Edge Detection in Point Clouds for TLS Monitoring of In-Plane Displacement

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Abstract

Deformation monitoring of objects with a terrestrial laser scanner (TLS) focuses in practice on detecting displacements in the direction normal to the surface (out-of-plane). However, detecting displacements along the plane of objects (in-plane) on smooth, homogeneous objects remains a major challenge (an example is monitoring displacements in landslides).

In our research, we tested the detection of displacements along the plane using edge detection. We used the Riegl VZ-400 and tested a monotonically smooth plate, which we moved horizontally from 0.1 mm to 5 mm at distances of 5 m and 13 m. We detected edges in two ways, using a Gaussian model and an Edge function with the Canny algorithm. The results showed that at 5 m, it is possible to reliably detect displacements greater than 1 mm (standard deviation between 0.23 mm and 0.55 mm), and at 13 m, displacements greater than 2 mm (standard deviation between 0.32 mm and 0.96 mm). All correctly detected displacements are statistically significant at a 95% confidence level.

As an additional experiment, we also detected displacements by detecting features on a surface with a larger number of features. We simulated displacements by changing the TLS inclination at distances of 5 m, 10 m, and 20 m. We detected the displacements we tested, with slightly larger deviations from the reference values at a movement of approximately 2 mm at 10 m and 4 mm at 20 m. All displacements are statistically significant at a 95% confidence level.

The results show that TLS reliably detects in-plane displacements in the range of a few millimeters, which enables the monitoring of objects on landslides and similar cases where the traditional out-of-plane approach cannot be used. When detecting edges, we recommend multiple scan repetitions for more reliable movement detection.

1 Introduction

When monitoring deformations of objects, we usually monitor displacements in horizontal and vertical directions. With TLS monitoring, monitoring is usually performed in the direction normal to the plane or (out-of-plane) displacements. In this case, we use measurements of the distances between the scanner and the object. With TLS monitoring, however, there is a problem with monitoring displacements in the plane of the surface (in-plane), especially on flat surfaces without distinctive geometric features.

A typical example is an object in a landslide area, where the object moves together with the ground. Due to the danger below or above the landslide, TLS measurements are only possible from the side, where the distance between the scanner and the object remains practically unchanged. In this case, the question arises as to how to reliably detect and quantify in-plane displacements of flat surfaces based on point clouds obtained with TLS. The problem becomes even greater when dealing with monotonous smooth surfaces where no features can be detected.

1.1 Use of TLS for deformation monitoring

Terrestrial laser scanning (TLS) is increasingly used for deformation monitoring because, instead of monitoring only specific points, it allows monitoring of the entire surface of an object. Despite the high density of points, determining displacements along the surface itself (so-called "in-plane" deformations) remains a major challenge. Established point cloud comparison methods, such as the M3C2 algorithm (Lague et al., 2013), are extremely effective in detecting changes in the direction of the normal to the surface, while they are often ineffective in detecting longitudinal displacements of the plane if the object does not have distinct geometric features (Medic et al., 2022). In a previous study (Kregar et al., 2022), the authors demonstrated that TLS can be used to reliably determine the parameters of a plane and detect its small inclinations and displacements, but that modeling the plane alone does not allow for the determination of displacements along the plane.

1.2 Motivation

The traditional approach to monitoring objects with TLS is usually related to monitoring in the direction of the normal plane or out-of-plane. In this article, we ask how to detect displacements along the surface of the plane itself (in-plane deformations).

Since we are monitoring smooth and homogeneous objects, traditional point cloud comparison methods do not detect these displacements. In this article, we will discuss an approach to detecting displacements by detecting the edges of a plate in several separate ways. In addition, we will evaluate a method for detecting longitudinal displacements of textured surfaces using feature detection. The goal is to find out how small displacements at specific distances can still be detected using different methods for several types of objects.

1.3 Literature overview

Point cloud deformation detection methods are based on comparing geometric models between time periods. Since TLS cannot scan the same points at various times, mathematical models of objects are used. Kregar et al. (2022) demonstrate that a plane is a suitable geometric primitive for modeling deformations, as TLS can detect changes in plane parameters in the millimeter range and inclinations of up to 150" for a 100 cm x 60 cm plate. Their study focuses on changes perpendicular to the plane.

Tan et al. (2025) use the M3C2 algorithm and plane fitting to detect global and local deformations of bridges and achieve sub-millimeter registration accuracy. Medić et al. (2022) demonstrate that shear (in-plane) displacements can also be detected by detecting key points in TLS intensity images. These approaches indicate that both radiometric and geometric analysis are necessary for comprehensive monitoring.

The main challenge in detecting displacements along a plane is that standard point cloud comparison methods (C2C, M3C2) are based on normal analysis and therefore do not detect displacements of smooth surfaces. To solve this problem, edges and other geometric features are used in practice. Che and Olsen (2017) present a fast method for edge detection based on normal analysis that is suitable for TLS data. Phan et al. (2025) develop an algorithm for automated edge detection on building facades using geometric analysis of the local environment. Ahmed et al. (2018) propose an approach for edge detection based on neighborhood symmetry that does not require the calculation of normals. These methods enable the identification of discrete geometric features that are crucial for establishing correspondence between epochs.

2 Methodology

2.1 Instrumentation

We used a Riegl VZ-400 scanner for our research task. Figure 1 shows the scanner, and Table 1 presents its technical specifications.

Fig. 1: Riegl VZ-400 Source: Wikimedia Commons ("VZ-400.png"), CC BY-SA 4.0 license.

Table 1: Riegl VZ-400 specifications

Riegl VZ-400	
Ranging Accuracy	5 mm
Ranging Precision	3 mm
3D Position Accuracy	3 mm @ 50 m, 5 mm @ 100 m
Angular Step Width	$0.0024° \leq \Delta\theta \leq 0.288°$ (Vertical)
	$0.0024° \leq \Delta\varphi \leq 0.5°$ (Horizontal)
Angular Accuracy	0.0028° (Vertical and Horizontal)
Angular Measurement Resolution	better 0.0005° (Vertical)
	better 0.0005° (Horizontal)

2.2 Experiment setup

To assess edge detection in horizontal displacements, we used a monotonically smooth wooden board measuring 100 cm x 60 cm, which was mounted on a mechanism that enabled movement using a small-stroke screw. The mechanism was stabilized on a tripod or pillar. To measure the displacements, we used a Bahco micrometer clock attached to a magnetic base. The scanner was stabilized on a concrete pillar. Figure 2 shows a sketch of the experiment.

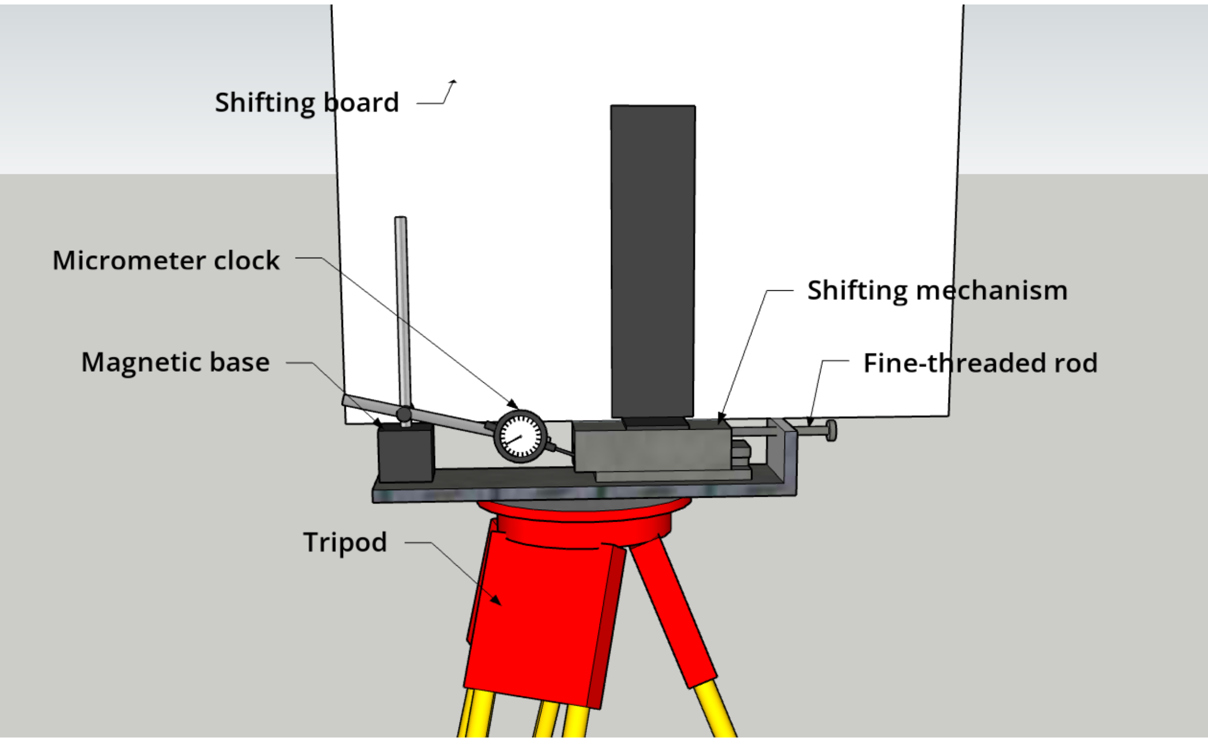

Fig. 2: Shifting test board setup

To test displacement detection with Feature Detection, we used a measuring tape and a Leica TS-10 tachymeter to calculate the angle caused by one turn of the screw on the base of the Leica GDF321 tribrach. We did this by hanging the tape vertically, measuring the initial value, turning the screw perpendicular to the measuring tape by one turn, and measuring the value again. We also measured the distance between tachymeter and measuring tape. In this way, we calculated the screw travel using the ratio between the turns and the change.

For scanning, we used a flat, rough concrete wall with a characteristic concrete texture (bubble holes in the concrete and visible lines formed between the formwork elements). Like determining the screw travel, we turned the screw perpendicular to the wall and scanned the wall each time.

2.3 Scanning

In the first experiment, we scanned at two distances, namely 5 m and 13 m. The density of all scans was 1 mm in both directions. We first scanned the plate at an initial value of 0 mm, then shifted it by 0.1 mm; 0.2 mm; 0.5 mm; 1 mm; 2 mm; 5 mm. We repeated five scans at each offset. In total, we performed thirty-five scans.

In the second experiment, we scanned at three distances: 5 m, 10 m, and 20 m. The scanning density was 1 mm in both directions. First, we scanned the wall with the scanner completely horizontal and then shifted it by the values given in Table 2. We performed one repetition for each combination of distance and shift. In total, we performed twenty-one scanning repetitions.

Table 2: Values of offsets, inclinations, and TLS displacements during the experiment

Knurls	1	2	5	10	20	45
Inclination	0' 40"	1' 21"	3' 22"	6' 45"	13' 28"	30' 19"
Displacement [mm] per 10 m	1,7	3,4	8,5	17,1	34,1	76,7

2.4 Edge detection methods

After scanning and clipping the point clouds, we first searched for points on the plane using the RANSAC algorithm. This was followed by the calculation of the plane parameters. We calculated these only once, as we wanted the coordinate axes of all plates to be the same. This was followed by the projection of points onto the plane. We interpolated the obtained points from the n x 2 matrix into a cell grid, where the values of individual cells are one where the points lie and zero where they do not. From there, we calculated the edges in two ways.

In the first method, we calculated the correlations using convolution or a moving window and then searched for the peaks of the curve separately for the left and right sides using the Gaussian model.

In the second method, we used convolution to find how many neighboring cells still contained points for each cell. This gave us values from 1 to 36 (the window was 6 x 12, with values of zero in the left half and one in the right half). Using the edge function and the Canny algorithm, we then searched for the left and right edges of the plate. In this case, we obtained a cell grid with values of zero and one, where the value one indicated the cell where the searched edge was located.

For both cases, we approximated a straight line and considered the value y-intercept of the line as the value of the left or right edge.

2.4.1 Statistical significance of edge detection displacement

In this experiment, we calculated the locations of the left and right edges for each offset. We calculated this for all five experiments. From these calculated values, we calculated the standard deviation for each side. We calculated the displacement from the reference value and the offset value.

$$D = \left|D_{i,j,0} - D_{i,j,k}\right| \tag{1}$$

$$var(D) = var\left(D_{i,j,0}\right) + var\left(D_{i,j,k}\right) \tag{2}$$

i = [Gauss, Canny], j = [Left edge, Right edge], k = [0,1; 0,2; 0,5; 1; 2; 5] mm

$$s(D) = \sqrt{var(D)} \tag{3}$$

T-test statistics:

$$T = D/s(D), \tag{4}$$

is distributed according to a standard normal distribution with n-1 degrees of freedom.

We defined the hypotheses of the test statistics as follows:

- Null hypothesis (H_0): there is no displacement, D = 0,
- Alternative hypothesis (H_1): there is displacement, D ≠ 0.

If test statistic T exceeds the critical value, $Z_{0.95}$ we reject the null hypothesis (H_0) and can say with 95% certainty that a displacement exists.

2.5 Feature detection methods

In the second method, we processed the initially obtained scans in an equivalent way as in the first experiment. We cropped the point clouds to the desired area, found the largest plane using the RANSAC algorithm, calculated the plane parameters for the first plane, and then used them for the others. We then projected the points onto the plane. Like the first experiment, we interpolated the points into a cellular network, except that instead of values 0 and 1, we interpolated intensity values representing the strength of the return signal into the cells. We then normalized the values in the cellular network.

We assessed several algorithms for feature detection, and the KAZE algorithm proved to be the best. We then linked the features together by matching them. Pairs whose mutual distances deviated too much from the average were removed with a 2-fold MAD or Median Absolute

Deviation value. For the remaining pairs, we calculated the average value, which represented our plane displacement relative to the initial plane.

2.5.1 Statistical significance of feature detection displacement

We wanted to check whether the displacements were statistically significant. First, we calculated the distance between the points, and the test statistic is distributed according to the standard normal distribution. We calculate the displacement D and its standard deviation using the following equations:

$$D = \sqrt{\bar{x}^2 + \bar{y}^2} \tag{5}$$

$$var(x) = \frac{\sum_{i=1}^{n}(\bar{x} - x_i)^2}{n-1} \quad , var(y) = \frac{\sum_{i=1}^{n}(\bar{y} - y_i)^2}{n-1} \tag{6,7}$$

$$var(D) = J * \Sigma * J^T \tag{8}$$

$$s(D) = \sqrt{var(D)} \tag{9}$$

T-test statistics:

$$T = D/s(D), \tag{4}$$

is distributed according to a standard normal distribution with n-1 degrees of freedom.

We defined the hypotheses of the test statistics as follows:

- Null hypothesis (H_0): there is no displacement, D = 0,
- Alternative hypothesis (H_1): there is displacement, D ≠ 0.

If test statistic T exceeds the critical value, $Z_{0.95}$ we reject the null hypothesis (H_0) and can say with 95% certainty that a displacement exists.

3 Results

3.1 Edge detection test results

Tables 3 and 4 present the results of displacements and standard deviations for the left and right edges for both methods. Displacements that are statistically significant are marked in green, while those that are not are marked in red.

Table 3: Results of edge detection experiment using the Canny algorithm

Canny	5m Left edge		5m Right edge		13m Left edge		13m Right edge	
Offset [mm]	s(D)	D	s(D)	D	s(D)	D	s(D)	D
0,1	0,29	0,05	0,33	0,09	0,82	0,49	0,49	0,33
0,2	0,26	0,01	0,45	0,53	0,96	0,28	0,51	0,54
0,5	0,25	0,45	0,32	0,26	0,92	0,20	0,37	0,40
1	0,28	0,89	0,31	0,92	0,94	0,49	0,38	0,86
2	0,29	1,97	0,40	2,16	0,89	1,45	0,53	1,77
5	0,33	4,97	0,40	5,02	0,83	4,53	0,49	4,93

Table 4: Results of the edge detection experiment with a Gaussian curve

Gauss	5m Left edge		5m Right edge		13m Left edge		13m Right edge	
Offset [mm]	s(D)	D	s(D)	D	s(D)	D	s(D)	D
0,1	0,39	0,03	0,23	0,02	0,42	0,05	0,39	0,02
0,2	0,44	0,11	0,33	0,02	0,40	0,16	0,38	0,34
0,5	0,41	0,50	0,55	0,38	0,34	0,09	0,44	0,26
1	0,42	1,04	0,30	0,81	0,39	0,58	0,38	0,67
2	0,42	2,06	0,27	1,85	0,35	1,47	0,32	1,58
5	0,37	5,09	0,34	4,87	0,39	4,58	0,33	4,87

Standard deviations between measurements when detecting the edge of the plate with a Gaussian curve and 5 m ranged between 0.23 mm and 0.55 mm, and between 0.32 mm and 0.44 mm at 13 m. When using the Canny edge detection algorithm, the standard deviations between measurements at 5 m ranged between 0.25 mm and 0.45 mm, and between 0.37 mm and 0.96 mm at 13 m.

At 5 m, we were able to detect changes greater than 1 mm with both methods, and at 13 m, we were able to detect displacements greater than 2 mm. This was also confirmed by statistical tests. At 5 m, we also detected displacements of 0.5 mm, but not in all cases, similarly at 13 m for displacements of 2 mm. At 13 m, there are greater deviations between the detection of individual measurements. A larger number of scan repetitions could solve this.

3.2 Feature detection test

3.2.1 Calculation of feature detection test results

For each position, we resampled seven images from seven scans. We compared the first image, which represents the initial value, with the images of all subsequent displacements. Figure 3 shows an example of a comparison of two images of a scanned wall.

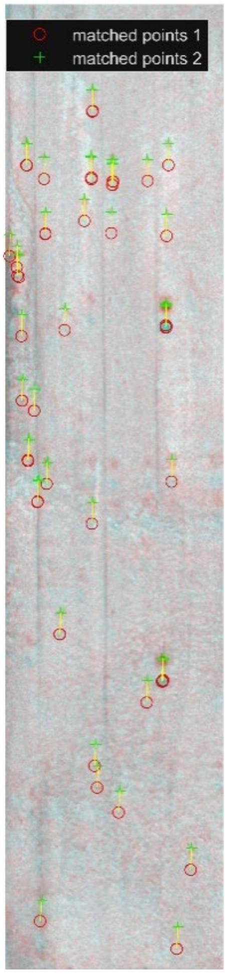

Fig. 3: Comparison of two images of a scanned wall

As we can see, all the displacements are vertical, as expected, given the rotation of the screw. This image was created after removing outliers, so no displacements stand out.

The tables below show the expected and measured displacements and a comparison of the deviations between them. All displacements are marked in green.

Table 5 shows the reference values, Table 6 shows the calculated values, and Table 7 shows a comparison of the deviations between the reference and calculated values.

Table 5: Reference values for the detection test

Reference values		Angle change					
		40''	1'21''	3'22''	6'45''	13'28''	30'19''
Distance	5	0,96	1,92	4,80	9,60	19,20	43,21
	10	1,70	3,41	8,52	17,05	34,10	76,72
	20	3,80	7,60	19,01	38,01	76,03	171,07

Table 6: Calculated values of the trait detection test

Computed values		Angle change					
		40''	1'21''	3'22''	6'45''	13'28''	30'19''
Distance	5	1,07	2,00	5,04	9,72	19,78	44,66
	10	1,17	4,00	9,00	18,02	35,65	81,48
	20	3,39	7,71	19,39	39,84	77,32	177,69

Table 7: Comparison of deviations between reference and calculated values

Comparison of reference and calculated values		Angle change					
		40''	1'21''	3'22''	6'45''	13'28''	30'19''
Distance	5	0,11	0,08	0,24	0,12	0,58	1,45
	10	-0,53	0,59	0,48	0,97	1,55	4,76
	20	-0,41	0,11	0,38	1,83	1,29	6,62

Using the KAZE algorithm, we detected several dozen features on two images and compared the displacements between them. The difference between the theoretically calculated displacements and those obtained by feature matching is mostly a few percent, except for the displacements of 1/45 of a circle for distances of 10 m and 20 m, where the deviations are greater.

3.2.2 Statistical test of calculated results of feature detection

In addition to calculating the displacements, we also calculated a test of the characteristics of the displacements. The critical value $Z\alpha$ at a 5% risk is 1.645. In our case, the test statistic T was greater for all displacements, which means that all displacements were statistically significant. We can therefore reject the null hypothesis and state with 95% certainty that the displacements are statistically significant.

4 Discussion and conclusion

In this paper, we addressed the problem of detecting in-plane displacements based on point clouds obtained with TLS in situations where objects can only be observed from the side. We presented two experiments. In the first one, we attempted to find the smallest displacement that can still be detected with TLS scanners on a smooth monotonic surface with a pronounced edge at different distances. We assessed two different edge detection methods, which we also evaluated statistically. The second experiment involved detecting matching features on two different scans and the distances between them. At three different distances, we assessed how small displacements we could still detect by changing the angle of the scanner.

First, we assessed a case where, due to the smooth monotonic surface, we could use two methods of edge detection: the Gaussian model and the Edge function with the Canny algorithm. We conducted the experiment at two distances, namely 5 m and 13 m. We shifted the plate by 0.1, 0.2, 0.5, 1, 2, and 5 mm, repeating the experiment five times for each distance and offset. The results showed that both approaches are capable of reliably detecting displacements greater than 0.5 mm at 5 m, and displacements of a couple of millimeters at 13 m. We also found that the displacements we detected at a given distance are statistically significant according to the standard normal distribution and a 5% risk.

In the second test, we assessed the case where the edge was not pronounced or where we had an object with walls with characteristic geometric properties. In this experiment, we used the Feature detection function with the KAZE algorithm. At 5 m, 10 m, and 20 m, we tested various changes in inclination with which we simulated the displacements of the object. We detected all displacements at all distances, with only the detected displacements at 10 m and 20 m and the 40’’ inclination change deviating from the calculated values. All displacements were statistically significant according to the standard normal distribution and a 5% risk.

The plan is to repeat the edge detection experiment at longer distances, which would be more meaningful for monitoring in nature. We would also repeat the experiment of detecting features at longer distances and on objects with different structures and geometric properties. The goal is also to transfer this experiment to the real world, where we detect changes on actual objects in real time.

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