INVESTIGATION OF CORRELATION BETWEEN SELF-CALIBRATION PARAMETERS OF TERRESTRIAL LASER SCANNING (TLS)

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ABSTRACT: To determine the robust self-calibration approach for Terrestrial Laser Scanner (TLS), the profound knowledge of Geodetic Network Design and Photogrammetry is required. For any photogrammetric tasks, three main predefined criteria - precision, correlation, and uncertainty of parameters - play a more vital role than other criteria. Geodetic network design is composed of four interrelated design orders: zero, first, second and third order of design to fulfil the mentioned criteria. Zero order design which is the core focus of this research reveals the correlation between estimated parameters in self-calibration of TLS. In other words, three types of parameters - calibration parameters (CP), exterior orientation parameters (EOP), and object points (OP) – as unknowns must be solved through bundle block adjustment (BBA) of TLS self-calibration. The current parametrization of exterior orientation used for TLS calibration, unlike camera calibration, is limited to collinearity conditions from one scan station. According to established concepts in computer vision, by adding the constraints of relative orientation (RO) to bundle block adjustment, the estimations of unknowns will be in higher quality and potentially lower correlation. Therefore, application of this principle must determine more precise and lower correlated parameters for TLS self-calibration. This research will evaluate the correlation of TLS self-calibration parameters between collinearity and coplanarity conditions and will identify the potential improvements in correlation and precision of parameters with the aid of the new formulation. An experiment of self-calibration was undertaken using Leica ScanStation P50 and implemented on MATLAB codes.

1. INTRODUCTION

Laser scanner is an active electro-optical sensor using the laser as the main source of illumination to capture the spatial data through the availability of the reflected signal from a scene. With the advent of first generation of laser scanners, data acquisition approaches in Photogrammetry and Engineering Geodesy have been revolutionised. Currently, the position of laser scanners especially with the terrestrial platform for data collection – terrestrial laser scanners (TLS) – is increasingly dominating in the other disciplines, particularly deformation monitoring, in order to guarantee the highly accurate deliverables.

Thus, the application of TLS based on the technical specifications provided by manufacturers can be acceptable within or under certain conditions of scanning configuration. On the other hand, the limitation imposed by manufacturers for providing the confidential information about manufacturer-oriented calibration procedure in the design and calibrating TLS and the consideration of a subset of unknown systematic errors are the second highlighted motivation of calibration. Thirdly, the determination of the internal characteristics of every sensor provides a Photogrammetric metric tool for data acquisition, similar to investigation of the interior orientation parameters of a camera. In this research, the sophisticated self-calibration principle of TLS from the perspective of geodetic network design with the major emphasise on zero order design (ZOD) leading to the new parametrization of exterior orientation parameters (EOP) to control the existing correlation between estimated parameters will be aimed.

2. LITERATURE REVIEW

The literature review contains the brief introductory of TLS and identification of the error sources of 3D point cloud measurements, and photogrammetric methods alongside geodetic network designs for the creation of self-calibration of TLS.

2.1 Terrestrial laser scanner (TLS)

TLS is a terrestrial laser-based instrument which delivers the 3D point coordinates in 3D spherical coordinates. In principle, TLS is a very high-speed and movable total station which is able to capture millions of points in a second as the consequence of measuring three spherical coordinates, range r, horizontal angle h and vertical angle v from the returned signal reflected from a single point received at TLS.

The conversion from 3D spherical into Cartesian coordinates is represented as follows:

$$\begin{bmatrix} x_i \\ y_i \\ z_i \end{bmatrix}_{i=1\ldots n} = \begin{bmatrix} r_i \cos v_i \cos h_i \\ r_i \cos v_i \sin h_i \\ r_i \sin v_i \end{bmatrix}_{i=1\ldots n} \qquad (1)$$

The index i indicates the number of measured points from 1 to n.

Reversely, the transformation can be applied from 3D Cartesian to spherical coordinates:

$$\begin{bmatrix} r_i \\ v_i \\ h_i \end{bmatrix}_{i=1\ldots n} = \begin{bmatrix} \sqrt{x_i^2 + y_i^2 + z_i^2} \\ \tan^{-1}\left(\frac{z_i}{\sqrt{x_i^2 + y_i^2}}\right) \\ \tan^{-1}\left(\frac{y_i}{x_i}\right) \end{bmatrix}_{i=1\ldots n} \qquad (2)$$

Similar to any geodetic measurements, the observations are prone to be contaminated as the results of deviations called errors. The systematic errors for TLS which can be mathematically modelled namely are instrumental imperfections, atmospheric effects, scanning geometry and measurement configuration, and object and surface related issues. Although all impacts simultaneously affect the entire configuration of scanning, the separation here is made to detach the scanner with scanning self-calibration. The underlying assumption here is the self-calibration of the scanner is only influenced as the result of instrumental imperfections, meaning that the influences of the remaining errors on TLS observations are considerably minor.

Therefore, the corrected range, and angular measurements $[r_c \quad h_c \quad v_c]$ are a function of observed values $[r_o \quad h_o \quad v_o]$ and corresponding correction factors of instrumental imperfections $[dr_{i.i} \quad dh_{i.i} \quad dv_{i.i}]$:

$$\begin{aligned} r_c &= f(r_o,\ v_o, h_o, dr_{i.i}) \\ v_c &= f(r_o,\ v_o, h_o, dv_{i.i}) \\ h_c &= f(r_o,\ v_o, h_o, dh_{i.i}) \end{aligned} \qquad (3)$$

2.2 Instrumental imperfections (i.i)

The instrumental misalignments and irregularities in the design and production of scanners are referred to as i.i in this paper. Here, only five additional parameters (calibration parameters (CP)) relating to physical systematic errors of i.i (i.e., a_1 is the constant zero offset, a_2 is transit offset, a_3 is vertical angle index offset, and a_4 and a_5 are mirror offset and mirror tilt angle, respectively) which are randomly selected for this investigation, and three empirical parameters as those being formulated based on several experiments and the analysis of the residuals $(ER, EV$ and $EH)$ are considered.

$$\begin{aligned} dr_{i.i} &= a_1 + a_2 \sin(v_o) + ER \\ dv_{i.i} &= \frac{a_2 \cos(v_o)}{r_o} + a_3 + EV \\ dh_{i.i} &= \frac{a_4}{r_o \sin(v_o)} + \frac{2a_5}{\sin\,(v_o)} + EH \end{aligned} \qquad (4)$$

It is worth mentioning the current parametrization of i.i was reported by (Muralikrishnan , et al., 2015), and there are many more calibration parameters involved, but not considered in this research.

There are several ways proposed to calibrate the TLS, similar to procedures taken for camera calibration. In brief, the component calibration concentrates on the calibrating of each component of misalignment individually using dedicated equipment and procedures resulting in separate result for corresponding components (Holst , et al., 2014; Lichti , 2007; Muralikrishnan , 2021). The examples of the component calibrations include calibration with the aid of pre-calibrated artifacts, in situ calibration, or a calibrated network of targets in volume measurements (Reshetyuk, 2009; Reshetyuk, 2010; Jafar , et al., 2018). On the other hand, the system calibration is carried out through the system using knowledge of components and their interactions. This is completed, in a majority of applications, through self-calibration (Holst , et al., 2018; Pareja , et al., 2013; Kresten & Lindstaedt , 2022; Li, et al., 2018; Li, et al., 2018; Medic, et al., 2019).

2.3 Photogrammetric perspective

The structure from motion (SFM) process solves the exterior orientation parameters (EOP) via several BBA techniques. Considering the problem of TLS self-calibration, BBA of EOP via collinearity conditions has been widely studied. The representation of EOP for self-calibrated TLS network will be as follows:

$$x_i^j = R_{11}(X_i - X_S) + R_{21}(Y_i - Y_S) + R_{31}(Z_i - Z_S)$$

$$y_i^j = R_{21}(X_i - X_S) + R_{22}(Y_i - Y_S) + R_{23}(Z_i - Z_S) \qquad (5)$$

$$y_i^j = R_{21}(X_i - X_S) + R_{22}(Y_i - Y_S) + R_{23}(Z_i - Z_S)$$

where $[x_i^j \quad y_i^j \quad z_i^j]$ = 3D point coordinates of a point i in the scanner j coordinate system,
$[X_i \quad Y_i \quad Z_i]$ = the corresponding object space coordinate of point i,
$[X_S \quad Y_S \quad Z_S]$ = scanner position S in the object coordinate system, and
R = element of rotation matrix including three Euler rotation angles ω, ϕ and κ around three axes.

Given equations 2, 4 and 5, the collinearity equations attempt to estimate three types of unknowns: exterior orientation parameters (EOP) for each scan station (ss) (three translations (X_S, Y_S and Z_S), and three orientations (ω, ϕ and κ)), eight calibration parameters (CP), and 3D object point coordinates (object points (OP) (X_i, Y_i and Z_i)). The number of unknowns will be given $m = 6(ss) + 8 + 3n$, while the number of measurements for the entire bundle will be $n = 3\ (ss)\ n$. Considering the definition of the datum and the existence of at least two scan stations, a minimum of eight known observations must be given to solve those parameters.

2.4 Correlation and precision

Two of the most important criteria of BBA of a self-calibration network are correlation and precision of estimated parameters. The ideal situation will be guaranteed by having lower correlation and higher precision. In principle, the precision of the parameters is judged as the results of the inversion of the Normal Matrix N, leading to variance and covariance matrix of unknowns in least square adjustment, and the dependency between variables called correlation is justified as the result of the computation of Pearson's coefficient which is the ratio between covariances $\sigma_{x_1x_2}$ and variances of two variables σ_{x_1} and σ_{x_2}.

$$\rho_{x_1x_2} = \frac{\sigma_{x_1x_2}}{\sigma_{x_1}\sigma_{x_2}} \qquad (6)$$

The closer to zero, the lower correlations, whereas highly correlated parameters are identified as close to -1 or $+1$. (Gruen. A., 2010) acknowledged, in camera calibration, correlation parameters higher than 0.7 will not be acceptable for photogrammetric tasks.

Four correlation analysis between estimated parameters (CP and EOP, CP and OP, and OP and EOP) and inter-parameters must be taken into account. However, only the most important one which is between CP and EOP ($\rho_{cp,eop}$) will be investigated here.

2.5 Geodetic network design

The fundamental idea of geodetic network optimization is to recognize whether it is possible to determine the desirable quality of network before any observations are made (Grafarend, 1974; Amiri-Simkooei, 1998; Amiri-Simkooei, et al., 2012). The initial order of optimization of a geodetic network embraces the zero order design (ZOD) focusing on the problem of optimal datum design. The major investigation of optimal datum definition is to create the Normal matrix invertible by removing its datum deficiency to make it full rank. In the 3D network, the datum will be presented as formerly defining seven datum parameters (three rotations, three translations and one scale) (i.e., at least three point coordinates must be known). The entire process of ZOD influences the correlation quality between individual estimated unknowns. To resolve the issue, minimal datum (free network, or inner) has been tried for self-calibration of TLS which both approaches lead to unsuccessful results due to the rise in correlation between parameters.

The remaining orders of network such as first order design (FOD) and second order design (SOD), must be indeed addressed for the whole geodetic network design concentrating on the other criteria (Lichti, et al., 2021). However, those will be expressed in future research.

3. METHODOLOGY

In the literature review, the concept of implementing of ZOD to reveal the correlation between the estimated parameters and unsuccessful results in definition of independent datum for self-calibration of TLS was shortly stated (Lichti , 2007). Thus, to have the profound knowledge of EOP might assist in predicting the lower correlation between parameters (Fraser, 2001; Mikhail , et al., 2001).

(Fraser, 2001) demonstrated determinability of camera calibration parameters and EOP is greatly enhanced by adding the constraints of relative orientations parameters (ROP) to the BBA, and more precise camera calibration parameters might lower their correlations. In other words, rather than one-step exterior orientation, relative orientation plus absolute orientation of two images will be implemented in bundle block adjustment.

In analytical photogrammetry, the corresponding methodology of relative orientation is to fix the EOP of left image (here left scan station to be fixed as zero) and to define the $base$ for one translation of right image (here right scan station) (i.e., distance between two origins of scanner coordinate systems is called base). Having those constraints help the reconstruction of coplanarity conditions with the existence of collinearity conditions (Figure 1).

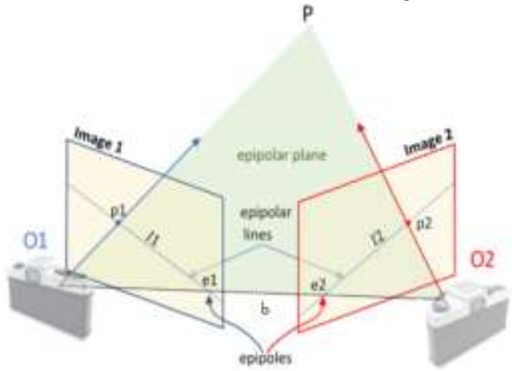

Figure 1. Collinearity, coplanarity and epi-polar conditions (Alsadik & Abdulateef, 2022).

Hence, when the relative orientation of two scan stations is solved, coplanarity constraints can be automatically constructed, and those conditions constrain the collinearity conditions. Clearly, at least two stations are needed, and in case of more than two stations, the constraint of base must be again defined and added between each two stations.

The availability of these constraints in collinearity equations will produce the unknowns in an arbitrary scale and in the reference of first scanner station coordinates which is assumed to be fixed.

Therefore, instead of the typical collinearity conditions of separate scan station solving 6 EOP for each scan station, we have only to estimate 5 EOP of second scan stations, given the EOP of the first scan station as known. Additionally, so far, CP are supposed to be block-invariant giving $m = 5 + CP + 3\ OP$; however, the number of observations here is $m = 5 + 2\ CP + 3\ OP$ in case of bundle-variant CP. Due to the nature of the problem, the iterative nonlinear least square adjustment (NLSA) must be applied to determine those parameters.

4. DATA ANALYSIS AND DISCUSSION

As it was explained, the aim of the ZOD in geodetic network design is the definition of datum in the reasonable manner leading to lowering the existing correlation between estimated parameters. Both conditions – collinearity conditions from one single scan station and collinearity conditions with the constraints of coplanarity conditions - have been implemented on the same data set in order to check and investigate the correlation and estimation of parameters. The field experiment through laboratory configuration at the Callaghan campus of the University of Newcastle, New South Wales, Australia was finalised on 29th May 2023. The data collection was completed via the Leica ScanStation P50[1] whose range and angular accuracy are $1.2\ mm + 10\ ppm$ and $8''$, respectively, as reported by Leica. Regarding the other systematic errors, particularly atmospheric effects, the lab test was undertaken with no variations of atmosphere during the measurements (Figure 2).

Figure 2. The laboratory configuration.

After the data acquisition, the post processing steps implementing the nonlinear least square adjustment via MATLAB codes to validate the approximations of - eight calibration parameters, six or five exterior orientation parameters of the second scan station, depending on the conditions, and object points - between two scan stations located in the distance of $6.2417\ m$ have been estimated. The NLSA was converged after the 6th iteration with a threshold of $\pm 0.8\ \times 10^{-4}\ m$ from measured slope distance by Leica Nova MS60 Total Station with range uncertainty of $1\ mm + 1.5\ ppm$ to the prism[2].

The following Tables summarise the precision of the selected parameters, resulting in the correlation investigations of the parameters.

The precision of parameters in both conditions have been carried out and highlighted in Table 1. It is understandable that the rotational angles of EOP – ω and φ - as expected are not precisely estimated, and notably adding the constraint in translation Y_S causes the lower precision for estimation of more parameters, meaning that the horizontal plane becomes totally inconsistent. For the CP, the precision is quite acceptable for the collinearity conditions apart from calibration parameters of vertical angle (i.e., a_2 transit offset, a_3 vertical angle index offset and assumed empirical error of vertical angles EV). This problem exists identically in the second condition. One of the prominent reasons for this result is the lack of targets on the tall ceiling which due to unflattens of the roof, we were not able to set the targets (Figure 2).

On the other hand, the empirical error of horizontal angle EH for both scan station has not been precisely estimated in the collinearity conditions with the imposition of the constraint compared to collinearity conditions with no constraints. The fact leads to more correlated calibration parameters in the horizontal direction (Table 2).

Finally, the imposition of the base constraint also degrades the precision of OP in Y direction (the same direction as the constraint).

From Table 1, it is concluded that adding one constraint of the base is not adequate to have the precise estimation of CP, assuming bundle-variant CP. Preferably, adding the other constraint of relative orientation in the vertical direction

[1] https://leica-geosystems.com/products/laser-scanners/scanners/leica-scanstation-p50_new
[2] https://leica-geosystems.com/products/total-stations/multistation/leica-nova-ms60

Table 1. Precision (1σ) of selected parameters under both conditions.

Parameters			Precision	
			Collinearity Conditions	Collinearity Conditions with Coplanarity Constraints
Exterior Orientation Parameters (EOP)		ω	24″	24″
		φ	7″	7″
		κ	1.5″	27″
		X_S	0.08 mm	2 m
		Y_S	0.3 mm	–
		Z_S	1 mm	1 mm
Calibration parameters (CP)	First station	ER	0.2 mm	0.2 mm
		EH	1″	55″
		EV	11″	11″
		a_1	0.2 mm	0.2 mm
		a_2	0.6 mm or $2'7''$	0.6 mm or $2'7''$
		a_3	11″	11″
		a_4	4″	4″
		a_5	0.2″	0.2″
	Second station	ER	0.2 mm	0.2 mm
		EH	1.5″	28″
		EV	14″	14″
		a_1	0.2 mm	0.3 mm
		a_2	2 mm or $6'18''$	2 mm or $6'5''$
		a_3	14″	14″
		a_4	4″	4″
		a_5	0.2″	0.2″
Object Points (OP)		X	0.3 mm	0.3 mm
		Y	0.1 mm	0.9 mm
		Z	0.2 mm	0.2 mm

Table 3 illustrates the correlation matrix between EOP and CP which is the most important existing correlation.

Table 2. Correlation matrix between CP for both scan station and EOP of second scan station.

Collinearity Conditions		Calibration Parameters (CP)															
		First Station								Second Station							
		ER	EH	EV	a_1	a_2	a_3	a_4	a_5	ER	EH	EV	a_1	a_2	a_3	a_4	a_5
Exterior Orientation Parameters (EOP)	ω	0.71	-0.10	-0.96	0.71	0.96	-0.96	0.07	-0.07	0.73	0.44	-0.97	0.73	0.49	-0.97	-0.08	0.08
	φ	-0.60	0.08	0.86	-0.60	-0.85	0.86	-0.05	0.05	-0.59	-0.37	0.79	-0.59	-0.37	0.79	0.05	-0.06
	κ	-0.58	0.11	0.47	-0.58	-0.50	0.46	-0.27	0.27	-0.57	0.27	0.45	-0.57	-0.29	0.45	0.32	-0.33
	X_S	-0.63	0.13	0.27	-0.63	-0.33	0.27	-0.30	0.30	-0.58	0.01	0.26	-0.58	-0.21	0.26	0.20	-0.20
	Y_S	-0.90	0.03	0.67	-0.90	-0.73	0.67	-0.02	0.02	-0.91	-0.52	0.71	-0.91	-0.49	0.71	0.03	-0.02
	Z_S	-0.36	0.01	0.33	-0.36	-0.36	0.33	-0.02	0.02	-0.56	-0.35	0.50	-0.56	-0.90	0.50	0.03	-0.03
Collinearity Conditions with Coplanarity Constraints		Calibration Parameters (CP)															
		First Station								Second Station							
		ER	EH	EV	a_1	a_2	a_3	a_4	a_5	ER	EH	EV	a_1	a_2	a_3	a_4	a_5
Exterior Orientation Parameters (EOP)	ω	0.71	-0.69	-0.97	0.71	0.96	-0.95	0.07	-0.07	0.73	-0.68	-0.97	0.73	0.50	-0.97	-0.08	0.08
	φ	-0.61	0.58	0.87	-0.61	-0.85	0.86	-0.05	0.05	-0.59	0.57	0.80	-0.59	-0.38	0.80	0.05	-0.06
	κ	-0.91	1.00	0.68	-0.90	-0.73	0.66	-0.03	0.03	-0.91	1.00	0.71	-0.91	-0.49	0.71	0.04	-0.04
	X_S	-0.90	1.00	0.66	-0.90	-0.72	0.65	-0.03	0.03	-0.91	1.00	0.70	-0.91	-0.49	0.70	0.03	-0.03
	Z_S	-0.36	0.38	0.33	-0.36	-0.36	0.32	-0.02	0.02	-0.56	0.38	0.50	-0.56	-0.98	0.50	0.03	-0.03

Under the collinearity conditions, only X_S and κ are not correlated with CP and can be independently estimated. The remaining EOP are not separatable. They are correlated with only range and vertical angle CP, meaning that under the same condition, the decorrelated horizontal angle CP are guaranteed.

ω, φ and Z_S experience the same direction and value of correlation coefficient with the identical CP under both conditions. The two exterior orientation parameters (i.e., X_S and κ), which are decorrelated with CP in collinearity conditions, have the highest correlation with three calibration parameters (close to +1) ER empirical errors in range, a_1 constant error in range and empirical error of horizontal angle EH in a newer parametrisation. This result was anticipated due to the precision outcome discussed above (Table 1). Furthermore, their correlation shifts from one CP to the other in different scan stations.

To sum up, adding one constraint in horizontal plane cannot be the optimal conditions for zero order design of network dealing with correlation and precision of the parameters. As it was expressed, the decorrelated and precise X_S, κ and EH became correlated and less precise in a newer formulation. The same situation holds comparing correlation matrix of OP and EOP. Additionally, the existing correlation shifts between parameters in range and vertical direction. To resolve the situation and make the horizontal plane more stable, it is recommended that the other constraint preferably ω, φ and Z_S having the identical correlation trend with CP is imposed for the reconstruction of coplanarity conditions.

The initial attempt is to add the constraint of ω alongside Y_S to the same coplanarity conditions. Thus, the precision analysis of the selected parameters has been illustrated in Table 3.

Table 3. Precision (1σ) of selected parameters under two constraints of coplanarity conditions in collinearity conditions.

	Precision														
	Exterior orientation Parameters (EOP)					Calibration Parameters (CP)							Object Points (OP)		
	φ	κ	X_S	Z_S	ER	EH	EV	a_1	a_2	a_3	a_4	a_5	X	Y	Z
First station	–	–	–	–	$0.1\ mm$	40"	3"	$0.1\ mm$	$0.1\ mm$ or 35"	3"	3.5"	0.2"	$0.2\ mm$	$0.6\ mm$	$0.2\ mm$
Second station	3"	15"	$1\ mm$	$0.7\ mm$	$0.1\ mm$	25"	3.4"	$0.1\ mm$	$0.9\ mm$ or 3'4"	3"	2"	0.5"			

Compared to Table 1, there is a significant improvement in estimation of the parameters. Not only do the EOP experience more precise values, but the approximations of CP for both scan stations are also enhanced as the consequence of adding two constraints (i.e., Y_S and ω).

Table 4 depicts the corelation between CP of both scan station and EOP of second scan station under collinearity conditions with two identical constraints.

Table 4. Correlation matrix between CP and EOP.

Collinearity Conditions with Coplanarity Constraints	Calibration Parameters (CP)															
	First Station								Second Station							
	ER	EH	EV	a_1	a_2	a_3	a_4	a_5	ER	EH	EV	a_1	a_2	a_3	a_4	a_5
Exterior Orientation Parameters (EOP) φ	0.02	-0.05	0.21	0.02	-0.16	0.22	0.03	-0.04	0.11	-0.05	-0.33	0.11	0.11	-0.33	-0.03	0.03
κ	-0.81	1.00	0.05	-0.81	-0.33	0.03	0.04	-0.04	-0.83	1.00	0.25	-0.83	-0.26	0.25	-0.06	0.06
X_S	-0.81	1.00	0.05	-0.81	-0.34	0.03	0.04	-0.04	-0.83	1.00	0.25	-0.83	-0.26	0.25	-0.07	0.07
Z_S	-0.16	0.20	-0.05	-0.16	-0.05	-0.05	0.01	-0.01	-0.45	0.19	0.63	-0.45	-0.98	0.63	0.00	0.00

It is obvious that this leads to the favourable results. *Firstly*, the correlation between φ and CP of both scan stations has been totally removed (Table 2). *Secondly*, adding the base imposes a greater number of correlated CP with κ; however, the existing correlation between two CP (ER and constant zero error a_1) and κ in a newer condition is lowered. *Furthermore*, all calibration parameters affecting vertical angles become decorrelated from κ. The same situation holds between decorrelated CP and X_S (Table 2). Here is the remarkable improvement. It is inferred that the inconsistency in the horizontal plane shown in Table 2 to a certain extent is controlled. *Finally*, three approximately full correlated parameters remain unchanged in both coplanarity conditions – κ and EH, X_S and EH and Z_S and a_2. It indicates that the change in EOP constraints is unable to reduce those correlations (i.e., they are EOP-independent). In order to address the issue, it is sufficient to change the object points (referring to first order design of the network (FOD)).

Consequently, the current situation is able to guarantee the acceptable and consistent correlation by solving 4 EOP of every scan station. From Table 1 and 3, it is inferred if the precision of estimation for range and angular parameters is lower than $\pm 1\ mm$ and ± 4", respectively, we might be able to expect reasonable correlation between those parameters.

Hence, the main questions arise here are whether we can replace ω with base to construct the coplanarity conditions, or how the configuration of object points must be proposed in the optimal manner (FOD).

5. CONCLUSIONS

To summarise, this research aimed to investigate the correlation of calibration parameters associated into self-calibration of TLS. The implementation under two conditions of SFM – collinearity conditions and collinearity conditions with the constraints of coplanarity conditions - without the aid of prior information of object points for datum definition has been completed. It is clearly seen adding the one constraint of relative orientation such as base, slope distance between two origins of scanner coordinate systems, to construct the coplanarity conditions, does not necessarily improve the precision and correlation of parameters, although the inter correlation between parameters is still a debateable issue. On the other hand, it was proven that applying two constraints into the BBA of self-calibration and different scanning geometry – potentially using the targets on the ceiling - are able to enhance the precision and correlation of eight chosen calibration parameters and exterior orientation parameters. The procedure must be employed on the entire 22 calibration parameters of TLS. In addition to that, a greater number of EOP in case of having more scan stations must be solved. It is worthwhile to mention that the proposal only concentrated on two scan stations to the reference of first scanner coordinate system. Furthermore, as a future work, it is recommended that the evaluation of the other orders of design of network - first order design (FOD) and second order design (SOD) - simultaneously provide better insight of precision, correlation and reliability of parameters.

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