Significance Study of Points and Line Constraints Adjustment for Static LIDAR Self-Calibration

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Abstract

Ensuring high-quality 3D data from terrestrial laser scanners (TLSs) requires meticulous calibration. While the current implementation of TLS point-based self-calibration often relies on precision-based methods without reference points, this study introduces accuracy-based approaches to TLS self-calibration. Using point-based and line-based constraints with reference points established via close-range photogrammetry (CRP), statistical analyses reveal that the line-based method significantly enhances accuracy by up to 60%, outperforming the point-based approach, which shows notable deviations. The evaluation focused on calibration parameters (CPs), standard deviation, residuals, and correlation coefficient. This study underscores the potential of accuracy-based approaches in enhancing TLS self-calibration, particularly using line-based constraints.

Keywords: TLS self-calibration; Close-range photogrammetry; Point-based constraint; Line-based constraint

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1.0 Introduction

In the rapidly evolving landscape of social and behavioural sciences, the demand for accurate 3D models has never been greater. These models are indispensable in critical fields such as urban planning, heritage preservation, infrastructure management, and environmental monitoring. They provide precise spatial data that not only informtheir decision-making but also enhances behavioural interventions and planning outcomes through a comprehensive understanding of physical environments (Aryan et al., 2021; Karataş et al., 2022; Y. Zhou et al., 2024). As the need for detailed and reliable 3D data grows, the methods for its acquisition must evolve to meet these demands.

Among the various methods for 3D data acquisition, terrestrial laser scanning (TLS) has emerged as a preferred choice due to its speed and accuracy in capturing detailed 3D information (Medić et al., 2021). TLS technology has revolutionized the way the physical surroundings are perceived and interacted with, offering unprecedented levels of detail and precision. However, despite the advancements in TLS technology, observations from terrestrial laser scanners (TLSs) remain susceptible to errors, including gross, random, and systematic errors that specifically impact the accuracy of measurements, and the reliability of the 3D models produced. Factors contributing to these errors include environmental conditions, sensor limitations, and calibration inaccuracies (Amer et al., 2018; Soudarissanane et al., 2011). Among the types of errors, systematic errors are particularly critical in TLS measurements because, unlike random errors that vary in an unpredictable manner, these errors consistently impact all measurements in the same way. This consistency introduces a persistent bias in the data, which means that inaccuracies in distance, angle, or position measurements are systematically repeated throughout the entire dataset. As a result, the 3D models created from such biased data may be subtly distorted, which can lead to misleading conclusions or ineffective decisions, especially in applications that demand high precision, like urban planning or infrastructure monitoring. Therefore, developing techniques to identify and correct these systematic errors is essential for improving the reliability and accuracy of TLS data. These systematic errors can be mitigated through appropriate calibration techniques, thereby significantly enhancing the overall quality of the 3D models.

In TLS, the raw observations consist of the range (r), horizontal direction (φ), and vertical angle (θ). To improve the accuracy of these measurements, it is essential to apply correction values for systematic errors. As noted by Lichti (2007), there are four significant systematic error models in TLS instruments that are crucial for enhancing measurement accuracy. This study will focus on these models, which are detailed as follows:

i. Systematic error model for range

$$\Delta r = a_0 \tag{1}$$

ii. Systematic error model for horizontal angle

$$\Delta\varphi = b_0 \sec\theta + b_1 \tan\theta \tag{2}$$

iii. Systematic error model for vertical angle

$$\Delta\theta = c_0 \tag{3}$$

Where,

a_0	=	Constant error
b_0	=	Collimation axis error
b_1	=	Trunnion axis error
c_0	=	Vertical circle index error

Practically, the procedure of current TLS point-based self-calibration only utilize precision-based methods, as no reference values were established. Although establishing reference points at calibration sites presents certain challenges, the comprehensive literature review in Section 2.0 has prompted the question: "Could the accuracy-based approach be effectively applied to TLS self-calibration to enhance the quality of TLS data?". Notably, this study defines accuracy-based approaches as those incorporating reference points to refine calibration and reduce systematic errors further. In response to this question, this study proposes an approach that not only integrates accuracy-based methods but also systematically compares these methods with current precision-based approaches. By applying reference points or known distances, the study seeks to introduce an alternative calibration methodology that is both innovative and effective. Therefore, this study aims to investigate the novel application of accuracy-based approaches in TLS self-calibration, utilizing two types of constraints: i) point-based, which involves the use of specific, known reference points, and ii) line-based, where known linear distances serve as calibration benchmarks. To achieve the aim of this study, the first objective is designed to evaluate the significance of both precision-based (current practice) and accuracy-based (proposed method) approaches within the point-based method. Whereas, the second objective investigates the effectiveness of the proposed line-based method using accuracy-based techniques, ensuring a thorough exploration of both methods and their contributions to enhancing TLS calibration outcomes. These dual objectives ensure a comprehensive assessment of accuracy-based calibration, providing clear insights into its advantages, limitations, and applicability across various scenarios.

By exploring these accuracy-based approaches, the study seeks to contribute to the ongoing efforts to improve the accuracy and reliability of TLS data, thereby enhancing the quality of 3D models used in various applications across social and behavioural sciences.

2.0 Literature Review

According to Abbas et al. (2015), TLS calibration represents a critical process aimed at identifying, modelling, and mitigating systematic errors that arise due to inherent sensor limitations or environmental conditions. This process involves capturing multiple scans from different positions or orientations and applying least squares adjustment (LSA) techniques to minimize measurement discrepancies, thereby ensuring that TLS data accurately represents the real-world environment. As illustrated in Figure 1, TLS calibration can be conducted through two primary approaches: component calibration and system calibration. Component calibration, as noted by Schulz (2007), requires specialized facilities to refine individual errors, while system calibration can be executed with minimal equipment through self-calibration, as described by Luhmann et al. (2006). TLS self-calibration can further be divided into point-based self-calibration and feature-based self-calibration. The latter utilizes object-related targets such as spheres, planar surfaces, and cylinders (Markiewicz et al., 2019). In contrast, point-based self-calibration employs 3D coordinates derived from the centroids of artificial targets, necessitating a robust network configuration to accurately quantify systematic errors (Medić et al., 2019). Given that feature-based methods rely on surfaces, this study focuses specifically on the point-based TLS self-calibration approach.

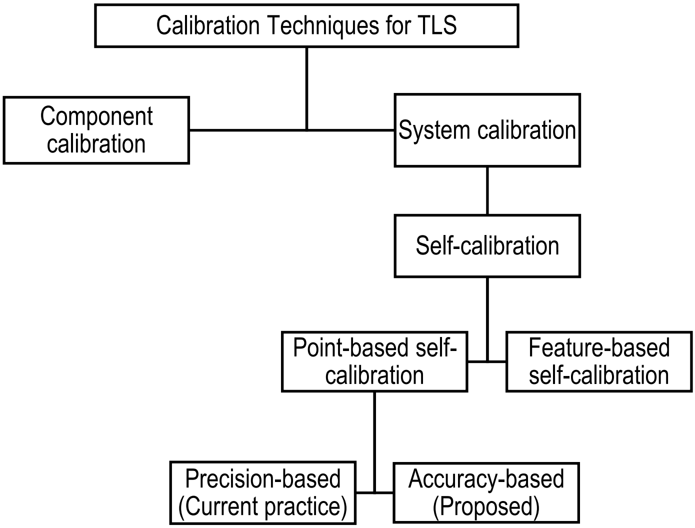

Figure 1: Calibration techniques for TLS

In the field of TLS point-based self-calibration, precision-based techniques are commonly adopted for their effectiveness and simplicity, as they eliminate the need for additional measurements to establish reference points (Abbas, 2015; Lichti et al., 2021; Qiao & Butt, 2023; T. Zhou et al., 2020). Consequently, the potential of accuracy-based approaches to enhance the quality of TLS-calibrated data remains underexplored, highlighting a gap in the current research literature. Despite the associated complexities, investigating accuracy-based methods is worthwhile, particularly in TLS applications where data quality is paramount. In fields such as photogrammetry and laser tracking, where accuracy-based calibration methods have been effectively employed, they have led to significant improvements in measurement precision and reliability.

For instance, El-Din Fawzy (2019) highlights that utilizing four control points on a camera calibration sheet, arranged at known distances from each other, helps to accurately determine camera intrinsic parameters, thereby ensuring the accuracy of the photogrammetric model. Similarly, Wiśniewski (2018) found that integrating a scale bar with a known reference length during laser tracker calibration significantly improved the system's accuracy, achieving an average measurement error of ±0.1 mm, well within the manufacturer's maximum permissible error (MPE). These examples illustrate the practical benefits of incorporating reference elements, which significantly enhance the derivation of CPs.

In conclusion, recent studies have shown that accuracy-based approaches can lead to more reliable and accurate calibration outcomes, especially when reference points are used. Building on these encouraging findings, this study aims to investigate the novel application of accuracy-based methods within TLS self-calibration. Should this study succeed, it could pave the way for further advancements in TLS calibration techniques, ultimately leading to improved performance and quality in 3D data acquisition. Moreover, such enhancements have the potential to make substantial contributions to the social and behavioural sciences by providing accurate spatial data that informs decision-making processes in various spatial data applications.

3.0 Methodology

This section outlines the methodology employed to ensure accurate and reliable results in the self-calibration of TLS. The selected approach is grounded in established practices in the field, which have been shown to enhance measurement accuracy significantly. The methodology encompasses the establishment of reference values (Section 3.1), the procedure of TLS self-calibration (Section 3.2), and the application of datum constraints in LSA (Section 3.3).

3.1 Establishment of reference values

To examine the applicability of accuracy-oriented approaches in TLS self-calibration, this study was conducted in a standard classroom located at the Star Complex, UITM Arau, Perlis. The classroom, as depicted in Figure 2, measures approximately 12 m (length) x 9 m (width) x 3 m (height), providing an ideal environment for testing due to its controlled setting and consistent geometry. Building on this, photogrammetry measurement was utilized to establish reference values for evaluating the results obtained from point-based and line-based constraints in accuracy self-calibration (ASC) methods due to its capability to achieve accuracy up to 1 mm (Luhmann et al., 2006).

This study conducted two measurements: TLS using a FARO Focus Premium scanner and CRP using a Nikon D7500 camera. To accommodate both measurement types, a specialized target was designed, as shown in Figure 3, to be compatible with both software systems to determine the target centroids: Cyclone for TLS data and Photomodeler Scanner for CRP data. Additionally, to ensure the accuracy of the CRP data, four strategically positioned scale bars were installed on each wall of the classroom, as indicated by the red and blue rectangles in Figure 2.

While the controlled indoor setting offers consistency for testing, it also presents a limitation. The results obtained may not fully capture challenges encountered in outdoor or more complex environments, such as varying lighting conditions, environmental disturbances (e.g., wind, vibrations), and uneven surfaces. These factors, which were not accounted for in this study, could affect the generalizability of the findings to real-world field conditions.

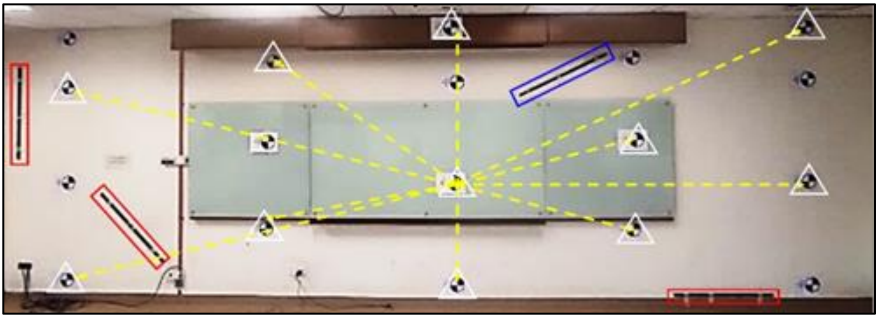

Figure 2: Ten independent vectors (yellow dashed line) established on Wall D with four scale bars.

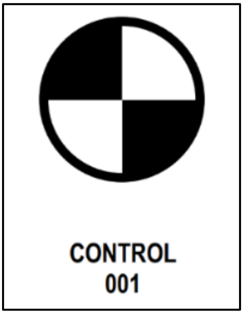

Figure 3: Specialized target with an outline of the region

3.2 Procedure of self-calibration

The self-calibration process for the Faro Focus Premium scanner in this study was meticulously designed to optimize error modelling and ensure reliable data quality. A total of 113 specialized targets were strategically placed throughout the scanning environment, specifically on all four walls and the ceiling of a classroom. This distribution pattern aimed to maximize the accuracy and robustness of the calibration process by creating a well-distributed network of points that the scanner could reference from multiple angles. Proper target placement not only enhances spatial coverage but also plays a critical role in error modelling, as suggested by Lichti (2007), who stressed the need for an adequate number of reference targets spread across scanned surfaces to achieve accurate self-calibration in TLS.

To strengthen the calibration accuracy further, the study incorporated geodetic network design principles, focusing on both zero-order design (ZOD) and first-order design (FOD) approaches as outlined by Reshetyuk (2009). The zero-order design (ZOD) approach, which is covered in detail in Section 3.3, involves establishing a stable datum or reference framework for the scan. Following ZOD, the first-order design (FOD) approach was applied, which emphasizes optimal positioning and orientation of the scanner to enhance data quality. Seven scan stations were set up within the classroom to ensure comprehensive spatial coverage, allowing for a thorough assessment of the scanner's self-calibration performance from multiple perspectives.

During each scan, the scanner was positioned equidistantly between the floor and ceiling, which helped reduce potential biases from uneven height differences. This setup ensured a balanced perspective for capturing targets on both the walls and ceiling, thereby enhancing the overall reliability of the calibration. Medium-resolution scans were chosen for all sessions to strike a balance between data accuracy and efficiency, allowing the scanner to capture fine details without creating excessively large datasets that would complicate processing. This approach enabled consistent and high-quality data collection, setting a strong foundation for the subsequent analysis of systematic errors and calibration accuracy.

3.3 Datum constraints in LSA

Least Squares Adjustment (LSA) is a well-established statistical technique that estimates unknown parameters by minimizing the sum of squared residuals, ensuring the model's parameters align as closely as possible with the observed data. In geodetic adjustments, datum constraints are employed to refine this process further. These constraints may fix the positions of certain control points or the orientation of the coordinate system. By applying datum constraints during the adjustment computation, the solution can be aligned with known reference values, thereby enhancing the accuracy and reliability of the TLS self-calibration process. To perform LSA, all observation equations are expressed in matrix form. According to Ghilani (2017), the minimised sum of the squared residuals is obtained using the matrices defined in Equation (4):

$$X = (A^T W A)^{-1} A^T W l \quad (4)$$

In equation 4, A is the matrix of coefficients derived from the linearized equations, W is the weight matrix for each observation, l is the vector of differences between observed and computed values, and X is the matrix of corrections applied to the approximate coordinates of the stations. To achieve the optimal solution, this adjustment process must be iterated until the corrections to the approximate coordinates become insignificant, due to the nonlinear nature of the equations involved in horizontal adjustments. Initially, the original form of matrix A is specified in Equation (5). However, to perform the constrained adjustment, the matrix A, as defined in Equation (5), requires modification.

$$n^{A}u = [A_{EO} \quad A_{CP} \quad A_{TG}] = \begin{bmatrix} A_{EO_1} & 0 & 0 & A_{CP} & A_{TG} \\ 0 & A_{EO_2} & 0 & A_{CP} & A_{TG} \\ 0 & 0 & A_{EO_0} & A_{CP} & A_{TG} \end{bmatrix} \tag{5}$$

In the current TLS self-calibration implementation, the precision-based approach applies minimal constraints by fixing the exterior orientation parameters for the first scanner station. Specifically, six elements of the exterior orientation (EO) are fixed, including three translation parameters (Tx, Ty, Tz) and three rotation parameters (Omega, Phi, Kappa). Therefore, based on the original form of the design matrix A, as shown in Equation (5), the application of minimal constraints is demonstrated through the modified matrices in Equations (6) and (7).

Removed

$$n^{A}u = \begin{bmatrix} A_{EO_1} & 0 & 0 & A_{CP} & A_{TG} \\ 0 & A_{EO_2} & 0 & A_{CP} & A_{TG} \\ 0 & 0 & A_{EO_0} & A_{CP} & A_{TG} \end{bmatrix} \tag{6}$$

$$n^{A}u = \begin{bmatrix} 0 & 0 & A_{CP} & A_{TG} \\ A_{EO_2} & 0 & A_{CP} & A_{TG} \\ 0 & A_{EO_0} & A_{CP} & A_{TG} \end{bmatrix} \tag{7}$$

Where,

n	=	Number of observations
u	=	Number of unknown parameters
A_{EO}	=	Design matrix for exterior orientation (EO) parameters
A_{CP}	=	Design matrix for calibration parameters (CP)
A_{TG}	=	Design matrix for targets (TG)

Focusing on implementing accuracy-based approaches in TLS self-calibration, this study examines both point-based and line-based constraints. The point-based constraint (ASC), as outlined by Ghilani (2017), involves applying minimal constraints by excluding exterior orientation (EO) and target reference points (TG) from the design matrix A as specified in Equation (8).

Removed Removed

$$n^{A}u = \begin{bmatrix} A_{EO_1} & 0 & 0 & A_{CP_1} & 0 & 0 & A_{TG_1} & 0 & 0 \\ 0 & A_{EO_2} & 0 & 0 & A_{CP_2} & 0 & 0 & A_{TG_2} & 0 \\ 0 & 0 & A_{EO_0} & 0 & 0 & A_{CP_3} & 0 & 0 & A_{TG_3} \end{bmatrix} \tag{8}$$

In contrast, the line-based constraint (ASC) is executed using Helmert's method, which was introduced by F. R. Helmert in 1872. Helmert's method, detailed in Equation (9), augments the standard matrix $(A^{T}WA)$ with constraint equations. A and W represent the design and weight matrices, respectively, and $L_{1/2}$ represents the difference between actual and approximate observations. This method incorporates line constraints into the parametric equations by adding rows C and columns (C^{T}), vectors X_2 and L_2 into the standard and constant matrices. For solving the parameter vectors X, the matrices in Equation (9) are arranged as shown in Equation (10). However, X_2 is not employed in the later procedure to derive unknown parameters.

$$\begin{bmatrix} A^TWA & \vdots & C^T \\ \cdots & \cdots & \cdots \\ C & \vdots & 0 \end{bmatrix} \begin{bmatrix} X_1 \\ \cdots \\ X_2 \end{bmatrix} = \begin{bmatrix} A^TWL_1 \\ \cdots \\ L_2 \end{bmatrix} \tag{9}$$

$$\begin{bmatrix} X_1 \\ \cdots \\ X_2 \end{bmatrix} = \begin{bmatrix} A^TWA & \vdots & C^T \\ \cdots & \cdots & \cdots \\ C & \vdots & 0 \end{bmatrix}^{-1} \begin{bmatrix} A^TWL_1 \\ \cdots \\ L_2 \end{bmatrix} \tag{10}$$

4.0 Results and Discussion

This section comprehensively evaluates the TLS calibration techniques employed in this study. The analysis is divided into systematic error assessment (Section 4.1), quality assessment of CRP measurement (Section 4.2), quality assessment of reference CPs (Section 4.3), and evaluation of accuracy-oriented approaches (Section 4.4), which is further divided into similarity analysis (Section 4.4.1) and accuracy assessment (Section 4.4.2).

4.1 Systematic error assessment

To ensure high data quality, identifying systematic errors in TLS data is essential, as these errors, even when minor, can introduce significant inaccuracies in applications that rely on precise spatial data, such as urban planning, infrastructure monitoring, and environmental studies. To identify the systematic errors in the raw TLS data, this study employed a z-test at a 95% confidence level, as outlined in Equation 11. The systematic errors modelled included a_0, b_0, b_1, and c_0. Table 1 demonstrates that, despite employing various TLS self-calibration techniques, the raw TLS data showed a lack of significant systematic errors. This outcome is consistent with expectations for a newly manufactured TLS scanner that has undergone precise factory calibration, effectively minimising the potential for such errors (Lichti et al., 2005). Based on this first assessment, significant synthetic errors (SE) (a_0 = 10 mm, b_0 = b_1 = c_0 = 30"), suggested by Abd Razak et al. (2023) were introduced to rigorously assess the resilience of TLS calibration methods under conditions that simulate real-world challenges. These values were strategically chosen to represent potential worst-case scenarios, such as those encountered in harsh environments or when equipment undergoes wear over time, allowing for a robust evaluation of calibration techniques.

$$z = \frac{X}{\sigma_X} \tag{11}$$

Where,

X = Parameter to be evaluated
σ_X = The standard deviation of parameter

Table 1: Significance of CPs in raw TLS data

TLS self-calibration techniques	Calculated z			
	a_0	b_0	b_1	c_0
Precision-oriented	1.34375	-0.00775	0.000	-0.14285
Point-based constraint (ASC)	**4**	1.27586	-1.27118	**-3**
Line-based constraint (ASC)	0.81818	0.03906	-0.03846	-0.125

Bold signifies significant CPs

4.2 Quality Assessment of CRP Measurement

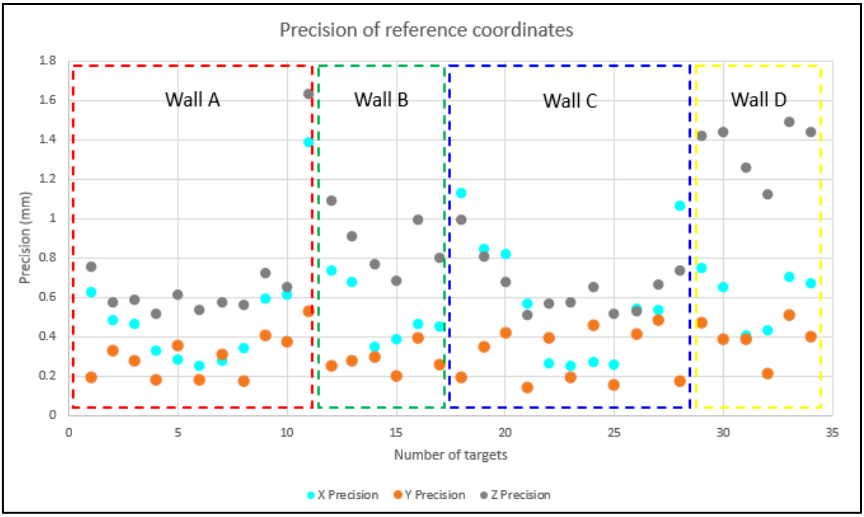

Figure 4: Precision of reference targets

After confirming that significant systematic errors were present in the raw data, the next step was to evaluate the quality of CRP measurements, which serve as the foundation for accurate calibration. Using the CRP approach, 34 well-distributed targets were selected as true values to evaluate different self-calibration techniques in enhancing the quality of scanned data. With the aid of specially designed targets, the average precision obtained from Photomodeler Scanner software for these 34 targets was approximately 1 mm for X, Y, and Z precision (refer to Figure 4). Notably, target 11 exhibited the highest precision values in the X and Z coordinates (1.385453 and 1.631969, respectively), likely due to a high incidence angle, as it was located at the edge of the wall (Abbas et al., 2019). The differences between the known and measured lengths of the scale bars were computed to ensure the accuracy of the established true values. The observed length discrepancies of

0.28 mm for wall A, 0.98 mm for wall B, 0.87 mm for wall C, and 0.65 mm for wall D demonstrated the reliability of the true values and reference constraints established using the CRP method.

4.3 Quality Assessment of Reference Calibration Parameters

The initial evaluation of accuracy-oriented approaches involved analysing CPs derived from these methods and comparing them to those obtained using a precision-oriented approach. To ensure the reliability of the CPs derived from the precision-oriented method as reference parameters, thirty (30) independent vectors were generated from both raw and calibrated data (precision-based method). The vectors were compared to true values obtained from the CRP measurement technique, where Figure 5 reveals that the accuracy of the raw TLS data was 5.06 mm. In contrast, the calibrated TLS data, using the precision-oriented method, demonstrated a 60% improvement, achieving a root mean square error (RMSE) of 2.07 mm. This finding is consistent with the study by Abbas et al. (2016), which also demonstrated the effectiveness of precision-oriented methods in reducing RMSE. This consistency with existing literature reinforces the conclusion that CPs derived from precision-oriented methods are reliable reference parameters for evaluating the accuracy-oriented approaches.

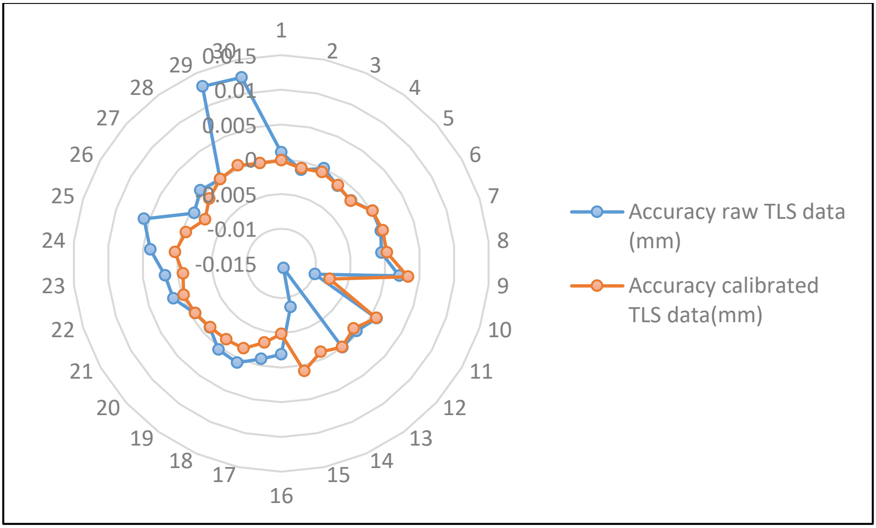

Figure 5: Accuracies of raw and calibrated TLS data

4.4 Evaluation of Accuracy-Oriented Approaches

4.4.1 Similarity Analysis

The results of the CPs derived from various methods are summarized in Table 2. These CPs, obtained using the proposed techniques, were compared to those from the precision-oriented method via a two-tailed z-test, with a critical value of ±1.96 at a 95% confidence level. As detailed in Table 3, point-based constraint exhibited substantial deviations from the reference CPs, with z-values significantly outside the critical range for constant error (-4.18750), collimation axis error (-16.86047), trunnion axis error (15.73282), and vertical circle index error (-24.71429). Conversely, line-based constraints produced z-values within the ±1.96 range, indicating no significant differences from the reference values for constant error (-0.53125), collimation axis error (0.05426), trunnion axis error (-0.05344), and vertical circle index error (0). To conclude, while point-based methods showed significant deviations from benchmark values, line-based methods aligned closely with them, suggesting higher consistency and accuracy in the latter approach.

Table 2: Derivation of CPs and standard deviations

Calibration parameters	Precision-oriented (mm/")	Accuracy-oriented (mm/")	
		Point-Based	Line-Based
$a_0 \pm \sigma_{a_0}$	14.4 ± 3.2	1.0 ± 0.2	12.7 ± 3.3
$b_0 \pm \sigma_{b_0}$	29.7 ± 12.9	-187.8 ± 57.8	30.4 ± 12.8
$b_1 \pm \sigma_{b_1}$	30.2 ± 13.1	236.3 ± 58.6	29.5 ± 13.0
$c_0 \pm \sigma_{c_0}$	29.9 ± 0.7	12.6 ± 1.5	29.9 ± 0.8

Table 3: Similarity assessment

Calibration parameters	Calculated 'z'	
Accuracy-oriented approaches	Point-based constraint	Line-based constraint
Constant error (a_0)	**-4.18750**	-0.53125
Collimation axis error (b_0)	**-16.86047**	0.05426
Trunnion axis error (b_1)	**15.73282**	-0.05344
Vertical circle index error (c_0)	**-24.71429**	0

Bold-Significant CPs

4.4.2 Accuracy Assessment

After verifying the similarity of CPs to the benchmark, techniques passing this test underwent a significance test to determine the effectiveness of CPs in enhancing TLS measurement quality. Despite the point-based constraint (ASC) method showing statistical differences from benchmarks, their reliability and precision were assessed to ensure method robustness and identify potential improvements.

All CPs were statistically tested using a z-test with a critical value of ±1.645. Table 4 shows that the null hypothesis was rejected for all CPs (a_0, b_0, b_1, c_0) using both point-based and line-based constraint (ASC) methods, indicating a significant influence on scanner observations. Consequently, significant parameters were applied to raw data, resulting in thirty new vectors. Table 5 shows accuracy improvements with precision-oriented, point-based constraint (ASC), and line-based constraint (ASC) methods. The precision-oriented technique achieved 2.07 mm accuracy (from 5.06 mm), line-based constraint (ASC) achieved 1.99 mm, and point-based constraint (ASC) achieved 2.16 mm, highlighting significant accuracy enhancements.

Table 4: Significance of CPs in raw TLS data (with known error)

Calibration parameters	Calculated 'z'	
	Point-based constraint	Line-based constraint
Constant error (a_0)	5	3.848484848
Collimation axis error (b_0)	-3.249134948	2.375
Trunnion axis error (b_1)	4.032423208	2.269230769
Vertical circle index error (c_0)	8.4	37.375

Table 5: Accuracy of different TLS self-calibration techniques

TLS Self-Calibration Techniques	RMSE (mm)
Raw data affected by SE	5.06
Precision-oriented	2.07
Point-based constraint (ASC)	2.16
Line-based constraint (ASC)	1.99

Based on the accuracy assessment, both proposed accuracy-oriented techniques were found to enhance calibration accuracy. Further analysis was conducted to identify the superior solution by examining the standard deviations of the CPs and the residuals. Comparing the two proposed techniques, the line-based constraint (ASC) method provides more stable CPs. As shown in Table 6, it has lower standard deviations: 5.3 mm for a_0, 15.5" for b_0, and 15.8" for b_1. In contrast, the point-based constraint (ASC) method has higher deviations: 0.2 mm for a_0, 57.8" for b_0, and 58.6" for b_1. Additionally, residuals, presented in Table 7, further highlight its superiority, with lower values in the horizontal direction (12.1 mm) and vertical angle (21.5 mm) compared to the point-based constraint (ASC) method (109.3 mm and 27.2 mm, respectively). This suggests that the line-based constraint (ASC) method is more effective for achieving consistent and accurate TLS calibration.

Table 6: Standard deviation

TLS self-calibration techniques	a_0 (mm)	b_0 (")	b_1 (")	c_0 (")
Precision-oriented (Benchmark)	3.2	12.9	13.1	0.7
Line-based constraint (ASC)	5.3	15.5	15.8	1.2
Point-based constraint (ASC)	0.2	57.8	58.6	1.5

Table 7: Residuals

TLS self-calibration techniques	Range	Horizontal direction	Vertical angle
Precision-oriented (Benchmark)	1.3	15.1	19.1
Line-based constraint (ASC)	2.9	12.1	21.5
Point-based constraint (ASC)	1.3	109.3	27.2

The line-based constraint (ASC) method was identified as the most effective based on standard deviations and residuals. To further validate this conclusion, correlation coefficients between CPs were analysed. As suggested by T. Zhou et al. (2020), this approach addresses potential issues with correlated parameters in point-based TLS self-calibration methods. The correlations were examined in two categories: i) between CPs and EO parameters (Figure 6a-6d) and ii) between CPs and object points (OPs) (Figure 6e).

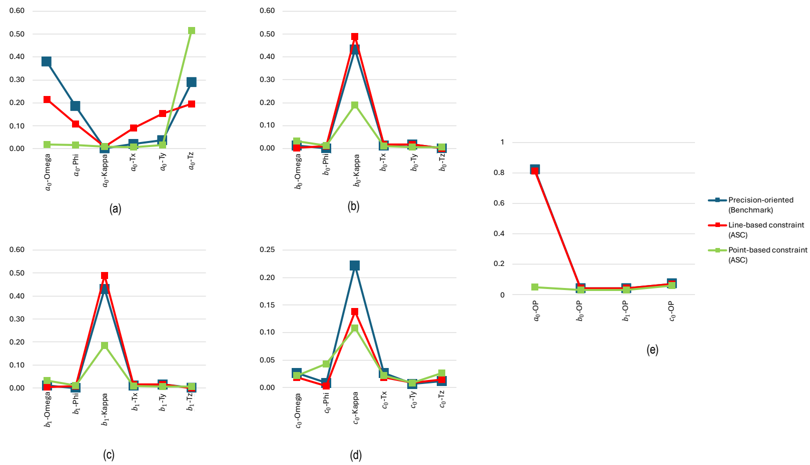

Figure 6: Correlations between TLS self-calibration parameters and exterior orientation: (a) constant error; (b) collimation axis error; (c) trunnion axis error; (d) vertical circle index error; (e) calibration parameters with object points

Overall, the analysis in Figure 6 indicates that both accuracy-oriented methods show weak positive correlations between CPs and the relevant measurements. While the point-based constraint (ASC) method displays the lowest correlation coefficients in most analyses, indicating the minimal impact of CPs on object points and exterior orientations, the line-based constraint (ASC) method demonstrates more consistent weak positive correlations. This suggests that the line-based constraint (ASC) method is more effective overall. Although the line-based constraint (ASC) method exhibits a moderate positive correlation between CPs and OPs, with the highest coefficient of 0.81, as indicated in Figure 6e, it does not attain a perfect correlation ($r = 1$). This result underscores the effectiveness of Lichti et al. (2011) recommendation to rotate the instrument by 90° at each scanner station, which successfully decorrelates the parameters. This absence of perfect correlation suggests that the method avoids overfitting and potential calibration issues, thereby maintaining a balance between model accuracy and generalizability.

5.0 Conclusion

This study has demonstrated the effectiveness of the line-based constraints (ASC) method, particularly in improving the quality of TLS measurements by addressing systematic errors more effectively. This approach marks a significant advancement in the development of self-calibration techniques, as it not only improves measurement accuracy but also offers a structured way to mitigate the impacts of systematic errors in TLS data. The line-based constraints (ASC) method enables more stable calibration results by leveraging linear reference elements, such as known distances, which help in refining the derived parameters and reducing systematic errors in the 3D model. This is particularly useful for applications that demand high accuracy, such as heritage documentation and infrastructure management, where precise 3D models are essential.

Although the point-based constraint (ASC) method exhibited weaker correlations among self-calibration techniques, indicating its relative independence from other parameters, it revealed inconsistencies in the parameters derived, pointing to the need for further refinement. These inconsistencies highlight a key limitation of the point-based (ASC) method, suggesting that while independence from other parameters is desirable, it may lead to unreliable calibration outputs.

While the line-based constraints (ASC) method has proven effective in enhancing the quality of TLS measurements, its implementation in this study involves extensive setup, requiring data from 7 scan stations, 27 lines, and 54 targets, making the process time-consuming. This highlights a limitation in scalability, particularly for large-scale projects or field environments where time and resources are constrained. Thus, it is recommended to optimize the network configuration to improve the efficiency by reducing the number of scan stations, lines, and targets, without compromising measurement accuracy. This optimization would improve the practicality of applying line-based calibration methods in broader field contexts.

Building on these recommendations, future research should also explore the feasibility of developing a dedicated calibration frame specifically designed for on-site TLS self-calibration. Such a frame would allow for real-time calibration adjustments and address any systematic errors directly in the field, reducing the need for extensive data processing post-scan. Implementing this calibration frame could significantly enhance TLS measurement accuracy in dynamic or outdoor environments, such as construction sites or geological surveys, where environmental changes are frequent.

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Article Contribution to Related Field of Study

This article contributes to the field of 3D data acquisition and calibration by introducing an accuracy-based approach to TLS self-calibration, which incorporates reference points to address and reduce systematic errors. By evaluating both point-based and line-based constraints, the study advances current practices beyond precision-based methods, providing insights that could improve the accuracy and reliability of TLS data. These findings may further benefit applications requiring high-accuracy 3D models, such as urban planning, heritage preservation, and environmental monitoring.

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