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Improvement in measurement accuracy for hybrid scanner

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Abstract. The capability to provide dense three-dimensional (3D) data (point clouds) at high speed and at high accuracy has made terrestrial laser scanners (TLS) widely used for many purposes especially for documentation, management and analysis. However, similar to other 3D sensors, proper understanding regarding the error sources is necessary to ensure high quality data. A procedure known as calibration is employed to evaluate these errors. This process is crucial for TLS in order to make it suitable for accurate 3D applications (e.g. industrial measurement, reverse engineering and monitoring). Two calibration procedures available for TLS: 1) component, and 2) system calibration. The requirements of special laboratories and tools which are not affordable by most TLS users have become principle drawback for component calibration. In contrast, system calibration only requires a room with appropriate targets. By employing optimal network configuration, this study has performed system calibration through self-calibration for Leica ScanStation C10 scanner. A laboratory with dimensions of 15.5m x 9m x 3m and 138 well-distributed planar targets were used to derive four calibration parameters. Statistical analysis (e.g. t-test) has shown that only two calculated parameters, the constant rangefinder offset error (0.7mm) and the vertical circle index error (-45.4") were significant for the calibrated scanner. Photogrammetric technique was utilised to calibrate the 3D test points at the calibration field. By using the test points, the residual pattern of raw data and self-calibration results were plotted into the graph to visually demonstrate the improvement in accuracy for Leica ScanStation C10 scanner.

1. Introduction

For some applications such as industrial measurement, deformation survey, reverse engineering and structure monitoring, accuracy has become an important issue. Most of the cases, the accuracy required is at millimetre level. In geomatic jargon, the selection of measurement techniques can determine the range of accuracy that will be achieved.

According to Luhmann [1], there are several measurement techniques that are able to provide accuracy less than millimetre (e.g. interferometry and industrial metrology). Though the achievable accuracies are adequate the price of the instruments used are quite expensive. As mentioned in González-Jorge et al. [2], the used of industrial metrology (e.g. coordinate measuring machines) is not suitable for economical investments, which lead them to evaluate the others measurement techniques (e.g. photogrammetry and terrestrial laser scanning). Results from their study have indicated the both evaluated techniques are significant for the industrial measurement.

With the speed and accuracy offered by TLS, this instrument has widely used for many purposes including for accurate 3D applications. For instance, Timothy et al. [3] have implemented TLS measurement for tunnel deformation survey. Results obtained from their study have shown that accuracies achieved are within tolerance even in the difficult field conditions of a railway tunnel. For another example, Delčev et al. [4] have employed geodetic method for fuel tank form inspection

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which required the measurement uncertainty of 1mm. The capability of TLS to provide dense 3D data has made it applicable in this high accuracy application to minimizing the interpolation errors between points surveyed by others high precision geodetic methods.

However, similar to other geomatic instruments, TLS has to be investigated and calibrated regarding instrumental and non-instrumental errors. This calibration procedure is necessary to model those systematic errors and subsequently can be applied to the raw data, in order to improve the accuracy. As discussed by Reshetyuk [5], there are many error sources to be modelled in TLS measurement. Two approaches available to investigate those errors, either separately (component calibration) or simultaneously (system calibration) based on statistical analyses. Though, due to the difficulty to afford the requirements of special laboratories and tools to performed component calibration [6], thus it is only implemented by academicians and manufacturers. Even it is applicable to investigate systematic errors but most of the component calibration was used to identify the best-suited applications of the calibrated TLS and also to compare the performance of TLS from different manufacturers. In contrast, system calibration only requires a room with appropriate targets to determine all significant systematic errors [5,7,8]. As a result, system calibration can be considered as more appropriate comparing to component calibration for investigation of systematic errors.

In this study, point-based self-calibration was adapted to investigate systematic errors for the hybrid scanner (Leica ScanStation C10). To evaluate the significant of self-calibration to improve the accuracy, 15 test points were established via photogrammetry technique at the calibration field. Those test points then were employed as benchmark to investigate the discrepancy obtained from TLS raw data and calibrated data, which afterward indicates the reliability of calibration procedure to improve the accuracy of TLS data.

2. Classification of terrestrial laser scanner

According to Reshetyuk [5], there are three classifications of TLS based on field of view (FOV): 1) camera scanner; 2) hybrid scanner; and 3) panoramic scanner. Camera scanner uses oscillating mirrors to deflect the laser beam about the horizontal and vertical axes of the scanner. The scanning head remains stationary during scanning process. It carries out the distance and angle measurement over a much more limited angular range and within a specific FOV. Hybrid scanner has the horizontal FOV of 360° and limited vertical FOV. This scanner employs the oscillating or rotating polygonal mirrors to deflect the laser beam in vertical and horizontal axes. With aid of servomotor, hybrid scanner is capable of rotating by a small step around the vertical axis (horizontally). It works by scanning the vertical profile using the mirror, and this step is repeated around the vertical axis until the scanner rotates for 360°. Monogon mirror used in panoramic scanner has improved the vertical FOV compared to hybrid scanner. Using the same mechanism as hybrid scanner which is based on servomotor, this scanner is also capable of providing 360° horizontal FOV. These advantages (360° horizontal FOV and nearly the same for vertical FOV) has made panoramic scanner very useful for indoors scanning.

3. Geometric model for self-calibration

As discussed earlier, raw data measured by TLS are in spherical coordinates system which consisted of range, horizontal direction and vertical angle. Therefore, the observations can be corrected by augmented the systematic error correction into functional model as follows [7]:

$$\text{Range, } r = \sqrt{x^2 + y^2 + z^2} + \Delta r \quad (1)$$

$$\text{Horizontal direction, } \varphi = \tan^{-1}\left(\frac{x}{y}\right) + \Delta\varphi \quad (2)$$

$$\text{Vertical angle, } \theta = \tan^{-1}\left(\frac{z}{\sqrt{x^2 + y^2}}\right) + \Delta\theta \quad (3)$$

Where r , φ and θ are spherical coordinates of point in scanner space (represent by range, horizontal direction and vertical angle, respectively); x , y , z are Cartesian coordinates of point in scanner space;

Δr , $\Delta\phi$, $\Delta\theta$ are the additional systematic error model for range, horizontal direction and vertical angle, respectively.

According to Lichti [8], the systematic error models can be classified into two groups, physical and empirical parameters. The first group can be considered as basic calibration parameters which are derived from the total station systematic error models. The other group of error models is not necessarily apparent and may be due to geometric defects in construction and/or electrical cross-talk and may be system dependent. Focusing to first group of systematic error models, this study has employed the most significant errors model as applied by Reshetyuk [5] for hybrid scanner which includes constant rangefinder offset error (a_0), collimation axis error (b_0), trunnion axis error (b_1) and vertical circle index error (c_0).

In order to perform self-calibration bundle adjustment, values of x , y and z in equation (1) need to be substituted by the rigid-body transformation equation in order to express the original laser scanner observations as function of the position and orientation of the laser scanner in a global coordinate system [9].

4. Methodology

4.1. Preparation of test points

In order to investigate the significant of self-calibration to improve the accuracy of TLS data, photogrammetry technique was utilised to establish fifteen test points (figure 1). As mentioned by Luhmann et al. [1], industrial or close range photogrammetry can provide less than millimeter accuracy, which has justified this measurement technique to be selected for determination of true values for those test points.

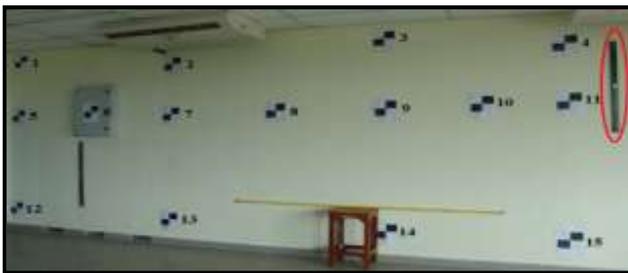


Figure 1. Test points established at calibration field.



Figure 2. Calibration of Sony DSC F828 camera.

In this study, Sony DSC F828 digital camera was employed to capture the images of test points. As a routine procedure, the camera should be calibrated before can be used for 3D measurement purposes. Figure 2 has shown the calibration procedure carried out for digital camera Sony DSC F828 and the processing of the calibration parameters was made with the aid of Photomodeler V5.0 software. To evaluate the accuracy of 3D coordinates of test points whether good enough to be considered as true value, several scale bars were positioned at the measurement field. One of the scale bar with red ellipse as depicted in figure 1 is used to investigate the accuracy of 3D test points yielded from photogrammetry technique.

To ensure those test points can be used to evaluate the accuracy of TLS raw data and calibrated data, fourteen independence vectors were generated. By comparing the vectors obtained from TLS (both raw and calibrated data) with photogrammetry data (considered as true value), the standard deviation of TLS data can be statistically calculate. Improvement in accuracy achieved from raw to calibrated data can indicate the significant of self-calibration to the scanner as well as the parameters yielded from reduced number of scan stations.

4.2. Self-calibration of hybrid scanner (Leica ScanStation C10)

As depicted in figure 3, a self-calibration has been established in a laboratory with dimensions 15.5m (length) x 9m (width) x 3m (height). There are 138 planar targets have been distributed on the four walls and ceiling based on conditions stated by Lichti [7]. Seven scan stations were established to capture the targets. As shown in figure 3, five scan stations were located at the each corner and centre of the room. The other two were positioned close to the two corners and the scanner orientation were

manually rotated 90° from scanner orientation at the same corner. In all cases the height of the scanner was midway between the floor and the ceiling.

In this experiment, scan resolution was set to the medium resolution since it is sufficient for Cyclone software to determine centroid of the targets except for those which have high incidence angle. After scanning process completed, a bundle adjustment was performed with precision setting based on the accuracy of the scanner which are 4mm for distance and 12" for both angles measurement. After 2 iterations, the bundle adjustment process converged.

To evaluate the effectiveness of calculated calibration parameters for the calibrated scanner, determination of significant parameters is very crucial. This procedure was performed by implementing the statistical analysis known as t-test [10].

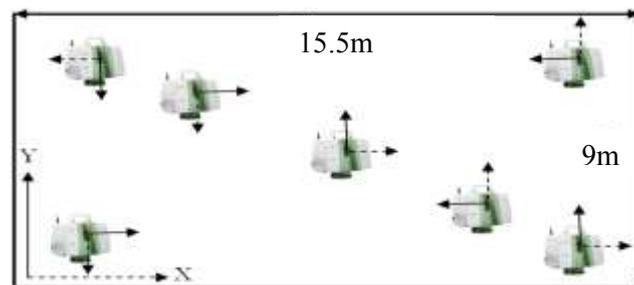


Figure 3. Scanner locations during self-calibration.

4.3. Evaluation of calibrated data

Having the significant value calculated for the calibration parameters, that information is applied to the raw data in order to remove the systematic errors which finally yield the calibrated data. With the aid of independence vectors established using photogrammetry technique, the accuracy of raw and calibrated data can be statistically calculate. This is performed by computing the discrepancy between true values of the vectors and values from both raw and calibrated data. Results obtained indicate the significant of self-calibration for the TLS measurement.

5. Results and analyses

Using a calibrated Sony DSC F828 digital camera and Photomodeler V5.0 software, fifteen accurate test points were successfully produced. According to table 1, average precision for all test points are below than 1mm and root mean square (RMS) of residuals are less than 0.5 pixels. Size for each pixel is equal to 0.0027mm, which means that maximum RMS residuals, is only 0.0014mm. To finalise the accuracy achieve for all test points, comparison have been made between true and measured values of scale bar (red circle) as shown in figure 1. The scale bar analysis has indicated that test points produce via photogrammetry technique have 0.06mm accuracy which is appropriate to be considered as true values in this study.

Table 1. Results for test points obtained from Photomodeler V5.0 software.

Test Points	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
X Precision (mm)	0.5	0.4	0.5	0.6	0.4	0.3	0.4	0.4	0.5	0.5	0.6	0.5	0.4	0.5	0.7
Y Precision (mm)	0.7	0.3	0.4	0.4	0.4	0.3	0.3	0.3	0.3	0.3	0.3	0.6	0.4	0.7	0.5
Z Precision (mm)	1.4	0.9	0.8	0.9	1.3	0.9	0.8	0.7	0.7	0.7	0.8	1.4	0.9	1.6	1.0
RMS Residual (pixels)	0.4	0.3	0.3	0.3	0.2	0.2	0.3	0.2	0.3	0.3	0.4	0.1	0.5	0.2	0.5

Due to the limitation of hybrid scanner as discussed in Lichti et al. [11], which is not applicable for identification of systematic errors via residual patterns, then statistical analysis has been used to verify the significant of calculated calibration parameters (CPs). Table 2 below presents the root mean square (RMS) of residuals for each observable group for the cases without and with self-calibration.

Table 2. RMS of residuals from the adjustments without and with systematic error models.

Observable	Range (mm)	Horizontal direction (")	Vertical angle (")
RMS (without)	2.3	47.5	18.4
RMS(with)	2.3	47.5	18.2

There is no change for range measurement and only a slight improvement is gained by adding CPs for the vertical angles measurement, which is expected since the magnitude of the CPs are very small as shown in table 3.

Table 3. Calibration parameters and their standard deviation.

Calibration Parameters	$a_0 \pm \sigma_{a_0}$	$b_0 \pm \sigma_{b_0}$	$b_1 \pm \sigma_{b_1}$	$c_0 \pm \sigma_{c_0}$
Values (mm/")	0.7 ± 0.2	-2.9 ± 43.7	10.7 ± 17.8	-45.4 ± 12.9

To examine the significant of the calibration parameters to the observations, all CPs were statistically tested using t-test. The null hypothesis, H_0 , of the test is the parameter is not significant while alternate hypothesis indicate that parameter is significant. Using 95% of confidence level, the critical value for 't' is 1.645 and the results of the test are shown in table 3.

Table 4. Significant test for calibration parameters.

Calibration parameters	Calculated 't'	Results
Constant rangefinder offset error (a_0)	3.5	Significant
Collimation axis error (b_0)	0.066	Not Significant
Trunnion axis error (b_1)	0.601	Not Significant
Vertical circle index error (c_0)	3.519	Significant

Results in table 4 show that null hypothesis was rejected for parameter of constant (a_0), and vertical circle index (c_0) errors. This indicates that those parameters are significant. For the collimation axis (b_0) and trunnion axis (b_1) errors, the null hypothesis has been accepted. In this study, only the significant errors were applied to the raw data to ensure the improvement in accuracy for the calibrated data.

By applying significant systematic errors to the raw data (test points), values of new fourteen vectors were calculated from raw and calibrated data. These values then were subtracted to the true values (obtained from photogrammetry measurement technique). To visualize the improvement in accuracy between raw and calibrated data, those subtracted results were translated into a graph as shown in figure 4, as well as true values for all vectors also have been attached.

According to the results shown in figure 4, even the accuracy discrepancies between raw and calibrated data are very small, but it still indicates improvement in accuracy. Based on these comparison values, statistical calculation has been made and the results shows that raw data has 1.9mm accuracy while calibrated data has 1.7mm accuracy. This accuracy improvement is equal to 10.5%, which has shown the important of calibration for TLS measurement especially for the applications that require high quality data.

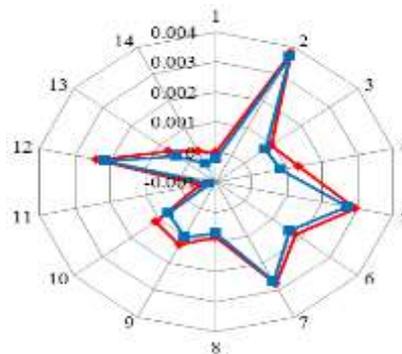


Figure 4. Accuracies comparison for raw (red) and calibrated data (blue).

6. Conclusions

A self-calibration of the Leica ScanStation C10 has been conducted over a dense 3D target field (138 well-distributed targets observed from 7 scanner stations). The adjustment results have been evaluated through statistical analysis procedures. The magnitude of calculated calibration parameters are very small which has caused the differences between RMS of residuals for adjustment without and with self-calibration are also small. Using the t-test statistical analysis, significant tests were performed and the results have shown that two (a_0 and c_0) of four calibration parameters are significant. To investigate the important of calibration for TLS measurement, this study established fourteen vectors using photogrammetry. The results obtained from comparing the true values of vectors with raw and calibrated data were used to statistically compute the accuracy of each data. With 10.5% improvement in accuracy, self-calibration was mathematically proven as significant procedure to enhance the quality of TLS data.

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