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A New Approach for Structural Monitoring Based on Terrestrial Laser Scan Data Using Control Planes

Nova Abordagem para o Monitoramento Estrutural Baseado em Varredura Laser Scanner Utilizando Planos de Controle

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Abstract

Laser scanning is a survey method that enables the obtaining of several data points on surfaces through the observation of horizontal and vertical angles and electronic distance measurements. The result of these observations is a set of 3D points named point clouds, which can be obtained from scans using total stations or the Terrestrial Laser Scanner (TLS). Currently, the use of TLS in geodetic structural deformation monitoring activities is under evaluation, since this technique can provide a greater number of points in a shorter period, when compared to scans performed by total stations. In this research, the feasibility of using control planes for geodetic monitoring was investigated in a controlled laboratory environment, exploring the current trend of parameterization of point clouds. From the development of an Experimental Plane Control (EPC) containing a flat surface that could be inclined in a controlled way, simultaneous scans with TLS and total station were carried out at different inclinations of the control plane. Both surveys were done in frontal scan mode (minimum plane inclination of 0º53' and maximum plane inclination of 3º28') and in oblique mode (plane inclination of 1º09'), where the plane inclination angles were generated by the rotation in EPC base, considering the first plane position as reference to inclination calculating. From parametrization of point clouds, a new approach was developed to test the significance of the estimated inclination angle of the plane in relation to a reference position. The results showed that it is possible to confirm that the inclined angles were statistically significant, but that the TLS scanning position can interfere in the determination of these data for monitoring purposes.

Keywords: Point cloud; Least Squares Estimation; Terrestrial Laser Scanner

Resumo

O escaneamento a laser é um método de levantamento que possibilita a obtenção de uma amostragem de dados pontos em superfícies por meio da observação de ângulos horizontais e verticais e medições eletrônicas de distâncias. O resultado dessas observações é um conjunto de pontos 3D denominados nuvens de pontos, que podem ser obtidos a partir de varreduras usando estações totais ou Laser Scanner Terrestre (LST). Atualmente, o uso de LST em atividades de monitoramento geodésico de deformações estruturais vem sendo investigado, visto que esta técnica pode fornecer um maior número de pontos em um período menor, quando comparado a varreduras realizadas por estações totais. Nesta pesquisa, foi investigada a viabilidade do uso de planos de controle para monitoramento geodésico, em ambiente controlado de laboratório, explorando a tendência atual de parametrização de nuvens de pontos. A partir do desenvolvimento de um Plano de Controle Experimental (PCE), contendo uma superfície plana que pudesse ser inclinada de forma controlada, foram realizadas varreduras simultâneas com LST e estação total em diferentes inclinações do plano de controle. Ambos os levantamentos foram feitos no modo de varredura frontal (inclinação mínima de 0º53' e máxima de 3º28') e no modo oblíquo (inclinação de 1º09'), sendo os ângulos de inclinação gerados pela rotação aplicada na base do PCE, tendo como referência para os cálculos a

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primeira posição de varredura do plano. A partir da parametrização de nuvens de pontos, uma nova abordagem foi desenvolvida para testar a significância do ângulo de inclinação estimado do plano em relação a uma posição de referência. Os resultados mostraram que é possível confirmar que os ângulos de inclinação obtidos foram estatisticamente significativos, mas que a posição de varredura TLS pode interferir na determinação desses dados para fins de monitoramento.

Palavras-chave: Nuvem de Pontos; Método dos Mínimos Quadrados; Laser Scanner Terrestre

1 Introduction

Currently, the advent of remote measurement technologies has enabled the acquisition of three-dimensional (3D) points in a short time through the use of instruments such as laser scanners. These systems are capable of providing dense three-dimensional data, with high precision (Petrie & Toth 2018).

Terrestrial Laser Scanner (TLS) has been explored for its application in the structural monitoring of buildings such as tunnels, bridges, dams and concrete towers. This activity makes it possible to mitigate the occurrence of different structural phenomena, like deformation and/or displacement during different periods, caused by external and internal factors (Lovas et al. 2008; Schneider 2006; Walton, Delaloye & Diederichs 2014).

Structural geodetic monitoring practice requires periodicity and reliability in determined information, since operation failure or the collapse of large structures may cause social, economic and environmental impacts. According to Ogundare (2016), the development of TLS in recent years has enabled the determination of structural displacements in the same order of magnitude as the measurements made with total stations, which may have higher accuracy than TLS.

According to Lindenbergh and Pietrzyk (2015), the challenges of monitoring structures are related to the displacement quantities investigated, which may have dimensions close to the nominal precision of the employed TLS. Currently, considering the majority of equipment available, the absence of instruments with forced centering or the impossibility of instrument orientation, as occurs in other monitoring methods, could distinguish this application from the traditional monitoring methods (Vosselman & Maas 2010).

Moreover, there is a research line that considers the use of artificial or natural geometric elements of the structure itself to manipulate the data by TLS, as indicated by Monserrat and Crosetto (2008). The investigation of discretization using geometric elements such as planes has shown a potential way to treat 3D data for purposes of comparison between measurement campaigns. The use of geometric elements provides greater precision for calculated parameters when compared to the precision of the 3D coordinates themselves.

Aydin (2012) suggested a method to detect displacements with statistical analysis for geodetic surveys, which aims to detect deformations based on a Global Test and Chi-Square distribution. Usually, a Global Test intends to detect blunders (gross errors) and systematic errors on measured data, in addition to errors in injunctions, in the stochastic model, among others (Klein et al. 2019).

Some structural monitoring works present satisfactory results in relation to an achievable quality in terms of positioning (Lindenbergh & Pfeifer 2005; Schneider 2006; Jaafar, Meng & Sowter 2017; Barbarella et al. 2018). Nonetheless, when the data derived from TLS scans are adjusted in geometric elements, investigations in laboratory regarding the use of a method that makes it possible to detect displacements between the elements tested based on a stipulated confidence level are still required. At the same time, such assessment must consider some challenges related to parameterization, for example the influence of the scanning stations position and an applicable mathematical model containing efficient parameters for the detection of unknown displacements (Holst & Kuhlmann 2016).

In this study, was developed a new approach to monitor structures using a control surface (plane element) obtained from a point cloud. The procedure consists on estimating the inclination angle between planes from two measurement campaigns and testing its statistical significance. The results showed that the inclined angles were statistically significant. The main difference of this approach in relation to other methods found in the literature is the application of the statistical test on the inclination angle between the planes, instead of applying it to the parameters of these planes.

2 Theory

According to Schneider (2006), TLS applied to the measurement of a 3D geometric element (such as planes and spheres) is a method developed by adjustment and parameterization of these point clouds. Determined parameters and their comparison through monitoring campaigns can identify a global or a local displacement of the monitored structure.

The possibility of obtaining a high point density can compensate for the low positional quality of points when observed in isolation and can improve the precision of the geometric parameters. Monserrat and Crosetto (2008) indicated that the amount of observations acquired favors high redundancy for the estimation of the parameters of the measured elements, based on Least Squares Estimation (LSE).

Pavan, Santos and Khoshelham (2020) used the RANSAC algorithm and normal vector estimation to automatically register point clouds through a plane surface, which was defined by the LSE. A surface-to-surface approach to estimate transformation parameters resulted in centimeter accuracy.

According to Osgood and Graustein (1921), when considering a three-dimensional coordinate system, the plane element α can be defined according to Equation 1, in view of an orthogonal line to it (normal vector n) containing coordinate points A, B and C, such that:

$$\mathrm{Ax} + \mathrm{By} + \mathrm{Cz} + \mathrm{D} = 0 \tag{1}$$

The element D does not define a plane (Erdélyi et al. 2017). The parameters A, B and C are the direction components of the normal to the α planes, which can be considered the normal vector decomposition of the plane. This expression is known as the general linear equation of a plane and is applicable to all points contained in a plane (Osgood & Graustein 1921).

The measurement of representative data on a surface occurs by multiple observations, which have inevitable inconsistencies, due to the impossibility of making exact measurements. On the other hand, there are methods that can minimize the uncertainties contained in observations. This fact enables the suitability of the conditions imposed by the mathematical expression (Ghilani 2018).

Therefore, LSE aims to calculate a representative x value, in order to make the sum of the residual squares minimal. Thus, the quadratic sum of the n differences (v_i) between x and the n values observed could be the smallest possible, as shown by Equation 2 (Ogundare 2016):

$$\sum_{i=1}^{n} v_i^2 = minimal \tag{2}$$

The LSE adjustment is a rigorous method, easily applicable, and allows pre-adjustment and post-adjustment analyses (Ghilani 2018). Indirect measurement is desired in order to adjust the parameters established by it. This approach enables the calculation of coefficients such as parametric representation of surfaces, which not only defines a specific geometric primitive, but also provides a better model to the measurement set.

Thus, as indicated before, each general equation of a plane is a linear model and correlates plane representative parameters (A, B and C) to each point measured (x, y and z coordinates). Consequently, this fact is conducive to applying the Gauss-Helmert model to plane description through the determination of parameters.

Looking at Equation 1 and based on indication of plane equalities when multiplied by a factor k ≠ 0, Equation 1 can be divided by the D parameter, since it does not define a plane. Thus, the unknown parameters can be expressed as a, b and c as the general model equation for the plane, given as follows (Equations 3, 4, 5, 6 and 7):

$$Ax + By + Cz + D = 0 \tag{3}$$

$$\frac{Ax}{D} + \frac{By}{D} + \frac{Cz}{D} + \frac{D}{D} = 0 \tag{4}$$

$$\frac{A}{D}x + \frac{B}{D}y + \frac{C}{D}z + 1 = 0 \tag{5}$$

$$\frac{A}{D} = a\,;\ \frac{B}{D} = b\,;\ \frac{C}{D} = c \tag{6}$$

$$ax + by + cz + 1 = 0 \tag{7}$$

Here, Equation 7 presents three observations of coordinate points (x, y and z) and unknown parameters. Consequently, the observation vector (l) was elaborated with n point measured coordinates, as shown in Equation 8. In addition, the number of lines is the observation point number on a plane multiplied by 3:

$$\ell = \begin{bmatrix} x_1 \\ y_1 \\ z_1 \\ x_2 \\ y_2 \\ z_2 \\ \vdots \\ x_n \\ y_n \\ z_n \end{bmatrix} \tag{8}$$

2.1 Calculation

A Global Test is a Chi-square test on observations and is applied to systematics errors and outliers detection, as well as Data Snooping procedure (Klein et al. 2019). However, Aydin (2012) showed the Global Test applied to a geodetic network deformation detecting approach, testing the changing in point significance. The methodology corresponds to a generalized significance Chi-square test and aims to test if any deformation occurred in a geodetic network.

Thus, displacement vector Δ in Equation 9 indicates that a physical body may displace from g_1 to g_2 between two campaigns (t_1 e t_2) (Aydin 2012):

$$\Delta = g_2 - g_1 \quad \textbf{(9)}$$

Setting of cofactor matrix Σ_Δ (Equation 10) was obtained through the sum of each epoch covariance matrices (Σ_{g1} e Σ_{g2}):

$$\Sigma_\Delta = \Sigma_{g1} + \Sigma_{g2} \quad \textbf{(10)}$$

The test result depends on rejection of null hypothesis; H_0 indicates absence of displacement between epochs (Equation 11). Therefore, alternative hypothesis is accepted: H_A demonstrates there were displacements between epochs on the physical body tested (Equation 12):

$$H_0: E(|\Delta|) = 0 \quad \textbf{(11)}$$

$$H_A: E(|\Delta|) > 0 \quad \textbf{(12)}$$

Teunissen (2006) emphasizes that the unilateral test is more powerful than the bilateral test, since the former must provide a correct null hypothesis rejection. In this context, the Chi-square test aims to assess whether the adjusted planes are statistically equal when plane measurement takes place in different epochs. Hence, if plane displacements occurred, then parameters that describe the position of each plane can be changed. This approach has been applied before, for example, in Monserrat and Crosetto (2008).

Considering now $\pi_1{:}a_1x + b_1y + c_1z + d_1 = 0$ and $\pi_2{:}a_2x + b_2y + c_2z + d_2 = 0$ as planes and their respective normal vectors as $n_1(a_1,b_1,c_1)$ and $n_2(a_2,b_2,c_2)$, the angle between π_1 and π_2 is the smaller value $\left(0 \le \theta \le \frac{\pi}{2}\right)$ calculated by normal vectors cross product. Thus, the internal vector multiplication is given as follows in Equations 13 and 14 (Osgood & Graustein 1921; Steinbruch & Winterle 1987):

$$\cos\theta = \frac{|\overrightarrow{n_1}.\overrightarrow{n_2}|}{|\overrightarrow{n_1}| \cdot |\overrightarrow{n_2}|} \quad \textbf{(13)}$$

$$\theta = \cos^{-1}\frac{|a_1a_2 + b_1b_2 + c_1c_2|}{\sqrt{{a_1}^2 + {b_1}^2 + {c_1}^2}\sqrt{{a_2}^2 + {b_2}^2 + {c_2}^2}} \quad \textbf{(14)}$$

Thus, here, a new statistical test is proposed to verify if the angle values of inclination are significant, based on each angle obtained and their respective variances, by Chi-square distribution. The hypotheses tests are given by (Equations 15 and 16):

$$H_0: E(|\theta|) = 0 \quad \textbf{(15)}$$

$$H_A: E(|\theta|) > 0 \quad \textbf{(16)}$$

Details related to derivatives indicated in Equation 17 are available in the appendix of Alves (2020). Variance of angles was calculated by the general law of propagation of variances (Ghilani 2018), considering the mathematical model and parameter precisions:

$$\sigma_\theta^2 = \begin{bmatrix} \frac{\partial\theta}{\partial a_1} & \frac{\partial\theta}{\partial b_1} & \cdots & \frac{\partial\theta}{\partial c_2} \end{bmatrix} \begin{bmatrix} \sigma_{a_1}^2 & \sigma_{a_1b_1} & \sigma_{a_1c_1} & 0 & 0 & 0 \\ \sigma_{b_1a_1} & \sigma_{b_1}^2 & \sigma_{b_1c_1} & 0 & 0 & 0 \\ \sigma_{c_1a_1} & \sigma_{c_1b_1} & \sigma_{c_1}^2 & 0 & 0 & 0 \\ 0 & 0 & 0 & \sigma_{a_2}^2 & \sigma_{a_2b_2} & \sigma_{a_2c_2} \\ 0 & 0 & 0 & \sigma_{b_2a_2} & \sigma_{b_2}^2 & \sigma_{b_2c_2} \\ 0 & 0 & 0 & \sigma_{c_2a_2} & \sigma_{c_2b_2} & \sigma_{c_2}^2 \end{bmatrix} \begin{bmatrix} \frac{\partial\theta}{\partial a_1} \\ \frac{\partial\theta}{\partial b_1} \\ \vdots \\ \frac{\partial\theta}{\partial c_2} \end{bmatrix} \quad \textbf{(17)}$$

The test statistic was calculated according to Equation 18:

$$\chi^2_{calculated} = \frac{\theta^2}{\sigma_\theta^2} \quad (18)$$

Null hypothesis rejection occurs if the $\chi^2_{calculated}$ is higher than the critical value based on the standard Chi-square table $\left(\chi^2_{\alpha,df}\right)$, by one degree of freedom and the significance level α.

3 Methodology and Data

As it can be seen in Figure 1, the work development had four steps: point cloud acquisition by TLS and total station; data post-processing; parameter determinations at each plane measurement; and plane displacement detection in different test scenarios.

3.1 Total Station and Terrestrial Laser Scanner

TS15 is a high precision robotic total station. This instrument has ± 1'' angular nominal accuracy and ± (2 mm + 2 ppm) linear nominal accuracy for surfaces without a prism, with a wavelength of 658 nm (Leica Geosystems 2015). The TLS used was the BLK360, which has an 830 nm laser wavelength, vertical rotating prism, and horizontal rotating base. BLK360 has 4 mm to 10 m and 7 mm to 20 m three-dimensional nominal precision per point (Leica Geosystems 2018).

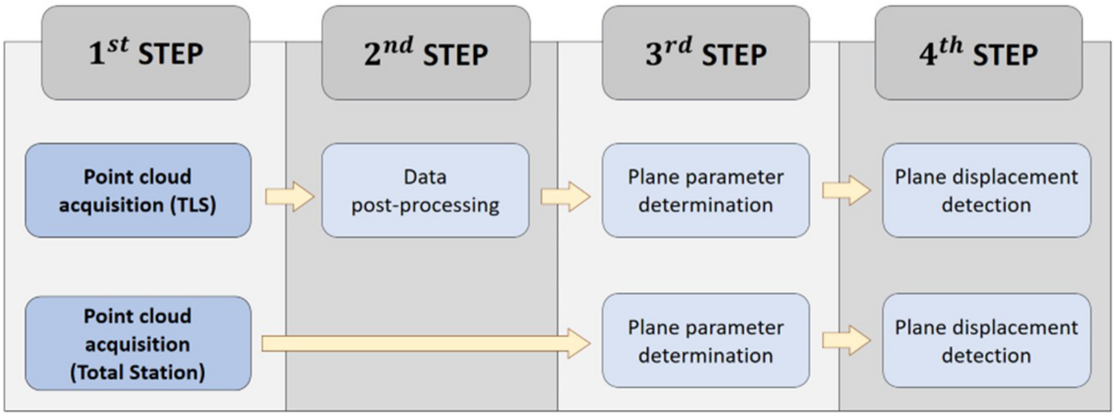


Figure 1 Workflow development.

3.2 Experimental Plane

The methodology for the laboratorial investigation initiated with the construction of a plane displacement prototype, which contained an experimental plane control surface (0.25 m²). The Experimental Plane Control (EPC) is a system fixed to a horizontal base by two metal hinges that enable plane movement through a parallax bar. This bar has a sub millimetric gradation and allows the plane movement quantifications. In order to maintain the plane movement proportional to the bar displacement, springs were fixed on the posterior face of the plane control (Figure 2). Additional information of EPC construction is available at Alves (2020).

As shown in Figure 3, the movement of the plane occurs through the rotation of the hinges (θ), which are fixed on the base of the EPC, and driven by the horizontal movement (l) of the parallax bar. That bar is parallel to the system base and perpendicular to the plane when also perpendicular to the EPC base (θ = 0º).

The height between the rotation axis and the incidence point of the parallax bar is 0.3279 m. Figure 4A shows the use of precision levelling by a DNA03 Leica digital level, used to measure the height difference between the EPC base and the parallax bar. The length between the EPC base and the hinge rotation axis (Figure 4B), as well as the difference between the upper parallax bar and the incidence point in the plane, were measured and discounted from the effective height used in the determination of the plane's angle rotation.

In this system, when the parallax bar moves, it is possible to determine the plane's rotation angle by trigonometry. Since the proposal is a statistical evaluation

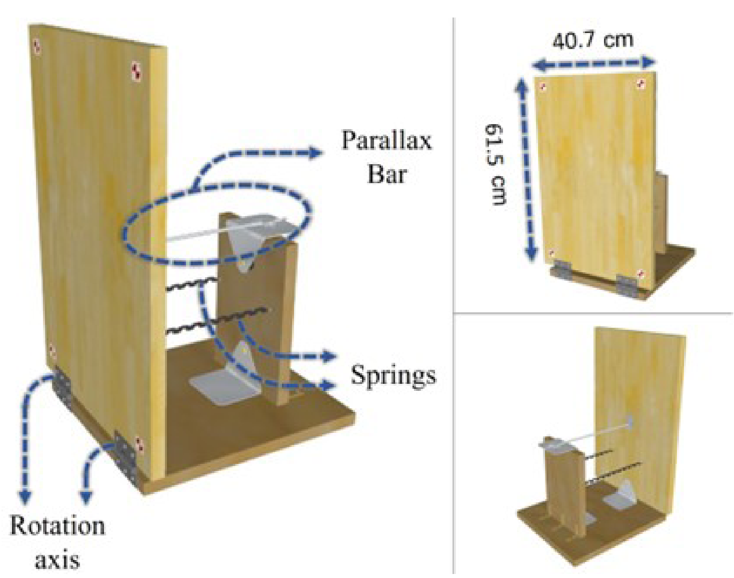


Figure 2 The experimental control plane prototype.

of structural monitoring methods, the variations on l were close to 10 and 15 mm. COPEL (2018) adopted these values as maximum tolerable variations. In his work, the author monitored a dam with point targets fixed using robotic total stations.

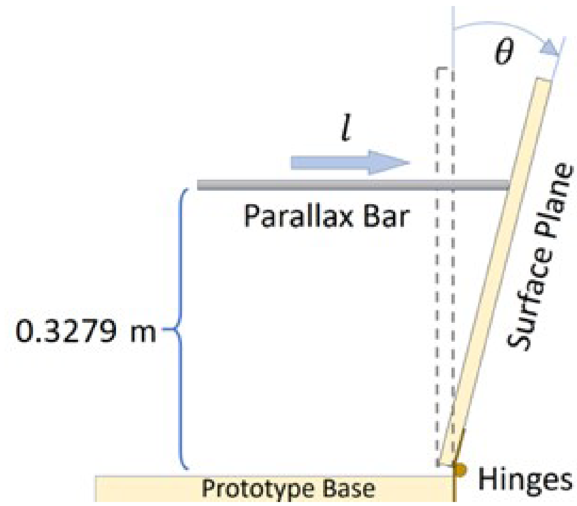


Figure 3 Experimental control plane movement.

3.3 Point Acquisitions on Plane Surface Control

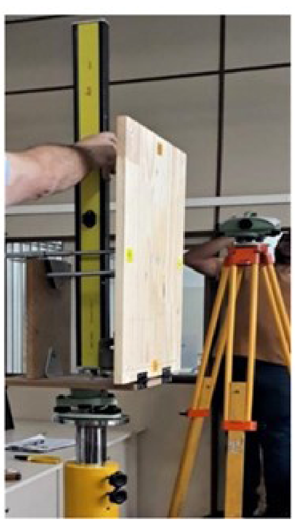
Experiments were carried out in a controlled laboratory environment. The aim was to detect plane displacements and inclinations at different epochs, as shown in Figure 5. In that case, the plane π_0 (used as reference) had displaced and rotated. It caused new plane positions, indicated as π_1 and π_2. The inclinations results are θ_1 and θ_2. Each plane position is determined by the plane's parameters.

Data acquisition was simultaneously conducted by TS15 and BLK360. The total station operated by regular grid scan (2.0 cm spacing). The acquisition process had two stages, which differed in terms of relations between control plane inclination and instrument position. The reference systems were maintained for each stage, enabling posterior identification and comparison of inclinations. Figure 6 shows the first stage, when total station and TLS are in front of the plane surface (EPC installed on an industrial tripod). Thus, the incidence angles of the laser beam were carried out close to 90º.

The point clouds obtained by the total station scan were limited to the plane area. However, in the point clouds by TLS, post-processing was applied with manual selection and exclusion of points out of EPC. Since the experiment was carried out in a controlled environment, no noise was observed in the data. Therefore, no filtering was applied. Additionally, extra information of point cloud acquisitions is available at Alves (2020).

In the second stage, instruments were moved to another position, which resulted in incidence angles near 45°. This configuration allowed for an investigation regarding the influence of instruments and laser incidence angles on plane measurements (Figure 7).

As shown in Figure 8, there were six different plane positions measured by BLK360 and TS15, varying the parallax bar and changing the inclination.



(A)

(B)

Figure 4 Determination of heights.

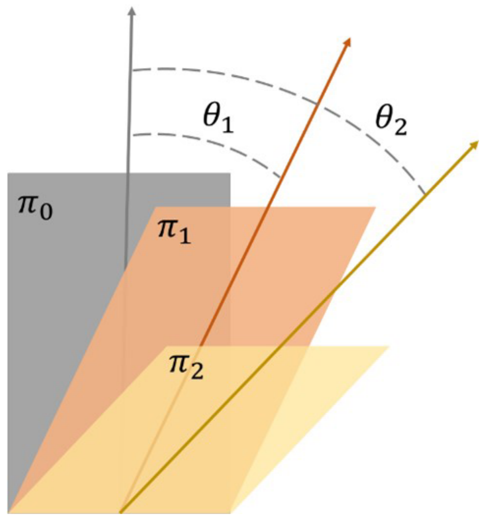


Figure 5 Plane displacement and inclination.

Subsequently, comparisons to detect changes were made relatively. Therefore, at the first stage, with the EPC leveled and the plane in a vertical position, 1st position was the reference for other positions in the frontal mode. At the second stage, also with the EPC leveled, 5th position was the reference for displacement detections in oblique mode. The 1st position and 5th position were both with the control plane in vertical position.

3.4 Evaluation of Plane Inclination

Using the 1st and 5th plane positions as references, Table 1 presents the test sequence carried out to evaluate the angles created by the position of the plane. There were two groups of tests: a group of four tests by TLS point clouds, and another by total station point clouds. The test statistics were obtained by Equations 14, 17 and 18.

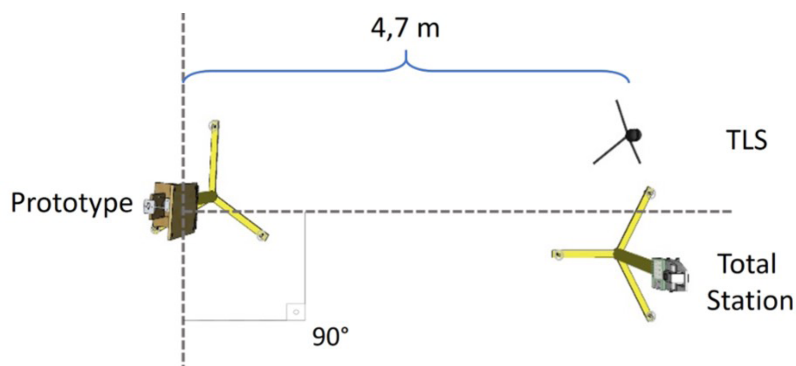


Figure 6 Instrument positions in experiment first stage.

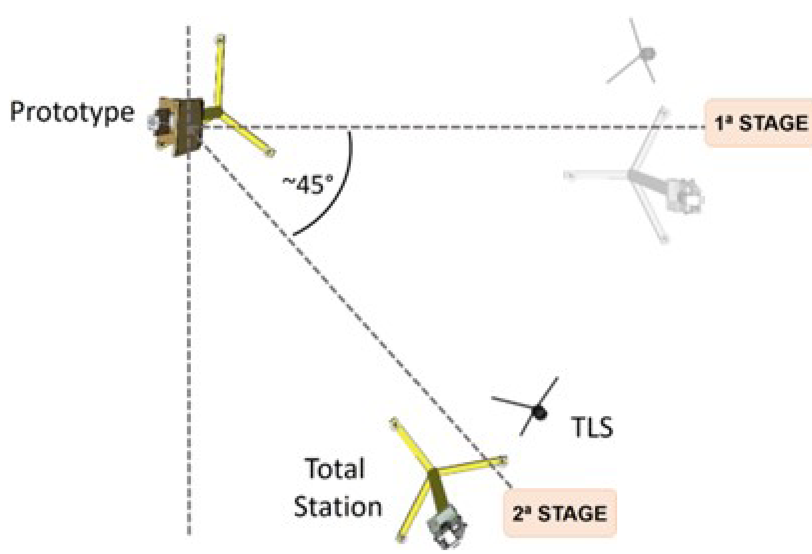


Figure 7 Instrument positions in experiment second stage.

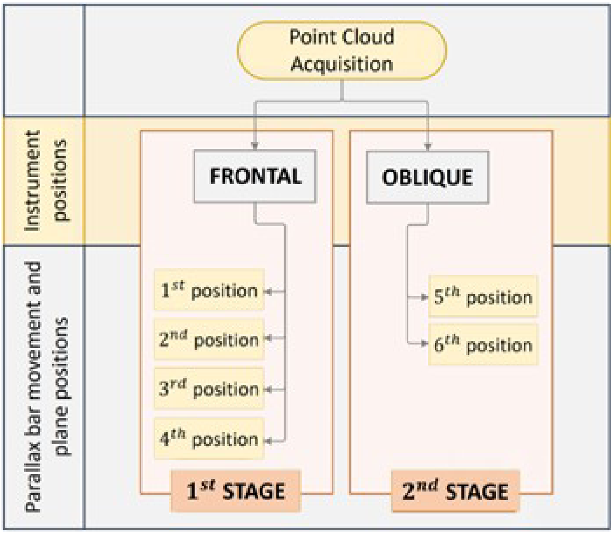


Figure 8 Steps to obtain point cloud samples.

As shown in Figure 1, the 4th step corresponds to plane displacement investigations. Figure 9 presents the sequence of investigation followed in this step. The evaluation of plane inclinations consisted on analyzing angle significances and comparing results, which were calculated using the EPC dimensions, and TLS and total station point clouds.

Angle inclinations were the approach used to evaluate differences in the plane positioning. As indicated, the parallax bar moves and hinges rotation at the EPC plane, resulting in angle displacements or plane inclinations. Subsequently, angle determinations were investigated by three approaches: EPC dimensions, TLS point clouds, and total station point clouds.

Considering parallax bar displacements (l), height from the parallax bar to the EPC base (h) and perpendicularity in reference positions (1st and 5th positions), the inclination angles were calculated from the EPC dimensions. As shown in Figure 5, Equation 19 provides an angle θ:

$$\theta = \tan^{-1}\frac{l}{h} \tag{19}$$

Angles obtained by total station, TLS and the EPC were compared by statistical approach. This step evaluates whether equivalent angles can be considered equal. Thus, being θ_{ET}, θ_{LST} and θ_P inclinations by total station, TLS and EPC, respectively, three null and alternative hypotheses were formulated in Equations 20, 21 and 22:

$$\begin{cases} H_0 : \theta_{LST} = \theta_P \\ H_a : \theta_{LST} \neq \theta_P \end{cases} \tag{20}$$

$$\begin{cases} H_0 : \theta_{ET} = \theta_P \\ H_a : \theta_{ET} \neq \theta_P \end{cases} \tag{21}$$

$$\begin{cases} H_0 : \theta_{LST} = \theta_{ET} \\ H_a : \theta_{LST} \neq \theta_{ET} \end{cases} \tag{22}$$

In this case, the concern is if the tested angle is statically different from the magnitude of the compared angle. Thus, a two-tailed test was the type of test chosen to perform the evaluation. Chi-square test was conducted using the following statistics in Equations 23, 24 and 25:

$$\chi^2_{\theta_{LST} \times \theta_P} = \frac{(\theta_{LST} - \theta_P)^2}{\sigma^2_{\theta_{LST}}} \tag{23}$$

$$\chi^2_{\theta_{ET} \times \theta_P} = \frac{(\theta_{ET} - \theta_P)^2}{\sigma^2_{\theta_{ET}}} \tag{24}$$

$$\chi^2_{\theta_{LST} \times \theta_{ET}} = \frac{(\theta_{LST} - \theta_{ET})^2}{\sigma^2_{\theta_{LST}} + \sigma^2_{\theta_{ET}}} \tag{25}$$

where $\sigma^2_{\theta_{LST}}$ e $\sigma^2_{\theta_{ET}}$ are inclination variance values to each tested approach (Equation 17), and $\chi^2_{\theta_{LST} \times \theta_P}$, $\chi^2_{\theta_{ET} \times \theta_P}$ e

Table 1 Tests performed to identify displacement between planes.

TLS Data		**Total Station Data**	
Frontal Position		Frontal Position	
Test 1	1st position x 2nd position	Test 1	1st position x 2nd position
Test 2	1st position x 3rd position	Test 2	1st position x 3rd position
Test 3	1st position x 4th position	Test 3	1st position x 4th position
Oblique Position		Oblique Position	
Test 4	5th position x 6th position	Test 4	5th position x 6th position

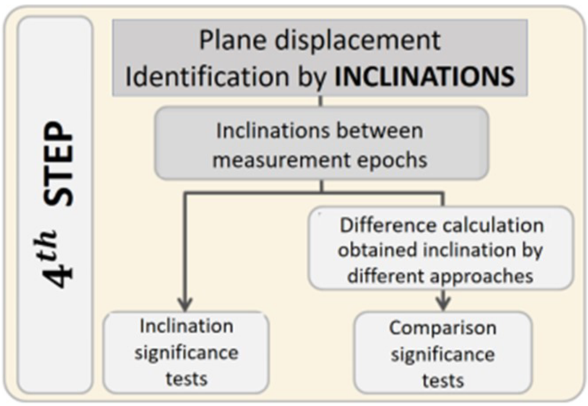


Figure 9 Workflow for the displacement detection step.

$\chi^2_{\theta_{LST}\times\theta_{ET}}$ are the statistics calculated for angle comparisons between TLS and EPC, total station and EPC, and TLS and total station, respectively. In this research, the inclination variances from the EPC were considered null, which increases the probability of null hypothesis rejection, that is, the possibility of angles determined by different instruments being indicated as statistically different.

4 Results

Based on the adjusted parameters, the inclinations of the plane and its variance were calculated in each test scenario by Equations 14 and 17. Table 2 presents the results obtained.

Observing the values in Table 2, the plane inclinations obtained by TLS and total station showed similar values, with a maximum difference of 3'. However, both samples showed greater differences when evaluated in relation to the angle inclinations of the EPC, mainly for oblique surveys, for which the difference was 14'.

Compatibility of derived results from point clouds previously indicated the efficiency of both measurement approaches applied to angle determination of inclinations, considering that it evidences the occurrence of plane displacements. However, the differences in relation to EPC values demonstrate that, although the experiment was carried out in a controlled manner, there was greater rigor when evaluating the determination of inclinations from the EPC dimensions.

By analyzing the results in Table 2, it can be highlighted that in the propagation for the angle of inclination the total station provided better precision, being 3 times greater in frontal cases and 10.25 times greater in the oblique case. These results indicate that scans taken from oblique positions with TLS can lower the data quality.

In order to ascertain whether the inclinations found are statistically significant, Table 3 shows the Chi-Square test values obtained by Equation 18.

Since the conditions are satisfied, the null hypothesis is rejected at 5% significance level, and the alternative hypothesis is accepted in all cases. Based on the outcome, the tested angle inclinations are statistically significant at 5% significance level.

Once more, the total station showed higher Chi-Square values in all cases. Although the choice of significance level is not the scope of this research, it could affect the conclusion of the test because the critical value increases considering the level of significance of 1%. Thus, Test 4 with TLS would not pass the analysis, accepting the null hypothesis that the angle of inclination is not statistically significant. In general, it can be concluded that the total station presented greater efficiency in the detection of inclinations in relation to the TLS due to chances of angles obtained by total station scanning having to be approved in the statistical test, especially with the data acquisition in the oblique mode.

Finally, direct comparisons between the values of the inclinations were performed, and the values of the test statistics obtained by Equations 23, 24 and 25 are shown in Table 4.

Table 2 Inclinations and precision of the plane positions.

	Inclination and precision by TLS (°)	Inclination and precision by total station (°)	Inclination by EPC (°)
Frontal Position			
Test 1	0°51' ± 0°15'	0°48' ± 0°05'	0°53'
Test 2	1°30' ± 0°15'	1°31' ± 0°05'	1°35'
Test 3	3°26' ± 0°15'	3°29' ± 0°05'	3°28'
Oblique Position			
Test 4	1°23' ± 0°41'	1°23' ± 0°04'	1°09'

Table 3 Statistics values $\chi^2_{calculated}$ for the inclination significance tests.

Evaluation	Chi-Square calculated for TLS	Chi-Square calculated for the total station	$\chi^2_{theoretical}$ (α=5%)	$\chi^2_{theoretical}$ (α=1%)
Frontal Position				
Test 1	12.22	95.26		
Test 2	37.65	343.35	3.84	6.63
Test 3	195.4	1785.62		
Oblique Position				
Test 4	4.14	380.19	3.84	6.63

Table 4 Statistics values of $\chi^2_{calculated}$ to compare the inclinations.

Evaluation	TLS x EPC	Total Station x EPC	Total Station x TLS	$\chi^2_{theoretical}$ $(\frac{5\%}{2})$	$\chi^2_{theoretical}$ $(1-\frac{5\%}{2})$	$\chi^2_{theoretical}$ $(\frac{1\%}{2})$	$\chi^2_{theoretical}$ $(1-\frac{1\%}{2})$
Frontal Position							
Test 1	0.02	0.45	0.05				
Test 2	0.11	0.10	0.01	0.001	3.17	0.00004	7.88
Test 3	0.02	0.28	0.03				
Oblique Position							
Test 4	0.12	0.02	0.0002	0.001	3.17	0.00004	7.88

Critical values for the bilateral test, with a degree of freedom and 5% of significance level, indicate the rejection of a null hypothesis for Test 4 for the total station x TLS. By changing the level of significance to 1%, the region of acceptance of the null hypothesis is expanded and, in this case, there is no significant difference between the inclinations.

In general, it can be noted that the angle values were not significant variables in this experiment both in frontal and oblique positions, since the angles obtained from both approaches presented similar values. However, the inclination angle identification obtained by the total station provided test statistics higher to those calculated by the TLS. This fact indicates that, in this evaluation, the scans by total station enabled inclinations statistically better than by TLS.

5 Conclusions

This research developed a new approach to geodetic monitoring, which aimed to use a control plane to evaluate inclination derived from terrestrial laser scanning in comparison to a robotic total station scanning. The experiment carried out in laboratory allowed for the minimization of variation factors, such as temperature, and the maintenance of equipment positions for survey campaigns.

Calculating inclinations by parameters, the statistical evaluation, based on the propagation of variances and the displacement magnitudes, made it possible to verify that in all cases the results were statistically significant. However, the statistic calculated close to the critical value of the test for the oblique TLS survey shows that equipment position can interfere significantly in monitoring activities. It is noteworthy that this approach and the results achieved in laboratory are unprecedented within the context of structural geodetic monitoring.

When assessing the effective use of this approach in monitoring activity, it is concluded that it is possible to add previous stages to the project, which may affect the results. The need to carry out more than one scanning station and campaigns at different times, as to determine plane inclinations, would imply in the practice of registering the point clouds acquired for joining and orienting the data, which would add errors to the data, consequently impacting plane determinations and inclination angles.

In general, statistical tests to detect differences in the plane showed better results with the data from the total station. The worst scenario was obtained from TLS at oblique position, which showed lower test statistics or less inclination detection power, demonstrating that the TLS scan is more sensitive to equipment position than the total station. Even so, the plane displacements were in general detected with both TLS and total station scans, considering 5% and 1% significance levels.

For future work, applying the proposed procedure in a non-laboratory environment and testing different distances between the equipment and the control plane. Other adjustment surfaces such as parabolas is recommended, as is the application of the adjustment reliability theory, estimating the smallest detectable inclination angle. Moreover, further studies on the appropriate determination of the significance level of the test seeking to reduce the occurrence of false negatives or false positives are also recommended.

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Conflict of interest

The authors declare no potential conflict of interest.

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Scripts and code are available on request.

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