

COMPARISON OF BUNDLE ADJUSTMENT SOFTWARE FOR CAMERA CALIBRATION IN CLOSE RANGE PHOTOGRAMMETRY

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ABSTRACT

Camera calibration has always been an essential component of photogrammetric measurement. Nowadays, with self-calibration being an integral and routinely applied operation within photogrammetric triangulation, especially in high-accuracy close-range measurement. Photogrammetric camera calibration is usually carried out together with the calculation of object coordinates such as principal distance; principal point and lens distortion are usually determined by a self-calibrating bundle adjustment approach. There is a variety of bundle adjustment software for camera calibration that is available in the market nowadays. Basically, each of the software has their own capabilities to calibrate the camera. The user has to select appropriate and correct software to suite their needs. This paper discusses about the investigation and assessment of several bundle adjustment software used to calibrate digital camera. In this study, a test field was designed and fabricated. Then the digital camera is calibrated by using bundle adjustment software. Normally the camera calibration parameters comprise of the unknown parameters of the interior and exterior orientation and the 3D object coordinates. The quality of the result depends on many factors; however, the network configuration is among the most vital factor. After motion the differences of camera parameters determined by self-calibration bundle adjustment software are reported in this paper. In this study the result showed that the flexible and powerful tool for camera calibration using bundle block adjustment method is the Australis software.

Keywords: Close-Range Photogrammetry, Digital Camera, Camera Calibration, Bundle Adjustment, Test-field.

1. INTRODUCTION

Close range Photogrammetry is one of the methods used to describe the technique when the extent of the object to be measured is less than 100 meters and camera are positioned close to it (Cooper, 1996). Close range Photogrammetry is commonly applied to mapping of objects from a friction of a millimeter to a maximum limit of 300 meters (Anuar Ahmad and Zulkarnaini Mat Amin, 1998). The end products or derived quantity of close range may be position, shape, size, volume, angle and lack of flatness to name a few. In some instances, time may be computed which can yield speed, acceleration and deformation.

Close Range measurement technique may be applied to any object whose image can be obtained with different prospective views (Atkinson, 1996). Close range photogrammetry also can be applied into several sectors including industrial, hospitality, architecture and engineering. The result of close range photogrammetry must generally be made available very quickly after acquisition of the images so that they can use for further processing related to the measured objects and its function (Cooper, 1996).

There are a lot of cameras that can be used for close range photogrammetry, divide into two categories which are metric cameras and non-metric cameras. The most common way to classify cameras as metric and non-metric is by the existence or non-existence of fiducial marks. Non-metric cameras can be used for close range photogrammetry if the calibration of the camera is applied to get an accurate images (Atkinson, 1996).

Camera calibration is a main feature in photogrammetric object restitution. Calibration parameters such as principal distance, principal point and lens distortion are usually determined by a self-calibrating approach, i.e. they are calculated simultaneously with the object reconstruction by a bundle adjustment based on the collinearity equations and additional correction functions. The adjustment results in the unknown parameters of the interior and exterior orientation and the 3D object coordinates (Peipe, and Tecklenburg, 2006). This paper reports on the investigation and assessment of several bundle adjustment software used to camera calibration.

2. CAMERA CALIBRATION

Camera calibration may have several objectives, which are evaluation of the performance and stability of a lens, and determination of the optical and geometry parameters of lens, camera system and also an imaging data acquisition system (Fryer, 1996). The method of camera calibration used for close range photogrammetry cameras consist of on-the-job calibration, self-calibration and analytical plumb-line calibration (Fryer, 1996).

Accurate camera calibration and orientation procedures are a necessary prerequisite for the extraction of precise and reliable 3D metric information from images. A camera is considered calibrated if the principal distance, principal point offset and lens distortion parameters are known. In many applications, especially in computer vision (CV), only the focal length is recovered while for precise photogrammetric measurements all the calibration parameters are generally employed. Various algorithms for camera calibration have been reported over the years in the photogrammetry and CV literature. The algorithms are generally based on perspective or projective camera models, with the most popular approach being the well-known self calibrating bundle adjustment, which was first introduced to close range photogrammetry in the early 1970s (Remondino and Fraser, 2006).

2.1 CAMERA CALIBRATION METHODS AND MODELS

In photogrammetric terms, departures from collinearity can be modeled such that the basic equations of perspective projection can be applied for the calibration process. The nature of the application and the required accuracy can dictate which of two basic underlying functional models should be adopted:

- A camera model based on perspective projection, where the implication is that the IO is stable (at least for a given focal length setting) and that all departures from collinearity, linear and non-linear, can be accommodated. This collinearity equation-based model generally requires five or more point correspondences within a multi-image network and due to its non-linear nature requires approximations for parameter values for the least-squares bundle adjustment in which the calibration parameters are recovered.
- A projective camera model supporting projective rather than Euclidean scene reconstruction. Such a model, characterized by the Essential matrix and Fundamental matrix models, can accommodate variable and unknown focal lengths, but needs a minimum of 6 - 8 point

correspondences to facilitate a linear solution, which is invariably quite unstable. Nonlinear image coordinate perturbations such as lens distortion are not easily dealt with in such models.

2.2 CAMERA CALIBRATION IN COMPUTER VISION

The calibration models for machine and computer vision have traditionally employed reference grids, the calibration matrix \mathbf{K} being determined using images of a known object point array (e.g. a checkerboard pattern). Commonly adopted methods are those of Tsai (1987), Heikkila & Silven (1997) and Zhang (2000). These are all based on the pinhole camera model and include terms for modeling radial distortion.

Tsai's calibration model assumes that some parameters of the camera are provided by the manufacturer which to reduce the initial guess of the estimation. It requires n features points ($n > 8$) per image and solves the calibration problem with a set of n linear equations based on the radial alignment constraint. A second order radial distortion model is used while no decentering distortion terms are considered. The two-step method can cope with either a single image or multiple images of a 3D or planar calibration grid, but grid point coordinates must be known.

The technique developed by Heikkila & Silven (1997) first extracts initial estimates of the camera parameters using a closed-form solution (DLT) and then a nonlinear least-squares estimation employing a the Levenberg-Marquardt algorithm is applied to refine the IO and compute the distortion parameters. The model uses two coefficients for both radial and decentering distortion, and the method works with single or multiple images and with 2D or 3D calibration grids.

Zhang's calibration method requires a planar checkerboard grid to be placed at different orientations (more than 2) in front of the camera. The developed algorithm uses the extracted corner points of the checkerboard pattern to compute a projective transformation between the image points of the n different images, up to a scale factor. Afterwards, the camera interior and exterior parameters are recovered using a closed-form solution, while the third- and fifth-order radial distortion terms are recovered within a linear least-squares solution.

The term self-calibration (or auto-calibration) in CV is used when no calibration object is employed and the metric properties of the camera and of the imaged scene are recovered from a set of 'uncalibrated' images, using constraints on the camera parameters or on the imaged scene. Self-calibration is generally adopted in 3D modeling to upgrade a projective reconstruction to one that is metric (i.e. determined up to an arbitrary Euclidean transformation and a scale factor). In general, three types of constraints are applied (separately or in conjunction) to perform self-calibration: scene constraints, camera motion constraints, or constraints on the camera intrinsic parameters. All of these have been tried, but in the case of an unknown camera motion and unknown scene, only constraints on the IO can be used (Remondino and Fraser, 2006).

3. SELF-CALIBRATION

Self-calibration is an extension of the concept embodied in on-the-job calibration. The observations of discrete targeted points on the object are used as the data required for both object point determination and for the determination of the parameter of camera calibration (Fryer, 1996). Self-calibration used to determine the systematic error (interior orientation) simultaneously with other system parameters for example bundle block adjustment by using the concept of additional parameter estimation. Thus, self-

calibration is just one particular technique for estimating and compensating systematic error among any others (Gruen and Beyer, 2001).

The concept of self-calibration which is can be explain if single-frame camera data processed, for instance in CCD camera applications, the geometric sensor model is that of perspective projection, leading to the so – called “bundle adjustment method”. The bundle adjustment method is considered the most flexible, general and accurate sensor model. Long time before it became a standard procedure in aerial photogrammetry it was used in a variety of close range applications (Gruen and Beyer, 2001).

4. BUNDLE BLOCK ADJUSTMENT

Bundle adjustment is the problem of refining a visual reconstruction to produce jointly optimal 3D structure and viewing parameter (camera pose and/or calibration) estimates. Optimal means that the parameter estimates are found by minimizing some cost function that quantifies the model fitting error, and jointly that the solution is simultaneously optimal with respect to both structure and camera variations. The name refers to the ‘bundles’ of light rays leaving each 3D feature and converging on each camera center, which are ‘adjusted’ optimally with respect to both feature and camera positions.

Bundle adjustment is really just a large sparse geometric parameter estimation problem; the parameters being the combined 3D feature coordinates, camera poses and calibrations. Almost everything that we will say can be applied to many similar estimation problems in vision, photogrammetry, industrial metrology, surveying and geodesy. Adjustment computations are a major common theme throughout the measurement sciences, and once the basic theory and methods are understood, they are easy to adapt to a wide variety of problems (Triggs *et. al*, 2000).

The bundle adjustment provides a simultaneous determination of all system parameters along with estimates of the precision and reliability of the extracted calibration parameters. Also, correlations between the IO and exterior orientation (EO) parameters, and the object point coordinates, along with their determinability, can be quantified. The self-calibrating bundle adjustment can be performed with or without object space constraints, which are usually in the form of known control points. A minimal constraint to define the network datum is always required, though this can be through implicit means such as inner constraint, free-network adjustment, or through an explicit minimal control point configuration (arbitrary or real).

Calibration using a test field is possible, though one of the merits of the self-calibrating bundle adjustment is that it does not require provision of any control point information. Recovery of calibration parameters from a single image (and a 3D test field) is also possible via the collinearity model, though this spatial resection with APs is not widely adopted due to both the requirement for an accurate test field and the lower accuracy calibration provided (Remondino and Fraser, 2006).

One of the traditional impediments to wider application of the self-calibrating bundle adjustment outside the photogrammetry community has been the perception that the computation of initial parameter approximations for the iterative least-squares solution is somehow ‘difficult’. This is certainly no longer the case, and in many respects was never the case. As will be referred to later, self-calibration via the bundle adjustment can be a fully automatic process requiring nothing more than images recorded in a suitable multi-station geometry, an initial guess of the focal length (and it can be a guess), and image identifiable coded targets which form the object point array (Remondino and Fraser, 2006).

The advantages using bundle block adjustment method:

- **Flexibility:** Bundle adjustment gracefully handles a very wide variety of different 3D feature and camera types (points, lines, curves, surfaces, exotic cameras), scene types (including dynamic and articulated models, scene constraints), information sources (2D features, intensities, 3D information, priors) and error models (including robust ones). It has no problems with missing data.
- **Accuracy:** Bundle adjustment gives precise and easily interpreted results because it uses accurate statistical error models and supports a sound, well-developed quality control methodology.
- **Efficiency:** Mature bundle algorithms are comparatively efficient even on very large problems. They use economical and rapidly convergent numerical methods and make near-optimal use of problem sparseness. (Triggs *et. al*, 2000).

5. CALIBRATION TOOLS

In this study, the main tools that is used to calibrate the camera consist of calibration software, non-metric camera, and a test field.

5.1 CALIBRATION SOFTWARE - AUSTRALIS

The *Australis* photogrammetric software package is designed to perform highly automated off-line measurements from monoscopic / convergent digital image networks, either using digital cameras or scanned film imagery (Figure 1). It is equally useful for high-precision metrology applications using ‘metric’ digital cameras (or scanned imagery) or low- to moderate accuracy measurement employing off-the-shelf, amateur still video CCD cameras. Through the integrated image measurement, preliminary orientation and bundle adjustment functionality, one can quickly and easily obtain three dimensional object point coordinates and sensor calibration data from multi-sensor, multi-image networks of an effectively unlimited number of object points. Moreover, depending on the provision of an exterior orientation (EO) device and high contrast targets, the photogrammetric orientation/ triangulation and calibration processes can be carried out fully automatically, in semiautomatic mode, or even with manual image point measurement and a more sequential processing flow. *Australis* is thus ideal for the teaching of photogrammetric principles and practices and it a valuable tool in both research and for practical measurement applications.

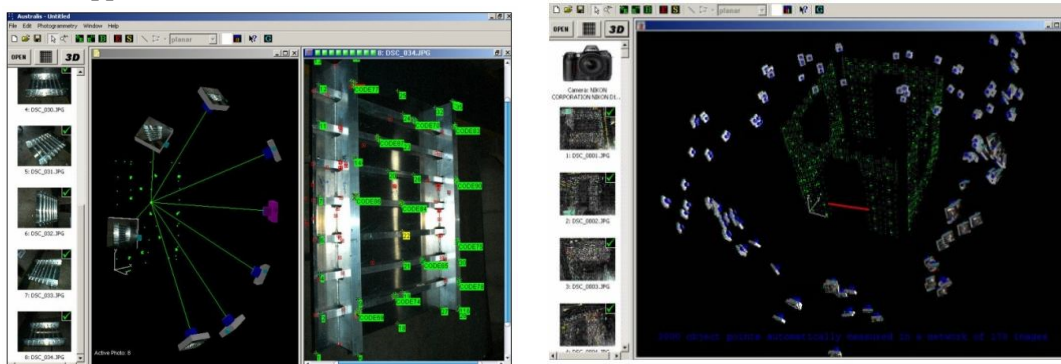


Figure 1: Australis Software

5.2 NON-METRIC CAMERA

There are two types of cameras that can be used for close range application that is metric camera and non-metric camera. Camera are classify as non-metric camera when the internal geometry is not stable and unknown, as is the case with any “normal” commercially available camera. However, these can be very expensive and technically highly developed professional photographic devices. Photographing a test field with many control points and at a repeatable fixed distance setting (for example at infinity), a “calibration” of the camera can be calculated. In this case, the four corners of the camera frame function as fiducials. However, the precision will never reach that of metric cameras. Therefore, they can only be used for purposes, where no high accuracy is demanded. But in many practical cases such photography is better than nothing, and very useful in cases of emergency. The non-metric cameras consist of digital camera, video camera and digital SLR camera. In this study, Nikon D70 and Canon Digital Ixus950 IS digital cameras are used. Figure 2 shows several make and model of non-metric cameras and Table 1 shows their respective specification.



Figure 2: Non-metric camera using for close range application

Table 1: Specification of the non-metric camera

	Nikon D1	Nikon D70	Olympus CAMEDIA E-10	Canon Digital Ixus 950 IS
Image sensor	23.7 x 15.6 mm RGB CCD	23.7 x 15.6 mm RGB CCD	Type 2/3 RGB CCD	Type 1/1.8 RGB CCD
Unit cell size in μm	11.8 x 11.8	7.8 x 7.8	3.9 x 3.9	3.6 x 3.6
Number of recording pixel	2,000 x 1,1312	3,008 x 2,000	2,240 x 1,680	1,600 x 1,200
Lens	24 mm, F2.8	24 mm, F2.8	9-36 mm, F2.0-2.4	5.8-13mm, F2.8

5.3 TEST FIELD

The comparison between different camera and software of camera calibration will be performing using a test field. There is variety of test field that can be used such as calibrate plate.

In this study, a simple calibration plate consists of straight lines on the edges, a scale bar with at least one known reference distance, and 66 targets is used (Figure 3). These targets do not have to be known by their coordinates. Assuming that an image is taken by aiming the camera perpendicularly to the plate center, camera constant can be determined by scaling. For this purpose we will measure the distance between the camera and the calibration plate, and the length of the reference distance on the image. The straight lines on the edges will be then used for defining the radial and decentering optical distortions.

After a good approximation for radial and decentering distortions, the values for the rest of the calibration unknowns will be estimated based on collinearity equations. For this purpose we take four pairs of convergent images from the plate. Within each pair the camera should be rotated 90° . The parameters of decentering distortion will be kept fixed during the bundle adjustment. The procedure is iterative and should be repeated until the principal point is determined with sufficient accuracy.

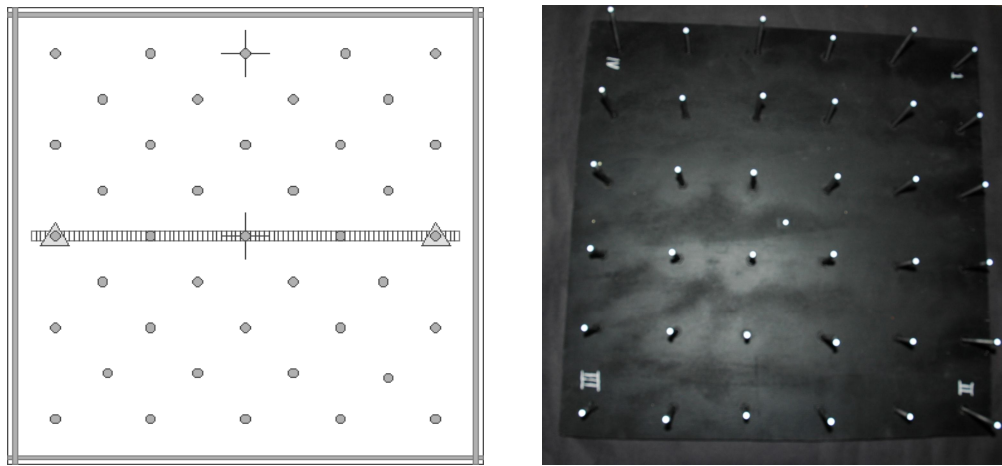


Figure 3: Calibration Plate

6. ANALYSIS AND RESULT

In this study, we used camera with different resolution which is Nikon SLR D70 and Canon IXUS 950 IS. Five round of camera calibration for each camera were conducted. Each round of camera calibration utilizes a set of 8 images (4 normal images and 4 rotated 90° images). All the images processed using camera calibration software which is Australis. This study is carried out to investigate the precision of calibration results of non-metric camera.

6.1 Camera Calibration Using Australis

Within the self calibration bundle adjustment of Australis, parameter values can be constrained via initially assigned standard error. The result of the calibration, as assessed by the resulting RMSE of image coordinates observations and RMSE of object point XYZ coordinates against their true values, are listed in Table 2. The main quality indicator of the calibration is the RMSE values of object point coordinates in Table 2 and here it can be seen that the bundle adjustments yield superior results. The differences in the RMSE residuals between the centre of gravity due to high values registered on the retro-reflective targets

Table 2: RMSE and Sigma from the different camera.

CAMERA	RMSE (μm)	Sigma	RMSE_XYZ
NIKON D70	0.362	0.86	0.014/0.014/0.035
CANON IXUS 950 IS	0.22	0.53	0.020/0.018/0.069
CANON IXUS 950 IS (shake)	0.228	0.546	0.022/0.021/0.078

6.2 Inner Orientation Parameters

The geometry of the photogrammetric network has an important role in the process of recovering the inner orientation parameters. The convergent configuration network enables recovery of the additional inner orientation parameters for the camera as shown in Table 3. If the estimated values are smaller than the standard error, then the estimated parameters are statistically insignificant and the least square solution is over parameterized. Insignificant additional parameters are due to high correlation between estimated parameters, typically attributable to weak geometry (Anuar Ahmad and Chandler, 1999).

In this study, parameters of the focal length need to be calibrated to obtain the exact value of focal length for the cameras. When the camera captured the images; the lenses are not stable and will give a different value of the focal length. Principal point also can be calibrated using the calibration software. The results of the camera calibration shown for the non-metric cameras are not stable. Table 3 shows the inner orientation parameters for two non-metric cameras.

Table 3: Inner Orientation parameters for D70 and IXUS 950 cameras

Camera	Focal Length (mm)	Xp	Yp	X	Y	K1	K2	K3	P1	P2
D70	16.1626	0.1695	0.0563	0.014	0.014	0.0007847	-0.00000714	0.000000107	-0.00006721	-0.00004683
IXUS 950	5.907	0.1079	-0.3033	0.019	0.018	0.005492	-0.0001283	0.000000407	-0.00002055	-0.00009129
IXUS 950 (shake)	5.953	0.1172	-0.3945	0.02	0.019	0.005274	-0.0000832	-0.000004027	-0.000002228	-0.00010513

7. CONCLUSION

From this study, by comparing the two non-metric cameras it was found that the results of Nikon D70 are much better than the Canon IXUS 950 (i.e based on the RMSE). The results also showed different values for the Inner Orientation parameters for the two non-metric cameras. For the Canon IXUS 950, the results showed slight differences in the RMSE even though the camera is shake.

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