LENS DISTORTION FOR SIMPLE C-MOUNT LENSES.

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ABSTRACT

For many photogrammetric applications involving bundle adjustments, it is desirable to have *a priori* knowledge of the lens distortions, both radial and decentering. For close range applications involving focussing, other interior orientation parameters of principal distance and the location of the principal point may not be well known. A technique has been developed to determine the parameters of radial and decentering lens distortions for the simple style (as distinct from the more complex zoom) C-mount lenses used with an array of CCD cameras for digital photogrammetry at City University, London. It has been shown previously that the parameters of decentering distortion and the offsets of the principal point are highly correlated in convergent bundle adjustments, so the only remaining unknown of the interior orientation is the principal distance (Fryer and Fraser, 1986). Initially, a set of taut string-lines were imaged and used to precisely determine the radial and decentering distortions for the lenses at several camera to object distances. A modification of this technique in the form of a rectangular frame which is imaged with the object, or just prior to the measurement of the object, has proved a quick and reliable way to obtain accurate values of lens distortion at the moment of data capture.

1. INTRODUCTION.

The importance of lens calibration for all machine vision applications, especially photogrammetric ones cannot be underestimated. The calibration of the video cameras themselves has received considerable attention in the last decade. Curry et al.(1986), Gulch (1986), and more recently Beyer (1992) have detailed methods for calibrating their geometric and radiometric properties. Perhaps because of the exciting future awaiting these devices and the opportunities for robotic, automatic inspection, and close range measurement applications, the more mundane, but equally important, calibration of their lenses has received less attention.
The poor quality of most C-mount lenses, in comparison to those used on good quality 35mm single lens reflex cameras has been commented upon in the past (for example, Fryer, 1987). Most lenses used with digital cameras have been constructed with the intention of providing minimum amounts of lens distortion at infinity focus. The situation in many close range robotic applications is quite different from that ideal, and the size of the radial lens distortion at very close range may be several times that for infinity focus.

Unlike photogrammetric applications involving film cameras, where the concept of trying to keep the focus for a particular lens stationary throughout the series of exposures is well known and where it is unlikely that more than one camera will be involved in recording what are generally static scenes, digital cameras offer new possibilities. The cost of small format digital cameras is less than their analogue counterparts, so it is economic and practical to use multiple cameras in an array to image an object. Also, since the processing may be entirely automatic, there is no penalty for capturing many more images than one would normally expect if manual reading of film images was involved. Consequently, operators of digital cameras do not feel constrained to keep a single focus setting on their camera and may 'experiment' with the imagery to try and fill the frame on every exposure, get close-ups, etc. It is therefore most important to have a rapid and reliable technique to determine lens distortions at the same time as the imagery of the object is captured.

2. THE PLUMBLINE METHOD.

This technique for determining radial and decentering distortions for a particular focus setting of a lens can be attributed to Brown (1971). It is based on the principle that in a perspective projection a straight line in object space should project as a straight line into the image space. Any deviations from linearity can be attributed to radial and decentering distortions in the lens. In his early experiments, Brown (ibid) suspended thin plumblines from the ceiling in a laboratory, thereby providing the title to this method. However, the lines do not have to be vertical, merely straight. Exponents of this technique have since used a variety of features displaying straightness to calibrate lenses for a wide range of focus settings. Lenses examined by this technique have ranged from aerial cameras photographing straight, level sections of railway lines (Fryer and Goodin, 1989), to medium format metric cameras focused at infinity imaging the edges of large glass panels on the facades of city buildings, to video cameras fitted with close-up adapter lenses focusing on the lines printed on a writing pad (Fryer and Mason, 1989).

In order to obtain reliable results for both the parameters of radial and decentering distortion, it is logical to obtain line imagery in both the x and y directions. Since the radial distortion model which is being sought is symmetric about the 'centre' of the image frame, it is also relevant to gather data from each quadrant of the image frame. Typically, the type of data gathered consists of approximately ten lines in a 'vertical' and ten lines in a 'horizontal' sense. These lines will usually be stretched between supports and held approximately vertical to avoid any sag due to gravity. The rotation of the camera through 90 degrees is the easiest way of obtaining both sets of lines. Most users of this technique recommend 30 to 50 data points be recorded per line, these can be selected from the 500-750 points available from the image. Such a collection of data usually provides a result which is accurate enough for even the most stringent of photogrammetric tasks.

For the plumbline calibrations described in this paper, a 1.5 metre square frame of timber with white nylon string stretched tightly across it was used as the calibration frame. To provide as much contrast as possible, a backdrop made of black velvet curtains was used. This backdrop was placed 1.5 metres behind the calibration frame so that symmetric side-lighting could be used to illuminate the white string and not the curtain (see Figure 1 & 2). The results shown below, and other work undertaken by Clarke, Cooper and Fryer (1993), would indicate that an image which has a contrast of 5-8 bits and a spread covering at least five pixels will result in good subpixel image location. However, some difficulty was experienced in obtaining these settings in all circumstances because of the conflicting demands of keeping the image in focus and providing enough lighting on the lines, yet not illuminating the background. For many of the images it was possible to use natural lighting from a large window which was directly behind the camera. In terms of the accuracy required for the measurement of the camera parameters, the fact that no pixel clock was used or the image conditions were not ideal, does not present a problem because of the high level of redundancy available.

Figure 1. Setting up the camera for measurement.

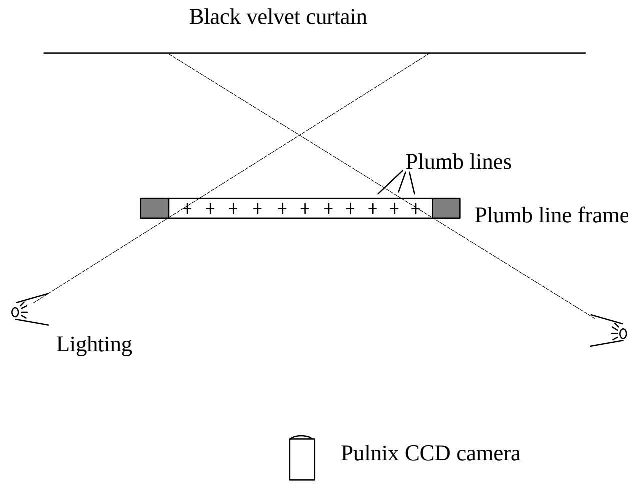

Figure 2. The configuration of the lines (plan view).

Some images were initially collected at a camera to plumb line distance of 0.5 metres, however, at this position, a problem was noted which originated in the type of string used. Figure 3 shows that under these conditions the sensor was able to resolve the fine weave of the string. For most of the photogrammetric close range measurement envisaged for the equipment an object to camera distance of 0.5 to 1.0 metres is unlikely so it was not considered necessary to build a new plumbline rig for this distance and the data from 0.5 metres was not further used in this study.

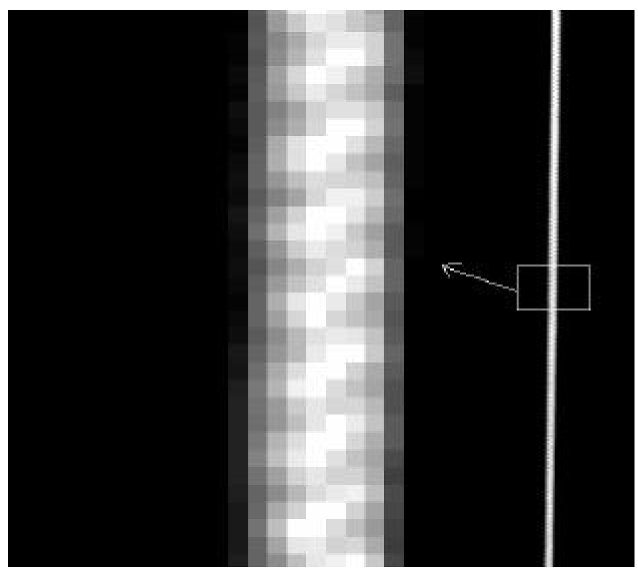

Figure 3. Close up view of the string at 0.5 metres.

3. SOME LENS DISTORTION RESULTS.

Three Pulnix CCD cameras (Pulnix, 1991) each fitted with a, seemingly identical, Fujinon 25mm C-mount lens were calibrated on the plumbline range at City University over camera to object distances of 4, 2 and 1 metres. Each combination of camera, lens and distance was tested, resulting in 27 determinations of the parameters of radial and decentering distortion. These have been summarised in Tables 1 and 2 and a graph of the mean results is shown as Figure 4.

Camera	Lens	Camera to	Object	Distance
No.	No.	4m	2m	1m
1	1	11.9µm	13.8µm	13.6µm
	2	13.7µm	14.3µm	16.0µm
	3	12.8µm	12.6µm	14.8µm
2	1	12.5µm	14.2µm	15.6µm
	2	12.9µm	13.9µm	15.2µm
	3	12.9µm	13.7µm	15.1µm
3	1	13.1µm	14.5µm	16.0µm
	2	13.7µm	14.1µm	17.1µm
	3	12.7µm	13.4µm	15.2µm

Table 1. Radial Lens Distortions in micrometers at a Radial Distance of 4 millimetres for Three Pulnix Cameras, Three Fujinon 25mm Lenses and Three Camera to Object Distances, derived using approximately Ten Horizontal and Ten Vertical Plumblines.

Lens No.	Camera to 4m	Object 2m	Distance 1m
1	12.5µm	14.2µm	15.1µm
2	13.4µm	14.1µm	16.1µm
3	12.8µm	13.2µm	15.0µm
Mean	12.9µm	13.8µm	15.4µm

Table 2. Summary of Table 1, showing Mean Values for Radial Distortion in micrometers for a Radial Distance of 4 millimetres for Three Fujinon 25mm Lenses fitted to Three Pulnix Cameras.

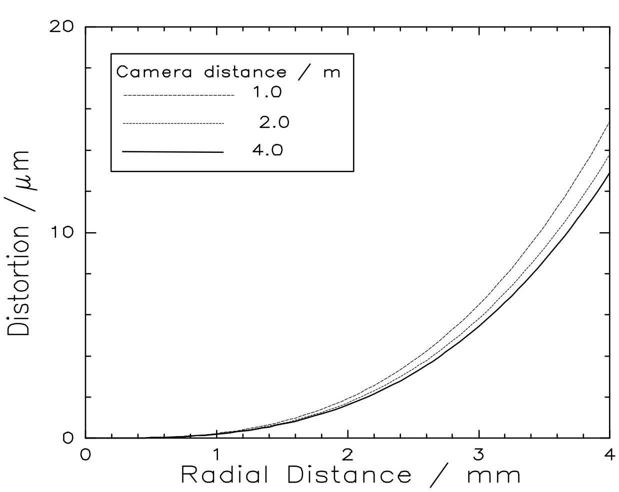

Figure 4. Graph of mean results.

Several tests were made on this data, probably the most significant being to determine if all the commonly used three parameters for radial distortion were significant for such a, relatively, long focal length lens. The tests showed conclusively that only the first term (the K_1 term, see for example Karara, 1989), was required to describe the 'barrel' distortion effect. This proved to be a most important finding because it enabled the much simplified approach to the determination of lens distortion which is presented in the following section. This new technique presents opportunities for the determination of the actual distortions present at the time of digital image capture.

Inspection of Table 1 shows the small range of the results for any one focus distance, remembering that three different cameras and lenses were involved. Table 2 shows a summary of the results of Table 1. Note that the maximum radial distance which it was practical to reach in the corner of the Pulnix CCD frame is only 3.8mm, so extrapolation of the results to 4mm should heighten any real differences in the lenses. Note also that at a radial distance of 2mm, within which most imagery will probably be captured, the size of the radial distortion will be only one-eighth as large as those figures shown in the tables (because the coefficient of K_1 is r^3), so the differences between lenses will be accordingly smaller.

The decentering distortion profiles are shown in summary form in Table 3. The increase in decentering distortion for closer focussing is quite understandable, as the lens elements are moved towards the object by approximately 0.30mm in focusing from 2m to 1m, whereas the lens is only moved forward by 0.15mm in proceeding from 4m to 2m focus. Again the values at a radial distance of 4mm have been shown. Applying the same reasoning as above, if most imagery is captured within a radial distance of 2mm, this corresponds to a worst case decentering distortion of 1µm (the decentering distortion coefficient is basically a quadratic term, so halving the radial distance reduces the effect to a quarter).

Plumbline Type	Camera to 4m	Object 2m	Distance 1m
10 Horizontal 10 Vertical	1.5µm	1.6µm	3.7µm
2 Horizontal 2 Vertical	2.6µm	2.0µm	3.0µm

Table 3. Summary of Values of the Decentering Distortion Profiles in micrometers at a Radial Distance of 4 millimetres for Various Camera to Object Distances for Three Fujinon 25mm Lenses fitted to Three Pulnix Cameras.

Although the decentering distortions found here are up to an order of magnitude smaller than radial distortion, they should not be ignored, as has often been the case in the past with conventional film cameras where they display an equivalent disparity in size. The radial and decentering distortion profiles have been detected with a precision approaching 0.2µm, so it would seriously degrade the whole photogrammetric result not to apply the effect of the decentering.

Another facet of the decentering result is worth noting. It has been shown by Fryer and Fraser (1986) that the actual effect of applying decentering distortion is the same as knowing and applying the offsets of the principal point from the fiducial axes. In fact, those researchers demonstrated a strong link between the offsets of the principal point and the parameters of decentering distortion. The correlation between these two sets of parameters is very high in a convergent bundle adjustment. To include both sets could be said to be over-parameterisation, which in turn can lead to poor conditioning of the normal equation matrix with adverse effects on the finally determined values for the co-ordinates of the object points. Therefore, the use of the parameters of decentering distortion means that there is no need to determine the offsets of the principal point, a task which is not easily accomplished when alterations to the focus settings are made during the capturing of images which will be used in the same bundle adjustment.

4. FRAMING THE FIELD OF VIEW.

The results of the precise determinations of the lens distortions using the plumbline method with approximately ten horizontal and ten vertical lines showed conclusively that for the 25mm Fujinon C-mount lenses tested, only the first term of radial distortion was significant. It was therefore decided to repeat the entire set of tests using only two horizontal and two vertical lines. These lines were of white nylon string, placed on a wooden frame, not unlike a picture frame, which had been painted matt black.

The data capture was again automatically undertaken, and the results for all 27 tests, that is for three cameras, three lenses and camera to object distances of 4, 2 and 1m are shown in Table 4. A summary of the results is presented in Table 5, where it can be seen from comparison with Table 2 that the results are, to a high level of statistical confidence, identical.

Camera	Lens	Camera to	Object	Distance
No.	No.	4m	2m	1m
1	1	11.1µm	13.1µm	13.9µm
	2	13.2µm	14.4µm	15.6µm
	3	13.9µm	12.6µm	15.3µm
2	1	12.7µm	14.4µm	15.6µm
	2	12.8µm	13.6µm	15.8µm
	3	13.1µm	13.5µm	15.5µm
3	1	13.6µm	14.0µm	15.9µm
	2	14.1µm	14.0µm	15.9µm
	3	13.1µm	14.2µm	15.3µm

Table 4. Radial Lens Distortions in micrometres at a Radial Distance of 4 millimetres for Three Pulnix Cameras, Three Fujinon 25mm Lenses and Three Camera to Object Distances, derived using only Two Horizontal and Two Vertical Plumblines.

Lens	Camera to	Object	Distance
No.	4m	2m	1m
1	12.5µm	13.8µm	15.1µm
2	13.4µm	14.0µm	15.8µm
3	13.4µm	13.4µm	15.3µm
Mean	13.1µm	13.7µm	15.4µm

Table 5. Summary of Table 3, showing Mean Values for Radial Distortion in micrometers for a Radial Distance of 4 millimetres for Three Fujinon 25mm Lenses fitted to Three Pulnix Cameras.

The utility of this result is that a technique has emerged which allows the 'instantaneous' determination of the radial and decentering distortions at the time of digital data capture. A frame need only be placed around the object being recorded, and regardless of the amount of focussing (or indeed defocussing) which takes place, the lens distortions and, in effect, the offsets of the principal point, are determined for that epoch of exposure. This technique will not, of course, suit every application, but in many instances where the digital camera is placed remotely in a hostile environment and focussing and aperture settings are under automatic control, then this technique is seen as having an important role.

5. RESULTS OF USING THE QUICK CAMERA CALIBRATION TECHNIQUE.

To test the use of the quick calibration method a number of images of a target test field and the calibration frame were taken. Figure 5 shows the target test field and frame, and Figure 6 shows one of the images collected for processing. The plumblines were extracted from one of the images and used in the plumbline program to compute an estimate of the K_1 parameter of 2.183 x 10^{-4}. The target co-ordinates for each of the images was then used to compute a bundle adjustment where K_2, and K_3 were suppressed and K_1 was free. The value of K_1 that was produced was 2.098 x 10^{-4}. The small difference of 0.09x10-4 is equivalent to only 0.2µm at a radial distance of 3mm, that is near the practical limit of the image format where the radial distortion effect is at its maximum.

The target co-ordinates were then adjusted using the value of K_1 from the quick method and the bundle adjustment re-computed. The resulting K_1 was 2.258 x 10^{-5}, a factor of 10 less, showing that the major systematic effect of radial lens distortion has been removed. The RMS values for the test field in object coordinates were: x = 0.021mm, y = 0.025mm, z = 0.027mm for both methods. The corresponding values in image space for x and y were both 0.48µm. An overall expression of the accuracy obtained was of the order of 1:50,000.

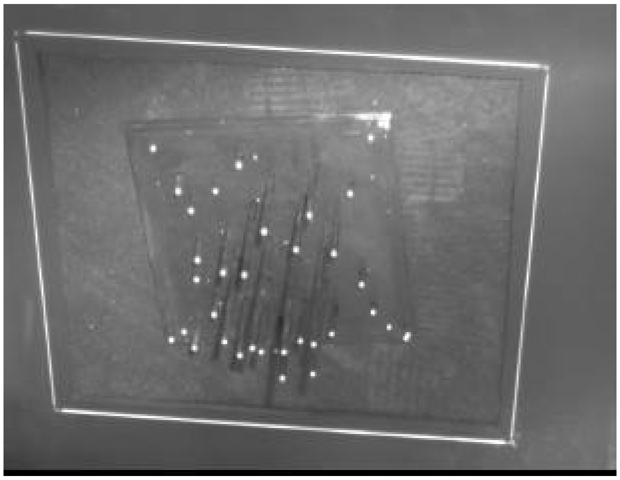

Figure 5. View of target test field and frame.

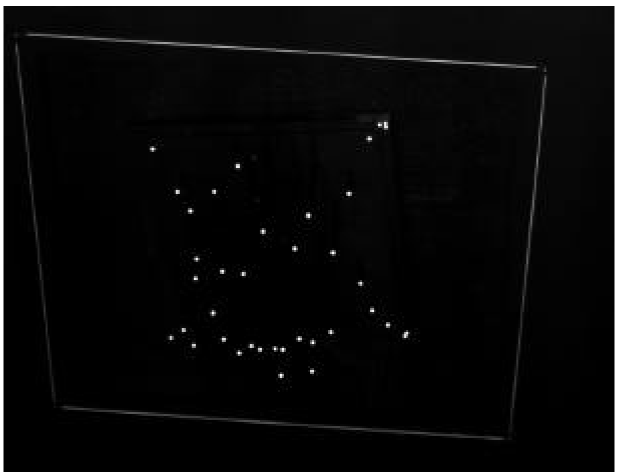

Figure 6. Image used to compute K1 and bundle.

6. CONCLUSIONS.

The radial and decentering lens distortions for three Fujinon 25mm lens fitted to three Pulnix digital cameras have been determined by the plumbline method with residuals of the order of only 0.2µm. A study of the parameters of radial distortion showed that only the first term in the series was sufficient to describe the radial distortion present in these lenses. Further tests showed that the plumbline test field in the laboratory could be reduced to only two horizontal and two vertical lines attached to a lightweight frame without significant loss of accuracy. Bundle adjustments of a test field incorporating this technique showed accuracy results of the order of 1:50,000. Caution should be used in extrapolating these results to shorter focal length lenses where the radial distortion has been shown to be up to an order of magnitude larger than the lenses tested here (Beyer, 1992).

This result meant that a new technique for rapidly capturing the actual lens distortions present at the time of image capture was available. Given the proven high correlation between the parameters representing decentering distortion and the offsets of the principal point from the fiducial axes, the number of unknown parameters of interior orientation which must then be solved as additional parameters in any convergent bundle adjustment reduces to only the uncertainty in the principal distance per camera station.

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