many cases and confirm the nominal accuracy of 6 mm at 50 m range given by the manufacturer. The variability of the values is caused by the random selection of the single point. On the other hand, the results of plane fitting and distance evaluation between parallel planes are clearly improved. The three cases under study for the laser scanner (raw data, octree and raster 2.5D filters) show accuracy values of less than 1 mm. There are not any important differences between them. Neither is there a perceptible dependence as regards the range. The data are also similar to those obtained by the total station using plane fitting and distance evaluation. They are better than those obtained for the total station in single point configuration.

Figure 8 shows the accuracy per unit of length $\Delta L_{\%}$ and its relationship with displacement and range (Eq. (2));

$$\Delta L_{\%} = \frac{\Delta L}{L_A} \times 100\% \tag{2}$$

The displacements over 3 mm show accuracy values lower than 10% for all the data, except those provided by a single point laser scanner which reaches values over 25%.

It must be noted that this procedure could be perfectly adapted to situations where the field of view or the requirements about the angle of the incident ray are larger, which affect to the laser scanner accuracy and cannot be compared with these ideal cases [20]. In those cases, the aluminum plate could be tilted or moved to extreme angular positions to be useful for this kind of situations.

This procedure shows, in a simple manner, the suitability of the RIEGL LMS Z390i laser scanner to detect deformations around few millimeters. RIEGL LMS Z390i achieves accuracy close to that typically obtained with the classic topographic methods. The simplicity of the procedure opens up many possibilities for users of laser scanning systems to verify their metrological characteristics. This procedure can be useful when purchasing such systems to verify their real possibilities. These characteristics are not always included in the technical specifications provided by the manufacturer. On the other hand, this methodology could be implemented by users of laser scanners in order to verify the metrological drift of the system during its lifetime and its accordance or not with service requirements.

4. Conclusions

Laser scanning systems have been shown as a reliable technology for monitoring deformations in engineering structures, especially for the accurate and dense point clouds generated. The behavior of the system before its use in real conditions is evaluated using a laboratory procedure that mainly consists in the precision movement of an aluminum plate.

Displacements of the aluminum plate can be measured by means of the geodetic instrumentation as a distance between the planes fitted to the sets of point clouds generated. The procedure is tested using a RIEGL LMS Z390i laser scanner and a Leica TCR1102 total station. In addition, the results appear suitable for deformation monitoring, with accuracies less than 1 mm. The test is also repeated for single point measurements, using the laser scanner and the total station. The results obtained in this case are poor, all of them around the accuracy of data provided by the manufacturer. The present procedure is important in that it allows checking the real technical specifications of laser systems for detection of deformations, which are not typically collected in the datasheet provided by the manufacturers. This information could be essential to determine whether a system passes the evaluation prior to the purchasing or when the need arises to recalibrate a laser scanner.

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