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AUTOMATED DIGITAL PHOTOGRAMMETRY ON A SHOESTRING

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Abstract

A system capable of automatically deriving the three dimensional co-ordinates of well defined binarized targets is described. Significantly, the system comprises cheap "off the shelf" hardware and software, requiring a minimum of development. Comparative tests using imagery obtained with a Hasselblad semi-metric camera and a 35 mm SLR camera are presented. By means of automated sub-pixel measurement, the results achieved are equivalent to those undertaken through manual target measurement using a first order analytical plotter.

Introduction

The aim of this paper is to describe the potential of "off the shelf" hardware and software for providing the foundation of a digital photogrammetric system capable of determining three dimensional co-ordinates of points, with a high degree of automation. The benefits of such a system are independence from totally proprietary solutions, improved understanding of the processes involved and, perhaps most importantly, minimal financial outlay. This last aspect is particularly crucial to academic users; fortunately much of the software is available at very competitive prices if its use is restricted to research purposes.

The technologies embraced by the experimental system include small/medium format cameras to acquire the imagery, the Kodak Photo CD system to convert the analogue photographs into digital form, PC based software packages to automatically measure the locations of targeted points and, finally, a self calibrating bundle adjustment to combine all the measurements in a unified least squares estimation. Tests involving convergent imagery of a non-planar 4 m testfield using both a 35 mm and a semi-metric Hasselblad camera have been carried out and are described. Results indicate that a measurement precision approaching 0·1 pixel can be obtained for each individual target and, with an appropriate network, such a system is capable of deriving object co-ordinates to sub-millimetre precision.

Incessant advances in technology in diverse areas unrelated to photogrammetry provide ample opportunities for photogrammetrists. The Kodak Photo CD system is one example and has been recognized by Hanke (1994) to provide a means of deriving scanned imagery. The Kodak DCS200 digital camera offers great potential (Maas and Kersten, 1994); accuracies of 1:80 000 (Fraser and Shortis, 1994 and 1995) have been achieved through a combination of strong network geometry and high data redundancy. Standard PC based software packages have already been exploited by photogrammetrists. CorelDraw and Aldus PhotoStyler (Georgopoulos and Tournas, 1994) have been used to develop a system capable of rectifying digital imagery on a PC and Ogleby (1994) used Adobe PhotoShop and PC-Erdas on both Macintosh and PC systems to record and restitute Aboriginal rock art.

System Components

All photogrammetric measurement systems require the ability to acquire imagery, and to measure and compute three dimensional co-ordinates in an arbitrary co-ordinate system. The components of the system developed by the authors are considered in more detail.

Acquisition of Photography

Although the use of fully metric cameras is usually recommended for accurate measurement, it has been long recognized that non-metric (Faig, 1976) imaging techniques offer potential for photogrammetry (Schwidefsky, 1970; Murai *et al.*, 1980). These methods have been used successfully to solve a wide range of measurement problems (Chandler *et al.*, 1989), particularly at close ranges (Maas and Kersten, 1994; Stirling *et al.*, 1994; Trinder *et al.*, 1994). Cameras used for photogrammetry may be classified into three groups based upon the information available concerning the inner orientation of the camera (Faig, 1976). For the current measurement system, the use of both a "non-metric" and a "semi-metric" camera are considered for recording an image. Trials were conducted, with conventional photographic emulsion, using an "off the shelf" 35 mm Minolta non-metric camera equipped with a zoom lens (focusing range from 28 mm to 70 mm) and a modified Hasselblad ELX "semi-metric" camera. The latter was fitted with a 25-cross réseau plate and an 80 mm focal length lens capable of being pinned at a desired focal setting. These two camera types represent two possible imaging systems which can be assembled for less than £1000.

Analogue to Digital Conversion

The system developed is based upon a "hybrid" imaging system in which conventional analogue photographs are converted to a digital form by scanning. The term "hybrid" is valuable because it distinguishes this cost effective method of acquiring digital imagery from fully digital systems which make use of online CCD cameras (Helava, 1988).

The conversion of the analogue photograph to a digital or discretized representation is a crucial step in which various systematic errors may be introduced; there are a variety of technologies available to carry out this process. At one end of the price/geometric stability range are the high precision systems designed for photogrammetric production, typified by the PhotoScan or PS1 systems marketed by Zeiss and Intergraph. This type of instrument is capable of scanning full aerial format imagery at a resolution as small as 7 μm, with high geometric accuracy. At the other extreme are the more modest desktop systems designed for scanning A4 documents suitable for document publishing. Such systems scan at an optical resolution of 400dpi (60 μm), with a consequent degradation of accuracy. An alternative, intermediate level technology, which was considered to be worth investigating, is the Kodak Photo CD system. This product has been developed for both consumer and commercial use, primarily for the archiving of images, digitizing photographs for publishing, and presenting material (business and family images) on a computer monitor. Kodak Photo CD technology appeared to offer potential to photogrammetry for a variety of reasons. The image is scanned at a range of resolutions (Table I), including an optimum possible resolution of 4096 lines $\times$ 6144 pixels. For medium format (60 $\times$ 60 mm) imagery, this scanning accuracy corresponds to an optimum potential pixel dimension of 10 μm. All data are stored on CD ROM, which solves a rarely discussed management problem associated with digital imagery: storing the large image files which are generated (up to 72 Mb per image for medium format imagery). Standard Photo CD is also very cheap; 36 photographs of 35 mm format can be scanned and stored for less than £20 and both greyscale (256 levels) and colour images (true colour) are supported using the Kodak devised colour coding system, metric Photo YCC (Kodak, 1994). The Standard Photo CD film scanner is only capable of scanning 35 mm formats but the Pro Photo CD scanner can handle a variety of formats including 120 mm roll and 5 $\times$ 4 inch cut film formats.

A major concern with the use of this non-standard technology for photogrammetry is the geometric stability of the scanner and consequent accuracy of the scanned image. Hanke (1994) has assessed these aspects by measuring the image co-ordinates of a series of imaged réseau crosses using both a first order analytical

TABLE I. Photo CD characteristics: medium format (60×60 mm), 256 grey levels.

Photo YCC	*Base/16*	*Base/4*	*Base (TV resolution)*	*Base × 4 (HDTV)*	*Base × 16*	*Base × 64 (Pro CD only)*
Dimensions						
lines × pixels	128×192	256×384	512×768	1024×1536	2048×3072	4096×6144
Pixel size (μm)	468×312	234×156	117×128	58×39	29×19	15×10
File size (Mb)	0·02	0·09	0·38	1·50	6·00	24·00

plotter and manual measurement of a Photo CD scanned image. A difference of 1 per cent in scale in the x, y image directions was apparent but, significantly, a six parameter affine transformation (applied globally) removed these systematic effects with residuals of ± 5 μm (Hanke, 1994).

It was decided that this technology would be examined further by using Kodak Photo CD as a means of scanning both 35 mm and Hasselblad imagery and carrying out full photogrammetric system tests where derived measurements from convergent photographs are combined in a least squares estimation.

Image Measurement

The development of any photogrammetric system implies that the measurement of points or features recorded in the plane of the image will be involved. It is appropriate to distinguish between the measurement of points originating in the object space (for example targets) and those reference points which are internal to the camera system (for example fiducials/réseau). It was the authors' intention to develop a system with a high degree of automation and it is well established that measurement of both targets and fiducials can be automated if lighting and illumination are carefully controlled (Davies, 1990). This principle is widely used in photogrammetry and machine vision, particularly with regard to the use of retro-reflective targets illuminated by flash gun adjacent to the camera (Clarke and Robson, 1993; Fraser and Shortis, 1994; 1995; Dold and Maas, 1994). The technique is typified by the GSI AutoSet video scanning film reader capable of automatic measurement of image co-ordinates to accuracies surpassing 0·5 μm (Fraser and McGee, 1995). A similar approach was adopted for this cheaper system, with the combination of retro-reflective targets and a flash gun used to isolate the required targeted points from background detail through the use of an appropriate threshold.

Software tools necessary to measure and determine the centre of the imaged targets had to be either developed in house or existing proprietary software had to be used for the purpose. The costs and availability of commercial packages capable of carrying out this task were investigated (Khorous, Optimas), including a package called Visilog, developed by the French company Noessis. This software is of particular significance for university users because it is available under one of the CHEST (Combined Higher Education Software Team) arrangements at a reduced price for academic use.

Visilog is particularly suited to research and development work through its modular approach to image processing and analysis; it is supported on a variety of platforms within both Microsoft Windows and UNIX environments. The package has a comprehensive suite of image processing libraries including the following: convolution and spatial filters; edge detection, linking and approximation; frequency domain processing; and, notably, global analysis of objects following application of a labelling technique (Boyle and Thomas, 1988). This latter feature includes a series of "measurements" which can be obtained for all detected particles or objects, two of which include the "centre of gravity" (X and Y grey first order moments) derived from the original greyscale image. Visilog is also equipped with a "C interpreter" which allows the user to record, develop and refine sequences of image processing operations necessary to carry out a particular task. The annotated script (Table II) indicates the stages of data processing used to determine the centre of the targets in

TABLE II. Annotated Visilog script for the determination of the centre of the targets in the two dimensional pixel co-ordinate system using the centre of gravity operator.

```
MeasCofG ()
{
    read(, ,"init",0    );                     /* Load an image file */
     init.IWINDOW = 0;
    PopUpImageWindow();                        /* Display image */
    Display("init");
    UpdateLut(NORMAL);\
    UpdateLut(NORMALF);

    RmSetPause(TRUE);                          /* Threshold image to identify */
    Threshold("init", {215, 255},"bin" );      /* binarised targeted points using */
    RmSetPause(FALSE);                         /* Global threshold, set visually using slide bar*/

    UpdateLut(NORMALF);
    label("bin","lab"    );                    /* Label image, ie transform clumps of pixels */
    RmSetVal(M_selectmenu,1);                  /* into a mask which identifies each target */
    WRmPopUp(W_graph[1]);
    UpdateLut(BINARY);
    analyze(1,"s1","lab","init","", {0, 0, 0,  /* Determine centroid of targets using original */
      0, 0, 0, 1, 1, 0, 0, 0, 0, 0, 0, 0, 0,   /* grey scale scale image and binarised image */
      0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0});    /* as a mask. Import measurements into an editor */
                                               /* via Windows Clipboard */
}
```

the two dimensional pixel co-ordinate system using the centre of gravity operator.

This simple procedure was extended to derive a weighted mean based upon the square of the original grey values, which is widely used in digital photogrammetry (Chen and Clarke, 1992; Nilsen and Hådem, 1994). The annotated script (Table III) indicates how this alternative was instigated in Visilog.

Measurement of reference/fiducial/réseau marks was carried out with the PC based product, Aldus PhotoStyler, which was used to access the Kodak Photo CD image files. This particular package is equipped with two "rulers" which enable manual measurement of points to be made to sub-pixel precision ($\pm 0{\cdot}2$ pixel). All reference marks were measured using this facility and derived pixel co-ordinates were merged into the file of automatically measured target co-ordinates using a standard

TABLE III. Annotated Visilog script for the derivation of a weighted mean based upon the square of the original grey values.

```
MeasWeighted ()
{
    read(, ,"in",0    );                         /* Load an image file */
     in.IWINDOW = 0;
    PopUpImageWindow();                        /* Display image */
    Display("in");
    UpdateLut(NORMAL);
    UpdateLut(NORMALF);

    convert("in",6,"init"    );                /* Convert image to long integer */
    multiply("init","init","init"   );         /* Square pixel values, overwriting input file */

    threshold("init", {40000, 65536},"bin");   /* Threshold image to identify binarised targeted */
    UpdateLut(NORMALF);                        /* points using a Global threshold */
    label("bin","lab"    );                    /* Label image, ie transform clumps of pixels */
    RmSetVal(M_selectmenu,1);                  /* into a mask which identifies each target */
    WRmPopUp(W_graph[1]);
    UpdateLut(BINARY);
    analyze(1,"s1","lab","init","", {0, 0, 0,  /* Determine centroid of targets using SQUARED */
    0, 0, 0, 1, 1, 0, 0, 0, 0, 0, 0, 0, 0,     /* image and binarised image as a mask */
    0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0});      /* Import measurements into an editor */
                                               /* via Windows Clipboard */
}
```

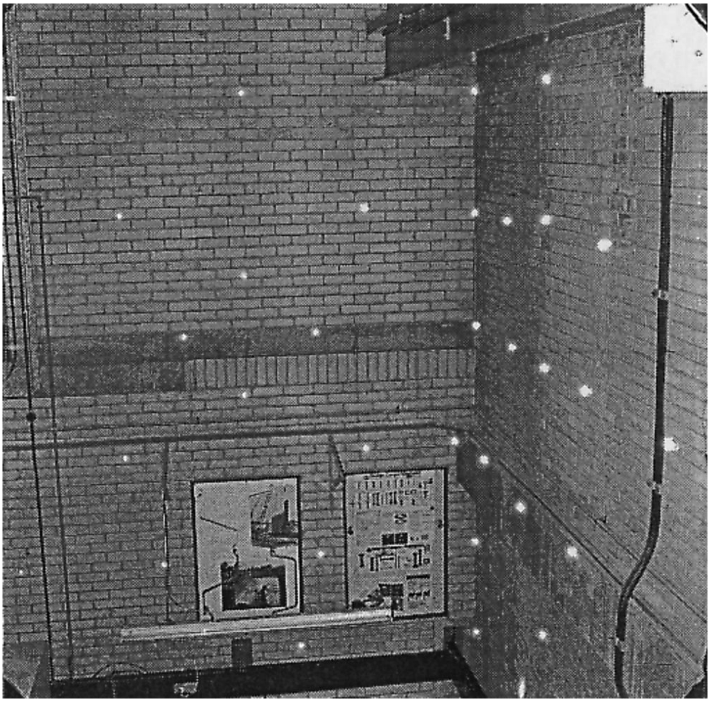

FIG. 1. Hasselblad image (850×850 pixels).

text editor. Investigations were carried out to examine the efficacy of measuring engraved réseau crosses automatically using Visilog. These tests suggested réseau crosses can be only measured automatically when the overall illumination within the object space is bright and evenly distributed. Engraved réseau crosses tended to disappear on these test images where the background object was dark (Fig. 1).

Data Processing

There are two key stages of data processing necessary to transform the measured pixel co-ordinates into three dimensional object space co-ordinates. The measured pixel co-ordinates from each frame must be first transformed into photoco-ordinates, then these photoco-ordinates from all frames can be combined in a bundle adjustment. The imagery was acquired using non-metric and semi-metric imaging systems and so it is important to use a self calibrating version of the bundle adjustment (Brown, 1976; Kenefick *et al.*, 1972; Granshaw, 1980; Chandler *et al.*, 1989).

An additional step carried out prior to the two stages of data processing is a data sorting or formulation stage. This procedure is necessary to ensure that only relevant measurements are included and to check that all measurements are identified correctly. The identification of targeted points using a simple global threshold often includes other unwanted points, where specular reflection of the flash illumination is high (such as from glass and shiny surfaces normal to the camera axis). It was possible, using Visilog, to filter out a proportion of these unwanted measurements automatically using the expected size and shape of the target image, but a few unwanted points had to be edited out manually. Identifying or numbering the measurements correctly and automatically necessitated the development of the program "SortId". This program used the approximate co-ordinates of all targets and the exterior orientation of each frame to estimate the likelihood of each automatically measured point representing an expected image point using a minimum distance criterion. Accepted points were then identified automatically using the desired point numbering system defined by the file of approximate target co-ordinates.

Following the recommendation of Hanke (1994), a six parameter affine transformation program was developed and used to transform the measured pixel co-ordinates to the required photoco-ordinates. The parameters of this transformation were derived using least squares based on the measured and calibrated co-ordinates of the fiducial marks for the Hasselblad imagery and the corners of the format for the 35 mm imagery. The program developed included an alternative option to perform a local bilinear transformation on all measurements (Chandler *et al.*, 1989) if adjacent réseau measurements were available.

A self calibrating bundle adjustment was used to combine all measurements in a unified least squares estimation. The particular version used is known as GAP and was developed originally at City University (Chandler and Clark, 1992). Estimated parameters included both the inner and exterior orientation parameters and the X, Y, Z co-ordinates of all targeted points.

Data Analysis

Following Cooper and Cross (1988), the terms "precision" and "reliability" are used in this paper to describe the quality of a data set with respect to random and gross errors respectively. The term "accuracy" is used to describe quality with respect to systematic errors. An important aspect of any least squares estimation is refinement of both the functional and stochastical models until a "satisfactory" estimation has been achieved. Such a decision can only be based upon examination of data generated by the bundle adjustment.

The a posteriori variance factor provides a single summary measure of the quality of the estimation, but is weak because it is based upon both the functional and stochastic models selected. A χ^2 test can be carried out on the variance factor, but this is unable to differentiate between a scaling problem in the stochastic model or a more serious deficiency in the functional model. Estimates of reliability are based upon measurement residuals, and conventional analysis of the output involves detailed examination and scrutiny of each. In many least squares estimation problems involving a large number of measurements this task simply becomes impracticable; software had been developed prior to this study (Chandler and Still, 1994) to analyse photogrammetric and survey residuals in a graphical manner (Figs. 2 to 5).

An additional part of data analysis is ensuring that all parameters used to model the internal geometry of the camera are estimated with statistical significance. Although a statistical test can be carried out, it is more typical to merely ensure that the value of any estimated parameter is larger that the associated standard error.

TESTS

Test Field Design and Construction

A photogrammetric test field represents a useful investment; it can be used to examine various photogrammetric issues and it provides a facility to calibrate the internal geometry of differing imaging devices. Experience had demonstrated the value of constructing a fully three dimensional test field rather than relying upon more simple planar arrays, primarily due to the difficulty of recovering a precise estimate of the principal distance using self calibration procedures. A corner of a laboratory was identified as a suitable site which could provide a three dimensional field 4×4 m in extent (Fig. 1). The added benefit of this location was its proximity to a gantry crane which could be used to place a camera in a wide variety of locations in three dimensional space, so providing the possibility of obtaining convergent imagery. Using standard retro-reflective safety tape stuck onto grey triangular blocks, 45 retro-reflective targets were constructed. The targets were designed with a diameter of 30 mm which would be capable of generating a target image with a minimum size of 4×4 pixels for the most distant target with an image of resolution 1000×1000 pixels.

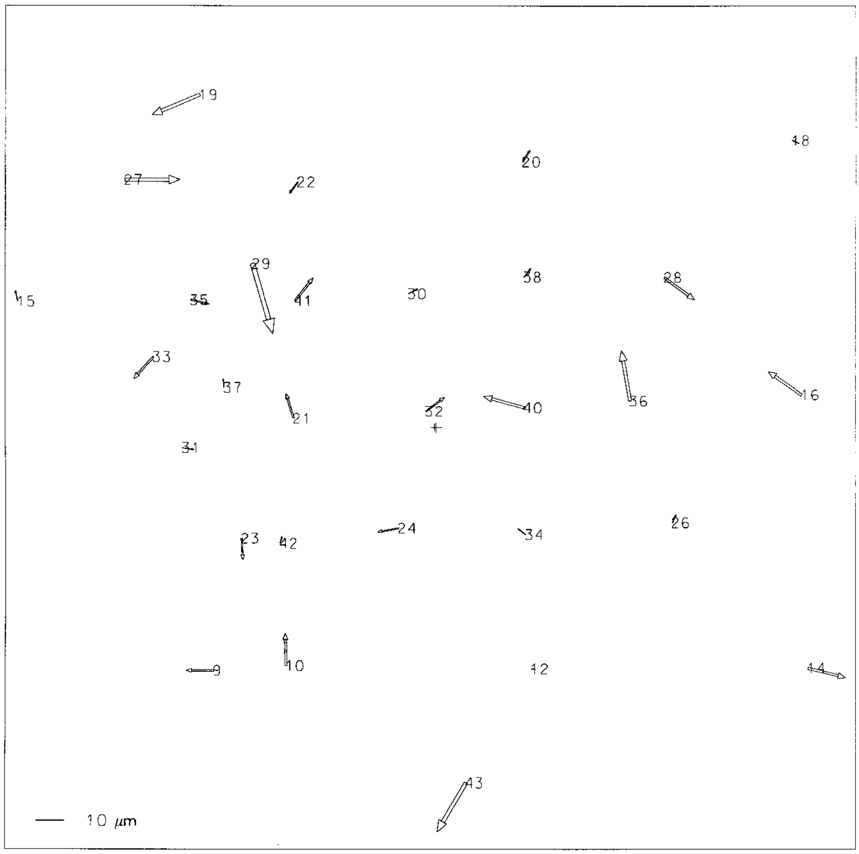

FIG. 2. Centre of gravity residuals. R.m.s. values: 8·7296 μm in X; 8·9785 μm in Y.

Such an image is capable of being manipulated easily by a 486 DX2 Personal Computer with 16 Mb memory and can be generated using either Photo CD or even a 400 dpi desktop scanner. The 45° grey blocks were used so that the targets would point in the same direction as the angle bisecting the two walls, an average camera direction for convergent imagery.

Pre-analysis of the envisaged photogrammetric network entailed using approximate co-ordinates of the 45 targets, taking the exterior orientation from six envisaged, convergent Hasselblad photographs, generating photoco-ordinates and processing using a self calibrating bundle adjustment. This analysis suggested that the root mean square (r.m.s.) precision of all targets would exceed ± 3 mm if image co-ordinates were measured to a precision of $\pm 0{\cdot}1$ pixel.

A control survey was carried out in the form of a three dimensional spatial intersection technique, observed from two stations using a Leica T1610 tacheometer. The three dimensional co-ordinates of all targeted points were determined using a "variation of co-ordinates" procedure, producing a r.m.s. precision of $\pm 0{\cdot}35$ mm in X, Y and Z.

Acquisition of Photography

Imagery of the testfield was acquired using both a Hasselblad small format camera and a Minolta 35 mm camera, whilst suspended in a basket from the gantry

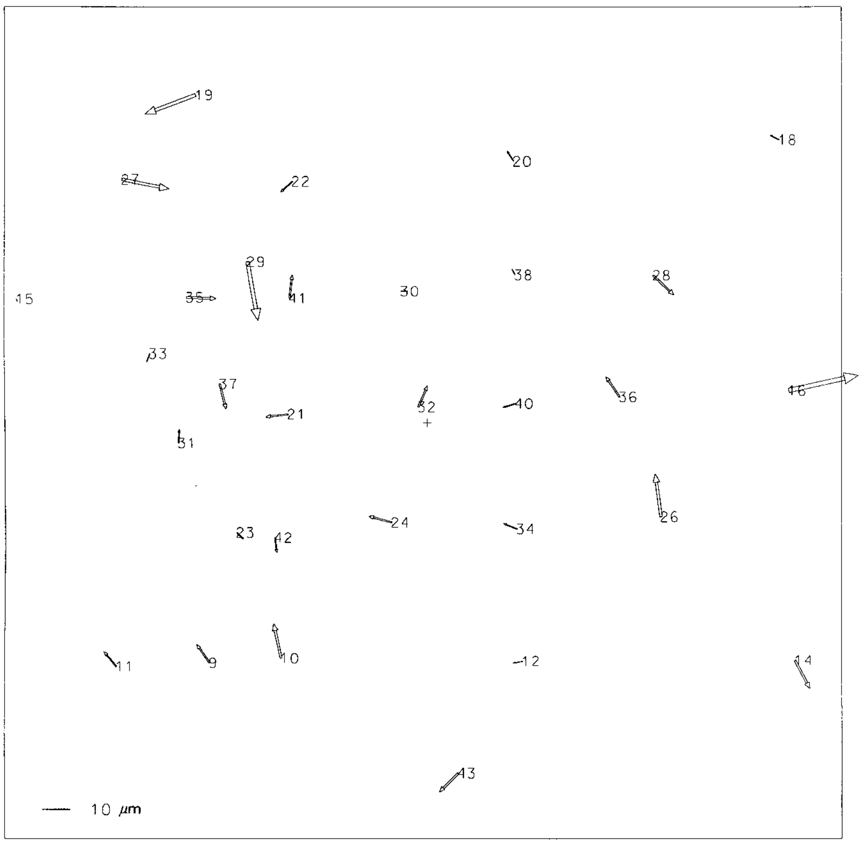

FIG. 3. Weighted mean residuals. R.m.s. values: 8·4987 μm in X; 7·9625 μm in Y.

crane. A standard SLR flash gun was used (Cobra 400 AF-MI), mounted adjacent to each camera lens. Images were deliberately under exposed by 2·5 to 3·5 stops, to ensure that the important targets could be distinguished from background objects.

Hasselblad Camera, 60 × 60 mm Format. Ilford FP4 plus film was used for the ELX Hasselblad small format camera, with apertures ranging from f/5·6 to f/8 at an exposure time of 1/125 s. The imagery obtained was processed and then nine images were selected and dispatched for scanning and conversion into Photo CD format (Fig. 1). The particular Hasselblad camera used is equipped with a 25-cross glass réseau plate, resulting in a usable image area within the corner fiducials of 45 × 45 mm. Once converted into Photo CD, these nine images were retrieved at the Base × 4 resolution, producing images with effective dimensions of 850 × 850 pixels and 0·95 Mb in size.

Pixel co-ordinates for the four corner fiducials were measured manually using PhotoStyler, to a precision of ± 0·2 pixel. The Visilog package was then used to determine pixel co-ordinates for each of the targets using the centre of gravity operator (Table II). These image co-ordinates were transformed into photoco-ordinates using an affine transformation and initially the relevant point identifiers were edited manually. The nine sets of photoco-ordinates were then combined using

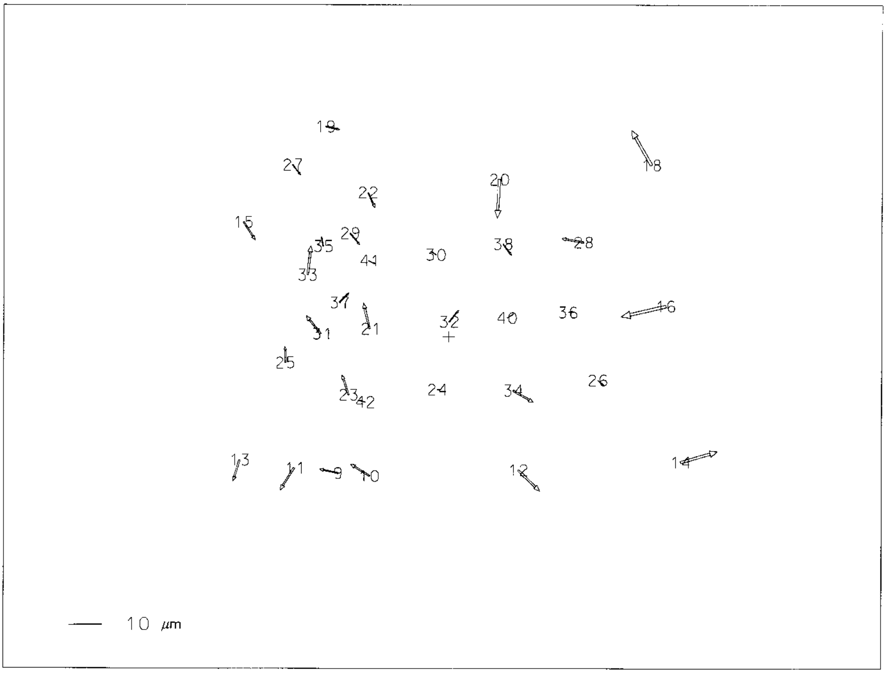

FIG. 4. 35 mm camera residuals. R.m.s. values: 5·5309 μm in X; 5·8514 μm in Y.

a self calibrating bundle adjustment, which produced the "Hasselblad centre of gravity" results.

An additional set of photoco-ordinates was generated using Visilog and the weighted mean operator (Table III). These data were transformed into photoco-ordinates and, now that exterior orientation parameters were available, their arbitrary point identifiers were numbered automatically using the program SortId. This data set

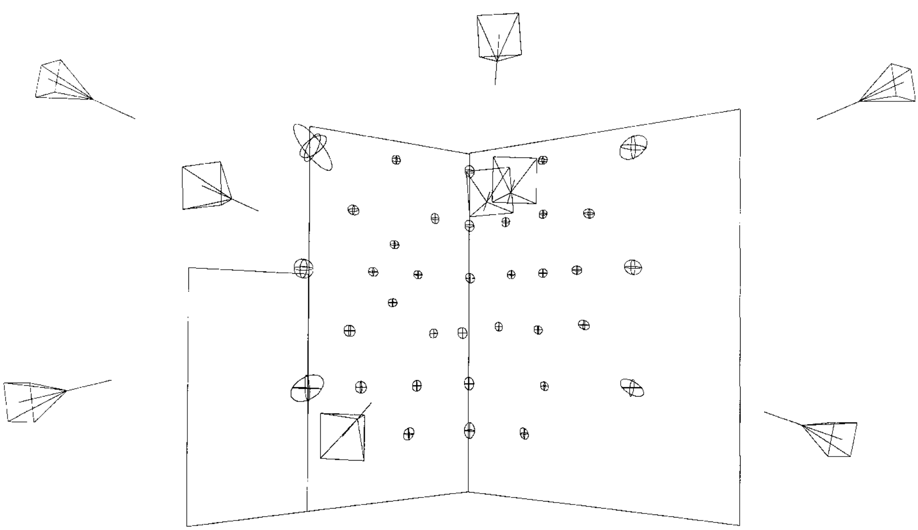

FIG. 5. Hasselblad camera: variation in precision (shown by error ellipses) and camera locations.

was processed using the bundle adjustment, producing the "Hasselblad weighted" solution.

Minolta Camera, 35 mm Format. A Minolta Dynax 7000i SLR camera equipped with a Sigma 28 mm to 70 mm zoom lens was used to acquire the 35 mm photography. The autofocus facility was switched off and the lens was taped at a focal length setting of 8 m, approximately 40 mm. TMAX 100 ASA emulsion was used, with apertures ranging from f/5·5 to f/8 with a shutter speed of 1/125 s, producing bracketed exposures of between 2·5 and 3·5 stops under the recommended exposure.

Eight shots were selected for scanning onto Photo CD but the initial scans were found to be unusable. The Minolta was not equipped with a réseau plate and so either the format corners or the edges would have to be used to define the photoco-ordinate system. Unfortunately the 36×24 mm mask used in both the Standard and Professional Photo CD scanner is approximately 2 mm undersized and so the original format edges and corners are not included in the scan. Significantly, the position of the mask is totally arbitrary and so cannot be used to define a stable reference system between frames. This problem was solved by using one of the masks designed for the larger 60×45 mm film formats and assuming that film unflatness would not present a severe problem. From a financial perspective this is a limitation, because the larger format options are only a feature of the more expensive Professional Photo CD Scanner.

Once scanned acceptably, the images were measured and processed by a final year student using the centre of gravity operator. All aspects of data processing were similar to the Hasselblad data and generated the "35 mm results".

Results

Although the significant output produced by a self calibrating bundle adjustment is usually the estimated co-ordinates of the object points, when examining the accuracy of a photogrammetric measurement system the additional data generated are also important. Of particular significance are an assessment of the recovered inner orientation parameters; an analysis of measurement residuals; and an appreciation of the stochastical properties of the estimated co-ordinates. Finally, if "true" or "accepted values" for the targeted co-ordinates are available, then it is possible to compare the estimates with these accepted values.

Inner Orientation Parameters

Table IV indicates the estimates and standard deviations for the inner orientation parameters used in the self calibrating bundle adjustment procedure. Both radial and tangential components of lens distortion are represented by the adopted lens model, formulated by Karara and Abdel Aziz (1974).

TABLE IV. Inner orientation parameters: estimates and standard deviations.

Type of measured photoco-ordinates	*X shift (mm)*	*Y shift (mm)*	*Focal length (mm)*	k_1 (m^{-2})	k_2 (m^{-4})	k_3 (m^{-6})	P_1 (m^{-1})	P_2 (m^{-1})
Hasselblad centre of gravity	0·1536 ±0·0458	0·7446 ±0·1594	80·9465 ±0·0667	12·459 ±0·524	Fixed	Fixed	Fixed	−0·026 ±0·009
Hasselblad weighted	0·1028 ±0·0325	0·6507 ±0·1235	80·8763 ±0·0584	−1·621 ±0·991	Fixed	Fixed	Fixed	−0·021 ±0·007
35 mm centre of gravity	1·2524 ±0·0836	−0·7944 ±0·0747	39·639 ±0·0451	−3·954 ±1·871	Fixed	Fixed	−0·123 ±0·020	0·159 ±0·017

k_1, k_2, k_3, P_1, P_2 are the distortion parameters.

TABLE V. Measurement residuals.

Type of measured photoco-ordinates	*Standard error X photoco-ordinate (μm)*	*Standard error Y photoco-ordinate (μm)*	*Degrees of freedom*	*Variance factor*
Hasselblad centre of gravity	±8·5	±9·5	392	1·072
Hasselblad weighted	±7·5	±8·1	388	1·060
35 mm centre of gravity	±6·0	±6·5	347	1·250

Measurement Residuals

Space prevents the inclusion of all the graphical data generated to display the size and form of the measurement residuals. Figs. 2 to 4 represent the residuals for one frame from each of the three sets of measured input photoco-ordinates.

In addition to this type of graphical display, it is pertinent to tabulate (Table V) the stochastical qualities of the photoco-ordinate measurements used in the bundle adjustment and the computed a posteriori variance factors.

Stochastical Properties of Co-ordinates

Strictly, the variation of precision within the spatial field should be analysed in full three dimensions. A series of three dimensional CAD files was generated with the required information, so allowing error ellipses to be viewed from all spatial directions. These data, projected onto a single two dimensional plane, were used to produce plots representing this spatial variation (Fig. 5). Also represented in Fig. 5 are the positions and orientations of the nine frames used in the bundle adjustment for the Hasselblad imagery. Summary statistics based upon the precision of all estimated co-ordinates are included in Table VI, together with the overall precision derived between two widely separated points, a total distance of 6 m. It should be noted that the larger error ellipses are associated with points towards the four corners of the test field. These points were imaged on as few as three frames and their consequent weak precision degrades the precision of the overall network.

Target Co-ordinate Discrepancies

The precision of the control survey was ±0·35 mm in *X*, *Y*, *Z* and these estimated co-ordinates were accepted as the best estimates or "true values" for the test field targets. This decision was based upon the belief that there were fewer uncertainties in the functional models used to relate the survey measurements and consequent co-ordinate estimates than would be the case for the photogrammetry. Space prevents the inclusion of plots generated to demonstrate discrepancies between the estimated

TABLE VI. Stochastical properties of co-ordinates.

Type of measured photoco-ordinates	*Precision X co-ordinate (mm)*	*Precision Y co-ordinate (mm)*	*Precision Z co-ordinate (mm)*	*Precision X, Y, Z (mm)*	*Network precision*
Hasselblad centre of gravity	±0·67	±1·40	±0·64	±0·90	1 in 6700
Hasselblad weighted	±0·55	±1·23	±0·54	±0·77	1 in 7800
35 mm centre of gravity	±0·85	±1·35	±0·73	±0·98	1 in 6200

TABLE VII. R.m.s. discrepancies: differences between "true values" and estimated co-ordinates.

Tpye of measured photoco-ordinates	*Discrepancy X co-ordinate (mm)*	*Discrepancy Y co-ordinate (mm)*	*Discrepancy Z co-ordinate (mm)*	*Discrepancy X, Y, Z (mm)*	*Accuracy*
Hasselblad centre of gravity	1·65	2·00	1·16	1·60	1 in 3800
Hasselblad weighted	1·56	2·63	1·23	1·73	1 in 3500
35 mm centre of gravity	3·55	1·17	3·38	2·70	1 in 2200

co-ordinates derived using the three different measured data-sets and the accepted "true values". It is probably more useful to generate and tabulate other summarizing data, notably the r.m.s. discrepancies (Table VII).

DISCUSSION

Inner Orientation

It is important to judge the significance of any recovered inner orientation parameters by comparing the estimated value in relation to their stochastical properties. If the standard error is larger than the computed parameter, then the parameter is statistically insignificant and the least squares solution is over parameterized. The geometry of the photogrammetric network has a fundamental role in the precision of any additional parameters computed and the configuration used revealed the significance of the displacement of the principal point, the focal length and one parameter for both radial and tangential lens distortion. A displacement of the principal point was expected for these semi-metric cameras and in the 35 mm camera. Large values for these parameters fit fully with the uncertainty associated with defining a photoco-ordinate system through the use of format corners. A second radial lens distortion parameter was marginally significant for the Hasselblad weighted data, but it was decided to withhold this parameter to allow a comparison between the stochastical properties of estimated parameters associated with the two Hasselblad solutions.

Measurement Residuals

The three plots of measurement residuals (Figs. 2 to 4) suggest that residuals in the image space are randomly distributed and no systematic trends are in evidence. These plots also reveal that there is a good distribution of measured points over the whole format which is important for the derivation of reliable lens distortion parameters. A comparison between the two Hasselblad frames with data measured using the centre of gravity and the weighted mean technique suggest that the r.m.s. residuals are slightly lower in the case of the weighted mean. This difference is quite small and less significant than may perhaps be expected. It is suggested that this may be due to the very high values registered for those pixels representing the retro-targets. Tests revealed that 95 per cent of these pixels recorded values of 255 out of the 0 to 255 possible levels of grey. This high level of "saturation" reduces the significance of the weighting based upon recorded grey values used in the weighted mean technique and has been reported by Fraser and Shortis (1995).

Table VIII attempts to indicate the accuracies actually achieved through use of both the centre of gravity and weighted mean technique for each camera. The a posteriori variance factors derived from the final measurement residuals are insignificantly different from unity (the a priori value) and so it can be assumed that photoco-ordinates have indeed been measured to an accuracy associated with the precision of the original input measurements. It is important to emphasize that this analysis is based upon a full system restitution including self calibration of the

TABLE VIII. System measurement precision and accuracies.

Type of measured photoco-ordinates	*Standard error X photoco-ordinate (μm)*	*Standard error Y photoco-ordinate (μm)*	*Image dimensions (mm)*	*Image dimensions (pixels)*	*Standard error X photoco-ordinate (pixels)*	*Standard error Y photoco-ordinate (pixels)*
Hasselblad centre of gravity	8·5	±9·5	45×45	950×950	±0·18	±0·20
Hasselblad weighted	±7·5	±8·1	45×45	950×950	±0·16	±0·17
35 mm centre of gravity	±6·0	±6·5	36×24	1500×1000	±0·25	±0·27

camera. The accuracy and suitability of the final functional model selected has an important influence on these residuals and so raw image measurement precision is likely to be superior to the figures estimated. The precision of measurement using automated methods is also controlled by the number of pixels that are associated with a target and therefore used in the determination of the object centre. Tests revealed that between 60 pixels and 120 pixels were used for the determination of each target location, with perhaps an average target registering a patch 8×8 pixels in size.

From such an analysis it can be concluded that both the centre of gravity and weighted mean operator were found to be entirely suitable for determining the image co-ordinates of targeted points to sub-pixel precision, with the latter offering a slightly improved result (±0·16 pixel/±7·5 μm) over the former. Although this accuracy is comparable with manual measurement of conventional imagery using an analytical plotter (Chandler and Still, 1994), other authors are achieving higher accuracies using digital photogrammetric methods. These range from the exceptional, as suggested by Fraser and Shortis (1994) who quote values of ±0·02 pixel/±0·18 μm, whilst Dold and Maas (1994), for example, quote a more regularly achievable level of ±1 μm. It should be remembered that these results are achieved using equipment which is both geometrically more stable and expensive than that involved with this particular case study.

Target Co-ordinate Precision and Accuracy

For the Hasselblad imagery, the r.m.s. discrepancies between the estimated co-ordinates for each data set and the assumed true values derived from the control survey are within the expected precision bounds. Evaluation of the dimensions of the triaxial ellipsoids for the 95 per cent confidence region requires scaling of the computed standard errors of the discrepancy vectors by a factor of 2·79. This reveals that in the case of the Hasselblad imagery mean discrepancies are lower than the critical value. The 35 mm camera does not perform as well, only satisfying this criteria of quality for the *Y* ordinate. This result suggests that some minor systematic errors have not been fully accounted for during the self calibration procedures, which degrades the accuracy. It is suggested that this could possibly be associated with uncertainties in defining a photoco-ordinate system, film unflatness during scanning or perhaps non-linearities within the scanning device. A further student project will be used to assess these aspects further.

CONCLUSIONS

A digital photogrammetric measurement system comprising cheap off the shelf hardware and software components has been described and demonstrated. It has been proved that the Kodak Photo CD imaging technology is of value to photogrammetry, as a means of both scanning and storing digital imagery. The study has shown that the Visilog image processing package can be used to automatically measure the image co-ordinates of retro-reflective targeted points and the necessary software scripts have been provided. Tests have revealed that such a system is capable of determining the spatial co-ordinates of points to a precision of 1:7800 and an accuracy of 1:3800, useful for tackling many measurement problems. Although other systems are both more precise and accurate, the approach outlined can be instigated by anyone with an interest in photogrammetry and will be of particular interest to anyone with access to only a minimal budget.

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REFERENCES

Brown, D. C., 1976. The bundle adjustment—progress and prospects. *International Archives of Photogrammetry,* 21(3). Paper 3 03. 33 pages.

Boyle, R. D. and Thomas, R. C., 1988. *Computer vision.* Blackwell Scientific, Oxford. 210 pages.

Chandler, J. H., Cooper, M. A. R. and Robson, S., 1989. Analytical aspects of small format surveys using oblique aerial photographs. *Journal of Photographic Science*, 37(7): 235–240.

Chandler, J. H. and Clark, J. S., 1992. The archival photogrammetric technique: further application and development. *Photogrammetric Record,* 14(80): 241–247.

Chandler, J. H. and Still, A. L., 1994. Analytical photogrammetry and the refurbishment of the CAT Reformer, BP Refinery, Grangemouth, Scotland—lessons learnt. *International Archives of Photogrammetry and Remote Sensing*, 30(5): 28–34.

Chen, J. and Clarke, T. A., 1992. The automatic recognition, location and labelling of targets in digital photogrammetric engineering measurement. *Ibid.,* 29(5): 686–693.

Clarke, T. A. and Robson, S., 1993. Building a digital close range three dimensional measuring system for less than £5000. *Photogrammetric Record,* 14(82): 675–680.

Cooper, M. A. R. and Cross, P. A., 1988. Statistical concepts and their application in photogrammetry and surveying. *Ibid.,*12(71): 637–663.

Davies, E. R., 1990. *Machine vision: theory, algorithms, practicalities*. Academic Press, London. 547 pages.

Dold, J. and Maas, H.-G., 1994. An application of epipolar line intersection in a hybrid close range photogrammetric system. *International Archives of Photogrammetry and Remote Sensing,* 30(5): 65–70.

Faig, W., 1976. Photogrammetric potentials of non–metric cameras. *Photogrammetric Engineering and Remote Sensing,* 42(1): 47–49.

Fraser, C. S. and McGee, R. G., 1995. Dynamic measurement of undulating water surfaces in a lock fill. *Ibid.,* 61(1): 83–87.

Fraser, C. S. and Shortis, M. R., 1994. Vision metrology in industrial inspection: a practical evaluation. *International Archives of Photogrammetry and Remote Sensing,* 30(5): 87–91.

Fraser, C. S. and Shortis, M. R., 1995. Metric exploitation of still video imagery. *Photogrammetric Record,* 15(85):107–122.

Georgopoulos, A. and Tournas, E., 1994. Digital rectification using a PC. *International Archives of Photogrammetry and Remote Sensing,* 30(5): 102–108.

Granshaw, S. I., 1980. Bundle adjustment methods in engineering photogrammetry. *Photogrammetric Record,* 10(56):181–207.

Hanke, K., 1994. The Photo-CD – a source and digital memory for photogrammetric images. *International Archives of Photogrammetry and Remote Sensing*, 30(5): 144–149.

Helava, U. V., 1988. On system concepts for digital automation. *Ibid.,* 27(2): 171–190.

Karara, H. M. and Abdel Aziz, Y. I., 1974. Accuracy aspects of non–metric imageries. *Photogrammetric Engineering,* 40(9): 1107–1117.

Kenefick, J. F., Gyer, M. S. and Harp, B. F., 1972. Analytical self calibration. *Ibid.,* 38(11): 1117–1126.

Kodak, 1994. *Kodak Photo CD fact file*. Kodak House, Hemel Hempstead. 4 pages.

Maas, H.-G. and Kersten, T. P., 1994. Experiences with a high resolution still video camera in digital photogrammetric applications on a shipyard. *International Archives of Photogrammetry and Remote Sensing*, 30(5): 250–255.

Murai, S., Nakamura, H. and Suzuki, Y., 1980. Analytical orientation for non–metric camera in the application to terrestrial photogrammetry. *International Archives of Photogrammetry*, 23(5): 515–525.

Nilsen, J. H. and Hådem, I., 1994. Digital photogrammetry used for the tracking of submerged tracer particles in modelled ocean flows. *International Archives of Photogrammetry and Remote Sensing,* 30(5): 283–292.

Ogleby, C. L., 1994. Digital image processing in the documentation and conservation of rock art. *Ibid.,* 30(5): 293–297.

Schwidefsky, K., 1970. Precision photogrammetry at close ranges with simple cameras. *Photogrammetric Record,* 6(36): 567–589.

Stirling, D. M., Bridger, A. M. and Shortis, M. R., 1994. Photogrammetric modelling of a commuter

airliner flightdeck for reverse engineering purposes. *International Archives of Photogrammetry and Remote Sensing,* 30(5): 374–381.
TRINDER, J. C., NADE, S. and VUILLEMIN, A., 1994. Application of photogrammetric measurements in medicine. *Ibid.,* 30(5): 396–400.

Résumé

On décrit un système permettant d'obtenir automatiquement les coordonnées tridimensionnelles de cibles bien définies et numérisées. En fait le système repose sur des matériels et des logiciels bon marché et disponibles, à partir desquels on n'a eu qu'à faire un minimum de développement.

Les essais comparatifs effectués sur une imagerie tirée d'une chambre Hasselblad semi-métrique et une chambre SLR 35 mm sont également présentés.

Si l'on procède à des déterminations automatiques sub-pixellaires on obtient des résultats équivalents à ceux provenant de mesures manuelles effectuées sur ces cibles avec un restituteur analytique de premier ordre.

Zusammenfassung

Es wird ein System beschrieben, das automatisch dreidimensionale Koordinaten von gut definierten Zielpunkten bestimmen kann. Bedeutsam ist, daß das System billige Standard- Hard- und Software nutzt, die ein Minimum an Entwicklung erfordern. Vergleichende Tests mit Bildern, die mit einer semimetrischen Kamera von Hasselblad und einer 35 mm SLR-Kamera aufgenommen wurden, werden dargestellt. Mit Hilfe automatischer Messungen im Subpixel-Bereich wurden Ergebnisse erzielt, die denen entsprechen, die durch manuelle Zieleinstellung mit Hilfe eines analytischen Auswertegerätes 1. Ordnung gewonnen wurden.