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A NOVEL SINGLE-STEP PROCEDURE FOR THE CALIBRATION OF THE MOUNTING PARAMETERS OF A MULTI-CAMERA TERRESTRIAL MOBILE MAPPING SYSTEM

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ABSTRACT: Mobile Mapping Systems (MMS) can be defined as moving platforms which integrates a set of imaging sensors and a position and orientation system (POS) for the collection of geo-spatial information. In order to fully explore the potential accuracy of such systems and guarantee accurate multi-sensor integration, a careful system calibration must be carried out. System calibration involves individual sensor calibration as well as the estimation of the inter-sensor geometric relationship. This paper tackles a specific component of the system calibration process of a multi-camera MMS – the estimation of the relative orientation parameters among the cameras, i.e., the inter-camera geometric relationship (lever-arm offsets and boresight angles among the cameras). For that purpose, a novel single step procedure, which is easy to implement and not computationally intensive, will be introduced. The proposed method is implemented in such a way that it can also be used for the estimation of the mounting parameters among the cameras and the IMU body frame, in case of directly georeferenced systems. The performance of the proposed method is evaluated through experimental results using simulated data. A comparative analysis between the proposed single-step and the two-step, which makes use of the traditional bundle adjustment procedure, is demonstrated.

1. INTRODUCTION

The demand for fast and cost-effective geo-spatial information collection along with technological advances in the last few decades have triggered considerable changes in the mapping survey practice. Currently, most of the mapping systems consist of mobile multi-sensor systems usually referred to as Mobile Mapping Systems (MMS). A MMS is a kinematic platform that integrates multiple sensors for the acquisition of images, geographic locations, velocity, orientation parameters, distances, ranges, as well as three-dimensional spatial and attribute information of any object. An overview of mobile mapping technology and its applications can be found in El-Sheimy (2005). The MMS is a multi-task system that usually comprises: (i) a platform and power supply, (ii) a control module, (iii) an imaging module, (iv) a positioning and orientation module (in case of directly georeferenced systems), and (v) a data processing module. The kinematic platform can be a land vehicle (El-Sheimy, 1996), a human operator (Ellum and El-Sheimy, 2001; Ellum, 2003), an aircraft (Mostafa et. al, 2001) or a marine vehicle (Adams, 2007), either manned or un-manned Perry (2009), that provides sufficient power supply for mission operation. The control module is responsible for data acquisition based on time or distance interval. The imaging module could include video cameras, digital cameras, and/or laser scanners. Directly georeferenced systems will have the positioning and orientation module, which encompasses a GPS receiver, an inertial measurement unit (IMU), a dead reckoning (DR) system and/or a distance measurement instrument (DMI).

In order to fully explore the potential accuracy of such systems and guarantee accurate multi-sensor integration, a careful system calibration must be carried out (El-Sheimy, 1992; Cramer and Stallmann, 2002; Pinto and Forlani, 2002; Honkavara, 2003; Habib el. al, 2010). System calibration involves individual sensor calibration and the estimation of the mounting parameters relating the system components (e.g., the GPS, IMU, and the imaging sensors). The photogrammetric system calibration, which is the focus of this paper, deals with the camera and the mounting parameters calibration. For multi-camera systems, the mounting parameters encompass two sets of relative orientation parameters (ROPs) (El-Sheimy, 1992): the ROPs among the cameras as well as the lever-arm offsets and boresight angles between the cameras and the navigation sensors (i.e., the IMU body frame as the navigation solution usually refers to its coordinate frame). The calibration of the boresight angles and lever-arm offsets between the cameras and the navigation sensors is necessary for directly georeferenced multi-camera systems. This paper will focus on the estimation of the ROPs among the cameras although the proposed method can also be used for the estimation of the ROPs among the cameras and the IMU body frame. Since the cameras are rigidly mounted on a platform, their geometric relationships are assumed to be invariant. Accurate estimation of the ROPs is very important since they will be assumed as constants in future survey projects. Moreover, the knowledge of the cameras' ROP can be also useful for directly georeferenced systems since they can be used as prior information in the calibration of the ROPs between the cameras and the IMU body frame to improve the accuracy of the estimated parameters.

The ROPs among the cameras can be determined using either a two-step or single-step procedures. The two-step procedure for the estimation of the ROPs among the cameras is based on comparing the cameras' EOPs determined through a conventional indirect geo-referencing (bundle adjustment) procedure. Although this procedure is easy to implement, its reliability is highly dependent on the imaging configuration as well as the number and distribution of tie and control points since these factors control the accuracy of the estimated EOPs. The single-step procedure, on the other hand, incorporates the ROPs in the bundle adjustment procedure. The commonly used single-step approach to determine the system mounting parameters is based on the expansion of traditional bundle adjustment procedures with constraint equations (El-Sheimy, 1992; Lerma et. al, 2010; King, 1992). Such constraints are used to enforce the invariant geometric relationship among the sensors. Constraint equations have been extensively used in analytical photogrammetry to enforce geometric or physical relationships that exist between parameters of an adjustment to obtain a solution of higher quality. For instance, King (1992) has proposed the optimization of conventional bundle adjustment procedures by constraining the base distance and the convergence angles of the camera axes (dot products of each pair of X, Y and Z axis) to the mean computed for all stereo-pairs taken from two cameras rigidly fixed. Similarly, in El-Sheimy (1992), the ROPs among the cameras are estimated by adding constraint

equations to enforce the invariance of the base distance and the boresight matrix among the cameras for different epochs. The base distance constraint is also used by Lerma et al. (2010) to improve the self-calibration quality. The drawback of incorporating constraint equations to enforce consistent ROPs among the sensors is the associated complicated procedure for doing that, e.g., extensive partial derivatives as well as manual formatting of the camera pairs to be utilized in the relative orientation constraints (ROC). These complexities are intensified as the number of cameras onboard gets larger.
In this paper, a novel single-step procedure, which is more suitable for multi-camera systems, is introduced. In contrast to the commonly-used constraint equations in previous work, the proposed method is much simpler. The implementation of the proposed procedure is not affected by the number of the involved cameras and the number of utilized epochs. The introduced single-step procedure utilizes the concept of modified collinearity equations, which has already been used by some authors in integrated sensor orientation (ISO) procedures involving directly georeferenced single camera systems (Ellum, 2003; Pinto and Forlani, 2002; Habib et. al, 2010). A similar concept of modified collinearly equations has been also proposed for a two-camera system (King, 1992), where the colinearity equations for the right camera are written in terms of the left coordinate system instead of the object coordinate system. The proposed method in the current paper is an extension to the work presented by King (1992) for a multi-camera system using a more general model for the collinearity equations, i.e., the same modified collinearity equations can be used for all the cameras. Moreover, the proposed single-step procedure has the flexibility to also be used for the estimation of the ROPs between the cameras and the IMU body frame in case of directly georeferenced systems, since it is implemented using a general Least Squares Adjustment (LSA) procedure.

The paper starts by presenting the traditional two-step for the estimation of the ROPs among the cameras. Then the proposed single-step procedure is detailed followed by experimental results using simulated data. Finally, the paper presents some conclusions and recommendations for future work.

2. RELATIVE ORIENTATION PARAMETERS CALIBRATION

In this section, the two-step procedure based on the traditional bundle adjustment and the introduced single-step procedures for the estimation of the ROPs among the cameras will be described.

2.1 Two-step Procedure: Conventional Colinearity Equations

The two-step procedure utilizes the cameras' EOPs determined through a traditional bundle adjustment procedure, which is based on the mathematical model shown in Equation 1. The final form of the conventional colinearity equations (Equation 2) can be obtained by dividing the first two equations in Equation 1 by the third one after moving the image coordinates $x_j^{c_i}, y_j^{c_i}$ to the left side of the equations. One should note that the scale factor $\lambda_j^{c_i}$ is eliminated through the division process.

$$r_j^G = r_{c_i}^G(t) + \lambda_j^{c_i} R_{c_i}^G(t) \begin{bmatrix} x_j^{c_i} - x_p{}^{c_i} - dist_x{}^{c_i} \\ y_j^{c_i} - y_p{}^{c_i} - dist_y{}^{c_i} \\ -c^{c_i} \end{bmatrix} \tag{1}$$

where r_j^G : ground coordinates of an object point j;

$r_{c_i}^G(t)$: vector from the origin of the ground coordinate system to the ith camera perspective centre at a given time (t);

$R_{c_i}^G(t)$: represents the rotation matrix relating the ground and the ith camera coordinate systems at a given time (t);

$\lambda_j^{c_i}$: scale factor specific to the ith camera and the jth point combination;

$x_j^{c_i}, y_j^{c_i}$: image coordinates of the jth point observed in an image acquired by the ith camera;

$x_p{}^{c_i}, y_p{}^{c_i}, c^{c_i}, dist_x{}^{c_i}, dist_y{}^{c_i}$: principal point coordinates, principal distance and the distortions associated with the ith camera.

$$x_j^{c_i} = x_p{}^{c_i} - c^{c_i}(N_x^{c_i} / D^{c_i}) + dist_x{}^{c_i} \tag{2}$$
$$y_j^{c_i} = y_p{}^{c_i} - c^{c_i}(N_y^{c_i} / D^{c_i}) + dist_y{}^{c_i}$$

where $N_x^{c_i} = f_{N_x^{c_i}}(r_j^G, r_{c_i}^G(t), R_{c_i}^G(t))$;

$N_y^{c_i} = f_{N_y^{c_i}}(r_j^G, r_{c_i}^G(t), R_{c_i}^G(t))$;

$D^{c_i} = f_{D^{c_i}}(r_j^G, r_{c_i}^G(t), R_{c_i}^G(t))$.

After the bundle adjustment procedure, the ROPs of the cameras w.r.t. a reference camera can be determined by comparing the cameras EOPs (i.e., $r_{c_i}^G(t)$ and $R_{c_i}^G(t)$) with the EOPs of the reference one (i.e., $r_{c_R}^G(t)$ and $R_{c_R}^G(t)$). To come up with an estimate for the ROPs of the cameras w.r.t. the reference one, Equations 3 and 4 can be utilized.

$$R_{c_i}^{c_R}(t) = \left(R_{c_R}^G(t)\right)^{-1} R_{c_i}^G(t) \tag{3}$$

$$r_{c_i}^{c_R}(t) = \left(R_{c_R}^G(t)\right)^{-1} \left(r_{c_i}^G(t) - r_{c_R}^G(t)\right) \tag{4}$$

where $R_{c_i}^{c_R}(t)$: is the rotation matrix relating the reference camera and the ith camera coordinate systems, defined by the boresight angles (Δω, Δφ, Δκ), at a given time (t),

$r_{c_i}^{c_R}(t)$: is the lever-arm offset vector (ΔX, ΔY, ΔZ) between the reference and the ith camera perspective centers, defined relative to the reference camera coordinate system, at a given time (t);

It should be noted that the derived ROPs in Equations 3 and 4 are time-dependent since each exposure instance will give an estimate for the ROPs between any of the utilized cameras and the reference camera. An averaging process is usually performed to obtain mean values for the ROPs as well as their standard deviations. The advantage of the two-step procedure for the estimation of the ROPs is its simplicity, i.e., any bundle adjustment software can provide EOP values for the ROPs calibration. However, in order to have reliable estimates, the geometric strength of the imaging configuration as well as the number and distribution of ground control points should be carefully established.

2.2 Single-step Procedure: Modified Colinearity Equations

The single-step estimation of the lever-arm offsets and boresight angles (i.e., ROPs) among the cameras can be done by incorporating such parameters in the bundle adjustment procedure. One of the methods for doing that consists of extending existing bundle adjustment procedures with additional constraints. The second approach would be the direct incorporation of the ROPs among the cameras in the collinearity equations (i.e., through the modification of the conventional collinearity equations). The latter method has been already used for directly georeferenced single camera systems and for two-camera systems and has been adapted in this research for use in systems composed of several synchronized cameras since it is the most appropriate solution and allows for easier implementation. The mathematical model used is shown in Equation 5. The final form of the modified colinearity equations are shown in Equation 6 (here again, they are obtained by dividing the first two equations in Equation 5 by the third one after moving the image coordinates $x_j^{c_i}, y_j^{c_i}$ to the left side of the equations). The concept for the modification of the collinearity equations is that the exterior orientation parameters refer to the platform rather than

a specific image. More specifically, the platform position and orientation is defined by the reference camera ($r_{c_R}^G(t)$ and $R_{c_R}^G(t)$) and the position and orientation of the other cameras are defined relative to the reference camera, i.e., by $r_{c_i}^{c_R}$ and $R_{c_i}^{c_R}$, which represents the ROPs of the cameras with respect to the reference one. This way of implementation reduces the number of unknown parameters when compared to a traditional bundle adjustment procedure from *n_cam*n_epochs*6* to *n_epochs*6+6*(n_cam-1)* (where *n_cam* is the number of cameras and *n_epochs* is the number of epochs). Moreover, the invariant geometric relationship among the cameras is enforced, strengthening the accuracy of the estimated parameters.

$$r_j^G = r_{c_R}^G(t) + R_{c_R}^G(t) r_{c_i}^{c_R} + \lambda_j^{c_i} R_{c_R}^G R_{c_i}^{c_R} \begin{bmatrix} x_j^{c_i} - x_p{}^{c_i} - dist_x{}^{c_i} \\ y_j^{c_i} - y_p{}^{c_i} - dist_y{}^{c_i} \\ -c^{c_i} \end{bmatrix} \tag{5}$$

$$\begin{aligned} x_j^{c_i} &= x_p{}^{c_i} - c^{c_i}(N_x^{c_i} / D^{c_i}) + dist_x{}^{c_i} \\ y_j^{c_i} &= y_p{}^{c_i} - c^{c_i}(N_y^{c_i} / D^{c_i}) + dist_y{}^{c_i} \end{aligned} \tag{6}$$

where $N_x^{c_i} = f_{N_x^{c_i}}(r_j^G, r_{c_R}^G(t), R_{c_R}^G(t), r_{c_i}^{c_R}, R_{c_i}^{c_R})$;

$$N_y^{c_i} = f_{N_y^{c_i}}(r_j^G, r_{c_R}^G(t), R_{c_R}^G(t), r_{c_i}^{c_R}, R_{c_i}^{c_R});$$
$$D^{c_i} = f_{D^{c_i}}(r_j^G, r_{c_R}^G(t), R_{c_R}^G(t), r_{c_i}^{c_R}, R_{c_i}^{c_R}).$$

After deriving the linearized equations (Equation 7), the corrections to the approximate values of the unknown parameters $\hat{x}$ can be derived through Equation (8).

$$y = Ax + e \qquad e \sim (0, \Sigma) \quad \text{where } \Sigma = \sigma_o^2 P^{-1} \tag{7}$$

where *y:* is the *nx1* vector of differences between the measured and computed observations using the approximate values of the unknown parameters;
x: is the *mx1* correction vector to the approximate values of the unknown parameters;
A: is the *nxm* design matrix (i.e., partial derivative matrix w.r.t. the unknown parameters);
e: is the *nx1* vector of random noise, which is normally distributed with a zero mean and variance-covariance matrix Σ;
σ_o^2 : is the a-priori variance factor; and
P^{-1} : is the *nxn* weight matrix of the noise vector.

$$\hat{x} = (A^T PA)^{-1} A^T Py = N^{-1}C \tag{8}$$

The bundle adjustment procedure is implemented through a general Least Squares Adjustment (LSA) procedure, i.e., the involved quantities in the mathematical model can be treated either as unknowns, stochastic variables or error free (constant) parameters. Initially, all the quantities on the right side of Equations 6 are treated as unknowns. In order to treat a parameter as a stochastic variable, pseudo observation equations can be added for such parameter. On the other hand, to treat a specific parameter as a constant (e.g., the parameter corresponding to the ith row of *x*), zero values are set for all the elements occupying the ith row and ith column of the normal matrix (*N*) in Equation 8, except for the element occupying the ith diagonal element, which is set as a one. Also, the ith row of the *C* vector in Equation 8 is also set to zero. This implementation allows for the possibility of utilizing the same model for GPS/INS- assisted systems for the estimation of the lever-am offsets and boresight angles between the IMU body frame and the cameras. More specifically, the GPS/INS derived position and orientation can be used to define the position and the orientation of the platform, which are considered as observations (stochastic variables). In such a case, the terms $r_{c_R}^G(t)$ and $R_{c_R}^G(t)$ in Equation 5 should be regarded as the position and orientation of the IMU body frame: $r_b^G(t)$ and $R_b^G(t)$, respectively. Similarly, the terms $r_{c_i}^{c_R}$ and $R_{c_i}^{c_R}$ in Equation 5 should be regarded as the ROPs of the ith camera w.r.t. the IMU body frame: $r_{c_i}^b$ and $R_{c_i}^b$, respectively, as shown in Equation 9.

$$r_j^G = r_b^G(t) + R_b^G(t) r_{c_i}^b + \lambda_j^{c_i} R_b^G R_{c_i}^b \begin{bmatrix} x_j^{c_i} - x_p{}^{c_i} - dist_x{}^{c_i} \\ y_j^{c_i} - y_p{}^{c_i} - dist_y{}^{c_i} \\ -c^{c_i} \end{bmatrix} \tag{9}$$

3. EXPERIMENTAL RESULTS

In this section, experimental results using simulated data are presented to test the validity of the introduced single-step procedure. Moreover, a comparative analysis with the two-step procedure, which makes use of the traditional bundle adjustment procedure, is performed. The comparative analysis is performed in terms of the quality of the estimated ROPs (their precision and closeness to the simulated parameters) and the quality of the photogrammetric object space reconstruction.

3.1 Dataset Description

Figure 1 illustrates the simulated terrestrial multi-camera mobile mapping system along with the utilized definition for the ground and the image coordinate systems. The coordinate system definition was chosen to avoid correlations between omega and kappa in the conventional bundle adjustment (indirect geo-referencing) procedure, and correlations between omega and kappa and between the boresight angles Δω and Δκ in the indirect geo-referencing while enforcing the relative orientation constraint among the cameras (single-step procedure). The system consists of five cameras whose characteristics and interior orientation parameters are described in Table 1.

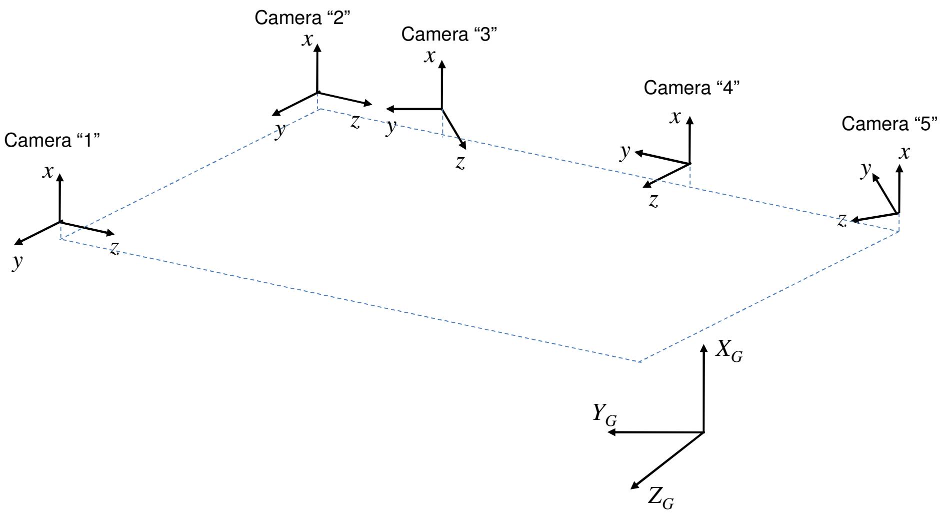

Fig. 1. Configuration of the simulated terrestrial MMS and the utilized definition for the ground and image coordinate systems

Tab. 1. Simulated camera IOP

Camera	CCD array size	Pixel size	Camera IOP*		
			x_p (mm)	y_p (mm)	c (mm)
"1"	7.1456 X 5.4296 mm	4.4µm	-0.0643	-0.0166	4.8691
"2"			-0.0588	-0.0923	4.8809
"3"			-0.1110	0.0911	6.1710
"4"			0.0224	0.0308	6.1729
"5"			0.0815	-0.0635	6.1750

* The simulated cameras have no inherent distortions.

To evaluate the impact of the data configuration geometry on the results from the two and single-step procedures two configurations are tested. The first tested configuration comprises 60 images acquired at 12 epochs from 4 different directions (refer to Figure 2). The second tested configuration, on the other hand, entails 30 images captured at 6 epochs from 2 different directions (Figure 3). The simulated object space is composed of well distributed points along four walls. Five control points with accuracy of ±5cm are used in the experiments for both configurations.

Tab. 2. Simulated lever-arm offsets and boresight angles w.r.t. Camera "1"

	Δω (deg)	Δφ (deg)	Δκ (deg)	ΔX (m)	ΔY (m)	ΔZ (m)
Camera "2"	1	-0.5	-2	-0.05	-1.45	0.05
Camera "3"	-41	-0.2	-1	-0.05	-1.50	0.60
Camera "4"	-89	2	-0.7	-0.05	-1.50	1.70
Camera "5"	-128	0.5	-0.4	-0.05	-1.45	2.45

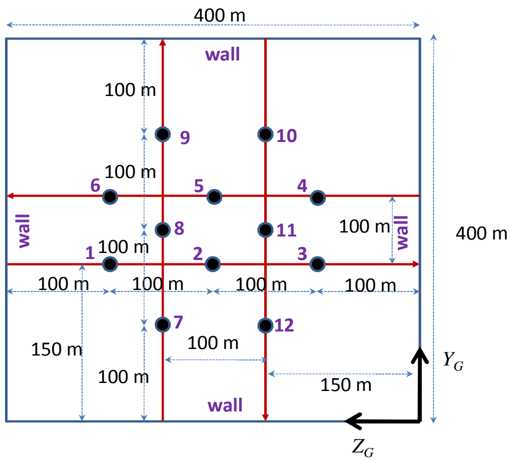

Fig. 2. Imaging configuration I

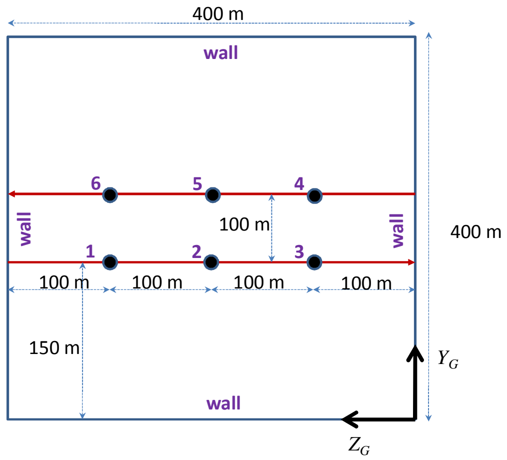

Fig. 3. Imaging configuration II

3.2 Results

Tables 3 and 4 present the results (i.e., the estimated ROPs among the cameras, their standard deviations, and their difference from the simulated parameters) from the conventional two-step and the proposed single-step procedures using configurations I and II, respectively. The impact on the photogrammetric object space reconstruction is evaluated through RMSE analysis (check point analysis using 350 check points), which are reported in Tables 5 and 6 for configurations I and II, respectively. In all experiments, camera "1" is taken as the reference camera (i.e., the position and the orientation of the platform refer to the position and orientation of camera "1"). The two-step procedure results were obtained using the derived EOPs from a conventional bundle adjustment (indirect geo-referencing) procedure using Equations 3 and 4. In the single-step procedure, the ROPs are estimated in the bundle adjustment procedure using the modified collinearity equations (Equation 6). Overall, the reported values in Tables 3 and 4 reveals improved results from the proposed single-step procedure when compared to the results from the two-step procedure, i.e., reduction in the standard deviations of the estimated parameters and closeness to the simulated parameters. Also, a closer look at those tables reveals a more significant improvement when configuration II is used (Table 4). The same behaviour is observed in terms of the quality of the object space reconstruction in Tables 5 and 6. The improved results when using the single-step procedure should be expected since the relative orientation constraint is explicitly enforced. Also, the larger improvement when using the proposed single-step procedure on a poorer geometric configuration (i.e., configuration II) is also expected since the two-step procedure is highly dependent on the geometric strength of the imaging configuration as well as the redundancy in the data acquisition.

Tab. 3. Simulated lever-arm offsets and boresight angles w.r.t. Camera "1" using configuration I

	Δω (deg± sec) Diff (sec)	**Δφ (deg± sec) Diff (sec)**	**Δκ (deg± sec) Diff (sec)**	**ΔX (m± m) Diff. (m)**	**ΔY (m± m) Diff. (m)**	**ΔZ (m± m) Diff. (m)**
Two-Step Procedure						
2	0.97878 ±131.0 -76.40	-0.51214 ±202.0 -43.69	-1.99917 ±48.1 2.98	0.04 ±0.1752 0.09	-1.45 ±0.1205 0.00	0.04 ±0.0690 -0.01
3	-40.94704 ±258.4 190.65	-0.20276 ±225.9 -9.95	-1.00556 ±155.9 -20.03	0.01 ±0.3206 0.06	-1.41 ±0.2432 0.09	0.61 ±0.1793 0.01
4	-89.00140 ±222.5 -5.03	2.00476 ±186.0 17.15	-0.70162 ±205.6 -5.85	-0.03 ±0.3142 0.02	-1.40 ±0.2180 0.10	1.59 ±0.2009 -0.11
5	-127.97194 ±224.7 101.03	0.52884 ±201.2 103.82	-0.40032 ±186.7 -1.14	0.01 ±0.2028 0.06	-1.53 ±0.2750 -0.08	2.35 ±0.2000 -0.10
Single-Step Procedure						
2	0.97546 ±34.6 -88.3	-0.50059 ±44.3 -2.1	-2.00420 ±13.5 -15.1	-0.04 ±0.0137 0.09	-1.45 ±0.0156 0.00	0.04 ±0.0256 -0.01
3	-40.99576 ±61.0 15.3	-0.19540 ±73.7 16.6	-1.00341 ±31.8 -12.3	-0.04 ±0.0221 -0.01	-1.53 ±0.0320 -0.03	0.60 ±0.0465 0.00
4	-89.01440 ±47.6 -51.8	2.00491 ±55.9 17.7	-0.70039 ±44.7 -1.4	-0.06 ±0.0238 -0.01	-1.50 ±0.0398 0.00	1.73 ±0.0383 0.03
5	-128.01093 ±59.9 -39.3	0.52393 ±65.4 86.1	-0.40435 ±37.3 -15.7	-0.02 ±0.0331 0.03	-1.49 ±0.0651 -0.04	2.43 ±0.0554 -0.02

Tab. 4. Simulated lever-arm offsets and boresight angles w.r.t. Camera "1" using configuration II

	Δω (deg± sec) Diff (sec)	**Δφ (deg± sec) Diff (sec)**	**Δκ (deg± sec) Diff (sec)**	**ΔX (m± m) Diff. (m)**	**ΔY (m± m) Diff. (m)**	**ΔZ (m± m) Diff. (m)**
Two-Step Procedure						
2	0.98510 ±248.3 -53.63	-0.51121 ±328.3 -40.34	-1.99896 ±16.3 3.74	-0.04 ±0.1995 0.01	-1.00 ±0.2570 0.45	0.26 ±0.1256 0.21
3	-40.88884 ±503.0 400.17	-0.20609 ±347.8 -21.92	-1.01302 ±175.5 -46.88	-0.22 ±0.2927 -0.17	-1.48 ±0.2960 0.02	0.49 ±0.1936 -0.11
4	-88.81986 ±446.4 648.50	1.97576 ±197.1 -87.25	-0.74197 ±345.7 -151.09	-0.20 ±0.1636 -0.15	-1.61 ±0.1846 -0.11	1.44 ±0.2233 -0.26
5	-127.90363 ±697.0 346.93	0.52421 ±240.0 87.15	-0.43335 ±292.5 -120.07	-0.32 ±0.2299 -0.27	-1.57 ±0.3347 -0.12	2.14 ±0.4006 -0.31

			Single-Step Procedure			
	0.99464	-0.49871	-1.99754	-0.05	-1.41	0.04
2	±59.2	±85.7	±22.9	±0.0305	±0.0298	±0.0585
	-19.3	4.6	8.9	0.00	0.04	-0.01
	-40.93311	-0.18745	-1.00512	-0.06	-1.47	0.51
3	±185.5	±157.5	±71.3	±0.0376	±0.0096	±0.0999
	240.8	45.2	-18.4	-0.01	0.03	-0.09
	-88.89261	1.97754	-0.72412	-0.05	-1.45	1.47
4	±167.4	±128.3	±132.0	±0.0582	±0.0847	±0.1173
	386.6	-80.9	-86.8	0.00	-0.05	-0.23
	-127.94220	0.50934	-0.42085	-0.01	-1.44	2.20
5	±242.0	±191.7	±150.3	±0.1130	±0.1778	±0.2015
	208.1	33.6	-75.1	0.04	-0.01	-0.25

Tab. 5. A-posteriori variance factor and RMSE Analysis using configuration I

	Two-step	**Single-step**
$(\sigma_o)^2$	$(0.0039)^2$	$(0.0039)^2$
RMS_X (m)	0.185	0.183
RMS_Y (m)	0.268	0.259
RMS_Z (m)	0.263	0.253
RMS_{TOTAL} (m)	0.418	0.406

Tab. 6. A-posteriori variance factor and RMSE Analysis using configuration II

	Two-step	**Single-step**
$(\sigma_o)^2$	$(0.0039)^2$	$(0.0039)^2$
RMS_X (m)	0.245	0.219
RMS_Y (m)	0.350	0.312
RMS_Z (m)	0.706	0.613
RMS_{TOTAL} (m)	0.825	0.722

4. CONLCUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

In this paper, a novel single-step procedure for the estimation of the ROPs among the cameras of a multi-camera MMS has been presented. The contributions of the proposed method can be summarized as follows: (i) The modified collinearity equations, which have been implemented in previous work for two-camera and directly georeferenced single camera systems only, is expanded in this research work to handle multi-camera systems, (ii) In contrast to the commonly-used additional constraints, the proposed method is much simpler, i.e., it does not require extensive partial derivatives as well as manual formatting of the camera pairs to be utilized in the relative orientation constraints (ROC), which might be cumbersome specially when the number of utilized cameras and the number of involved stations get larger, (iii) In the proposed single-step procedure, a reduction in the size of *N* matrix is obtained due to decreased number of unknown parameters, reducing the storage

and execution time requirements, (iv) The introduced method is developed to allow for a single-step estimation of two sets of ROPs (i.e., the ROPs among the cameras (when GPS/INS is not available) or the ROPs among the cameras and the IMU body frame).
Experimental results using simulated data have demonstrated that the proposed single-step procedure provides improved results in the precision of the estimated ROPs as well as in the object space reconstruction when compared to the two-step procedure. More significant improvements have been observed when the imaging configuration acquisition gets weaker. The single-step procedure provides more accurate results for the ROPs among the cameras due to the fact that the relative orientation constraint is explicitly enforced.
Future work will focus on more testing using simulated and real datasets from terrestrial and airborne systems to verify the performance of the proposed system/methods as well as investigating the optimum imaging and control configurations for reliable estimation of the ROPs. Also, future implementation will be extended to include previously estimated ROPs among the cameras as prior information when estimating the ROPs between the cameras and the IMU body frame in the developed single-step procedure. In other words, previously estimated relative orientation parameters among the cameras will be included as additional constraints during the single-step estimation of the mounting parameters relating the IMU body frame and involved cameras.

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