Digital camera calibration methods
Considerations and comparisons

DIGITAL CAMERA CALIBRATION METHODS:
CONSIDERATIONS AND COMPARISONS

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Commission V, WG V/1

KEY WORDS: Camera calibration, Accuracy, Zoom, Distortion

ABSTRACT:

Camera calibration has always been an essential component of photogrammetric measurement, with self-calibration nowadays being an integral and routinely applied operation within photogrammetric triangulation, especially in high-accuracy close-range measurement. With the very rapid growth in adoption of off-the-shelf digital cameras for a host of new 3D measurement applications, however, there are many situations where the geometry of the image network will not support robust recovery of camera parameters via on-the-job calibration. For this reason, stand-alone camera calibration has again emerged as an important issue in close-range photogrammetry, and it also remains a topic of research interest in computer vision. This paper overviews the current approaches adopted for camera calibration in close-range photogrammetry and computer vision, and discusses operational aspects for self-calibration. Also, the results of camera calibrations using different algorithms are summarized. Finally, the impact of chromatic aberration on modelled radial distortion is touched upon to highlight the fact that there are still issues of research interest in the photogrammetric calibration of consumer-grade digital cameras.

1. INTRODUCTION

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. Analytical camera calibration was a major topic of research interest in photogrammetry over the next decade, though in research terms is attracts less attention today.

One plausible reason for camera calibration not being a current 'hot' research topic is certainly that analytical self-calibration in many respects reached maturity in the mid 1980s. Self-calibration was also of research interest in the early days of digital cameras, but maturity could be said to have again been reached in the mid 1990s with the development of fully automated vision metrology systems (e.g. Ganci & Handley, 1998). In such systems, calibration parameters are essentially viewed as 'nuisance parameters', which are necessary but not of any great interest in their own right. This has recently changed, however, with the application of consumer-grade digital cameras to a host of measurement tasks in which the network geometry is not conducive to self-calibration. These include accident reconstruction and some heritage recording projects, for example. There is consequently a renewed interest in stand-alone photogrammetric calibration approaches, especially fully automatic calibration.

Camera calibration continues to be an area of active research within the CV community, with a perhaps unfortunate characteristic of much of the work being that it pays too little heed to previous findings from photogrammetry. Part of this might well be explained in terms of a lack of emphasis on (and interest in) accuracy aspects, and a basic premise that nothing whatever needs to be known about the camera which is to be 'calibrated' within a linear projective rather than Euclidean scene reconstruction.

Much could be said on the continued misrepresentation of photogrammetric approaches in CV literature as being complex and not amenable to full process automation, the handling of zoom lenses, or unstable interior orientation (IO), etc. However, such issues will not be addressed here and the authors will concentrate upon camera calibration techniques that have potential for practical application. In many respects it is difficult to comprehensively compare calibration approaches from the two communities, since the focus of attention can be so different in each. Whereas a photogrammetric calibration might be designed to support a subsequent object space measurement demanding 1:20,000 accuracy, a calibration requirement for a structure from motion application may need to position object points to an accuracy of only, say, 5% of the camera-to-object distance. The focus of this paper will be upon calibration approaches that lend themselves to photogrammetric application, even at a low accuracy level.

There is an extensive body of literature on the calibration of digital cameras, with topics ranging from overall reviews (Fryer, 1996; Fraser, 2001) to general investigations (Bösemann et al., 1990; Fraser & Shortis, 1995; Jantos et al., 2002), low-cost digital cameras (Kunii & Chikatsu, 2001; Läbe & Förstner, 2004; Cronk et al., 2006), stability of parameters (Shortis & Beyer, 1997; Peipe & Stephani, 2003; Läbe & Förstner, 2004), behaviour of IO parameters (Wiley & Wong, 1995; Läbe & Förstner, 2004) and accuracy aspects (D'Apuzzo & Maas,

1999; Salvi et al., 2002; Fraser & Al-Ajlouni, 2006). In order to recall and reiterate salient and occasionally overlooked principles of camera calibration, common models and methods employed will now be reviewed, with selected algorithms being tested and the results analyzed.

2. CALIBRATION METHODS AND MODELS

In photogrammetric terms, departures from collinearity can be modelled 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. Non-linear image coordinate perturbations such as lens distortion are not easily dealt with in such models.

Further criteria can also be used to classify camera calibration methods:

- Implicit versus explicit models. The photogrammetric approach, with its explicit physically interpretable calibration model, is contrasted against implicit models used in structure from motion algorithms which correct image point positions in accordance with alignment requirements of a real projective mapping (Hall et al., 1982; Wei & De Ma, 1994).

- Methods using 3D rather than planar point arrays (Triggs, 1998; Zhang, 2000). Whereas some CV methods and photogrammetric self-calibration can handle both cases – with appropriate network geometry – models such as the Essential matrix cannot accommodate planar point arrays.

- Point-based versus line-based methods (Fryer and Brown, 1986; Caprile & Torre, 1990). Point-based methods are more popular in photogrammetry, with the only line-based approach of note, namely plumbline calibration, yielding parameters of lens distortion, but not of IO.

A more specific classification can be made according to the parameter estimation and optimization technique employed:

- Linear techniques are quite simple and fast, but generally cannot handle lens distortion and need a control point array of known coordinates. They can include closed-form solutions, but usually simplify the camera model, leading to low accuracy results. The well-known DLT (Abdel-Aziz & Karara, 1971), which is essentially equivalent to an Essential matrix approach, exemplifies such a technique.

- Non-linear techniques such as the extended collinearity equation model, which forms the basis of the self-

calibrating bundle adjustment, are most familiar to photogrammetrists. A rigorous and accurate modelling of the camera IO and lens distortion parameters is provided (Brown, 1971) through an iterative least-squares estimation process.

- A combination of linear and non-linear techniques where a linear method is employed to recover initial approximations for the parameters, after which the orientation and calibration are iteratively refined (Faugeras & Toscani, 1986; Tsai, 1987; Weng et al., 1992; Heikkilä & Silven, 1997). This two-stage approach has in most respects been superceded for accurate camera calibration by the bundle adjustment formulation above, which is also implicitly a two-stage process.

3. CAMERA CALIBRATION IN COMPUTER VISION

The calibration models for machine and computer vision have traditionally employed reference grids, the calibration matrix **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 modelling radial distortion.

Tsai's calibration model assumes that some parameters of the camera are provided by the manufacturer, 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. A final non-linear minimization of the reprojection error, solved using a Levenberg-Marquardt method, refines all the recovered parameters. Zhang's approach is quite similar to that of Triggs (1998), which requires at least 5 views of a planar scene.

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 modelling 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.

The majority of the so-called self-calibration algorithms described in the CV literature treat intrinsic camera parameters as constant but unknown (Faugeras et al., 1992; Hartley, 1994; Pollefeys & Van Gool, 1996; Heyden & Åström, 1996; Triggs, 1997). The problem of variable IO parameters has also been studied by Pollefeys et al. (1997) and Heyden & Åström (1997). Self-calibration can be problematic with certain critical motion sequence networks (Sturm, 1997), where the motion of the camera is not generally sufficient to allow for the recovery of calibration parameters and an ambiguity remains in the 3D reconstruction. Moreover only the focal length is usually determined while lens distortion and other internal parameters are neglected, assumed known, or considered as unknown and are recovered without any statistical testing for significance.

From the foregoing discussion, one feature of CV approaches to camera calibration is apparent: there is at yet no accepted one-step method that is either reasonably universal or amenable to full automation. This is not really surprising given the imaging hardware characteristics (e.g. variable zoom lenses) and image geometries adopted across the spectrum of CV applications.

4. PHOTOGRAMMETRIC CAMERA CALIBRATION

4.1 Overview

Different camera models have been formulated and used in close-range photogrammetry, but generally sensor orientation and calibration is performed with a perspective geometrical model by means of the bundle adjustment (Brown, 1971). A review of methods and models of the last 50 years is provided in Clarke & Fryer (1998). The basic mathematical model is provided by the non-linear collinearity equations, usually extended by correction terms (i.e. additional parameters or APs) for the IO and radial and decentering lens distortion (Fraser, 1997; Gruen & Beyer, 2001). 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.

A favourable network geometry is required, i.e. convergent and rotated images of a preferably 3D object should be acquired, with well distributed points throughout the image format. If the network is geometrically weak, correlations may lead to instabilities in the least-squares estimation. The use of inappropriate APs can also weaken the bundle adjustment solution, leading to over-parameterisation, in particular in the case of minimally constrained adjustments (Fraser, 1982).

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 testfield 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 testfield) 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 testfield and the lower accuracy calibration provided.

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.

4.2 The Additional Parameters (APs)

The most common set of APs employed to compensate for systematic errors in CCD cameras is the 8-term 'physical' model originally formulated by Brown (1971). This comprises IO parameters of principal distance and principal point offset (x_p, y_p), as well as the three coefficients of radial and two of decentering distortion. The model can be extended by two further parameters to account for affinity and shear within the image plane, but such terms are rarely if ever significant in modern digital cameras. Numerous investigations of different sets of APs have been performed over the years (e.g. Abraham & Hau, 1997), yet this model still holds up as the optimal formulation for digital camera calibration.

The three APs used to model radial distortion Δr are generally expressed via the odd-order polynomial $\Delta r = K_1 r^3 + K_2 r^5 + K_3 r^7$, where r is the radial distance. A typical Gaussian radial distortion profile Δr is shown in Figure 1, which illustrates how radial distortion can vary with focal length. The coefficients K_i are usually highly correlated, with most of the error signal generally being accounted for by the cubic term $K_1 r^3$. The K_2 and K_3 terms are typically included for photogrammetric (low distortion) and wide-angle lenses, and in higher-accuracy vision metrology applications. The commonly encountered third-order barrel distortion seen in consumer-grade lenses is accounted for by K_1. Recent research has demonstrated the feasibility of empirically modelling radial distortion throughout the magnification range of a zoom lens as a function of the focal length written to the image EXIF header (Fraser & Al-Ajlouni, 2006).

Decentering distortion is due to a lack of centering of lens elements along the optical axis. The decentering distortion parameters P_1 and P_2 (Brown 1971) are invariably strongly projectively coupled with x_p and y_p. Decentering distortion is usually an order of magnitude or more less than radial distortion and it also varies with focus, but to a much less extent, as indicated by the decentering distortion profiles shown in Figure 1. The projective coupling between P_1 and P_2 and the principal point offsets increases with increasing focal length and can be problematic for long focal length lenses. The extent of coupling can be diminished through both use of a 3D object point array and the adoption of higher convergence angles for the images.

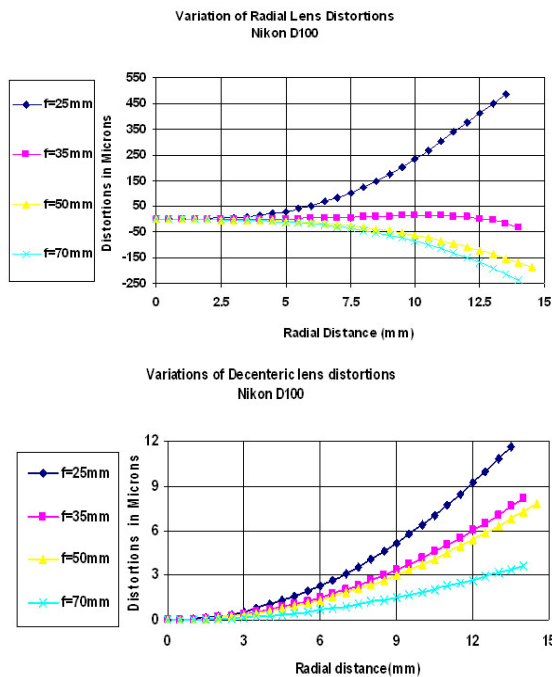**Variation of Radial Lens Distortions**
Nikon D100

Figure 1. Radial and decentering distortion profile for a digital camera set at different focal length.

Within the bundle adjustment, the APs can be treated as:

- Camera- or focal setting-invariant, where one set of APs is used for all images from either a given camera or given focus setting in a multi-sensor self-calibration which incorporates, say, different zoom settings from the same camera. This is the most common AP arrangement and it can be applied to multi-camera as well as to single-camera self-calibration.

- Frame-variant, where a set of APs is used for each image, usually as a consequence of having a network formed by images from different cameras or where each image might have been acquired at a different zoom setting (Remondino & Borlin, 2003), as in robotics or machine vision inspections. The adoption of frame- or image-specific APs can be very problematic due to the strong prospects for over-parameterisation and network adjustment singularities. This approach should be avoided unless there is a 3D testfield with control points in place.

It is also possible to carry a combination of camera-invariant and image-variant APs, though there seems less practical justification for this with modern digital cameras. The approach was used in the past to model both frame-specific image deformation, and to constrain variations in lens distortion to be linear in multi-focal setting self-calibration (Fraser, 1980).

The procedure of self-calibration using APs introduces new observations and unknowns into the bundle adjustment, which can influence the quality of the functional and stochastic model. The improper use of APs can weaken the condition of the normal equation system and adversely affect the determinability of all system parameters. Therefore, a statistical testing of APs is recommended (Gruen, 1981). This is especially so in cases where the network geometry is not optimal for system calibration or there is a strong likelihood of excessive projective coupling between the APs themselves, or between the APs and the EO parameters (high correlation between the APs and the object point coordinates is rarely an issue of concern).

5. PROJECT CONSIDERATIONS

Critical to the quality of the self-calibration is the overall network geometry, and especially the camera station configuration. Various experimental studies in close-range photogrammetry (e.g. Fraser, 1996; Fryer, 1996; Clarke et al., 1998; Gruen & Beyer, 2001; El-Hakim et al., 2003) have confirmed that:

- The accuracy of a network increases with increasing convergence angles for the imagery. Increasing the angles of convergence also implicitly means increasing the base-to-depth (B/D) ratio.

- Accuracy is enhanced by increasing the number of rays to a given object point, though the rate of improvement is proportional to the square root of the number of images 'seeing' the point. Thus, the gains in precision effectively level off after, say, 8 rays per point.

- Accuracy increases with the number of measured points per image, but the incremental improvement is small beyond a few tens of points. More important is that extra points within an image offer better prospects for modelling departures from collinearity throughout the full image format.

- Self-calibration is only reliable when the network geometry is favourable, i.e. the camera station configuration comprises highly convergent images, orthogonal roll angles and a large number of well distributed object points. A compensation for departures from collinearity might well be achieved in a bundle adjustment with APs for a weak network, but the accurate and reliable recovery of representative calibration values is less likely to be obtained.

- A planar object point array can be employed for camera calibration if the images are acquired with orthogonal roll angles, a high degree of convergence and, desirably, varying object distances. What is sought is the maximum possible imaging scale variation throughout the image format.

- As mentioned, orthogonal roll angles must be present to break the projective coupling between IO and EO parameters. Although it might be possible to achieve this decoupling without 90° image rotations, through provision of a strongly 3D object point array, it is always recommended to have 'rolled' images in the self-calibration network.

6. EXPERIMENTAL TESTS

Selected results of experimental self-calibration tests are presented in this section, with three issues being briefly covered. The first is the distinction in attainable accuracy between the CV and photogrammetric approaches. The second highlights the often overlooked problems associated with inappropriate network geometry for calibration, and the third is included to illustrate that there remain issues of research interest in camera parameter modelling.

6.1 Camera calibration using a 3D object

A comparison between different methods was carried out using a 3D testfield and 10 images acquired with a Leica Digilux 1 digital camera at an image resolution of 1120 x 840 pixels. The 3D object point array and camera station geometry are illustrated in Figure 2. The focal length was fixed at minimum zoom (widest angle) and the network included four images with

±90° roll angles. The following camera calibration software suites or algorithms were employed:

- DLT (Abdel-Aziz & Karara, 1971), implemented at IGP-ETH Zurich, without distortion corrections.

- Tsai (Tsai, 1987), with the first term of radial distortion correction; accessed via www-cgi.cs.cmu.edu/afs/cs.cmu.edu /user/rgw/www/TsaiCode.html.

- Heikkila (Heikkila & Silven, 1997), with the 2 terms for both radial and decentering distortion correction; available at www.ee.oulu.fi/~jth/calibr/.

- Photomodeler (www.photomodeler.com), with full set of APs, without control points.

- Australis (www.photometrix.com.au), with full set of APs, in free-network mode.

- SGAP, implemented at IGP-ETH Zurich, with full set of APs, in free-network mode.

Within the self-calibration process of Photomodeler, Australis & SGAP, parameter values can be constrained via initially assigned standard errors, while few options are available for the other methods. The results of the calibrations, as assessed by the resulting RMSE of image coordinate observations (triangulation misclosures) and RMSE of object point XYZ coordinates against their true values, are listed in Table 2. The recovered radial distortion profiles from each solution are also shown in Figure 2, but it should be recalled that from a photogrammetric standpoint the main quality indicator of the calibration is the RMSE values of object point coordinates (Table 2) and here it can be seen that the bundle adjustments yield superior results.

Software/algorithm	RMSE_xy (μm)	RMSE_XYZ (mm)
DLT	39.7	0.287
Tsai	0.29	0.033
Heikkila	0.34	0.036
Bundle adjustments		
PhotoModeler	0.36	0.01/0.01/0.02
Australis	0.29	0.01/0.01/0.02
SGAP (IGP-ETHZ)	0.30	0.01/0.01/0.02

Table 1. Object point accuracy and residuals from the different calibration computations.

6.2 Camera calibration using a planar target array

A further camera calibration test was also performed, this time with a planar object point array, namely a black and white checkerboard pattern. The image data was obtained from http://www.vision.caltech.edu/bouguetj/calib_doc/, where a camera calibration toolbox developed by J.V. Bouguet from Caltech is available. The 25 images used had resolutions of 640 x 480 pixels. In this instance the camera was fixed and the planar point field, shown in Figure 3, was moved through various orientations – though notably without any 90° rotations.

Self-calibrations for this test were again carried out using Photomodeler, Australis, SGAP and the methods of Tsai and Heikkila, and the Zhang method was also applied. Although the recovered camera parameters were quite similar, the statistical quality measures available in Australis and SGAP indicated that the network is essentially singular because of the lack of roll

angle variation. This leads to very high projective coupling between the IO and EO parameters. In fact, one can essentially substitute any plausible value for the principal point offset (x_p, y_p) and a satisfactory and close to constant RMSE of residuals (between 0.57 and 0.63 microns) will be obtained, as indicated in Figure 3. The same is true for the decentering distortion parameters P_1 and P_2, and their inclusion or omission makes no difference to the recovered RMSE values of image residuals. This means that the network (without rotated images) can accommodate any principal point offset (within reason) and therefore it does not have the strength to recover the 'true values'. This renders the 'calibration' process essentially worthless if scene independent camera parameters are sought.
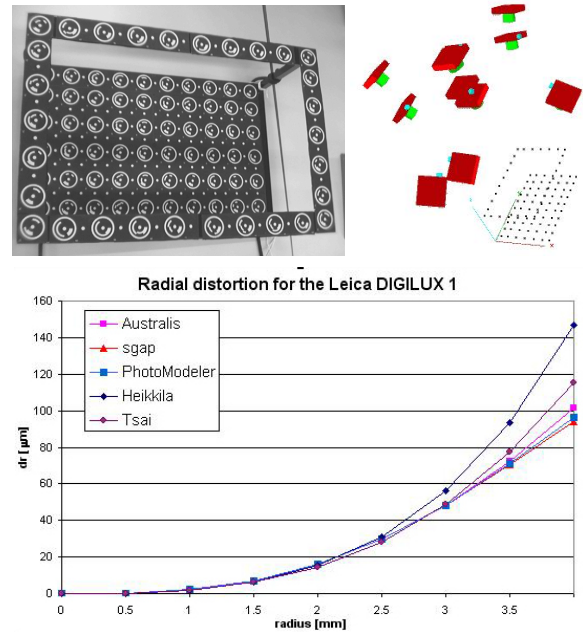

Figure 2. Calibration testfield and image network geometry (above), along with computed radial distortion profiles.
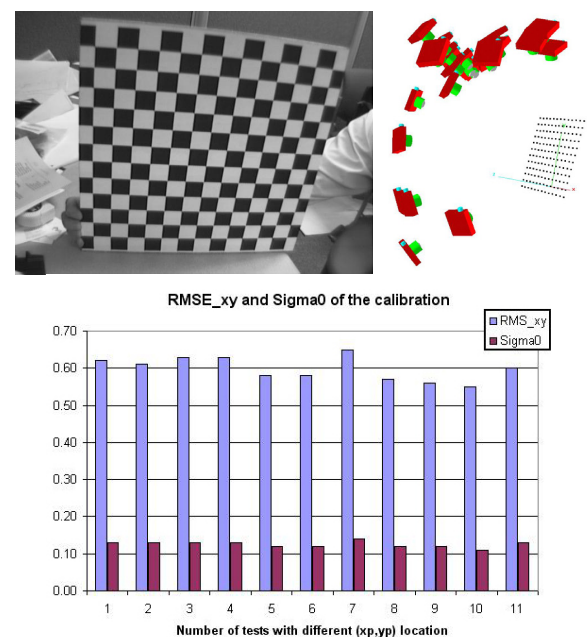

Figure 3. An image of planar testfield and the camera station geometry (above), along with the recovered residuals and a posteriori sigma0 values from 11 Australis runs (below).

6.3 Radial distortion in different colour channels

Nowadays, it is very difficult to find a monochrome off-the-shelf digital camera. For higher-accuracy photogrammetric measurement, new calibration issues arise with colour cameras. One such issue is the effect of chromatic aberration within the lens, which is usually divided into longitudinal (axial) and lateral (oblique) aberrations. The former generates blur effects, which are difficult to reduce, whereas the latter causes a degree of misregistration of the colour channels which can potentially be corrected in post-processing steps (Cronk et al., 2006). A factor that can adversely impact upon the accuracy of this registration and on the recovery of representative lens distortion profiles within a self-calibration adjustment is the distinction between the distortion profiles of separate colour channels.

This aspect was investigated for a SONY DSC F828 digital camera (8 Mega pixel) with a focal length of 10mm. The derived profiles, shown in Figure 4, indicate that radial distortion in the green channel is the smallest, whereas as that in the blue channel is the largest (the difference reaches about 10 pixels at the sensor edges). In photogrammetric measurement applications demanding high accuracy, it is necessary to take such differential distortion influences into account, especially given that most colour CCD cameras employ Bayer filters. Two possible options are, first, to record single-colour imagery through the use of an external filter (e.g. a green filter since the Bayer pattern has twice as many green pixels as red or blue) and secondly to self-calibrate the lens distortion for each colour and subsequently correct for distortion separately within each channel before the final 'registered' RGB imagery is measured. A practical difficulty with this approach is that it generally requires access to the 'raw' camera images, a feature which may or may not be available in lower cost cameras.
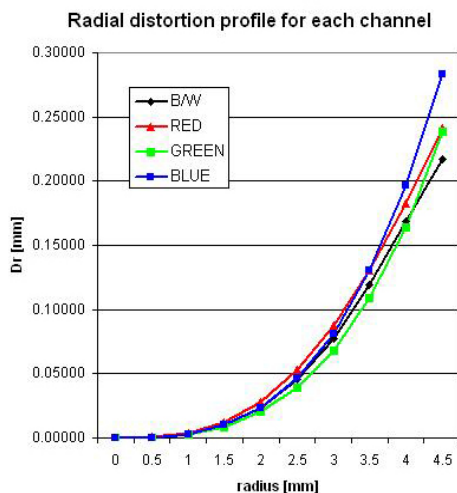

Figure 4. Radial distortion profiles for the 3 colour channels and demosaicked B/W image.

7. CONCLUSIONS

This article has reviewed different approaches to digital camera calibration. As use of consumer-grade cameras is becoming more and more common in photogrammetric applications, there is a requirement for adoption of appropriate calibration procedures. The self-calibrating bundle adjustment is a very flexible and powerful tool for camera calibration and systematic error compensation, and it provides for accurate sensor orientation and object reconstruction, while treating all the system unknowns as stochastic variables.

It is not always possible to perform self-calibration in practical close-range measurement projects. In fact, network geometries that are optimal for scene reconstruction are often quite different from those that support comprehensive camera calibration. Therefore, rather than performing a self-calibration simultaneously with the object reconstruction, it is often better to first calibrate the camera using an appropriate network, with the aim being to recover all significant parameters (not just focal length as in many CV applications). Nowadays, calibration can be a fully automatic procedure and experience has shown that the temporal variations in calibration parameters for consumer-grade cameras are generally not significant given that they are employed at low and medium accuracy levels.

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