MULTIPLE FOCUS CALIBRATION OF A STILL VIDEO CAMERA

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ABSTRACT

Still video cameras have been widely adopted for close range photogrammetry and machine vision applications. Due to the advantages of onboard storage of digital images, portability and rapid data processing, still video cameras are replacing medium format film cameras for measurement tasks such as heritage recording and industrial metrology. As for any photogrammetric application, the accuracy of the derived object data is dependent on the accuracy of the camera calibration, amongst many other factors. For the vast majority of photogrammetric applications, use of a simple model of lens distortion in conjunction with the collinearity equations is sufficient. However, the combination of very close ranges and the large distortions typically associated with the lenses used with still video cameras requires an extended lens model to account for variation of distortion within the object space. The fidelity of the calibration model becomes particularly important where stringent tolerances are set, for example in aerospace inspection tasks. This paper reviews previous research into distortion variation and outlines an initial investigation of the extent of distortion variation for two lenses used with a Kodak DCS420 still video camera.

1. INTRODUCTION

Close range photogrammetry has rapidly embraced the new technology of still video cameras. Until recently, videometric applications were limited by low resolution CCTV systems which require a dedicated computer or video recorder for image capture. Still video cameras are now available with medium to high resolution sensors, substantial on board image storage capability and of course complete independence of recording devices. These cameras are as portable and reliable as the film cameras they are replacing, with the added advantages of automated image measurement and rapid data processing (Fraser and Shortis, 1995).

Reported videometric applications of these cameras include architectural recording, large scale engineering metrology, low altitude mapping and tool inspection for the aerospace industry. This catalogue of uses will certainly increase as the cameras become more widely available, increase in resolution and become more cost effective. It is clear that in the near future only those aerospace applications with the most stringent tolerances are likely to remain the province of large format film cameras.

However, even the high accuracy domain is under threat due to advances in sensor technology and target image location algorithms. High resolution still video cameras and backs such as the Kodak DCS460 and Rollei ChipPack have CCD arrays up to 2000 by 3000 pixels in size. Target image location algorithms, such as the weighted centroid, have theoretical accuracies of 0.01 pixels, and internal precisions of 0.02 pixels have been achieved for many videometric applications using self-calibrating networks of many camera stations. In theory, the current limit of object space precision for networks captured with still video cameras is approximately 1 : 300,000, which is approaching the 1 : 500,000 image space precision which can be readily realised by the combination of large format film cameras and precise image comparators.

High resolution still video cameras are not yet competitors for large format film cameras because the discrepancy between the theoretical and actual accuracy is wider than the discussion above would suggest. Whilst internal precisions of 0.02 pixels are routinely reported, independent checking of photogrammetric networks utilising still video cameras indicates that the internal precision is not always a reliable indicator of external accuracy (Shortis et al, 1995). Relatively few applications have incorporated an independent measurement of the target object space coordinates, generally supplied using film cameras, theodolite systems or coordinate measuring machines. Although there is always an element of doubt associated with such comparisons due to the implicit assumptions of object stability and consistency of target location measurement, many independent tests have indicated a significantly degraded external accuracy when compared to internal precision.

Clearly, systematic or stochastic errors remain in the model for the optical and electronic components of still video cameras or the target location algorithms for image measurement. Because there are many possible sources of error, the best approach to the problem is one of elimination. One area of valid research is the common use of a simple lens model which assumes radial lens distortions are constant with respect to the distance between the lens and the target. This paper will concentrate on initial research toward the evaluation of an extended lens model. The intent of the research is the isolation of the effects of variation of distortion with focus distance and distance within the object space.

2. VARIATION OF DISTORTION

2.1 Variation with Focus Distance

An image is considered to be in focus at a specific distance, known as the focus setting or focus distance for the camera lens. The plane of best focus in the object field is a plane parallel to the image plane.

It is well known that lens distortion varies with lens focus. A change in the focus distance for a typical camera with a simple lens system is achieved by a change in the principal distance, which changes the image magnification produced by the camera lens. The change in the principal distance results in a change in lens distortion which is proportional to the principal distance and the focus distance.

Magill (1955) developed a formula for the computation of lens distortion at any specified focus distance, or magnification, based on two other determinations of lens distortion profiles. The computation uses a scale factor derived from the focal length and focus distances :

$$\delta r_S = \alpha_S \, \delta r_{S_1} + (1 - \alpha_S) \, \delta r_{S_2} \tag{1}$$

where

δr_S = required lens distortion at focus distance s

δr_{S_1} = predetermined lens distortion at focus distance s_1

δr_{S_2} = predetermined lens distortion at focus distance s_2

The scale factor α_S is derived from :

$$\alpha_S = \frac{s_2 - s}{s_2 - s_1} \cdot \frac{s_1 - f}{s - f} \tag{2}$$

where

s, s_1, s_2 = distances from the camera to specified focus planes in the object space

f = focal length of the camera (the principal distance at infinity focus)

The focal length of the camera may not be known, other than the nominal value given by the manufacturer. The principal distance at a specified focus distance can be computed using the thin lens formula :

$$\frac{1}{f} = \frac{1}{s} + \frac{1}{c} \tag{3}$$

where

c = principal distance

This formula can be re-arranged to conveniently give the focal length as a function of the principal distance and focus distance :

$$f = \frac{c \cdot s}{c + s} \tag{4}$$

A focal length value averaged from the two predetermined calibrations can be computed to provide the maximum accuracy. Once the focal length is known, the principal distance corresponding to the required focus distance used in Magill's formula can be computed using equation (3). Other parameters required for a full specification of the camera calibration, such as the principal point location, may be determined by averaging, or perhaps linear or non-linear prediction from a series of calibrations at different focus distances (Wiley and Wong, 1995).

The optimum accuracy of the new distortion parameters will be gained if the two pre-determined lens distortion profiles are as far apart in distance as possible. One set of profiles should be obtained at a focus distance of infinity, and a second set of profiles obtained at as short a focus distance as possible.

In practical terms, the predetermined profiles will generally be derived from a targeted test range calibration, a straight (or plumb) line calibration, or a combined test range and straight line calibration of the camera lens (Shortis et al 1995a). The proximity of the near focus distance calibration will be limited by field of view and depth of field considerations. The far focus distance calibration can generally be conducted at infinity focus, but again field of view may be a consideration. At the near focus distance the target or line density may be very low, whilst at the far focus distance the target array or straight lines may cover only a small portion of the image format, reducing the effectiveness of the calibrations.

Shortis et al (1995a) showed that the combination of target array and straight line calibrations realises calibration parameters with optimum accuracy and independence. Calibration using a target array, multiple convergent photographs or images and a self-calibrating collinearity solution can determine all parameters, but does not realise the parameters with a high degree of independence. Calibration using straight lines can determine only the lens distortions, albeit with a high level of independence and accuracy, however knowledge of all calibration parameters is required for the successful application of Magill's formula at other focus distances.

Magill's formula has been verified experimentally many times, commonly using a straight line calibration of conventional film cameras (Brown, 1971; Fryer and Brown, 1986). Straight line (Fryer and Mason, 1989) and targeted test range (Shortis et al, 1991; Wiley and Wong, 1995) calibrations have been successfully applied to machine vision and still video cameras, although generally no information on adherence to Magill's formula has been included.

2.2 Variation with Distance

Simple lens distortion models, derived from a calibration or the application of Magill's formula, are applicable only to the plane of best focus. If the camera is focussed on a single plane in the object space, or perhaps a very narrow depth of field within the object space, then the simple lens distortion model is sufficient.

However, lens distortion does vary within the object space, although the magnitude of the variation is typically much less than the variation with focus distance (Fraser and Shortis, 1992). The variation increases with magnification and distance from the plane of best focus, and so is most relevant to applications close range photogrammetry and machine vision where the object extends across a significant depth of field in the object space. In particular, applications which require high accuracy, such as tool inspection and surface characterisation for the aerospace and manufacturing industries, require an extended lens model to eliminate the systematic error caused by the variation.

Brown (1971) developed an extended lens model to account for the variation of distortion outside of the plane of best focus. The model is based on a function of the lens distortion at the plane of best focus and a scale factor derived from the geometry of the image :

$$\delta r_{ss'} = \frac{1}{\gamma_{ss'}} \, \delta r_{s'} \qquad (5)$$

where

$\delta r_{ss'}$ = radial distortion at an object distance s' for a lens focussed at an object distance s

$\delta r_{s'}$ = radial distortion at an object distance s' for a lens focussed at an object distance s'

s = focus distance for the camera

s' = distance to the plane of the target point

The scale factor is given by :

$$\gamma_{ss'} = \frac{c_{s'}}{c_s} = \frac{s'}{s} \cdot \frac{(s - f)}{(s' - f)} \qquad (6)$$

where

c_s = principal distance for the focus distance s

$c_{s'}$ = principal distance for the focus distance s'

Brown (1971) verified this extended lens model for medium format, glass plate cameras using straight line calibrations. However the camera lenses exhibited a relatively low magnitude of distortion, and Brown noted that there was some variability for different lenses.

Fraser and Shortis (1992) showed that Brown's extended model is not able to model the variations in distortion when the magnitude of the distortion, and therefore the gradient of distortion across the format, is very large. An alternative model was developed which expresses the lens distortion as a function of the distortions at the distances of the camera focus and the point of interest :

$$\delta r_{ss'} = \delta r_s + g_{ss'} \, (\delta r_{s'} - \delta r_s) \qquad (7)$$

where

$g_{ss'}$ = a constant value derived empirically

δr_s = radial distortion at an object distance s for a lens focussed at an object distance s

Fraser and Shortis (1992) verified this new extended lens model for large and medium format film cameras, again using straight line calibrations. The lens to lens variation was relatively low, although clearly present. Hence the empirically derived constant factor $g_{ss'}$ could be applied to any lens of a specific type and the model error was shown to be significantly less than the magnitude of the distortion variation.

3. EXPERIMENT DESIGN

In order to select an appropriate extended lens model for a typical still video camera, an experiment was designed to conduct a comprehensive camera calibration and accuracy test. The basis for the calibration was a test range set up to enable the simultaneous targeted test range and straight line calibration of a still video camera. The layout of the test range is shown in Figure 1. The range comprises the targeted test range, the straight line range, lighting for the straight lines and a number of relocatable camera station pillars.

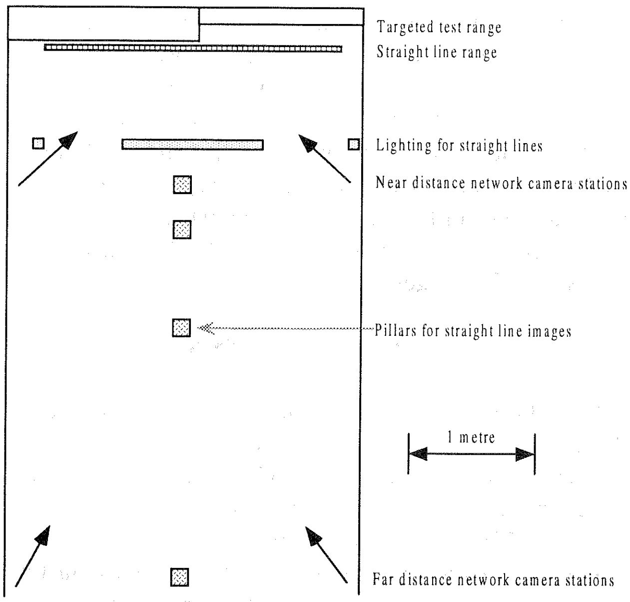

Figure 1. Layout of the calibration range.

The targeted test range covers an area of 2m by 1.5m by 0.3m on three different wall sections. Attached to the matt-black painted surface are 216 retro-reflective targets, each 10 mm in diameter with a central dot suitable for theodolite measurement. The straight line range covers an area of 2.5m by 2m with 20 vertical straight lines. The lines are under tension and vertical to assure their straightness. The straight lines occupy a single plane, in front of the targets and parallel to the plane of the wall. Four pillars are aligned on a perpendicular to the plane of the straight line range, set at increasing distances from the wall. The pillars are relocatable to a number of positions within the test range area, and can be used for both theodolites and cameras.

The still video unit selected for the calibration was a monochrome Kodak DCS420 because of the widespread use of this camera. Two Nikkor F-mount lenses were selected for calibration, a 20mm focal length non-fish-eye lens, and a 16mm focal length fish-eye lens. The focal lengths of the two lenses correspond to fields of view of 45° and 58° respectively for the 13.7mm by 9.2mm format of the DCS420 sensor. The two lenses therefore represent a reasonable working range of field of view for the camera, as well as affording a comparison of two quite different types of lens design.

Image capture for each camera and lens combination was designed to allow verification of Magill's formula for the plane of best focus, and test the significance of distortion variation out of the plane of best focus. The technique adopted here closely parallels that used by Brown (1971) and Fraser and Shortis (1992). Four focus distances were chosen for each lens, three of the distances in common for the two lenses, and the removable pillars placed accordingly. Image scales range from 1:70 to 1:190 and 1:90 to 1:250 for the 16mm and 20mm lenses respectively. For each focus setting, images of the straight line range were exposed at each pillar (see Figure 2), therefore providing information on distortion through a range of distances for each focus distance.

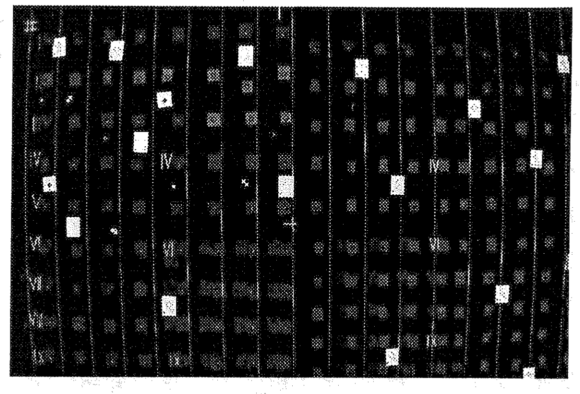

Figure 2. A typical image of the straight lines.

At each of the four pillar locations for each focus setting, the camera was carefully aligned to be parallel to the plane of the straight lines. Alignment was achieved through a combination of pointing direction and levelling of the camera roll mount. This action was taken to ensure that all the straight lines were in a single plane of focus. Three to four images at different roll angles were exposed at each pillar. The use of multiple images increases the available data set and therefore the final precision of the distortion parameters. The roll angle variation randomly varies the imaged locations of the straight lines within the image format area and enhances the independence of the derived distortion parameters. Four images were exposed at the near distance pillar to increase the effective density of data for these high magnification images.

As discussed in the previous section, straight line images alone are not sufficient to characterise the full set of camera calibration parameters. Convergent networks are necessary to quantify parameters such as principal distance, principal point location and sensor affinity. In accordance with the principle of providing the widest separation of the determinations, convergent networks were imaged at the near and far focus distances for each lens.

Each network comprised six camera stations with four image exposures at each station. Each of the four exposures was rolled by 90° and randomly perturbed in object space to reduce projective coupling in the networks and randomise the target image locations respectively. A standard flash unit was employed to under-expose the background and return an appropriate retro-reflective target response (see Figure 3).

Whilst the retro-targets and straight lines were exposed at the same grey level of approximately 160-190, the background intensities were substantially different at approximately 10 and 45 respectively. A further complication for the straight line images was the presence of many extraneous targets which, whilst not retro-reflective, were sufficiently bright to provide an unacceptable background level. Unfortunately these targets were necessary for the concurrent set up of an industrial theodolite system to provide an accuracy check.

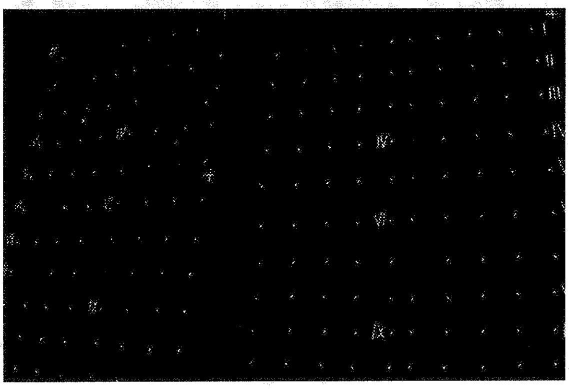

Figure 3. A typical image of the target array.

To avoid any physical changes to the camera calibration during image acquisition, the lenses were fixed at each focus distance using shims and adhesive tape. All images required at each focus distance were then taken in a single sequence. The CCD chip in the Kodak DCS420 camera was inspected to check the stability of the sensor with respect to the camera. Pressure marks on the sensor surround indicated that the CCD was firmly held within the camera body and no remedial action was taken.

As previously noted, 67 of the retro-reflective targets were coordinated using an industrial theodolite system to provide an accuracy check. The system comprises three Geodimeter 400 or 500 series total stations and the UPM on-line triangulation package, which uses a bundle solution based on spatial directions. The measurements were observed within a few days of the photography and the test range was undisturbed and stable during the intervening period. The average precision of the targets derived from the theodolite measurements was 0.05 mm in all three coordinates.

4. OBSERVATIONS

The straight line images were observed using a semi-automated scanning process whereby centroids of the lines were captured at every ten pixels in the image. Global thresholds were employed to remove the background, which was only partly successful due to the interference of the theodolite targets. The number of lines per image varied from 5 at the near distances to the full set of 20 at the far distances. The average number of plumb line observations per image varied from approximately 400 to 1500.

The targeted test range images were observed using a semi-automated resection/intersection procedure (Shortis et al, 1991). Image locations were computed from a weighted centroid within a local window (Shortis et al, 1995b). The use of local thresholds and the much lower background intensity for these images resulted in minimal noise in the data. The number of target image observations ranged from 3000 to 4800 for each of the four sets of 24 images.

5. INITIAL ANALYSIS

Sets of three or four straight line images for each focus distance and camera to object distance were first processed independently. The RMS (root mean square) image space errors ranged from 0.5 to 2.0 micrometres, or 1/18 to 1/5 pixels. This relatively poor result indicates that the image data is quite noisy and the images must be re-observed with local thresholds to improve the quality of the data. However the lens distortion data produced by the straight lines does indicate that there is a significant signal present for distortion variation in the two lenses. Example distortion profiles for the 16mm lens are given in Table 1. The 20mm lens exhibits slightly less variation for similar profiles.

Focus (m)	1.0	1.0	Infinity	Infinity
Distance (m)	1.1	3.0	1.1	3.0
Radius (mm)	Radial Distortion (μm)			
1.0	-1.47	-1.48	-1.48	-1.51
2.0	-11.70	-11.74	-11.78	-12.00
3.0	-39.03	-39.17	-39.31	-39.92
4.0	-91.03	-91.33	-91.71	-92.79
5.0	-174.25	-174.79	-175.61	-177.01

Table 1. Radial lens distortion profiles for the 16mm lens at various focus and distance settings.

Each set of network images has been processed independently as a self-calibrating, free network with a simple lens model. The results are summarised in Table 2. The larger RMS error for the 16mm lens at the near distance indicates that systematic errors are present in the network, caused by variation of distortion from the relatively large distance range for the targets, compared to the mean distance. In contrast, the much lower RMS error for the 20mm lens at the far distance can be reconciled against a smaller variation of distortion signal for this lens and a smaller ratio of the range of target distances to the mean distance. In essence, the network for the 16mm lens at near distance is most influenced by the depth of field in the images.

This tentative analysis does not preclude the presence of other systematic errors, such as sensor unflatness and centroid bias, however the clearly evident signal of the distortion variation is the most likely source of the larger RMS image error in the near distance network for the 16mm lens.

Lens (mm)	16		20	
Focus (m)	1.0	Infinity	1.8	Infinity
Distance (m)	1.1	3.00	1.8	3.00
Redundancies	6360	8835	5490	7785
RMS error (μm)	0.79	0.30	0.29	0.28

Table 2. Results summary for the four networks.

6. FURTHER ANALYSIS

The next stage in the data analysis will be the integration of the network and straight line data sets. Although an iterative solution of network and straight line solutions has been employed successfully, a fully integrated solution is more efficient (Shortis et al, 1995a). The integrated approach should improve the accuracy and independence of the calibration parameters to further isolate the variation of distortion as a systematic error.

Initial testing of a combined collinearity and straight line solution within a single network adjustment has produced encouraging results. The combined far distance network for the 20mm lens, comprising 4200 target and 3000 straight line observations all at a single focus distance, realised a slight inflation of the RMS image error along with a small but significant improvement in the precisions of the distortion parameters. The inflation of the RMS image error and small improvement in the precisions was expected due to the relatively noisy straight line data. The networks will be subject to further testing and analysis with re-measured straight line data.

The final stage in the analysis will be the incorporation of a number of extended lens models into the combined network and straight line solution. Distance interpolation, Brown's formula and the constant factor approaches will all be tested using the four networks. In each case a substantial reduction in systematic error, and therefore a smaller RMS image error, is expected. The efficacy of each approach will be compared using precision analyses of the network solutions and accuracy analyses against the theodolite coordinate data for the target array.

7. CONCLUDING REMARKS

This paper has reviewed existing algorithms, described the experimental design and given preliminary results for an investigation into the distortion characteristics of the lenses typically used with still video cameras. Whilst the data reduction and analysis has not progressed to the stage where definite conclusions can be drawn, it is clear that significant variation of distortion within the object space has been detected. It is expected that an extended lens model will be able to eliminate the systematic error introduced by the variation of distortion with distance. The analysis and modelling of this distortion variation will be reported in a future paper.

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