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ANALYZING OF THE TERRESTRIAL LASER SCANNER GEOREFERENCING USING GNSS

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ABSTRACT

Recent years have witnessed emerging the cutting-edge method for point cloud creation using terrestrial laser scanner (TLS). The TLS manufacturers declare accuracies of their instruments up to the millimeter level. However, different constraints could degrade the accuracy of point cloud created by TLS. One of the obvious factors that may directly affect the accuracy of the results is a method of registration and georeferencing. In this paper, the indirect georeferencing using GNSS has been researched. The real time kinematic (RTK) technique has been suggested to measure GNSS points. The conducted test shows that average of 30 minutes data RTK-GNSS is enough to coincide with TLS data. Also, test reveals no improvements when adding more GNSS points. Nevertheless, there is an improvement in accuracy when more scans are conducted.

KEYWORDS: Terrestrial Laser Scanner; TLS; Georeferencing; GNSS; HDS300; Registration.

1. INTRODUCTION

The principle of TLS operation is based on the transmission of a laser beam from a TLS instrument with visible light or near Infrared which is reflected by objects and return to the instrument, and the distance (R) is determined by the time of flight (TOF) or by the phase difference. By encoders, the vertical angle (Φ) and horizontal angle (θ) are determined and combined with distance. Then Cartesian coordinates (x, y, z) of objects is obtained from distance R and angle θ and Φ as follows (Armesto et al., 2010, Reshetyuk, 2009):

$$P_i = \begin{bmatrix} x_i \\ y_i \\ z_i \end{bmatrix} = \begin{bmatrix} R_i\ Cos\phi_i\ Cos\theta_i \\ R_i\ Sin\phi_i\ Cos\theta_i \\ R_i\ Sin\theta_i \end{bmatrix} \tag{1}$$

Where R_i, φ_j and θ_i are the measured distance, horizontal and vertical angle, respectively, to the i-th point in the point cloud, and (x_i, y_i, z_i) are its rectangular (Cartesian) coordinates in the scanner coordinate system.

In addition, the intensity I of the reflected laser beam is often recorded which represents a fourth dimension (x, y, z, I). The result of a scan is millions of 4D points which are called point cloud.

Therefore, to benefit from the created point clouds, it should be related to known coordinate system.

2. GEOREFERENCING

The georeferencing is defined as the procedure of transforming internal TLS coordinate system to local or national coordinate system (Reshetyuk, 2009). Georeferencing is required if the TLS point clouds need to be integrated with other geospatial data or sequent of scans need to be related to the same system. This may be the essential step for monitoring surveying using TLS. There are two methods for georeferencing: direct, and indirect.

3. DIRECT GEOREFERENCING

In this method, TLS is set up on a known point and oriented through another known point, as in Total Station (TS). Hence, the transformation parameters are set practically, i.e. the three translation parameters are determined when TLS set up and centred optically over a known point, while the rotation angles around X-axis and Y-axis are fixed through levelling procedures, finally, the rotation angle around Z-axis is set by orienting to a known point (Alba and Scaioni, 2007).

Some new generation of TLSs are integrated with other sensors, such as Global Navigation Satellite System (GNSS) and an Inertial Measurement Unit (IMU), to adopt direct georeferencing. However, this imposes additional expenses to the scanning system (Al-Durgham et al., 2014, dos Santos et al., 2013).

4. INDIRECT GEOREFERENCING

Indirect registration method is based on resection surveying technique to solve coordinates of station point and consequently the coordinates of all point clouds. A minimum of three known reference points is required, however, more points can be added to increase redundancy. Least Squares Adjustment is used to calculate six transformation parameters. Conventionally, with the absence of control points, surveying before scanning is required to distribute points relate to a local reference system, or to the national reference system if GNSS is used (dos Santos et al., 2013).

The indirect georeferencing is considered as the most accurate technique because the quality of results only depends on the accuracy of control points, the setting up of TLS will not affect the accuracy (Alba and Scaioni, 2007, Reshetyuk, 2009). Therefore, it is selected in this paper.

5. THEORETICAL BACKGROUND

The principle of the indirect georeferencing, which is employed in this research, is based on three-dimensional transformation. In our proposal, the first system is GNSS coordinates (X_G), while second system is scanner coordinates (X_S). Hence, if there are points known in both systems, the problem is solved and any point in one system can be transformed to another easily. This technique is known as 7-parameters transformation (Hofmann-Wellenhof et al., 2007, Reit, 1998).

$$X_G = T + \mu\, R\, X_S \qquad 2$$

Where:

X_G: Point vector in GNSS system= $[X_G \;\; Y_G \;\; Z_G]^T$

X_S: Point vector in scanner system= $[X_S \;\; Y_S \;\; Z_S]^T$

μ : Scale factor

R: Rotation matrix

T: Translation vector = $[T_X \;\; T_Y \;\; T_Z]^T$

$$R = R3(\alpha_3) * R2 * (\alpha_2) * R1(\alpha_1) \qquad 3$$

$$R1(\alpha_1) = Rotation\ matrix\ around\ X - axis\ with\ angle\ (\alpha 1) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\alpha_1 & \sin\alpha_1 \\ 0 & -\sin\alpha_1 & \cos\alpha_1 \end{bmatrix}$$

$$R2(\alpha_2) = Rotation\ matrix\ around\ Y - axis\ with\ angle\ (\alpha 2) = \begin{bmatrix} \cos\alpha_2 & 0 & -\sin\alpha_2 \\ 0 & 1 & 0 \\ \sin\alpha_2 & 0 & \cos\alpha_2 \end{bmatrix}$$

$$R3(\alpha_3) = Rotation\ matrix\ around\ Z - axis\ with\ angle\ (\alpha 3) = \begin{bmatrix} \cos\alpha_3 & \sin\alpha_3 & 0 \\ -\sin\alpha_3 & \cos\alpha_3 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Hence;

$$R = \begin{bmatrix} \cos\alpha_2\cos\alpha_3 & \cos\alpha_1\sin\alpha_3 + \sin\alpha_1\sin\alpha_2\cos\alpha_3 & \sin\alpha_1\sin\alpha_3 - \cos\alpha_1\sin\alpha_2\cos\alpha_3 \\ -\cos\alpha_2\sin\alpha_3 & \cos\alpha_1\cos\alpha_3 - \sin\alpha_1\sin\alpha_2\sin\alpha_3 & \sin\alpha_1\cos\alpha_3 + \cos\alpha_1\sin\alpha_2\sin\alpha_3 \\ \sin\alpha_2 & -\sin\alpha_1\cos\alpha_2 & \cos\alpha_1\cos\alpha_2 \end{bmatrix}$$

Consequently, if 7-parameters are known (T_X, T_Y, T_Z, μ, α_1, α_2 and α_3), any point can be transformed between two systems. However, in our case, these parameters are unknown and to be computed from a set of points known in both systems. As far as GNSS system and scanner system have a uniform scale, the scale factor (μ) is considered equa1. Consequently, two known points in both systems are enough to give absolute solution for six unknowns. Nevertheless, more points are used with Least Square Adjustment (LSA) to improve estimation.

To use LSA, equation **خطأ! لم يتم العثور على مصدر المرجع.** needs to linearize by Taylor series:

$$F = F(T_X, T_Y, T_Z, \alpha_1, \alpha_2, \alpha_3) \qquad 4$$

$$F = Fo + \frac{\partial F}{\partial T_X} dT_X + \frac{\partial F}{\partial T_Y} dT_Y + \frac{\partial F}{\partial T_Z} dT_Z + \frac{\partial F}{\partial \alpha_1} dT\alpha_1 + \frac{\partial F}{\partial \alpha_2} d\alpha_2 + \frac{\partial F}{\partial \alpha_3} d\alpha_3$$

Substitute in **خطأ! لم يتم العثور على مصدر المرجع.** with arrangement

$$X_G - Fo = \begin{bmatrix} \frac{\partial F}{\partial T_X} & \frac{\partial F}{\partial T_Y} & \frac{\partial F}{\partial T_Z} & \frac{\partial F}{\partial \alpha_1} & \frac{\partial F}{\partial \alpha_2} & \frac{\partial F}{\partial \alpha_3} \end{bmatrix} \begin{bmatrix} dT_X \\ dT_Y \\ dT_Z \\ dT\alpha_1 \\ d\alpha_2 \\ d\alpha_3 \end{bmatrix}$$

$$\frac{\partial F}{\partial T_X} = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}; \frac{\partial F}{\partial T_Y} = \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix}; \frac{\partial F}{\partial T_Z} = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}$$

$$\frac{\partial F}{\partial \alpha_1} = D_X = \begin{bmatrix} 0 & \cos\alpha_3 \sin\alpha_2 \cos\alpha_1 - \sin\alpha_3 \sin\alpha_1 & \sin\alpha_3 \cos\alpha_1 + \cos\alpha_3 \sin\alpha_2 \sin\alpha_1 \\ 0 & -\cos\alpha_3 \sin\alpha_1 - \sin\alpha_3 \sin\alpha_2 \cos\alpha_1 & \cos\alpha_3 \cos\alpha_1 - \sin\alpha_3 \sin\alpha_2 \sin\alpha_1 \\ 0 & -\cos\alpha_2 \cos\alpha_1 & -\cos\alpha_2 \sin\alpha_1 \end{bmatrix}$$

$$\frac{\partial F}{\partial \alpha_2} = D_Y = \begin{bmatrix} -\cos\alpha_3 \sin\alpha_2 & \cos\alpha_3 \cos\alpha_2 \sin\alpha_1 & -\cos\alpha_3 \cos\alpha_2 \cos\alpha_1 \\ \sin\alpha_3 \sin\alpha_2 & -\sin\alpha_3 \cos\alpha_2 \sin\alpha_1 & \sin\alpha_3 \cos\alpha_2 \cos\alpha_1 \\ \cos\alpha_2 & \sin\alpha_2 \sin\alpha_1 & -\sin\alpha_2 \cos\alpha_1 \end{bmatrix}$$

$$\frac{\partial F}{\partial \alpha_3} = D_Z$$

$$= \begin{bmatrix} -\sin\alpha_3 \cos\alpha_2 & \cos\alpha_3 \cos\alpha_1 - \sin\alpha_3 \sin\alpha_2 \sin\alpha_1 & \cos\alpha_3 \sin\alpha_1 + \sin\alpha_3 \sin\alpha_2 \cos\alpha_1 \\ -\cos\alpha_3 \cos\alpha_2 & -\sin\alpha_3 \cos\alpha_1 - \cos\alpha_3 \sin\alpha_2 \sin\alpha_1 & -\sin\alpha_3 \sin\alpha_1 + \cos\alpha_3 \sin\alpha_2 \cos\alpha_1 \\ 0 & 0 & 0 \end{bmatrix}$$

$$L + v = A\Delta \qquad 5$$

$\Delta = (A^T P A)^{-1} * (A^T P L)$

$\Delta = N^{-1} * n$

$N = A^T P A \quad (normal\ matrix)$

$n = A^T P L \quad (constant\ vector)$

$\Delta = [dT_X \quad dT_Y \quad dT_Z \quad dT_{\alpha_1} \quad dT_{\alpha_2} \quad dT_{\alpha_3}]^T$

$P: weight\ matrix$

$$\begin{bmatrix} T_X \\ T_Y \\ T_Z \\ T_{\alpha_1} \\ T_{\alpha_2} \\ T_{\alpha_3} \end{bmatrix} = \begin{bmatrix} T_X o \\ T_Y o \\ T_Z o \\ \alpha_1 o \\ \alpha_2 o \\ \alpha_3 o \end{bmatrix} + \begin{bmatrix} dT_X \\ dT_Y \\ dT_Z \\ d\alpha_1 \\ d\alpha_2 \\ d\alpha_3 \end{bmatrix}$$

$T_X o, T_Y o, T_Z o, T_{\alpha_1} o, T_{\alpha_2} o, T_{\alpha_3} o = approximate\ values\ for\ unknown$

For single point (i):

$$Ai = \begin{bmatrix} 1 & 0 & 0 & Y_S D_X(1,2) + Z_S D_X(1,3) & X_S D_Y(1,1) + Y_S D_Y(1,2) + Z_S D_Y(1,3) & X_S D_Z(1,1) + Y_S D_Z(1,2) + Z_S D_Z(1,3) \\ 0 & 1 & 0 & Y_S D_X(2,2) + Z_S D_X(2,3) & X_S D_Y(2,1) + Y_S D_Y(2,2) + Z_S D_Y(2,3) & X_S D_Z(2,1) + Y_S D_Z(2,2) + Z_S D_Z(2,3) \\ 0 & 0 & 1 & Y_S D_X(3,2) + Z_S D_X(3,3) & X_S D_Y(3,1) + Y_S D_Y(3,2) + Z_S D_Y(3,3) & 0 \end{bmatrix}$$

$$Li = \begin{bmatrix} X_G - Fo \\ Y_G - Fo \\ Z_G - Fo \end{bmatrix}$$

Since the translation vector between GNSS system and scanner is very long, and to reduce number of iterations for LSA, one GNSS point coordinates is considered as an approximate value for translation.

$[T_X o \quad T_Y o \quad T_Z o]^T = [X_G \quad Y_G \quad Z_G]^T$

The other approximate values ($\alpha_1 o$, $\alpha_2 o$, and $\alpha_3 o$) can be considered to equal zero.

6. EXPERIMENT

To quantify the accuracy of point cloud after georeferencing, five monitoring points (numbered P5 to P9) are employed. These points are luminous stickers which can be acquired automatically by Cyclone software, pasted on the wall (Fig. 1). On the other hand, the georeferencing points are integration of TLS HDS target and GNSS antenna, named in this paper as TLS_GNSS target (Fig. 2). TLS model Leica HDS 3000 and GNSS model Leica GS10 were used. In addition, Real Time Kinematic (RTK) technique is suggested for GNSS measurements, position is an average of RTK measurements.

Two tests are conducted at five days apart. Each test has different constraints, as follows:

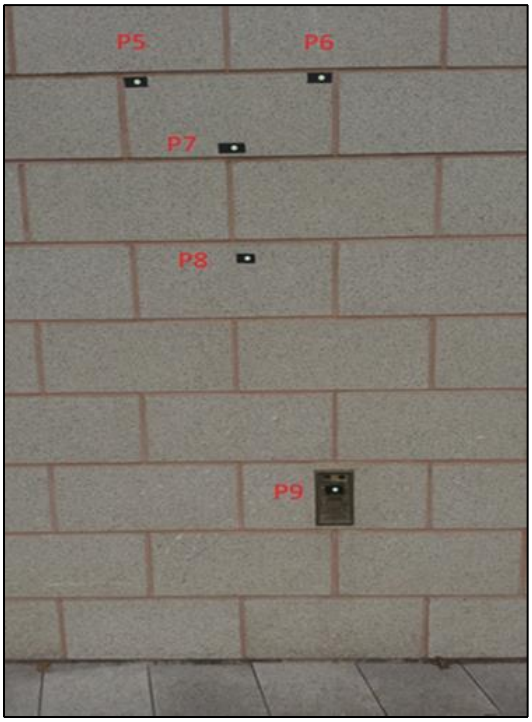


Fig. 1. Monitoring points.

Fig. 2. TLS_GNSS target.

6.1. First test

- TLS was set up at two arbitrary positions, maintaining the distance to monitoring points of about 10-15 m (Fig. 3).
- Four TLS_GNSS targets were used for the first and second scans. These targets were positioned (Fig. 3) according to some criteria:
  - ➢ Far from building to reduce the effect of multipath.
  - ➢ Distance between TLS and targets about 20m. This distance is the optimum distance for acquiring target automatically (Leica Geosystems, 2013).
  - ➢ Good geometry, different directions, and different elevations.
- For each scan position, TLS acquired TLS_GNSS targets as well as monitoring points.

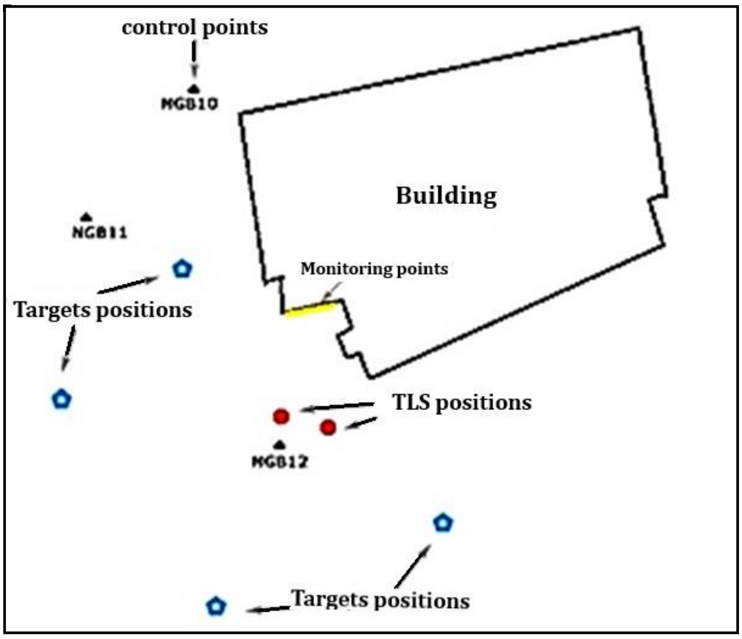


Fig. 3. Location of the first test.

6.2. Second test

- TLS was set up at three arbitrary positions disregard to the positions of the first test. However, the distance to monitoring points was maintained (between 10-15 m; Fig. 4).
- Eight TLS_GNSS points were used for the first scan, considering the criteria mentioned previously, to locate TLS_GNSS targets. Four TLS_GNSS points were used for the second and third scans.
- For each scan, TLS_GNSS targets and monitoring points were acquired.

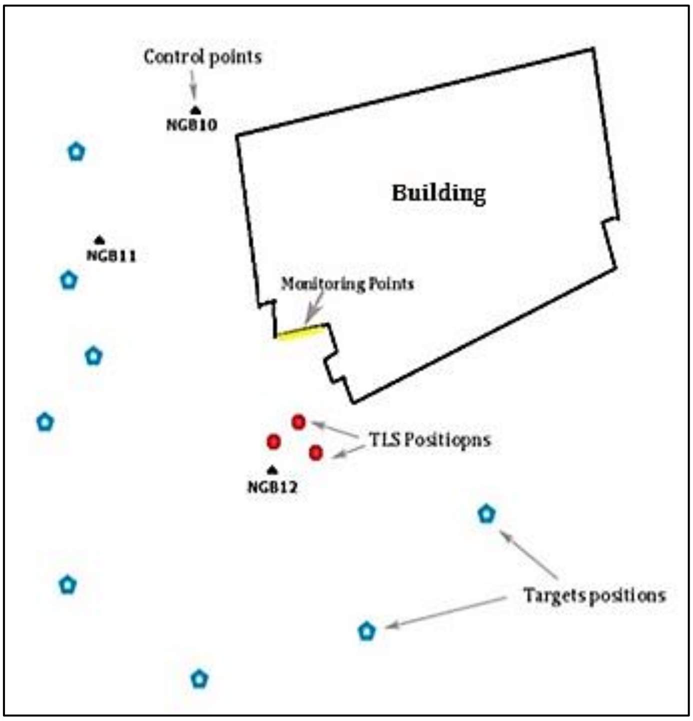


Fig. 4. Location of the second test.

6.3. Post-Processing

The Coordinates of TLS targets are the same as GNSS antenna, only corrected for elevation. The RTK technique is used to measure coordinates of these targets. The average of the recorded coordinates is used (Table 1 and Table 2)

For cloud points georeferencing, Cyclone7 software was used. In addition, MATLAB script is created as an alternative solution for Cyclone. The georeferencing is based on indirect technique with different constraints for each test. Table 3 shows six different alternatives for the first test and eight different alternatives for the second. The Root Square Errors (RSE) for fitting of different georeferencing are shown in Fig. 5 and Fig. 6 (Note: The MATLAB script is not designed to solve multiple scans, so there are no solutions for Re5 and Re6 by this script).

Table 1. Coordinates of TLS_GNSS targets in the first test.

No	Easting (m)	Northing (m)	Elevation (m)	Easting StDv (m)	Northing StDv (m)	Elevation StDv (m)
1	454916.897	339663.352	31.345	0.002	0.002	0.006
2	454897.972	339675.336	31.595	0.002	0.004	0.006
3	454901.655	339693.091	32.345	0.004	0.004	0.012
4	454907.881	339694.982	31.763	0.013	0.005	0.011

Table 2. Coordinates of TLS_GNSS targets in the second test.

	Easting (m)	Northing (m)	Elevation (m)	Easting StDv (m)	Northing StDv (m)	Elevation StDv (m)
1	454920.2	339669.01	31.210	0.002	0.002	0.005
2	454917.1	339658.08	31.414	0.003	0.002	0.006
3	454898.3	339675.31	31.697	0.002	0.003	0.009
4	454895.5	339689.36	31.766	0.004	0.004	0.015
5	454902.3	339693.18	32.279	0.009	0.010	0.017
6	454886.2	339697.39	31.538	0.004	0.004	0.013
7	454893.0	339704.48	32.421	0.004	0.006	0.013
8	454893.9	339718.31	31.671	0.004	0.007	0.010

Table 3. Georeferencing alternatives with different constraints.

No	code	Details	Test
1	RE1	ScanWold1 with GNSS_TLS targets	Both first and second
2	RE2	ScanWold2 with GNSS_TLS targets	Both first and second
3	RE3	ScanWold1 with ScanWold2	Both first and second
4	RE4	RE3 with GNSS_TLS targets	Both first and second
5	RE5	RE1 with RE2	Both first and second
6	RE6	ScanWold1, ScanWold2 with GNSS_TLS targets	Both first and second
7	3 Scan	ScanWold1, ScanWold2, ScanWold3 with GNSS_TLS targets	second test only
8	8 GPS	ScanWold1 with 8 GNSS_TLS targets	second test only

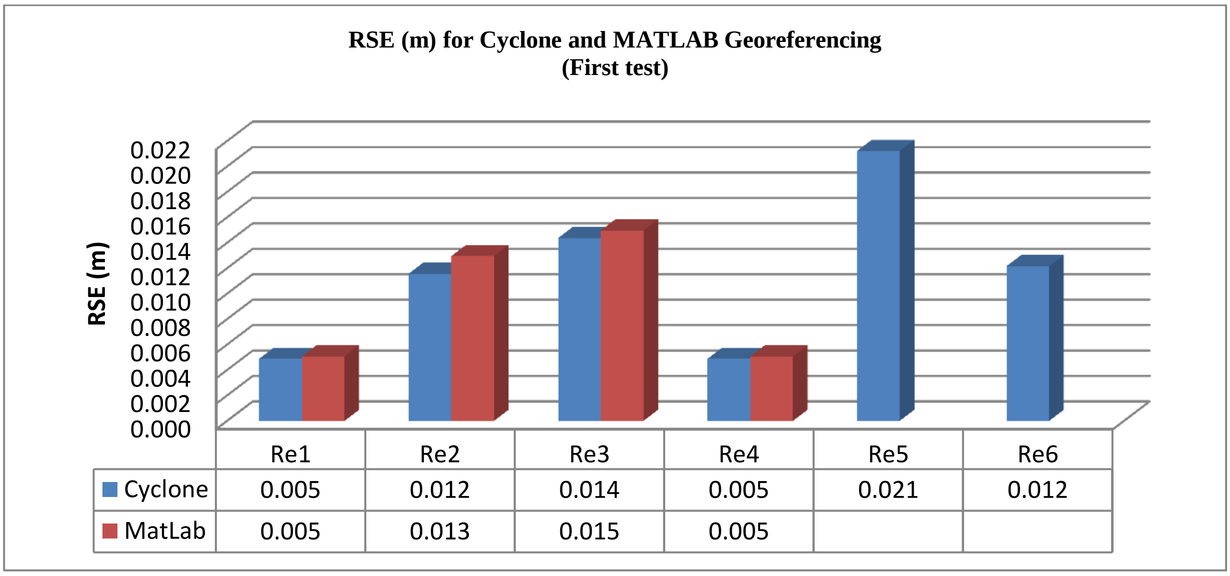
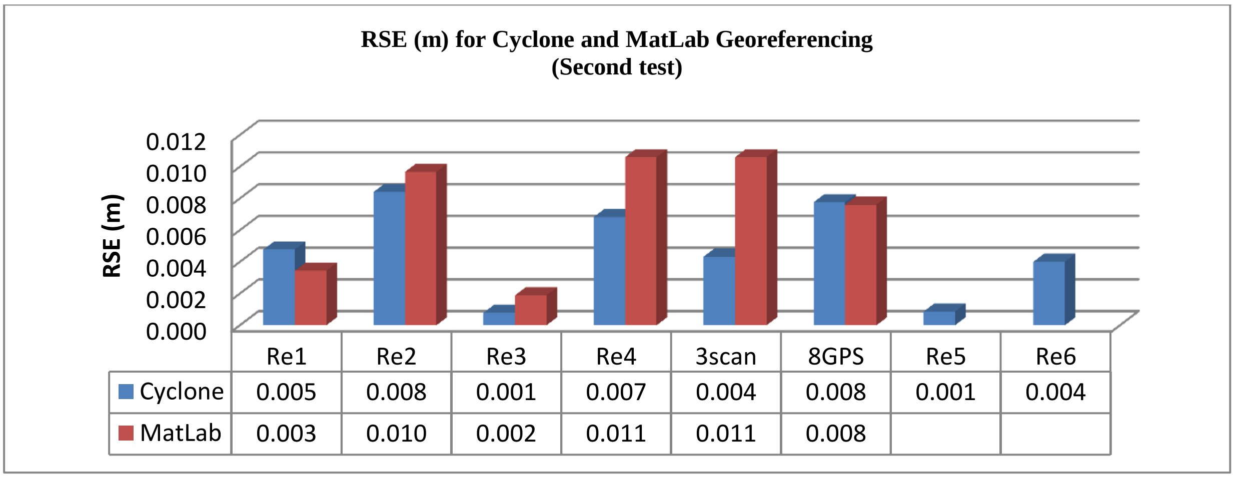


Fig. 5. Root Square Errors for different georeferencing alternatives for the first test.



	Re1	Re2	Re3	Re4	3scan	8GPS	Re5	Re6
Cyclone	0.005	0.008	0.001	0.007	0.004	0.008	0.001	0.004
MatLab	0.003	0.010	0.002	0.011	0.011	0.008		

Fig. 6. Root Square Errors for different georeferencing alternatives for the second test.

7. RESULTS AND DISCUSSION

In order to test the accuracy of different georeferencing alternatives, the coordinates of the monitoring points are measured in two tests and the differences are computed (Table 4 and Table 5)

It can be seen that the average is the most accurate solution for Cyclone results (Fig. 7, Fig. 8, and Fig. 9), likewise results of the MATLAB script (Fig. 10, Fig. 11, and Fig. 12). For Cyclone results, in average solution, the maximum differences reach to 4 mm, 7 mm, and 10 mm for easting, northing, and elevation respectively. While for MATLAB script, the maximum differences in average solution are 4 mm, 3 mm, and 13 mm for easting, northing, and elevation respectively. Therefore, it can be inferred that the results of Cyclone software are coincide with that of MATLAB script. In addition, the accuracy of monitoring points might consider better than GNSS accuracy. This may be because by averaging of multiple scans improved the whole accuracy of the point cloud.

Table 4. Monitoring points coordinate differences between two tests (using Cyclone).

Differences in Easting					
	P5	P6	P7	P8	P9
RE1	0.004	0.001	0.000	0.001	-0.002
RE2	0.007	0.004	0.003	0.001	-0.001
RE4	-0.002	-0.004	-0.005	-0.006	-0.010
RE5	0.005	0.002	0.001	-0.001	-0.003
RE6	0.004	0.002	0.001	0.002	0.001
Average	0.004	0.001	0.000	-0.001	-0.003
Differences in Northing					
	P5	P6	P7	P8	P9
RE1	0.004	0.005	0.005	0.006	0.003
RE2	0.011	0.009	0.007	0.008	0.006
RE4	0.001	0.000	-0.001	-0.002	-0.003
RE5	0.008	0.007	0.006	0.005	0.004
RE6_2	0.008	0.006	0.006	0.008	0.005
Average	0.007	0.006	0.005	0.005	0.003
Differences in Elevation					
	P5	P6	P7	P8	P9
RE1	-0.028	-0.032	-0.029	-0.028	-0.029
RE2	0.011	0.007	0.009	0.009	0.008
RE4	-0.023	-0.024	-0.023	-0.022	-0.022
RE5	-0.022	-0.026	-0.023	-0.024	-0.025
RE6	0.007	0.006	0.007	0.008	0.008
Average	-0.007	-0.010	-0.008	-0.008	-0.008

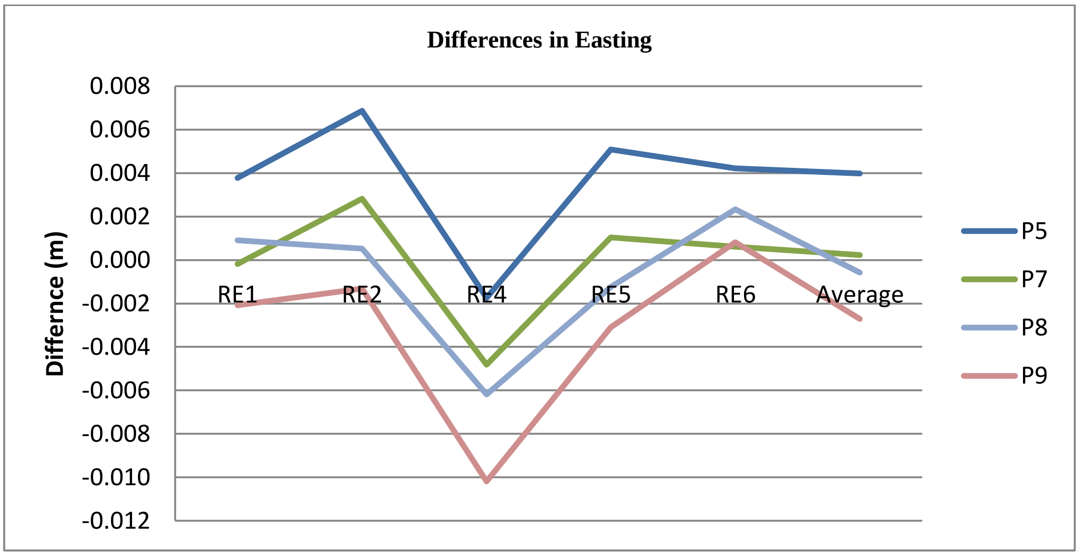


Fig. 7. Differences (m) in Easting coordinates for monitoring points (using Cyclone).

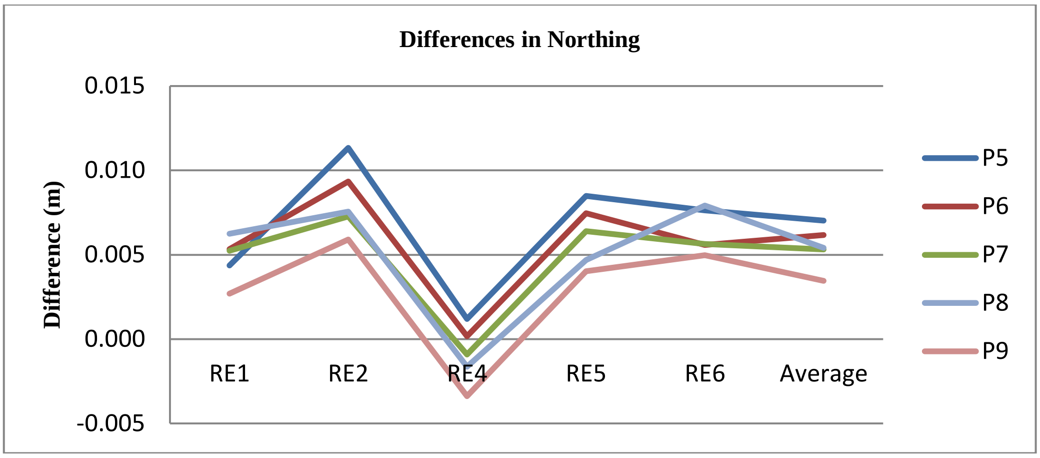


Fig. 8. Differences (m) in Northing coordinates for monitoring points (using Cyclone).

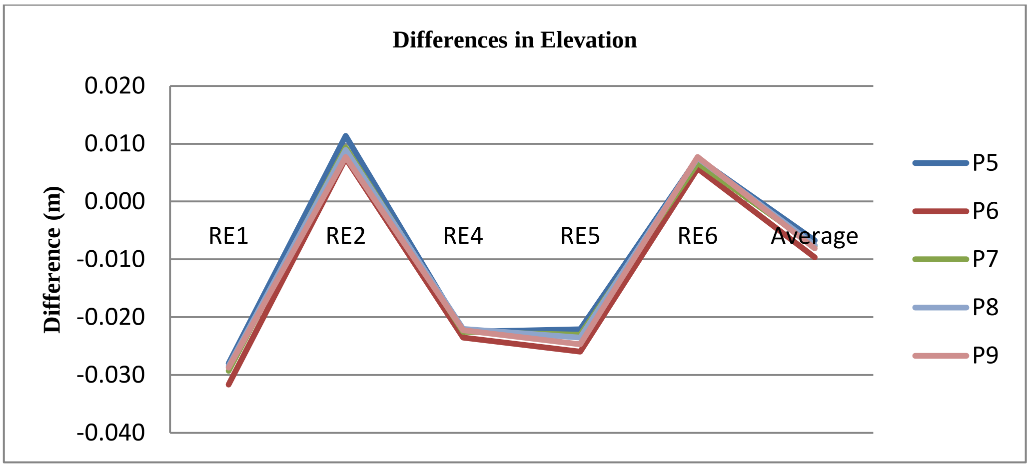


Fig. 9. Differences (m) in elevation for monitoring points (using Cyclone).

Table 5. Monitoring points coordinate differences between two tests (using MATLAB script).

			Differences in Easting		
	P5	P6	P7	P8	P9
Re1	-0.009	-0.010	-0.011	-0.010	-0.013
Re2	0.011	0.008	0.008	0.014	0.013
Re4	0.009	0.007	0.007	0.008	0.005
Average	0.004	0.003	0.001	0.004	0.002
			Differences in Northing		
	P5	P6	P7	P8	P9
Re1	-0.001	-0.002	-0.001	-0.002	-0.003
Re2	0.002	0.002	0.004	0.003	0.007
Re4	0.007	0.006	0.007	0.006	0.005
Average	0.002	0.002	0.003	0.003	0.003
			Differences in Elevation		
	P5	P6	P7	P8	P9
Re1	-0.008	-0.006	-0.007	-0.006	-0.001
Re2	0.054	0.054	0.055	0.055	0.057
Re4	-0.022	-0.021	-0.021	-0.020	-0.016
Average	0.008	0.008	0.009	0.010	0.013

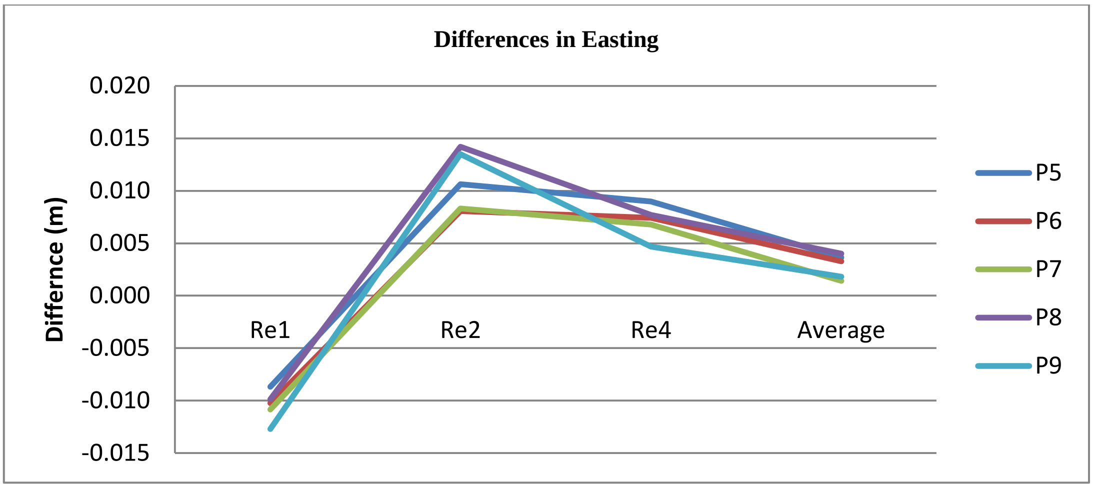


Fig. 10. Differences (m) in Easting coordinates for monitoring points (using MATLAB script).

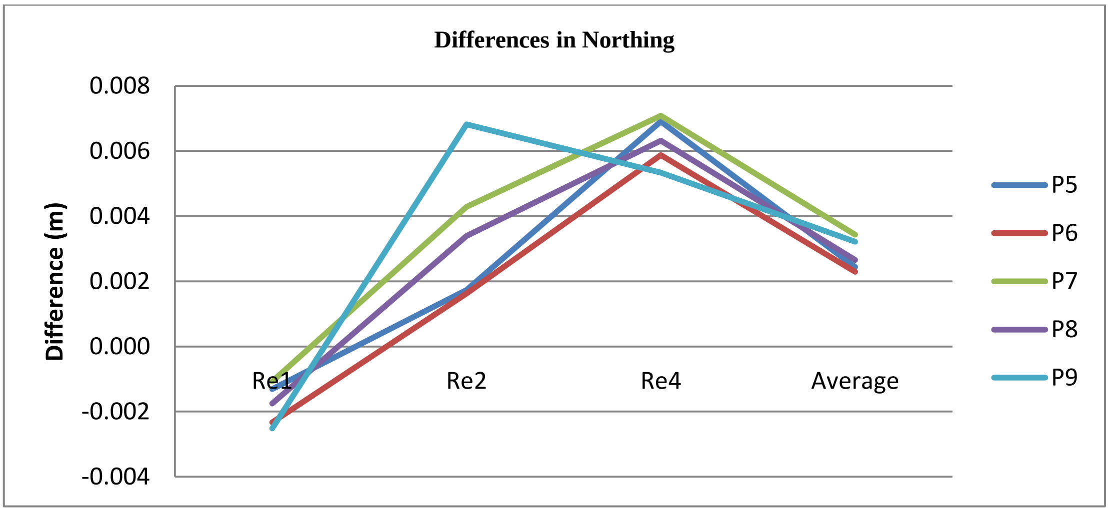


Fig. 11. Differences (m) in Northing coordinates for monitoring points (MATLAB script).

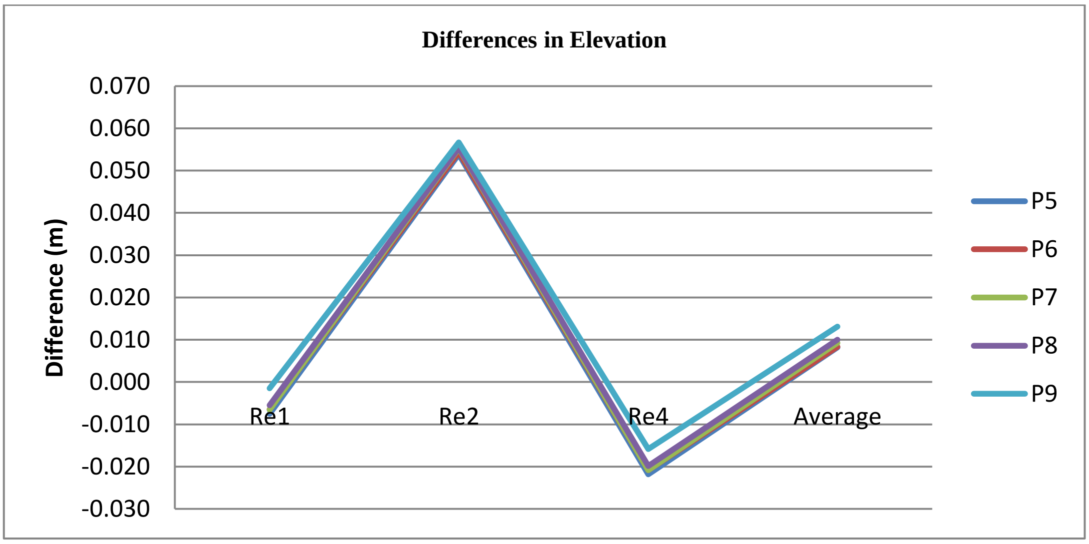


Fig. 12. Differences (m) in elevation for monitoring points (MATLAB script).

8. CONCLUSIONS

1. From the test, it can be concluded that there is no improvement when more GNSS points are added.
2. There is an improvement in accuracy when more scans are used. Therefore, it is suggested that more scans are made for areas of concern.
3. This technique can be used to measure absolute coordinates from indoor in addition to outdoor if TLS_GNSS targets are acquired through windows.
4. Obtaining absolute coordinates offers integration and comparison with other monitoring techniques.
5. In indirect georeferencing, error from the setup of the TLS instrument, levelling and centering, will not affect the final accuracy. However, levelling instrument will reduce unknown in rotation matrix; rotation around X-axis and Y-axis will be zero (α_1=0, and α_2=0).
6. To reach the required sub-centimeter accuracy, 30 minutes is enough for GNSS points.

9. ACKNOWLEDGEMENTS

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