SINGLE STATION SELF-CALIBRATION TECHNIQUES

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Abstract

Two of the leading photogrammetrists in the field of close range photogrammetry for the past two decades, Wilfried Wester-Ebbinghaus and Duane Brown, passed away in the period 1993-1994. Both these men had a strong influence on the camera calibration techniques which are now in common usage for close range photogrammetry, namely the plumb-line technique and the method of multi-station self calibration. It is not so well-known that both also proposed single station self-calibration techniques and as a tribute to their inventiveness, this paper describes and compares their techniques. The method attributed to Wester-Ebbinghaus was published in 1982, but that proposed by Brown was only disclosed to this author in private conversations during 1985 and, to my knowledge, has never been published.

The paper describes each technique and compares the advantages and disadvantages of their respective application. Numerical results for each single station self-calibration procedure are presented and compared to the results obtained when a more conventional multi-station procedure is implemented for the same digital camera.

INTRODUCTION

Wilfried Wester-Ebbinghaus was the Professor of Photogrammetry at Braunschweig University at the time of his unfortunate death by drowning in 1993. He was only 46 years old yet had an enviable reputation in the field of close range photogrammetry for his work on the theory of camera calibration, the exploitation of small format photogrammetry, architectural photogrammetry and the development of digital scanning reseau cameras. In 1982 he had published at the Commission V Symposium in York, England, a paper on single station self-calibration (Wester-Ebbinghaus, 1982, 533-550) and a summary is produced in the next section.

Duane Brown was clearly one of the most outstanding photogrammetrists of the latter half of the twentieth century. Many of the techniques which are regarded as commonplace today were the result of his fertile imagination. Perhaps no other photogrammetrist has been so successful in transferring from the government to the private sector and establishing a niche in the field of close range photogrammetry. The work carried out by the companies he spawned, DBA Systems (Duane Brown and Associates) and then GSI (Geodetic Services Incorporated), spread across the entire range of precise measurement procedures in highly technical fields. The aerospace, ship-building, car manufacturing and related industries use systems he developed. Defence contractors are also large users of techniques he pioneered, yet by the very nature of these industries, many of the exciting developments and projects he worked on will never be publicly acknowledged.

Many of Brown's earlier theoretical works are to be found in U.S. Air Force Technical Reports (for example, Brown, 1956, 1959 and 1964). As early as 1956 he had published a paper entitled "The Simultaneous Determination of the Orientation and Lens Distortion of a Photogrammetric Camera" and by 1960 had laid the foundations for the modern bundle adjustment method (see Brown, 1976,1). Brown is well-remembered for his plumb-line technique (Brown, 1971) and it was the good fortune of this author, while working with him during a six-month sabbatical at GSI in Florida in 1985, that Brown discussed his ideas for a single station self-calibration method. To my knowledge, his concepts had not been previously published nor were published subsequently as Brown worked on various other projects such as Autoset and his range of close range cameras (see, for example, Fryer and Brown, 1986).

SINGLE STATION CAMERA SELF-CALIBRATION

The 'traditional' method of camera self-calibration usually involves the bundle adjustment of a series of convergent photographs of target array taken from four to eight well-spaced camera stations with a range of camera orientations and roll angles. The single station techniques proposed by Wester-Ebbinghaus (1982) and by Brown (1985) require all images of the target array to be taken from a single point of exposure.

In the case of Wester-Ebbinghaus, the camera is tilted alternatively about + and − X and Y axes by approximately 30° to 45° after an initial image is obtained from a central viewpoint. Rotation of the camera around its optical axis after the first exposure aids the determination of the offsets of the principal point. The reliability of the solution for the camera and lens parameters is improved by using relatively large numbers of targets. In Wester-Ebbinghaus' paper (1982, 544) he showed that after approximately 50 well-distributed targets were imaged, further improvements arising from additional numbers of targets were only marginal.

Wester-Ebbinghaus acknowledged that it would be unrealistic to assume that the projection centre would remain fixed in space while the camera was inclined. He noted that the projection centre and the centre of rotation will not coincide during an actual calibration procedure and made allowance for this difference (he termed it "eccentricity") in his formulation of the bundle adjustment.

The single station self-calibration procedure proposed by Brown has not been documented. In fact the author is unaware of his concepts being discussed with anyone else, so the finer details of actual implementation of his calibration procedure were not developed. The main difference in Brown's approach was to use only an approximately linear row of targets (he suggested street lights along a road on the horizon) rather than an array of close range targets as in Wester-Ebbinghaus' technique. Brown was always interested in terrestrial techniques for the calibration of large format aerial cameras, so his thoughts were accordingly attuned to focus at infinity, hence his concept of a row of distant street lights.

Brown suggested that several images, say 8 to 10, be collected as the camera was tilted through its angular field of view. He further implied that after these rotations about the X axis, the camera would be rolled through 90° and the image capture be repeated about the Y axis. Since the camera to object distance would be relatively large, say 1 km or more, the slight eccentricity problem highlighted by Wester-Ebbinghaus would be insignificant to the solution of the camera's position. As the pioneer of the bundle adjustment, Brown was aware that as long as he had some approximate positions for his distant targets, and there was "reasonable" number of them (say 10 to 20), then he could produce parameters for camera and lens combinations without ever determining final values for his opportunistic targets. Wester-Ebbinghaus also noted that an accurate determination of the coordinates of the targets was not necessary. Of course, results for the principal distance will be reliant on knowing the relativity of the camera station and the target range.

EXPERIMENTAL COMPARISONS

To obtain some practical experience with these concepts of single station camera self-calibration, both procedures were used to calibrate a Fotoman camera. The Fotoman digital still camera has an array of 768 by 512 pixels, with a pixel size of 9 by 9 μm. The principal distance is approximately 9 mm and the cost of a Fotoman digital still camera in 1996 is close to US$1,000.

The three-dimensional test range of retro-reflective targets attached to an air-conditioning plant, associated piping and background wall in the laboratory building of the Department of Civil Engineering and Surveying at the University of Newcastle was used. The target array covers an area of approximately 4 m by 3 m by 1 m(depth).

With a camera to target distance of approximately 8 metres, the camera was effectively focused at infinity. Care was taken with the camera/tripod mounting so that 'eccentricity' effects of any offset between the projective centre and the centre of rotation were minimised. From the array of targets imaged for each exposure, a row of 19 targets were selected to simulate Brown's target criterion while the entire array of 80 targets were used in Wester-Ebbinghaus' procedure.

Nine sets of images taken about each of the X and Y axes (a total of 18 images) were used for the bundle adjustment based on Brown's hypothesis. A total of 9 images were used for the Wester-Ebbinghaus technique. These consisted of one central image and eight tilted images with the camera in both the normal and rolled positions in each of the + and - X and Y directions. The results are shown in Table 1.

Also shown in Table 1 is a more conventional bundle adjustment using 8 well spaced and convergent images. This 'normal' self-calibration bundle adjustment was computed to provide a comparison for the camera and lens parameters. In addition a plumbline calibration was performed to provide independent comparisons for the parameters of radial and decentering distortion. The best way to appreciate the results for the radial and decentering lens distortions is to examine Figures 1 and 2. The small spread of results even at the extreme edge of the sensor area is a testament to the effectiveness of all techniques.

Method	Camera Stations	No. Images	No. Targets per image	RMS x,y (μm)	Principal Distance (mm)	x_0, y_0 Offsets of Princ. Pt. (mm)
Plumbline	1	2	8 lines	1.0 x 1.0	-	Not determined
Conventional Bundle	8	8	80	1.4 x 1.3	8.415	- 0.059, - 0.018
Brown	1	18	19	1.4 x 1.4	8.513	- 0.068, + 0.017
Wester-Ebbinghaus	1	9	80	1.4 x 1.4	8.520	- 0.079, - 0.007

Table 1. Comparison of Techniques

DISCUSSION OF RESULTS.

To this author's delight (and relief) both the Wester-Ebbinghaus and Brown methods for a single station self-calibration worked with a minimum of fuss. There were some anxious moments in the office deciding on how it would be possible to rotate the camera while keeping the focus point stationary, but in practice in the laboratory it was not too difficult. Other fears of producing 'matrix singular' conditions in the solutions were similarly dispelled.

The result shown in Figures 1 and 2 indicate the high degree of reliability achieved. Table 1 shows that the root-mean-square value achieved on the images after adjustment were all similar at approximately one-seventh of a pixel for the Fotoman camera used. Given the relatively small size of the targets imaged (4 to 7 pixels in diameter), high accuracies were not anticipated.

The only real differences discernible are in the values for the principal distance and the offsets of the principal point. As noted earlier, uncertainties in the location of the single station camera location directly relate to uncertainties in the principal distance. The results of the bundle adjustments for the additional parameters of x_o, y_o and P_1, P_2 showed high correlation (greater than 0.85) in each case except for the Brown method where it was not so significant. This was a little surprising and may be related to the higher number of images used although further investigation may show this to be a function of the particular set of targets used.

CONCLUSIONS AND FUTURE USES.

The photogrammetric community, especially those working in the close range field, owe a tremendous debt of gratitude to men like Duane Brown and Wilfried Wester-Ebbinghaus. They pioneered many calibration procedures and whilst this paper concentrates on the relatively obscure topic of single station self-calibration, their contributions to our discipline were much wider.

Is there a future for single station self-calibration? As this paper shows, it is a technique which does work, but it is obviously not as robust nor convenient for most applications as is a conventional convergent self-calibration bundle adjustment.

One could think of obscure situations where it may be applied however. Consider a robot inside a nuclear power station which must automatically re-focus its video camera before taking some images of pipe-work. It is conceivable that it could be in a confined space and by taking several images with its camera tilted through the range of its angular field of view, it could generate its own self-calibrating data.

Perhaps other scenarios are more likely, including those in industrial situations where cameras are fitted to concrete plinths or bolted to frames for the taking of images of tooling jigs. Single station self-calibration may be used as a quality assurance event in such situations prior to the taking of the industrial imagery.

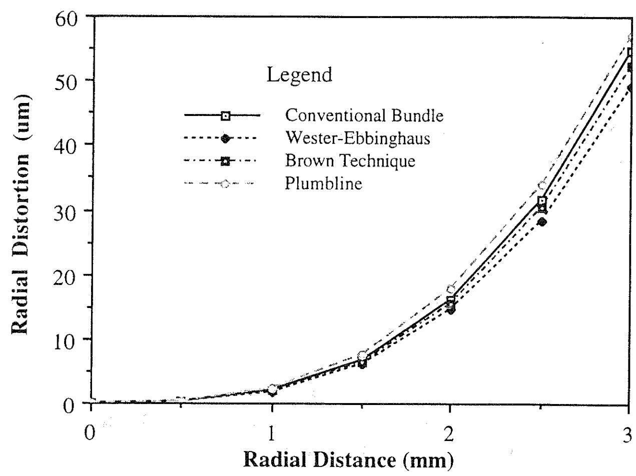

Figure 1. Radial Distortion

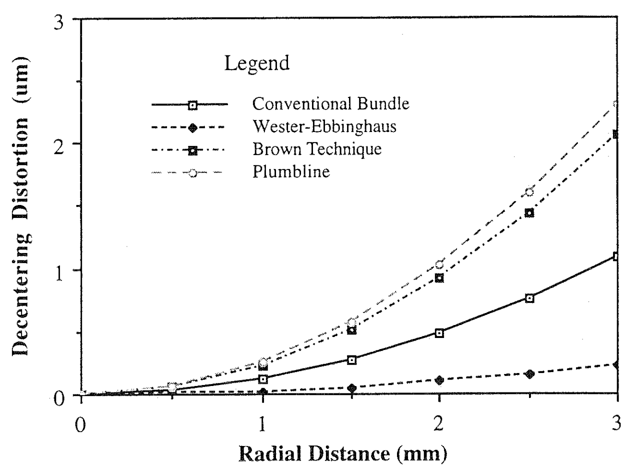

Figure 2. Decentering Distortion

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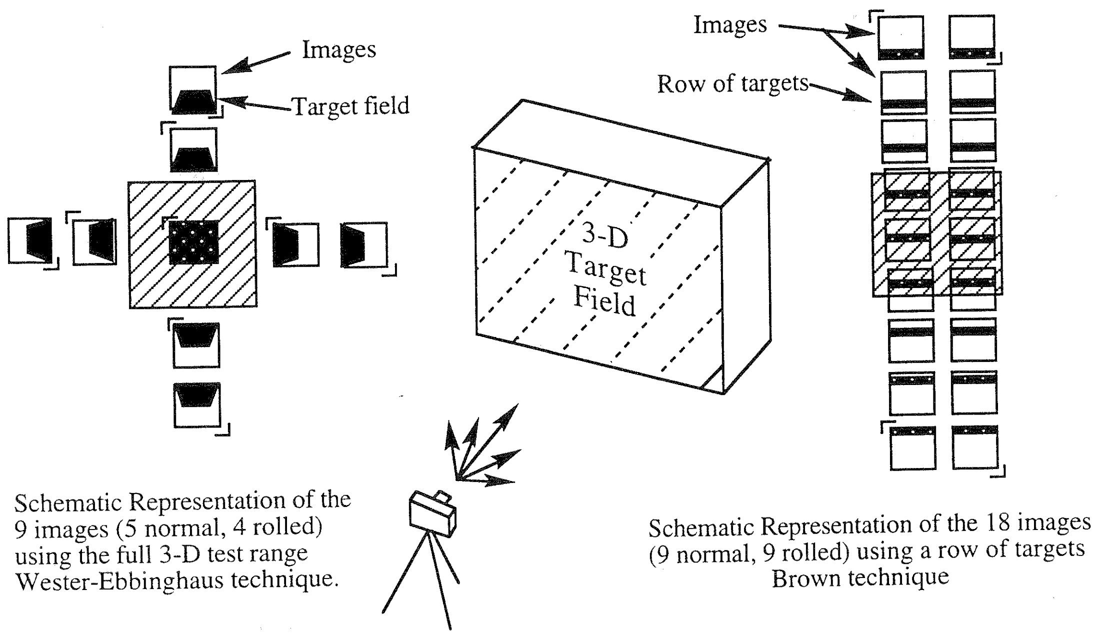

Figure 3. Schematic representations of Single Station Calibration Techniques attributable to Brown and Wester-Ebbinghaus

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