Terrestrial Laser Scanner Self-Calibration: Quantitative Evaluation of Minimum Network Configuration

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Abstract. Two approaches available for performing self-calibration are: 1) point-based and 2) feature-based. The reliance on planes in the feature-based approach is a restriction to the aim of finding a suitable approach for on-site calibration. Also, the requirement for a strong network configuration in point-based self-calibration has made it difficult to implement on-site. The aim of this study was to investigate the suitability of lowering the network configuration requirements. Investigations of minimum network configurations were carried out by analysing minimum dimension of real-world plane on which targets are distributed. Through network analysis, standard deviation and plotted error ellipses will be used to determine the reliability of each configuration during minimising network experiment. The outcomes of this study will benefit to TLS practitioner to ensure that the employed instrument reliable to yield quality data.

1. Introduction

Data quality assurance or calibration procedure is crucial to ensure on the quality of data delivered. As in the case of terrestrial laser scanner (TLS), it gathers millions of point clouds per second with high-accuracy measurement. Most of high-accuracy applications of TLS involve with deformation analysis, industrial measurement, reverse engineering, etc. [1-3]. This obtained data is quite fragile in terms of quality and expensive in value. In order to guarantee the integrity of data yielded, a prompt and regularly check for health level of the instrument is compulsory and as for TLS, self-calibration bundle adjustment was appropriate method for investigation of systematic errors. There are two (2) available approaches for this calibration method which are point-based and feature-based.

According to study on feature-based approach conducted by [4], it is found that the residual patterns from the adjustment was considerably differ from functional model which result in complication on identification of systematic errors. Besides, the requirement of planarity surface has limited the feature-based self-calibration for laboratory implementation only. The emerging of feature-based approach was to resolves on the main drawback of point-based approach that requires a huge number of target distributions. However, [5] have done a study on the optimum network configurations for point-based approach but also restricted to indoor applications. Other than that, [6] has performed self-calibration in both environments (indoor and outdoor) and reported that the external measurement conditions may affect the calibration parameters and not only influenced by the
instrument itself. These external measurement conditions may vary by measurement range, target design, angle between laser beam and object surface, and also the chosen angular resolution.

Hence, this result supported the necessity of on-site self-calibration and the term on-site itself refers to the calibration procedure that should be handled in the same environment as real situation. Therefore, a flexible on-site calibration procedure has become mandatory in order to be suit as an actual measurement condition and meet the true requirements of the job specification. For such purpose, this study focused on quantitative investigations of minimum network configurations for point-based self-calibration with the employment of phase-based (FARO Focus 3D) scanner in simulation. To ensure a thorough assessment, this pre-analysis experiment was performed via dimension reduction of real-world plane on which targets are distributed. Through network analysis, standard deviation and plotted error ellipses were utilised to determine the reliability of each configuration during minimising network procedure.

2. Operating principle of point-based self-calibration
Due to the very limited knowledge regarding the inner functioning of modern terrestrial laser scanners, thus, most of the researchers have made assumptions about the suitable error model for TLS based on errors involve in reflectorless total stations [7]. Since the data measured by TLS are range (r), horizontal direction (ϕ), and vertical angle (θ), hence, the equations (2.1) and (2.2) are augmented with systematic error correction model, respectively as follows [8]:

\[
\begin{align*}
\Delta r &= \text{Systematic error model for range.} \\
\Delta \varphi &= \text{Systematic error model for horizontal direction.} \\
\Delta \theta &= \text{Systematic error model for vertical angle.}
\end{align*}
\]

Equation (2.1) above represents the expression of conversion from cartesian to spherical coordinates system for each element of range, horizontal direction, and vertical angle. In contrast, equation (2.2) below shows the formulation of conversion from spherical to cartesian coordinates system.

\[
\begin{align*}
x &= (r - \Delta r) \times \cos(\varphi - \Delta \varphi) \times \cos(\theta - \Delta \theta) \\
y &= (r - \Delta r) \times \sin(\varphi - \Delta \varphi) \times \cos(\theta - \Delta \theta) \\
z &= (r - \Delta r) \times \sin(\theta - \Delta \theta)
\end{align*}
\]

As employed in [9] and [5], this study focusing on the most four (4) significant systematic errors impaired in TLSs measurement, e.g. constant error (a₀), collimation axis error (b₀), trunnion axis error (b₁), and vertical circle index error (c₀) Due to the use of panoramic scanner (FARO Focus 3D) in this study, the mathematical model for horizontal direction and vertical angle in equation (2.1) should be modified as follows:

\[
\varphi = \tan^{-1}\left(\frac{x}{y}\right) - 180° + b_0 \sec \theta + b_1 \tan \theta
\]
\[ \theta = 180^\circ - \tan^{-1}\left(\frac{x}{\sqrt{x^2 + y^2}}\right) + c_0 \]  

(2.4)

### 3. Experiments

With the determination to yield a calibration approach that is convenient to be employed at working site area, this study was planned to innovates on the optimal network configurations made by Abbas et al. [5] with respect to the dimension of surfaces (walls) for distribution of targets. As refer to that optimal configuration, the size of surfaces required are 3.0 m (height) × 9.0 m (width) which complicate to be projected as calibration frame for outdoor implementation and eventually resulting in restricted to indoor use only. Thus, this pre-analysis study performed shrinkage process on the surfaces dimension has been designed by gradually ten (10) percent reduction, which leads to up to sixty (60) percent of minimisation. The design of this dimension reduction was applied on both two (2) opposite walls which represents by a number of targets (Figure 1). Afterwards, the actual measured data of this reduced dimension were used for the simulation. Each reduction data was then undergoing coordinate transformation procedure using Australis software which yields adjusted coordinates together with its standard deviation values.

![Figure 1. Reduction of network configuration based on dimension to distribute targets.](image)

Later, the simulation by error ellipses analysis was done using MATLAB programming language software in order to scrutinise and portray on consistency and stability of the reduction process. Computation of error ellipses can be obtained from covariance matrix using formulation as shown in equation (3.1) below [10].

\[ Q_{xx} = \sigma_0^2 (A^TWA)^{-1} \]  

(3.1)

where:
- \( Q_{xx} \) = Covariance matrix.
- \( \sigma_0^2 \) = Reference variance.
- \( A \) = Jacobian matrix.
- \( W \) = Weight matrix.

Error ellipses are more reliable to illustrate the quality of adjusted data in graphical presentation rather than standard deviations derived from linear regression which only represent the numerical value. Besides, major advantage of error ellipses is that they offer a method in making visual comparison of the relative precisions upon scanned data which gained from two (2) different scan stations. By viewing the shapes, sizes and orientations of error ellipses, various data can be compared.
directly and meaningfully. Equation (3.2) describe in detail the algorithms used to yield the parameters required for plotting error ellipses [10].

\[
\tan 2t = \frac{2q_{xy}}{q_{yy} - q_{xx}} \\
q_{uu} = q_{xx} \sin^2(t) + 2q_{xy} \cos(t) \sin(t) + q_{yy} \cos^2(t) \\
q_{vv} = q_{xx} \cos^2(t) - 2q_{xy} \cos(t) \sin(t) + q_{yy} \sin^2(t)
\] (3.2)

where:
\( t \) = Orientation of error ellipse.
\( q_{uu} \) = Semi major of error ellipse.
\( q_{vv} \) = Semi minor of error ellipse.
\( Q_{xx} \) = \[
\begin{bmatrix}
q_{xx} & q_{xy} \\
q_{xy} & q_{yy}
\end{bmatrix}
\]

With the aid of pre-analysis experiment, the design quality of this surface dimension reduction can be mathematically (based on the computed precision) and graphically (via plotted error ellipses) assessed.

4. Results and analyses
The pre-analysis study on reduction of surfaces dimension with utilisation of error ellipses for analysis was deliberately made in order to investigate the ability to perform the reduction process. A total of seven (7) dimensions (including optimal dimension that acts as a benchmark, i.e. Set A) were produced to represent samples of calibration frame that would be used to distribute the targets. Each dimension reduction was evaluated based on their standard deviation values illustrated by the error ellipses. Figure 2 below shows the plotted error ellipses of all reductions from optimal to sixty (60) percent minimisation. The pattern or size of error ellipses has slightly enlarged in parallel with every contraction of dimensions as they gradually become weak in network strength. However, the results indicate in graphically stable for this shrinkage process except those (error ellipses) experienced with elongation on \( x \) and \( y \) axes, which might be due to distribution of points and also the high incidence angle factors [11].

![Figure 2. Error ellipses related to dimension reduction.](image-url)
Furthermore, through the integration of all standard deviations depicted by multi-line graph in figure 3 below, it can be seen that those sixteen (16) targets pasted on every dimension reduction (respectively represented by Set A until Set G) have yielded a uniform trend which leads to similar pattern with each other.

![Figure 3. Line graph of combined standard deviations.](image)

Moreover, figure 4 shows the bar chart of combined targets errors to numerically visualise and concretely support on the stability results yielded from the simulation for all dimensions reduction. Besides, they have relatively indicated on balanced fluctuations of combined targets errors for the whole configurations set and dramatically present the smallest value of 0.00864 in Set G (for 60% reduction, i.e. 3.6 m (width) × 1.2 m (height) over the minimisation process. This progress has directly convinced and positively stipulate towards the approval to perform reduction on surfaces size in network configuration of point-based self-calibration.

![Figure 4. Combined targets errors for each set of dimensions.](image)
5. Conclusions
With the aim to quantitatively examine the suitability of lowering network configurations for point-based self-calibration, this study has rigorously performed pre-analysis investigation with simulation of phase-based TLS. The experiment through contraction of surfaces dimension has positively indicates on the capability to reduce the size of real-world planes required, though there are some targets which represent the border of dimensions have slightly elongated. However, the results from combined standard deviations and combined targets errors have numerically and visually verify on approval of the proposed design. This conclusion is applicable for phase-based scanners. Further significant study via accuracy assessment with close-range photogrammetry technique is necessary to robustly proved towards the efficiency of the developed method.

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