LONG TERM STABILITY ANALYSIS FOR A MULTI-CAMERA PHOTOGRAMMETRIC SYSTEM

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ABSTRACT

Multi-camera photogrammetric systems used in applications such as mobile mapping, vision-aided navigation, biomedical sciences and infrastructure health monitoring have become widespread with the falling cost of solid state sensors and the off-the-shelf availability of digital cameras. These photogrammetric systems require a system calibration, i.e., calibration for both the interior orientation parameters of each camera, and the mounting parameters of each camera with respect to a body frame or a reference camera. The frequency of the system calibration depends on the build quality and on any external factors such as the working environment and the handling of the system components. Since these systems include consumer grade components, which are not necessarily built for engineering applications, the frequency of calibration must be investigated as to avoid extra labour, but at the same time preserve the desired level of precision. This investigation can be achieved through a system stability analysis, where the effects of any changes in the interior or mounting parameters are quantified and compared to a threshold. This paper describes a multi-camera photogrammetric system built for a biomedical application and used in a hospital setting. The system description includes the plausible factors that might cause system instability from one calibration session to another. The system was calibrated (bi-)weekly for the duration of six months. This long term stability analysis data will be analysed in order to decide if the calibration frequency was adequate and also to consult on improving the stability of future system prototypes.

KEYWORDS: digital close range photogrammetry, multisensor systems, geometric system calibration, system stability analysis

INTRODUCTION

Modern photogrammetric systems often consist of multiple digital cameras, which are rigidly mounted to a stationary or a portable platform. In order to have precise reconstruction of the object space of interest, the multi-camera system must be accurately calibrated. Applications for which an accurate system calibration is imperative include direct sensor orientation (Rau et al., 2011), dense matching (Remondino et al., 2008), infrastructure health monitoring (Detchev et al., 2013; Kwak et al., 2013), biomedical engineering (Detchev et al., 2011; Lichti et al., 2015), multi-sensor integration (Tommaselli et al., 2013), underwater photogrammetry (Harvey and Shortis, 1996), and others. Ideally, a photogrammetric system should be calibrated prior to its every use. However, this may not be always practical or possible. Thus, the frequency of calibration for a particular system must be investigated. This investigation can be achieved through a methodology referred to as system stability analysis (Habib et al., 2014; Shortis et al., 2000).

This paper first reviews a method for multi-camera system calibration. Then, a method for system stability analysis is also explained. These methods are then applied to the calibration and stability analysis of a multi-camera photogrammetric system used for a biomedical application in a hospital setting over the period of six months. The objective of this research study is to find out whether the currently implemented frequency of calibration is adequate for the mount of use and the type of handling of the system.

GEOMETRIC SYSTEM CALIBRATION

A system calibration consists of the estimation of both the interior orientation parameters (IOPs) of each camera and the relative orientation parameters (ROPs) of each camera with respect to a body frame or a reference camera. The IOPs include the principal point offset (x_p, y_p), the principal distance (c), and any additional paremeters describing image space distortions (e.g., k_1, k_2, k_3, p_1, p_2, a_1, a_2). The ROPs, also known as the mounting parameters, define the positional $(r_{c_k}^{c_r})$ and rotational $(R_{c_k}^{c_r})$ offsets of a particular camera (c_k) to, in this case, the reference camera (c_r). The positional offset is a 3x1 vector $\left[\Delta X_{c_k}^{c_r} \quad \Delta Y_{c_k}^{c_r} \quad \Delta Z_{c_k}^{c_r}\right]^T$, while the rotational offset is a 3x3 rotational matrix, which is a function of $\Delta\omega_{c_k}^{c_r}$, $\Delta\varphi_{c_k}^{c_r}$, and $\Delta\kappa_{c_k}^{c_r}$.

In this paper, the IOPs and the ROPs, as well as the exterior orientation parameters (EOPs) of the reference camera, $r_{c_r}^m(t)$ and $R_{c_r}^m(t)$, and the object space coordinates of any tie points, r_I^m, are solved in a single-step all inclusive bundle adjustment using the mathematical model listed in equation (1) (Habib et al., 2014; Rau et al., 2011):

$$r_I^m = r_{c_r}^m(t) + R_{c_r}^m(t) r_{c_k}^{c_r} + \lambda R_{c_r}^m(t) R_{c_k}^{c_r} r_i^{c_k}(t) \tag{1}$$

Note that the ROPs are considered time-independent. In fact, in this mathematical model both the IOPs and the ROPs are assumed to be block invariant, i.e., they remain stable for at least the duration of a given data collection campaign. Also, the EOPs of the reference camera represent the EOPs of the system platform.

In the situations when a system is first set up or it is re-assembled after it has been transported from one location to another, it is obvious that a system calibration must be performed. However, sometimes changes to the system are caused by more subtle factors such as a change in the atmospheric conditions or slight vibrations due to everyday handling. In these situations a multi-camera system stability analysis should be used to evaluate the significance of the suspected changes. One way of performing this system stability analysis is described in the next section.

SYSTEM STABILITY ANALYSIS

The aim of a system stability analysis procedure is to assess whether using sets of IOPs and ROPs from two calibration sessions or from two calibration configurations affects the 3D reconstruction process. That is, do the 3D reconstruction results differ depending on the set of system calibration parameters used (see Figure 1)? The methodology presented here will simultaneously compare two IOP sets, $IOP_i(t_1)$ and $IOP_j(t_1)$ with $IOP_i(t_2)$ and $IOP_j(t_2)$, and two ROP sets, $r_{c_j}^{c_i}(t_1)$ and $R_{c_j}^{c_i}(t_1)$ with $r_{c_j}^{c_i}(t_2)$ and $R_{c_j}^{c_i}(t_2)$, for two cameras, c_i and c_j, estimated from two calibration sessions or configurations, t_1 and t_2.

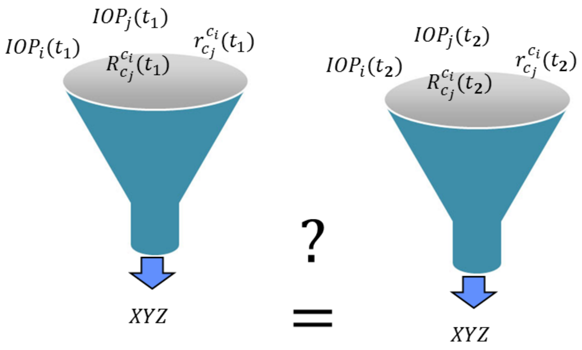
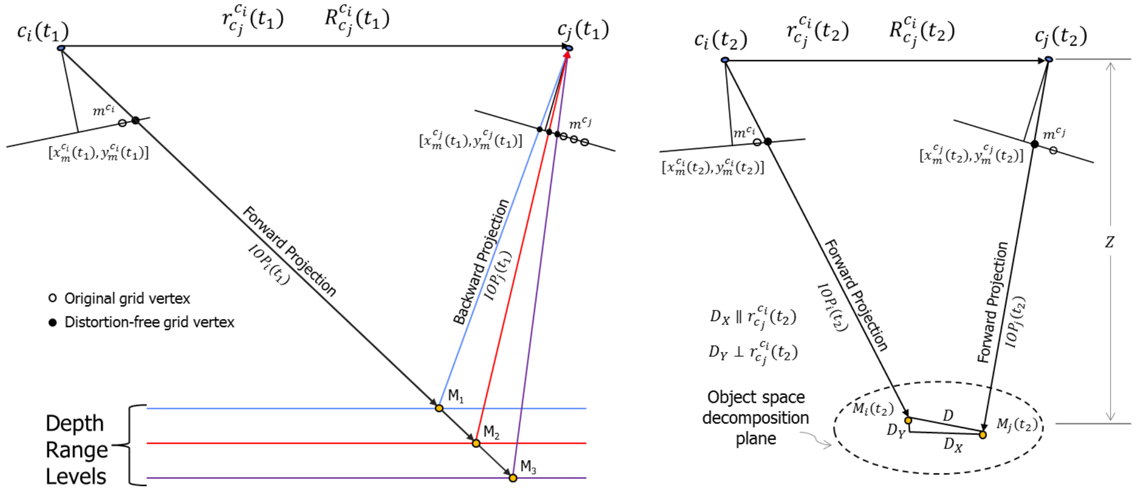


Figure 1. Conceptual diagram of system stability analysis

The methodology for system stability analysis is simulation-based, i.e., a synthetic grid in image space is used for evaluating the stability of the system parameters. However, the actual system parameters to be tested are real, not simulated. The method is briefly explained here:

- Define a synthetic regular grid in the image space of one of the cameras, c_i;
- Use the IOPs and ROPs of this camera from the first calibration session or configuration to remove the distortions at the grid vertices and compute the object space coordinates of each vertex by forward projecting them to a range of plausible object space depths (see Figure 2a);
- Compute the distortion-free image space coordinates of the grid points for the other camera, c_j, by backward projection using the IOPs and ROPs for the other camera from the first calibration session or configuration (see Figure 2a);
- Estimate the effect of the IOPs and ROPs obtained from another calibration session or configuration, in image units (i.e., pixels), for all simulated points and depth levels by computing the object space parallax (see Figure 2b). The object space parallax or discrepancy arising from the variations in the IOPs and ROPs for both cameras is evaluated by forward projecting the grid vertices within an object space plane (see Figure 2b). This object space parallax or discrepancy is decomposed into X- and Y-components, D_X and D_Y, where D_X is parallel, and D_Y is perpendicular to the baseline between the two cameras (see Figure 2b). These two components are then converted to image space units by scaling them with the ratio between the average principal distance, $c^{c_{ij}} = (c^{c_i} + c^{c_j})/2$, and the object space depth, Z;
- Compare the root mean squared error (RMSE) value for all the differences/offsets to the expected or required image space coordinate measurement precision; if the RMSE value is the smaller one, then the system is deemed stable or the two calibration configurations are considered compatible, and if the RMSE value is the greater one, the system would be deemed unstable or the two calibration configurations would not be considered compatible.

For more details on this method for system stability analysis one can refer to Habib et al. (2014).



(a) (b)

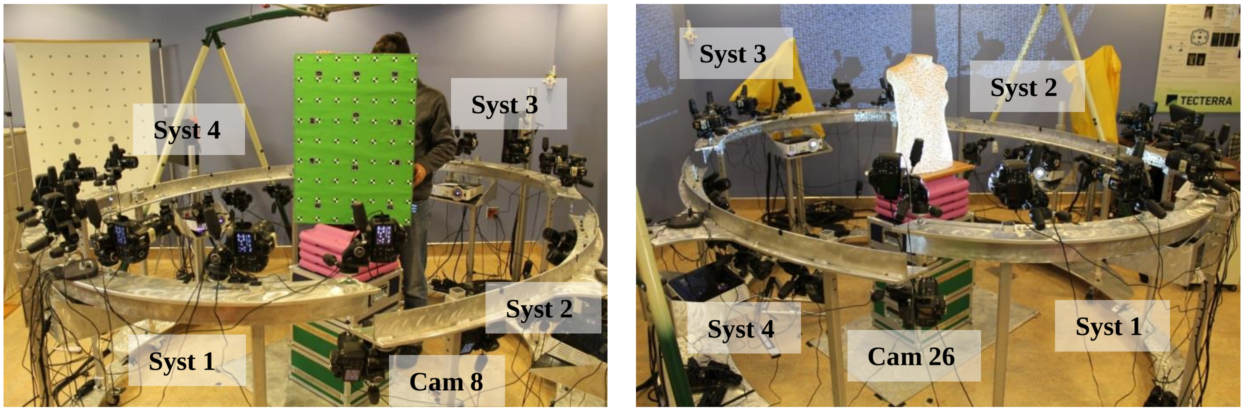
Figure 2. Forward and backward projections with the first set of system calibration parameters (a); forward projections with the second set of system calibration parameters for quantifying the object space parallax (b) (Habib et al., 2014)

PHOTOGRAMMETRIC SYSTEM DESCRIPTION AND USAGE

Four multi-camera photogrammetric systems were set up to be used for a biomedical application in a hospital setting. The application was related to monitoring the progression of scoliosis through modelling the outside surface of the human torso in three-dimensions (3D). System 1 (cameras #1 - #7) was used to image the back of the torso, System 2 (cameras #8 - #13) – one of the sides of the torso, System 3 (cameras #14 - #20) – the front of the torso, and System 4 (cameras #21 - #26) – the other side of the torso (see Figure 3). Each system consisted of six or seven

Canon EOS 1100D/Rebel T3 digital SLR cameras. This camera model had a 22.2 mm x 14.8 mm CMOS sensor divided into 4272 columns and 2848 rows of pixels or 12.2 mega pixels. The pixel size was approximately 5.2 µm x 5.2 µm. The principal distances of the lenses were set to the nominal value of 30 mm, and the lenses were focused to an approximate depth of 1.2 m. In order to minimize possible IOP instability, both the zoom and focus rings of the lenses were physically fixed with electrical tape. In addition, the automatic focus and image stabilization functions on the lenses were turned off. In order to avoid servicing the cameras as much as possible, AC adapters and USB cables were used. The AC adapters provided power without the need of recharging the camera batteries, and also there was no need to flip the on/off switches on the cameras. The USB cables provided a connection between the cameras and a computer. A custom Canon SDK software package was installed on the computer, which allowed for applying most of the relevant camera settings remotely, and also allowed for downloading the collected imagery without having to insert a memory card.

The cameras were attached to tripod heads with three degrees of freedom, which were bolted to one of four curved aluminum stands (see Figure 3). The stands were placed in a near circle such that there would be sufficient overlap between the point clouds coming from each system. This overlap would allow for the registration of the four point clouds to a single torso model. It should be noted that the stands rest on wheels, so that the systems could be wheeled in and out of a particular laboratory. Also, one of the systems, e.g., System 1, is being used as a door for the patients, medical staff and operators to move in and out of the imaged volume during data collection (see Figure 3).



(a) (b)

Figure 3. Setup of the four photogrammetric systems: overlap between System 1 and System 2; system calibration (a); overlap between System 4 and System 1; data collection (b)

The four systems are being used almost daily by non-photogrammetrists for 4-5 hours at a time. This type of frequent use of the systems leads to unknown and unpredictable changes to the ROPs and possibly the IOPs. Thus, relatively frequent calibrations, i.e., once or twice a week, help ensure that precise results can always be obtained. For detailed explanation of the implemented calibration routine, description of the calibration test field, the choice of coordinate system and datum definition, see Detchev et al. (2014).

LONG TERM STABILITY DATA ANALYSIS

The four photogrammetric systems were calibrated once or twice per week starting June 18 to December 19, 2014 with the exception of the period between August 15 and September 9, 2014, when there was no data collected. After every calibration session, the system calibration parameters were compared to the ones from the previous calibration session via the system stability methodology. The results for the four systems can be seen in Figure 4. Since the photogrammetric reconstruction applied on the imagery from these systems uses pixel level matching, it was decided that any root mean squared error (RMSE) value under two pixels would deem the two calibration sessions as stable. From Figure 4, it could be seen that only System 3 was completely stable during the entire duration of the data collection. This was not surprising as this system has not been moved at all since it was first installed. On the other hand, System 1, which served as a door for the patients, medical staff and system operators to enter or exit the imaged volume, was opened and closed multiple times during the data collection campaigns, and thus exhibited the most instability. System 2 and System 3 were generally stable with the exceptions of camera #8 and camera #26. Camera #8 is an end camera in System 2 (see Figure 3a), and it must have been disturbed on December 19, while camera #26 is an end camera in System 4 (see Figure 3b), and it must have been disturbed on three occasions in August, September and October.

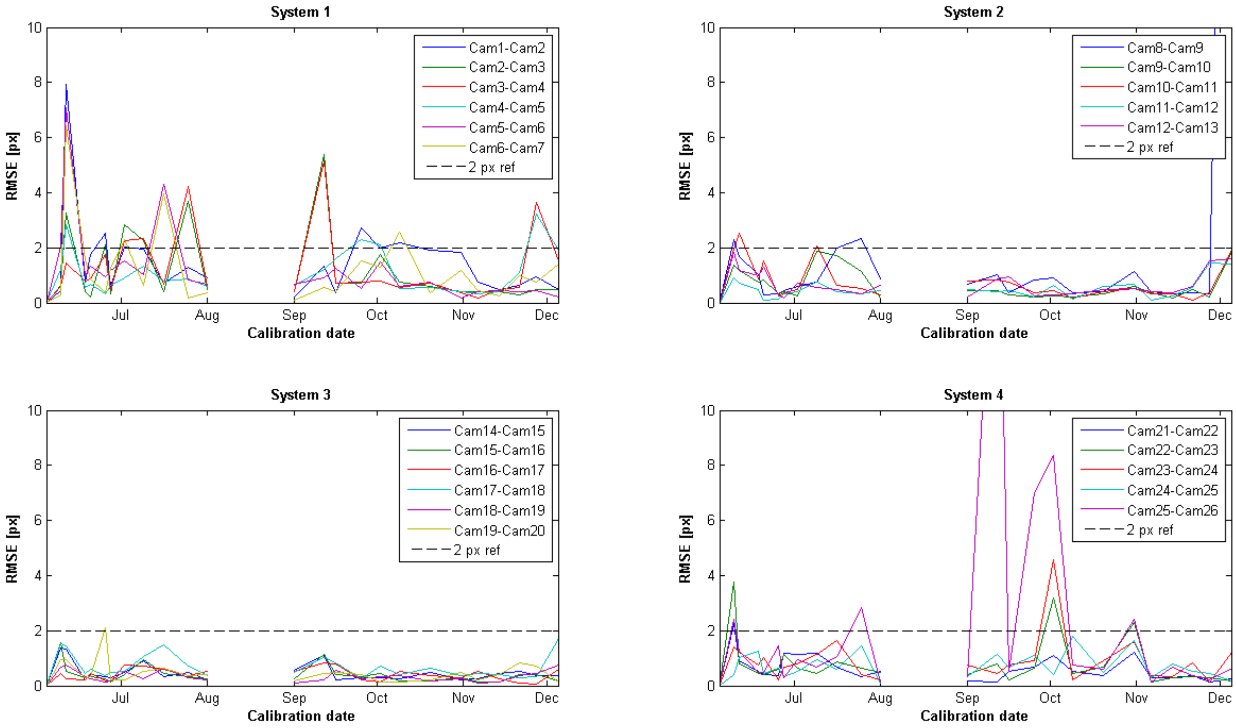


Figure 4. Results from the system stability analysis

In addition, the AC adapter for camera #7 failed to function before the data collection campaign was restarted in September. It had to be replaced, which required intrusive servicing. The change in the system calibration parameters before and after the adapter replacement is evident is Table 1.

Table 1. Example results from the system stability analysis

System # /	System 1: Aug 15 vs Sept 9, 2014		
Camera pairs	RMSE$_x$ [px]	RMSE$_y$ [px]	Total RMSE [px]
Cam1-Cam2	1.50	1.96	2.47
Cam2-Cam3	2.01	0.70	2.12
Cam3-Cam4	0.29	0.34	0.44
Cam4-Cam6	0.34	0.38	0.51
Cam5-Cam6	2.52	3.20	4.07
Cam6-Cam7	23.11	39.01	45.34

In order to minimize future instability, it would be recommended to shift camera #8 and camera #26 towards their neighbouring cameras, so that they do not extend past their respective metal stands (see Figure 3). This way they would not be disturbed by the patients or personnel going in and out of the imaged volume. In addition, extra support or more rugged wheels must be installed on System 1, so that its stability is not affected by its opening and closing. This system should also be calibrated more frequently than it currently is.

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

This paper reviewed a method for photogrammetric multi-camera geometric system calibration and a method for system stability analysis. The system stability analysis is a required methodology as it is not always possible or practical to re-calibrate a system before its every use. These two methodologies were used to calibrate and evaluate the stability of four photogrammetric systems used for a biomedical application in a hospital setting. Given the stability results, it is recommended to stabilize one of the four systems and calibrate it more frequently, and to also shift two of the cameras in two of the other systems. In terms of new methodology, future work will include solving for the system calibration parameters of all systems in a single adjustment. Also, work will be done to extract the most precise 3D models despite some of the evident instability of the system calibration parameters.

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