Rapid Lens Calibration of a Video Camera

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ABSTRACT: A video camera, frame grabber, and personal computer were used to test line- and edge-detection algorithms for the automated extraction of plumbline data. These data were used to automate the determination of the parameters of lens distortion of the video camera. Robust estimation was employed in an attempt to detect gross errors in the data. The use of this method for the rapid calibration of the lenses of small format cameras is proposed. Some preliminary experiences with small format transparencies of plumblines indicate a requirement for high quality imagery.

INTRODUCTION: IMPORTANCE OF LENS CALIBRATION

THE IMPORTANCE OF LENS CALIBRATION for all photogrammetric applications, whether metric, non-metric, or video-type cameras are involved, cannot be understated. The significant increases in accuracy which have been obtained with non-metric cameras over the last 15 years can be attributed, largely, to a greater understanding of the nature of radial and decentering distortion and the consequent improved modeling of the bundle or other photogrammetric solutions to incorporate their effects. Many researchers, notably Karara and Abdel-Aziz (1974) and Murai *et al.*(1984), have discussed various techniques for the incorporation of the parameters of lens distortion into photogrammetric solutions. They have reported results for metric and non-metric cameras.

The calibration of video cameras has received considerable attention in the past five years. Curry *et al.*(1985) and Gulch (1986), among others, have detailed methods for calibrating the geometric and radiometric properties of these devices. Perhaps because of the relative newness of these devices—and the exciting prospects for their future in photogrammetry, remote sensing, and robotics—the more mundane matters such as their lens calibration have not been given emphasis. Throughout this paper the term video camera has been used in a generic sense to incorporate all solid state cameras including CCD, CID, and other array devices.

Fryer (1987) noted that the types of lenses used on most commercially available video cameras are not of the quality found on good single-lens reflex cameras and they will most likely exhibit relatively large radial and decentering distortions. In fact, because zoom lenses are so popular on video cameras, the variations in radial and decentering distortions which will occur as the effective principal distance and focusing are altered will be much larger than most photogrammetrists have ever experienced with simple non-metric cameras. In another recent study, Fryer (1986) demonstrated the variation in radial and decentering distortion for a relatively expensive, good quality zoom lens. The magnitude of these effects is likely to be well in excess of the pixel size at the sensor plane, making algorithms for the detection of sub-pixel accuracy mere exercises in futility if lens distortions are not effectively modeled.

The rapid variations in the values of the radial and decentering distortions at very close range will be of special significance to users of video cameras. Most lenses have been constructed with their minimum distortions occurring at a principal distance equal to their focal length, i.e., focused at infinity. For very close range observations, such as may be expected in industrial robotic applications, the size of the radial lens distortion may be more than an order of magnitude larger than for distant focus. It is therefore most important to have a rapid and automatic means of calibrating the video camera at whatever focus setting it will be operating.

THE PLUMBLINE METHOD

The technique of lens calibration known as the plumbline method can be attributed to Brown (1971). It is based on the principle that a straight line in object space should perspectively project through a lens to become a straight line in image space. Any deviations from linearity are attributed to radial and decentering distortions in the lens. For a full description of the mathematics involved, readers are referred to Brown (1971).

Initially, Brown (1971) suspended thin plumblines from the ceiling in a laboratory environment and the photographic plates were painstakingly observed on a manually operated monocomparator. This observation procedure took at least two days, resulting in a root-mean-square precision on the plates of approximately 3 micrometres. In 1985 the plumbline technique underwent a significant revival with the advent of an automatic line following monocomparator, Autoset-1 (Brown, 1987), which could process the observations in one hour to a precision of better than 1 micrometre.

Although the automatic monocomparator can process the imaged lines in under one hour, these devices are still comparatively rare and cost in excess of $100,000. To obtain the most reliable calibration result, approximately 50 points on each of say nine or ten apparently horizontal and vertical lines must be digitized. Rotation of the camera through 90° is the simplest method of obtaining the horizontal and vertical sets of lines.

For extremely close-range calibrations, various investigators have used the edges of steel rulers or fishing line strung tautly across a contrasting background as their plumblines. In the experiments detailed below, very sharp lines on a printed writing pad and edges, conveniently provided by exposed X-ray film, were used as the plumblines to test the line- and edge-detection algorithms.

This paper examines the possibility of using a simple video camera to capture plumbline data from, for example, 35-mm frames taken with a non-metric camera. The observation period of one or two hours usually associated with the calibration of a lens for a small format camera should reduce with automation. Other reasons for undertaking this experiment were to independently check edge-and line-detection algorithms programmed for this task in conjunction with the video camera. Although no attempts at near-real-time processing of the lens calibration were contemplated, this future prospect deserves consideration.

CALIBRATION OF VIDEO CAMERAS

Interest generated in video cameras for close-range photogrammetric applications in recent years is not without foundation. Under suitable conditions accuracies of up to 0.01 pixels have been achieved for some object detection algorithms (Stanton *et al.*, 1987). Moreover, solid state sensors have distinct advantages when compared to film-based cameras, including

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- no film distortions,
- no emulsion problems,
- the possibility of mapping any geometric irregularities in the sensor, and
- the image coordinate system is inherent to the array itself and the need for fiducial marks is eliminated (Curry *et al.*, 1986).

However, before full realization of the potential of these devices is achieved, even with ever-increasing resolution, an understanding of calibration procedures is important. Calibration procedures must be able to account for sources of random and systematic errors. Errors in data recording and the approaches which have been taken to detect them differ greatly, not only between types of camera systems, but also from camera to camera (Gulch, 1986).

Recent investigations by Gulch (1986), Lenz (1987), Daehler (1987), and Beyer (1987) reveal that hardware effects may be significant at the sub-pixel to pixel level. Such effects include line-jitter, caused by imperfect synchronization of the video signal from camera and frame grabber, voltage fluctuations, and random time-related effects such as temperature induced drift of pixel coordinates. Moreover, it is difficult to obtain devices free of blemishes or fixed pattern noise (Harold, 1986) without a large capital expenditure, so it becomes obligatory to fully calibrate the electronic components of the camera.

Calibration of the lens on the video camera is also regarded as essential, especially when one considers that these cameras are conventionally fitted with lenses of a poorer quality than small format non-metric cameras. Lenz (1987) reported that at a target distance of 0.5m the inclusion of one radial lens distortion parameter into the camera model (a 12 parameter bundle solution with one parameter to model lens distortion) did not improve the model fit. This type of result has not been the experience of the authors of this paper and it could be suggested that the result was merely a function, in that case, of the actual lens used.

The location of the principal point was also determined by Lenz (1987). For some applications it is important to determine the location of the principal point because it may be up to 40 pixels off the center of the imaging array (Lenz, 1987). This can occur due to misalignment of the optical axis or the array chip not being aligned perpendicular to the optical axis. Various methods have been proposed for locating the principal point, with the self-calibrating bundle adjustment prominent among suggestions.

The use of the plumbline lens calibration method avoids any requirement for *a priori* knowledge of the principal point. The correlation which exists between the parameters of decentering distortion and the location of the principal point (see Fryer and Fraser, 1986) means that, provided the principal point is approximately determined to within, say five to ten pixels, the application of the parameters of decentering distortion will compensate for any uncertainty in the location of the principal point in a photogrammetric bundle adjustment.

SYSTEM DESCRIPTION

The image capture and processing system in the Department of Civil Engineering and Surveying at the University of Newcastle consists of three major elements: a video camera, a frame grabber operating within a PC AT computer, and a combination of proprietary and locally written software.

CCD-VIDEO CAMERA

A Video Logic brand CDR 460 camera with standard NTSC video signal output was used for this experiment (Figure 1). The resolution of this particular video camera was 512 columns by 220 rows. It was fitted with a standard Fujinon-TV 25-mm, *f*1.4 lens. The minimum focus distance of this system was 0.3 metres.

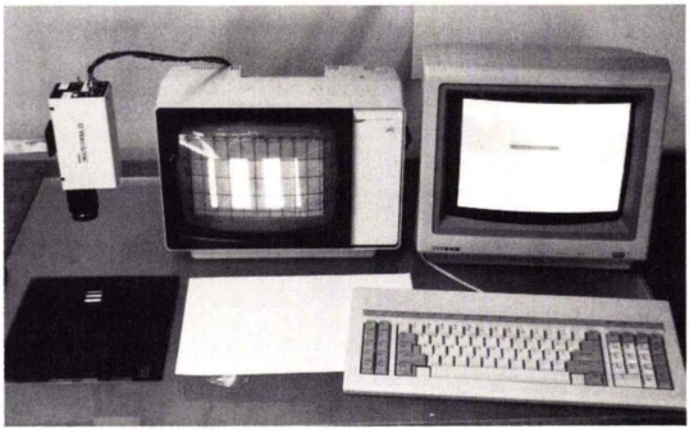

FIG. 1. Video system consisting of Video Logic camera and IBM PC clone with frame-grabber. The plumbline edges in the lower left are displayed on the TV monitor in the center of the picture via the frame-grabber.

This lens arrangement was not suited to the very close-range inspection, say 0.1 metres, needed to examine small format image frames for automatic extraction of plumbline data. To counter this restriction, two close-up filters (Hoya brand, 35.5-mm diameter) of power 1 and 2 dioptres were added to the front of the TV lens. These close-up lenses were of a different diameter to the main lens, and a mounting device was manufactured in the laboratory. Any non-alignment of the lens elements was recognized as a possible source of decentering distortion, and the considerable amount actually found confirmed this concern.

FRAME GRABBER

The PC Vision Plus frame grabber is a video digitizer capable of digitizing various standards of video signals as input. These are stored as a digital image in an on-board frame memory card within the computer. The characteristics of this particular frame grabber include

- operation at 30 frames per second,
- digitising of video signal to eight bits (256 grey levels), and
- capacity to store two 512 by 512 images in frame memory.

SOFTWARE

Apart from the software which accompanied the PC Vision Plus frame grabber, all programs were written specifically for the detection of plumblines or straight edges. Point data for each plumbline was formatted for processing in Adam Technology's MPS-2 camera calibration software (Elfick, 1986). More detailed descriptions of the line and edge detectors used are provided in a later section of this paper.

AUTOMATIC EXTRACTION OF PLUMBLINES

The fundamental task in the plumbline method of lens calibration is to calculate the deviations from a straight line of best fit to the digitized points. Usually, the digitized points are in millimetres relative to the principal point but, in video array space, pixels were chosen as the measuring units.

Variations in the parameters of radial distortion are significant for changes in focus, particularly for wider angled lenses. For very close range work—such as the imaging of 35-mm transparencies—it becomes necessary to calibrate the lens for every object distance. A scheme is outlined below for a precise and rapid automatic means of line detection which should lead to the determination of the parameters of lens distortion.

Figure 2 schematically represents the fundamental components of this system. Stage 1 is the digitization of the NTSC video signal into digital format. This is performed by the Video Logic

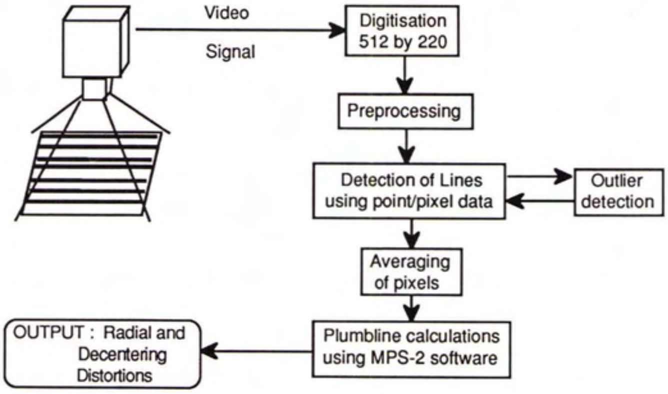

FIG. 2. Schematic representation of plumbline extraction.

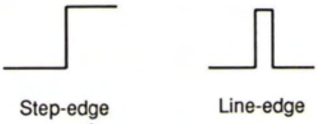

FIG. 3. Examples of edge-profiles before 'blurring' by the Imaging System (after Nalwa and Binord, 1986).

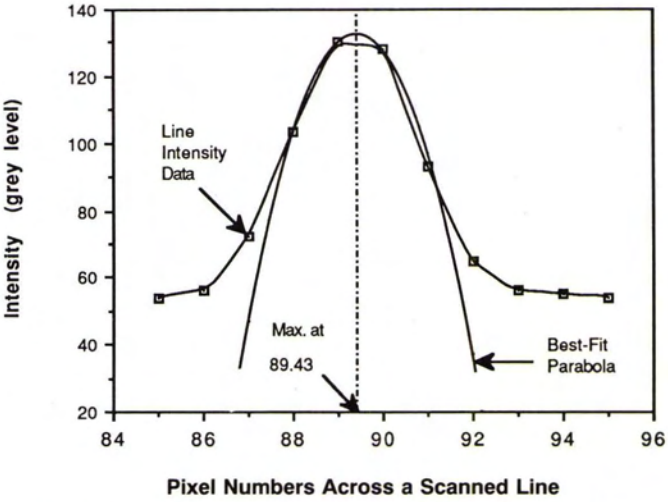

FIG. 4. Example of the operation of the line-detection algorithm.

CDR 460 camera and the PC Vision Plus frame grabber which produce a 512 by 220 array at 8-bit grey level intensity.

Currently the digital image is not preprocessed. Extension of the algorithm to include image subtraction of any fixed noise pattern, edge enhancement, and noise filtering is envisaged, if necessary, at a later date. This is shown as Step 2 in Figure 2.

The detection of lines, shown as Step 3, is a one-dimensional process. Assuming thin plumblines are used, the line detector searches across rows or down columns for vertical or horizontal lines. The maximum numbers of pixels for vertical and horizontal lines are 220 and 512, respectively. Because the MPS-2 software in its current configuration accepts a maximum of only 50 data points per plumbline, the quantity of pixel data had to be reduced by an averaging process (Step 5).

Step 4 is the detection of outliers and consists of using the method of robust estimation for the rejection of points with large residuals from the calculated line of best fit. This step can be included in the actual calculation of the parameters for lens distortion (Step 6) if the basic formulation of the plumbline method is revised. A discussion of the problems associated with the implementation of robust estimation is presented below.

The final step is the computation of the parameters of radial and decentering distortion from the reduced set of plumbline data. The MPS-2 camera calibration program not only computes the parameters of the Gaussian radial distortion but also produces a set of "balanced" parameters, i.e., a distortion curve exhibiting equal amounts of positive and negative corrections out to a preset radial distance. A radial distance of 300 pixels was used for the calibrations in this paper.

At this early stage of development, with substantial operator assistance, the average time for a complete lens calibration is less than 30 minutes. This involves the capture and extraction of all the plumblines and the processing of them to produce the parameters of lens distortion. This is two to four times faster than the manual method currently employed on the MPS-2 for non-metric cameras, and it is believed that further significant time savings are possible with refinements to the software.

LINE AND EDGE DETECTION ALGORITHMS

One aim of this research was to investigate the suitability of line-detection algorithms for the plumbline method. Up until this time lens calibrations at the University of Newcastle have been conducted using a test range consisting of thin plumblines. A majority of published edge-detection algorithms were unsuitable for this type of line imagery. These algorithms expect the intensity profile of the edge to be of the "step-edge" form, and not the "line-edge" as encountered here (see Figure 3) (also see Nalwa and Binford (1986)). Instead, an algorithm was devised and programmed to locate these line-edges to sub-pixel level. The effectiveness of this algorithm was tested against a step-edge algorithm of proven performance.

LINE-DETECTION ALGORITHM

The images of plumblines in the video array appear as a series of grey levels across a few pixels. These grey levels when plotted approximated a parabola (see Figure 4). A search was made for the pixel with the maximum intensity across each row (or down each column). Points were chosen on either side of this pixel so that a best-fit parabola could be calculated. Observation equations were used to find the turning point of the polynomial, i.e., where the first derivative equaled zero. In this way the peak of the polynomial could be found to sub-pixel level.

A least-squares approach, rather than a direct interpolation method (Tian and Huhns, 1986), was used to allow future extension of this algorithm to either a higher order polynomial, or for the inclusion of more pixels into the solution. The accuracy of either method clearly depends on the closeness of fit of the parabola to the sampled points.

EDGE-DETECTION ALGORITHM

The edge detector of Tabatabai and Mitchell (1984), which uses a moment-preserving technique to locate the edge of a grey level step to sub-pixel accuracy, was also programmed. This method, as Mikhail *et al*. (1984) note, is very simple to apply and yields unbiased estimates if the edge lies near the center of the area considered. To ensure this occurs, one method is to re-center the area being modeled with an initial solution. Alternatively, a thresholding technique can be used to first approximate the edge location.

This study applied the threshold algorithm of Wong and Ho (1986): i.e.,

$$\text{Threshold} = (\text{minimum pixel value} + \text{mean pixel value})/2$$

to each 40-pixel sample containing the edge. By selecting the pixel closest to the threshold value as the initial edge location, a sample of 15 pixels (seven to the left, seven to the right of center) was used to determine to sub-pixel level the correction distance of the edge from the center pixel.

Mikhail *et al*, (1984) report that the moment-preserving algorithm can achieve edge location accuracies better than 0.01 pixels (RMS)for a low noise image (e.g., signal-to-noise ratio, SNR = 100). It was also reported that for images with a high noise content (SNR = 10) the edge could be detected to better than 0.3 pixels (RMS). It is significant that very little computational effort is required.

DETECTION OF OUTLIERS : ROBUST ESTIMATION

In the plumbline technique, the first stage of the computation is the fitting of lines of best fit to the digitized points along the imaged plumblines. The second stage is to take differences from the line of best fit and use these values as data to determine the parameters of radial and decentering distortion. This procedure is iterative and converges after five to ten iterations.

Because the imaged lines are not straight (due to the lens distortions), there always arises a problem as to which digitized points contain significant observation errors. This dilemma is most prevalent at the extremities of the plumblines where the combination of poorer image quality, larger magnitudes of the distortions and, in the case of conventional cameras, film deformations, manifest themselves. The intervention of the photogrammetrist is usually required after the first set of calculations to decide whether or not to exclude some of the data.

An alternative to the conventional least-squares method of solution is robust estimation, or "re-weighted least squares" (Kubik *et al.*, 1988). The primary advantage of robust estimation techniques is that the estimated parameters (in this case the parameters of lens distortion) will remain relatively unaffected by the presence of blunders in the observations. The robust estimation technique should isolate and re-weight those observations containing blunders. This characteristic of robust estimation was especially significant in this project as, apart for geometric errors, radiometric errors may have also been present in the operation of the video camera. Radiometric influences such as poor image contrast could have biased the scanned images and degraded the overall result for the parameters of lens distortion.

Moreover, as this project required high precision in order to evaluate the line and edge detection algorithm, it became essential to eliminate any effects due to gross errors. If the parameters of the lens calibration contained errors, all future measurements with the video camera would be affected.

The detection of outliers did not present a problem with the "ideal" imagery used for the calibration of the video camera's lens but preliminary results indicated that, when imaged plumblines on small format film were scanned, any sub-standard imagery due to poor contrast, lighting effects, shadows, light fall-off in the corners of the frame, and so on, did result in difficulties for the robust estimation algorithm.

The robust estimation method used was based on the so-called "Danish Method" (Kubik *et al.*, 1987). The mechanics of this method are straightforward: rather than minimizing the (weighted) sum of the squares of the residuals, i.e.,

$$\Sigma v^2 = \text{min.} \qquad (1)$$

where v = residual from each observation equation, a weighting function

$$\Sigma P(v) \,.\, v^2 = \text{min, where} \qquad (2)$$

$$P(v) = 1 \text{ for } |v| < \alpha, \text{ and}$$

$$P(v) = \exp(-|v^2|/\alpha^2) \text{ for } |v| > \alpha, \qquad (3)$$

and α = designated confidence interval.

Explicitly, the method operates in the following manner:

(1) for the first iteration all observations are assigned a weight of 1.0;

(2) for successive iterations the weight of each observation is recomputed according to the function shown above as equation (3). Because an exponential function is used, observations outside α have rapidly decreasing weight and consequently have reduced influence onthe estimated parameters. Convergence of each adjustment is fast and

(3) the process is stopped if
  (i) the number of iterations exceeds a preset maximum or
  (ii) the differences between successive determinations of the estimated parameters falls below preset criteria or
  (iii) all weights remain equal to 1.0 after an iteration, and the solution has reached covergence.

TEST RESULTS

RADIAL AND DECENTERING DISTORTION

For the line extraction algorithm a set of nine lines on printed paper were illuminated by a light table 0.20 m below the camera (see Figure 1). These lines were rotated by 90° after the detection of the "horizontal" set to produce the "vertical" set of lines. Five separate tests were made with the lines placed in different orientations relative to the camera in order to test the precision of the results.

In the case of the edge-detection algorithm, the edge of a black X-ray image was used to create each plumbline. Again, five calibration tests were made. Each calibration consisted of nine horizontal and nine vertical sets of edges. To demonstrate the rapid changes of the parameters of lens distortion, a sixth test was made at an increased object distance of 0.32 m. Apart from this change in object distance, all other imaging conditions remained static throughout the tests.

Tables 1, 2, and 3 show the results for the radial and decentering components of the distortion in the lens of the video camera obtained from the use of both the line and edge detector methods.

TABLE 1. COMPARISON OF FIVE SETS OF BALANCED RADIAL DISTORTION RESULTS (IN PIXELS) FOR LINE- AND EDGE-DETECTION ALGORITHMS. CAMERA TO OBJECT DISTANCE 0.20M.

Method	Rad. Dist (pixels)	50	100	150	200	250	300
Line Detection	Mean	−0.06	−0.10	−0.10	−0.03	0.13	0.40
	St. Dev.	0.01	0.01	0.01	0.01	0.02	0.04
	Range	0.02	0.03	0.03	0.00	0.04	0.09
Edge Detection	Mean	−0.09	−0.15	−0.15	−0.04	0.19	0.58
	St. Dev.	0.02	0.02	0.02	0.01	0.04	0.09
	Range	0.04	0.06	0.07	0.01	0.09	0.19

TABLE 2. COMPARISON OF FIVE SETS OF DECENTERING DISTORTION PROFILES (IN PIXELS) FOR LINE- AND EDGE-DETECTION ALGORITHMS. CAMERA TO OBJECT DISTANCE 0.20M.

Method	Distance (pixels)	50	100	150	200	250	300
Line Detection	Mean	0.03	0.13	0.30	0.50	0.82	1.17
	St. Dev.	0.01	0.02	0.02	0.05	0.06	0.10
	Range	0.02	0.03	0.05	0.10	0.15	0.21
Edge Detection	Mean	0.04	0.16	0.36	0.64	0.95	1.36
	St. Dev.	0.01	0.02	0.05	0.10	0.12	0.17
	Range	0.01	0.03	0.08	0.13	0.20	0.29

TABLE 3. BALANCED RADIAL AND DECENTERING DISTORTION PROFILES (IN PIXELS). CAMERA TO OBJECT DISTANCE 0.32M. EDGE-DETECTION ALGORITHM.

Distance (pixels)	50	100	150	200	250	300
Distortion						
-Radial	−0.21	−0.34	−0.32	−0.08	0.43	1.24
-Decentering	0.03	0.11	0.25	0.44	0.69	0.99

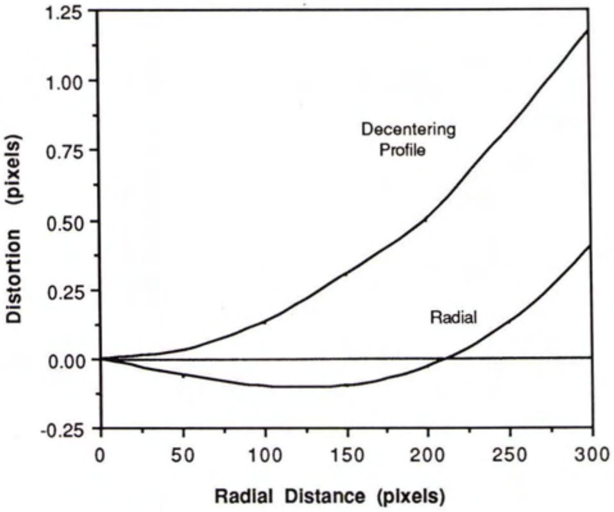

FIG. 5.Balanced radial and decentering distortion profiles. Camera to object distance 0.20m.

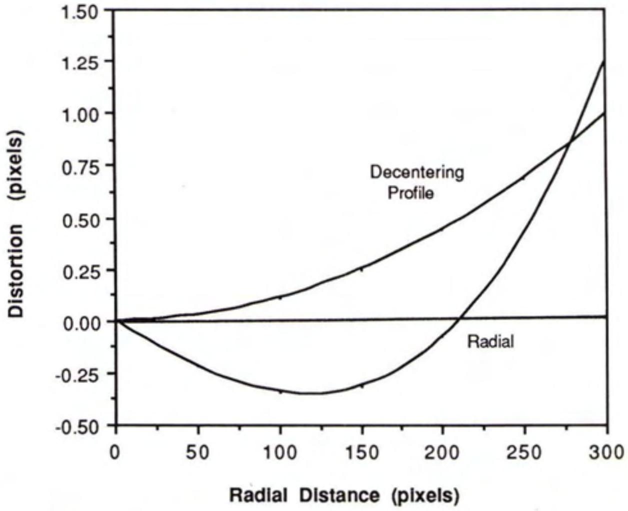

FIG. 6. Balanced radial and decentering distortion profiles. Camera to object distance 0.32m.

Figures 5 and 6 illustrate these findings. Note the values in all tables and figures are in terms of *pixels*. This is a departure from the usual method of recording results in millimetres and micrometres but it was considered appropriate for this study of a video camera.

Examination of Tables 1 and 2 reveals that there are no differences of statistical significance in the results from the line- or edge-detection algorithms. Although it would be unwise to make definitive statements from a set of only ten tests, it does appear that the repeatability of the line-detection algorithm is slightly superior. The range of values across the five tests and the standard deviations of the distortions for both the radial and decentering distortion profiles are smaller for the line-detection algorithm.

The final selection of the most suitable algorithm must also consider operational efficiency. It would be premature to draw any firm conclusions at the present time as the use of video cameras for the automated extraction of plumbline data is still in a developmental stage. Nevertheless, the edge-detection method avoids any least-squares operations, thereby saving computer processing time, and would appear to be the most time-effective.

Table 4 indicates the number of points rejected from each test. Despite the apparently small percentage of rejected points (less than 0.5 percent of all points processed), a trend in the location of outliers was noticed. Almost without exception, all rejected points were located on lines closest to the edges of the CCD chip. The source of this apparent instability at the sensor extremities demands further investigation.

Figure 6 indicates the results for the lens distortion when the camera-to-object distance was increased from 0.20 m to 0.32 m.

EXPERIENCES WITH ROBUST ESTIMATION

The value of robust estimation for photogrammetric tasks such as relative and absolute orientation has been demonstrated by Kubik *et al*. (1988) and others. It became evident during the present tests, however, that the method of robust estimation applied to the fitting of a straight line to a set of automatically extracted points which physically lie on a curve may be too simplistic.

The intention of this project was for any techniques developed to be operational across a broad range of image conditions. Specifically, with sub-standard imagery, the percentage of gross errors in sets of plumbline data points increased from less than one percent on ideal imagery to approximately ten percent on data extracted from some small-format 35-mm transparencies.

It has been well documented (for example, Chen *et al*. (1987)) that, with small data sets and/or when the observations include more than one outlier, difficulties arise in the identification and localization of the outliers. Preliminary tests on plumblines imaged on 35-mm transparencies demonstrated this to be the case: in all data sets with a large percentage of outliers, the initial estimates of the parameters of lens distortion and of the best-fit line were poor. Consequently, many good points were rejected with subsequent iterations leading to a false solution.

This failure cannot be attributed entirely to the method of robust estimation. If several outliers are present, the first attempt at line fitting may be so erroneous that the outliers cannot be detected. The basic formulation for the plumbline method could be altered to include as input some first approximations to the parameters relating to each line of best fit.

CONCLUSIONS

The work reported in this paper has demonstrated a rapid method of lens calibration for a video camera system using the plumbline technique in combination with line- or edge-detection algorithms. It is believed that it could be applied to robotics or real-time photogrammetry in the future. A more immediate

TABLE 4. COMPARISONS OF NUMBERS OF POINT REJECTIONS USING ROBUST ESTIMATION. THE AVERAGE NUMBER OF REJECTIONS PER LINE OF 50 DATA POINTS IS INDICATED. THERE WERE NINE HORIZONTAL AND NINE VERTICAL LINES IMAGED PER TEST.

Test No.	1	2	3	4	5	Ave./line
Line Detection	10	15	17	21	17	0.8
Edge Detection	19	10	17	26	24	1.0

application is the determination of the parameters of lens distortion for small format cameras by using the video system to scan transparencies of imaged plumblines.

One feature of the automated processing of small-format photography deserves further mention. It became obvious that no amount of sophisticated software will overcome a basic reality known to photogrammetrists for over a century – the quality of the imagery *must* be optimized if the best possible results are to be derived!

It has been shown that it is necessary to calibrate the video camera for the photogrammetric parameters of lens distortion as well as for electronic effects. The electronic calibration will provide a method for preprocessing the imaged data before entering any lens calibration software packages. To fully achieve benefits from this form of automated processing, the detection of gross errors must also be reliable, rapid, and automatic. The use of robust estimation for this task was analyzed and has been shown to be successful when the numbers of outliers were small.

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