RESULTS OF AN ATTEMPT TO CARRY OUT PHOTOGRAMMETRIC RESTITUTION OF PHOTOMACROGRAPHS

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Abstract

In the field of mechanical engineering, fatigue tests of materials have been carried out for a number of years. These simulate rolling contact surfaces with the use of lubricants,as may occur, for example, in bearings using rolling elements, in curved bearing surfaces, friction drives, gearwheels etc. Where failure is not due to other causes, such as structural failure, corrosion etc, rolling components ultimately fail due to fatigue. A specimen produced by a fatigue-testing apparatus for rolling contact surfaces was made available for photogrammetric analysis.

In general, it is recognized that spalling and pitting resulting from fissuring in a test component provide useful informationon conditions where fatigue maxima are exceeded. Accordingly, it was decided to make a detailed study of their form and depth.

An M400 photomacroscope was used for obtaining photographs of the test piece. For calibrating the photomacrographs, a special control plate was made on whose steel surface control points were etched optically and measured to an accuracy of ± 1μm. The parameters for the inner orientation of the photomacrographs were determined by means of the ORIENT general bundle program. All measurements required for calibration, together with a graphic plot and digital restitution were carried out on the AVIOLYT AC1 / AVIOTAB TA2 analytical photogrammetric system.

1 Introduction

In recent years, photogrammetric restitution techniques have been used increasingly in a number of non-topographic fields.

This paper presents an example taken from the field of microscopy (hereafter referred to as microstereophotogrammetry) and discusses the experience obtained, problems that have arisen, results and recommendations.

Whilst in theory there are no fundamental differences between photogrammetry and microstereophotogrammetry, the second of these cannot at present achieve results of the accuracy that would be theoretically possible.

The fact that in microscopy a number of conditions required in photogrammetry cannot be fulfilled (e.g. model formation by means of control points, the precise definition of inner orientation for the camera system used etc) calls for a number of a priori assumptions:

Amongst assumptions which cannot in fact be satisfied in practice are the requirements that the optical path from object to image plane conform to the image-forming equations of central projection, that the outer orientation of photomicrographs be known beforehand etc.

The development of modern photographic and photogrammetric restitution systems which use not only conventional opto-mechanical components but also electronic hardware and software permits 'compensation' of such assumptions.

Whilst in the recent past a number of methods have been developed for quantitative data acquisition in the field of microscopy, such as stereology, interferometry, digital image analysis etc, microstereophotogrammetry remains a 'credible' restitution technique which provides results having a relatively high degree of accuracy.

This paper describes an attempt to apply photogrammetric restitution methods to a metal specimen produced for a study of material fatigue at the Imperial College of Science and Technology, London. For restitution, M400 photomacrographs were used, and for certain test stages M7A stereoscopic photomicrographs were also utilized. Restitution was carried out on a Wild AVIOLYT AC1 photogrammetric analytical plotter.In addition to AC1 system and application software, outside off-line software was also used, i.e. the ORIENT general bundle program from the Institute for Photogrammetry at the Technical University, Vienna.

2 Outline of problem

In mechanical engineering, the problem of rolling-contact fatigue is of considerable importance.

Rolling-contact fatigue (also known as spalling or pitting) is a limiting factor in the useful life of many mechanical components, such as rolling-element bearings, gears, cams, traction drives etc.

In these components, relatively small volumes of metal undergo very high cyclic stressing due to surface contact. Metal-to-metal contact is usually avoided by the presence of a thin lubricating film.

Repetition of high contact stresses leads to the development of fatigue microcracks, some of which are further extended to produce macrocracks and finally cause detachment of piecesof metal from the contact surface, forming pits.

In experimental investigation of the problem and in post-failure analysis in practical situations, optical methods are commonly used to analyze the origin, appearance, geometrical characteristics (depth, angle etc) and the surface texture of the cracks. This approach provides a fair amount of information on various aspects of the fatigue process and illuminates the problem from the viewpoint both of basic research and of an analysis of failures in real situations.

For example, the origin of the cracks may be found by assessment of the final shape of the pitted surface, of the depth of the pit and the steepness of its sides.

For this type of analysis, researchers have to date used the optical microscope and the electron microscope in examining the cause of failure (whether of surface or sub-surface origin), the effect of lubricant during the development of cracks, the effect of additional mechanical stresses etc.

The authors hope that the photogrammetric method described in this paper may prove a useful tool for the further investigation of the rolling-contact fatigue process.

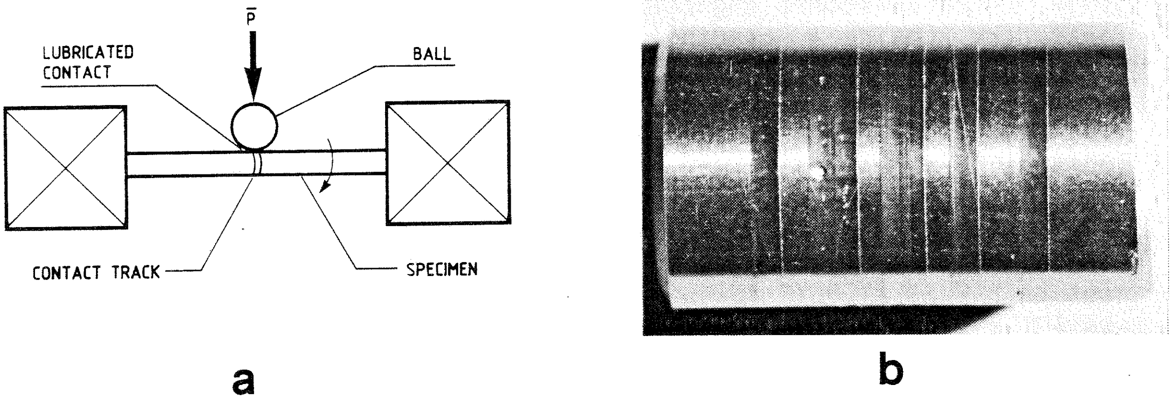

Fig. 1 a: Diagram of system used for testing fatigue in various materials (Imperial College of Science and Technology, London; Douzinas, 1983)

b: Specimen steel cylinder made available for investigation the Imperial College of Science and Technology.

3 Photography

In the past, various attempts have been made at restitution from photographs produced with macroscopes and both optical and electron microscopes (e.g. Bennett, 1976; Smith, 1978; Waldhäusl, 1978; Layton et al, 1980). In all these, exposure conditions were always determined by the limited possibilities of analog plotters. Since the hardware and software of analytical plotting systems have reached a sufficiently high level of development, the exposure conditions are determined almost exclusively by the limitations of the camera system itself.

3.1 Exposure conditions

The M7A stereomicroscope and M400 photomacroscope made by Wild Heerbrugg Ltd (fig. 2) were used to photograph the specimen.

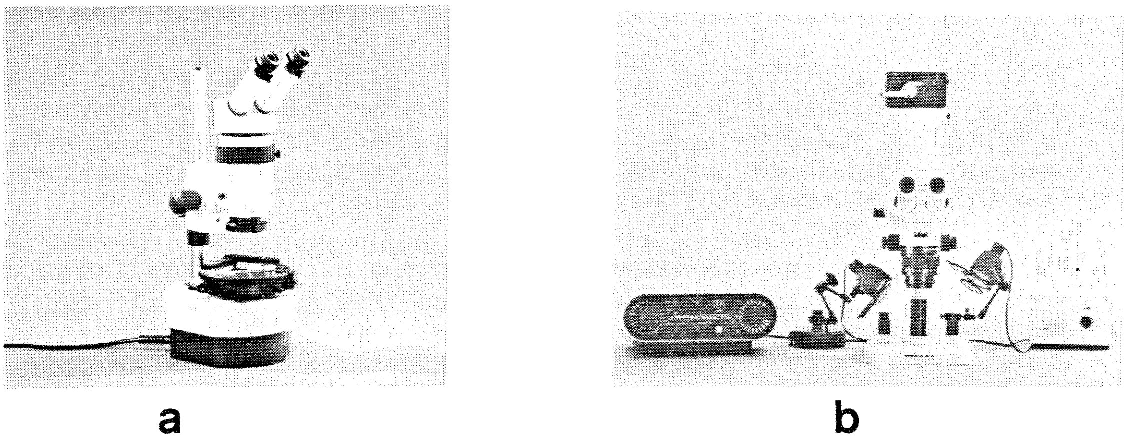

Fig. 2 a: M7A stereomicroscope with measuring stage. The pair of stereophotographs is in this case produced by beam-splitting, resulting in convergent photographs.

b: M400 photomacroscope with camera attachment and MPS 55/51 Photoautomat. Here, stereophotographs are produced by parallel displacement of the object.

Amongst the numerous alternative means of producing a pair of stereophotographs (Vierling, 1965), two seemed suitable for this project.

a: Convergent exposures:

Convergent photographs were made with the M7A stereo- microscope (fig. 2a). The object to be photographed being immobile, a single camera could be used to produce pairs of photographs, by fitting the camera alternately to the two eyepieces of the M7A while maintaining the same environmental conditions (lighting, temperature etc). In this case, convergence was achieved by splitting the beams reflected by the object. This type of exposure is also possible by using a conventional microscope or macroscope with a tilting measuring stage (Vierling, 1965, Layton et al, 1980; fig. 3b).

b: Parallel exposures:

An alternative to convergent photographs (by tilting the object or by moving the camera) is provided by parallel displacement of the object in order to produce a pair of stereophotographs. In this case the camera remains stationary and the object is displaced between the two sequential exposures. The specimen was photographed by this method with the M400 photomacroscope (fig. 2b). To ensure accurate control of the displacement, the measuring stage shown in figure 3a was used (cf section 3.3).

3.2 Photographic problems

In microstereophotogrammetry, the problem of the limited depth of field available is of far greater importance than in other contexts. Two further and equally important problemsare the determination of the parameters for inner and outer orientation of the photographs and the geometry of the optical path coupled with achieving the best possible conditions of lighting.

In theory, the problem of the depth of field can be solved by the correct choice of aperture (i.e. as small as possible)and longer exposure times. In practice, however, these values are subject to the restrictions imposed by the camera system as a whole (microscope or macroscope, camera and film used).

Until recently, the parameters for inner and outer orientation of the photographs have almost always been taken from the technical data provided by the manufacturer of the camera and/or the complete camera system. By combining high-precision photogrammetric mono- or stereo-restitution systems and special software, the parameters for inner and outer orientation can now be accurately computed. With these it is also possible to determine mathematically a large part of systematic errors which occur in exposure.

The assumption is still accepted that the optical path through a microscope or macroscope from the object plane to the image plane conforms to the laws of central perspective. This is due to the fact complexand time-consuming, and all conventional analog and analytical stereo-restitution systems have been designed and built on this assumption.

The problems that arise in choosing the correct type of lighting can be solved by using incident light from a combination of ring and oblique point and/or linear sources. As a rule, more favourable lighting conditions can be achieved in convergent photographs by tilting the object, but this also reduces the depth of field.

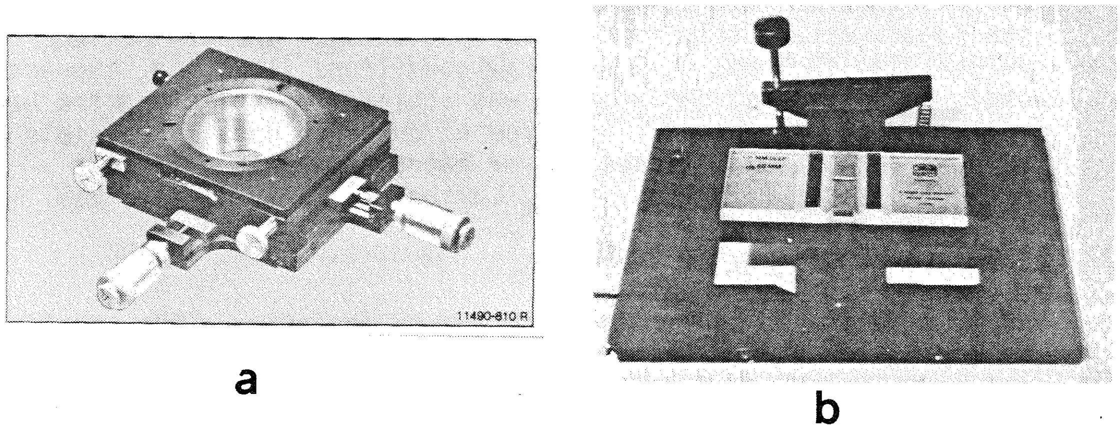

Fig. 3 a: Measuring stage for producing pairs of stereophotographs by parallel displacement of the object
b: Tilting measuring stage for producing convergent photographs (Layton et al, 1980)

3.3 Photographic data

As stated, the specimen made available for this study was photographed with the M7A stereomicroscope and the M400 photomacroscope.

The M7A photographs were taken on Agfaplan (15 DIN) roll film at 12x magnification with an 0.8x phototube, using the split beam provided by the left and right eyepieces alternately.

The M400 photographs were taken at 10x magnification with a 1.0x phototube and the MPS 55/51 Photoautomat, and with parallel displacement of the specimen. For greater accuracy, 15 DIN super-plane film was used instead of roll film, providing 120mm x 90mm negatives.

In both cases, the specimen was photographed under incident light using a combination of fluorescent ring, coaxial oblique (6V/20W) and fibre-optics illuminators. The section of the specimen to be studied was cut out of the cylinder (fig. 1)* and positioned at the most suitable height by means of the adjusting screw of the control plate (see 4.1) while keeping it under constant stereoscopic observation. This ensured that full and correct use was made of the depth of field and magnification factor.

The camera base used in the M400 photographs was 2.55mm in the object and was determined by means of the measuring stage. Figure 4a shows a pair of stereomacrographs of the specimen and the points of the control plate (cf 4.1), and figure 4b shows two stereomodels (three exposures) of one of the two control grids used for calibrating the photographs(cf 4.1).

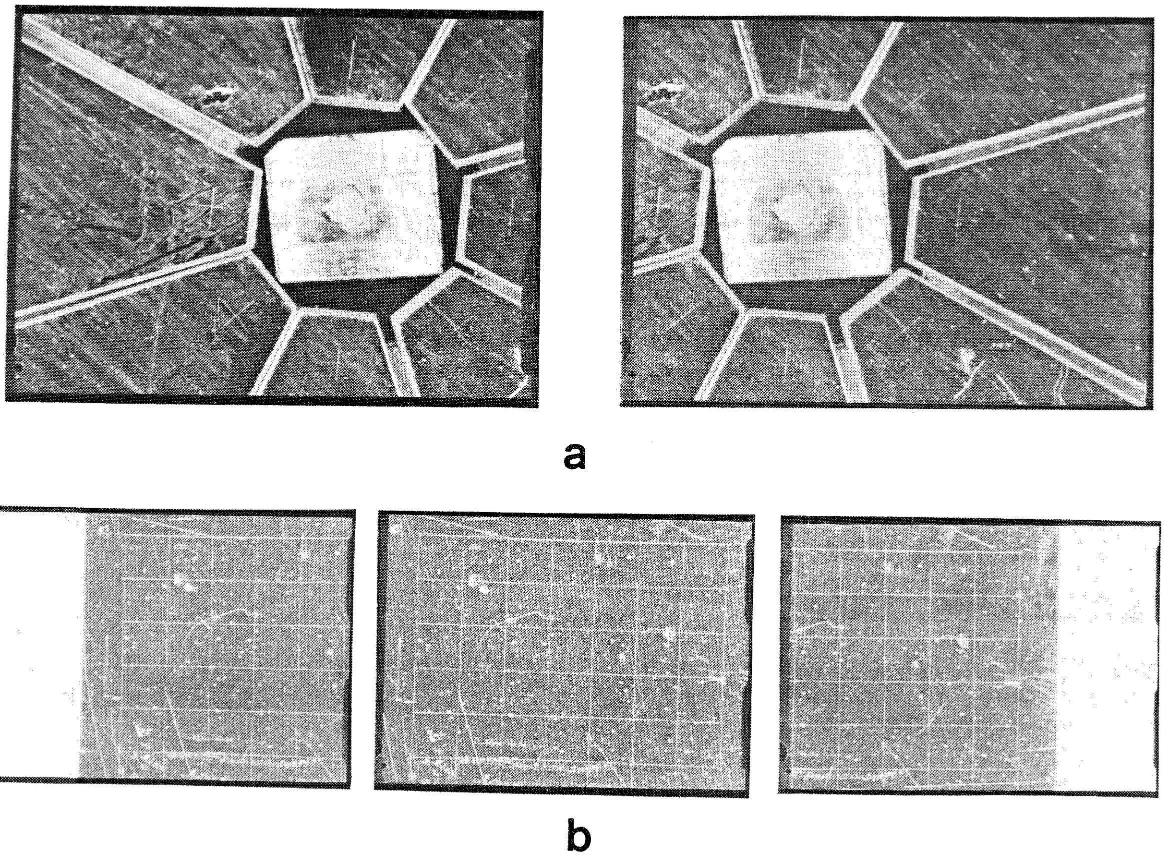

Fig. 4 a: M400 stereophotographs (reduced) of specimen, together with control points on control plate
b: The three photographs (two stereomodels) at reduced scale of the G100 control grid used for calibration of the camera system

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* The heat produced in cutting out a small portion of the specimen doubtless modified the shape of the sample used for photogrammetric restitution. However, since this project merely consisted in testing the photogrammetric technique and the accuracy that could be achieved by it, this fact has been disregarded.

The same camera was used in both cases. Neither the stability of inner orientation of the camera between the various photographs nor the repeatability of systematic errors of the complete camera system were analyzed in this particular case. In other words, it was assumed that under the same environmentalconditions, the inner orientation of all photographs is the same.

4 Calibration

For determining the parameters of inner orientation and the systematic errors of the photomacrographs, and of the coordinates for the control points used for model formation, the ORIENT universal bundle program (Kager, 1980) was used. For this it was necessary to design and make a steel control plate for control purposes.

The calibration process was carried out before the sample was photographed and after all photographs of the sample had been completed. Since there were only very minor differences in the results before and after the photographs of the sample, the calibration values before exposure were used in restitution.

In all projects from the field of microscopy carried out to date by means of analog plotters, inner and outer orientation has been taken a priori as known and free from error by reference to the technical data provided by the manufacturer on the camera system or from the camera stations. So, for example, for the camera layout 3a, the normal case was used, in which the model scale is determined by the displacement of the object. Inaccurate results were produced due to the instability of the measuring stage, the camera axes not being perpendicular to the object plane, and the inaccuracy of inner orientation.

In order to eliminate these handicaps, the control plate was used not only for determining the parameters for inner orientation of the photographs but also for model formation and restitution.

4.1 Control plate (fig. 5)

A steel plate having a thickness d = 15mm ground perfectly plane and having a radius of R = 72mm was used as a control plate. Since the depth of field determined by the camera positions was 0.015mm, eight steel abutments (TESA 90mm x 30mm) were bonded to the plate with IS-45 contact adhesive.The height difference between the first and eighth abutment was 0.012mm in steps of d = 0.002mm.

An adjusting screw (fig. 5b) was fitted to the rear surface of the plate to allow the pit in the sample removed from the specimen to be positioned correctly for photography and subsequent restitution, thus allowing the available depth of field to be fully utilized.

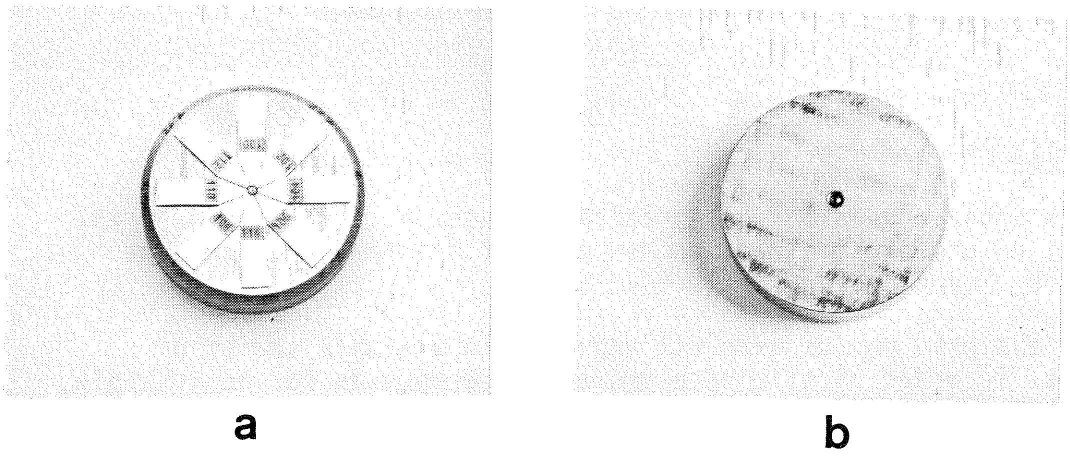

Fig. 5 a: Control plate
b: Adjusting screw for taking full advantage of the depth of field

A cross having a line thickness of 0.010mm was etched optically about the centre of each of the steel abutments. On each of the steel abutments d1 = 1.000mm and d2 = 1.008mm an 8x8 grid having the same line thicknesses was also etched optically.

For the calibration, the grid points and the points of intersection of the crosses were adjusted while the latest have been used only for model formation and restitution.

4.2 Measurements

The coordinates of the points of intersection of the crosses and the two grids were measured in three independent three-dimensional local systems, using a MU-214B universal measuring equipment made by SIP Geneva. The stated measuring accuracy of this is ±0.001mm.

All cross and grid points were then measured with the AVIOLYTAC1 in each photograph in which they appear. These measurements were made binocularly but monoscopically (MMO monocomparator module, Kreiling, 1982).

These measurements were made in the same environmental conditions as the UM-214B measurements, to eliminate any sources of error as far as possible.

Since there are no fiducial marks on the photographs, consideration was given to using the comparator coordinates directly by use of DLT direct linear transformation (Abdel-Aziz and Karara, 1971). Although the ORIENT bundle program can also make use of uncorrected comparator coordinates, it was decided to operate with transformed image coordinates into the centre point of the photograph, in order to ensure compatibility with the software available in Heerbrugg.

For this, the theoretical points of intersection of the straight lines forming the sides were used as fiducial marks. These straight lines are defined in the MMO module by measuring two points per side.

The comparator and image coordinates obtained by this means, together with other relevant data such as the three-dimensional coordinates of cross and grid points, approximate values for the parameters of inner and outer orientation etc, were transferred from the AC1 installed at the Technical University Vienna to the DEC-SYS 20 of the university's computer centre where the ORIENT program is also running at present.

4.3 Results

The bundle program used for calibration is based on the theory for the adjustment of photogrammetric, geodetic and fictitious observations presented by Kager and Kraus (1976).

The cross and grid points were all adjusted in a single series of operations. In order to eliminate systematic errors as far as possible, additional parameters were introduced in this adjustment, based on the well-known equation for central projection:

$$x = x_0 - c \cdot \frac{r_{11}(X-X_0) + r_{21}(Y-Y_0) + r_{31}(Z-Z_0)}{r_{13}(X-X_0) + r_{23}(Y_0-Y_0) + r_{33}(Z-Z_0)}$$

$$y = y_0 - c \cdot \frac{r_{12}(X-X_0) + r_{22}(Y-Y_0) + r_{32}(Z-Z_0)}{r_{13}(X-X_0) + r_{23}(Y-Y_0) + r_{33}(Z-Z_0)} \qquad (1)$$

where:

x,y	reduced image coordinates of an object point
x_0,y_0	image coordinates of principal point of photograph
c	camera constant
X,Y,Z	coordinates of object point in local UM-142B system
X_0,Y_0,Z_0	coordinates of projection centre in local UM-142B system
$r_{ij}(i,j=1,2,3)$	elements of rotation matrix $\underline{R}(\underline{r_1},\underline{r_2},\underline{r_3})$

The additional parameters can be obtained from the following equations.

$$x = \xi_0+a_1\cdot 0+a_2\cdot 0+a_3\cdot\xi\cdot(p^2-1)+a_4\cdot\xi\cdot(p^4-1)+a_5\cdot(p^2+2\cdot\xi^2)+a_6\cdot(2\cdot\xi\cdot n)$$

$$x_0=n_0+a_1\cdot\xi+a_2\cdot n+a_3\cdot n\cdot(p^2-1)+a_4\cdot n\cdot(p^4-1)+a_5\cdot(2\cdot\xi\cdot n)+a_6\cdot(p^2+2\cdot n^2) \qquad (2)$$

where

ξ, n	coordinates of a point transformed into the centre point of the photograph
ξ_0, n_0	coordinates of principal point of photograph tranformed into he centre point $p^2=\xi^2+n^2$, $\xi=x/p_0$, $n=y/p_0$
p_0	standard radius (in this case: p_0 = 30mm)

Geometrically, the additional parameters introduced in (2) represent the scale in x (a_1), affinity (a_2), the radial (a_3, a_4) and tangential (a_5, a_6) distortion.

The calibration results allow not only the inner orientation to be defined but also the geometry and stability of the whole camera system to be checked. So, for example, the results have shown that whilst the rotation angles ω and φ remain almost the same for all photographs

$$\omega \pm 6_{\omega} = 0.102\text{gon} \pm 0.10\text{gon}$$
$$\varphi \pm 6_{\varphi} = -0.245\text{gon} \pm 0.10\text{gon}$$

The rotation angle κ varies in different photographs, e.g. from κ_1 = -1.21948gon to κ_2 = 0.31178gon.

The object coordinates of all cross and grid points were introduced as unknowns. The points of the two grids were introduced in adjustment as two independent from each other. The eight centre points of the crosses were determined in a higher-order three-dimensional coordinate system, for use as control points in further restitution on the AC1. These coordinates proved to have a mean square error of ±0.007mm. The mean square error of any observation (image-coordinate measurement) was determined with ORIENT following adjustment as ±0.012mm.

When the instability of the rotation angles κ is combined with the relatively large variations in the base length between different models (± 0.018mm in X and ± 0.024mm in Y) this shows that the translation of the sample was not carried out with sufficient accuracy.

The calibration results also proved the 10x magnification set on the M400 (c = 212.420mm, Z_0 = 21.603mm).

Figure 6 shows the distortion vectors computed by ORIENT, distributed over an 8x6 grid at 10mm intervals in the image, together with the lines of equal distortion (isolines) interpolated from them.

The radial components in the four semi-diagonals of the photograph (at 10mm intervals) were computed from these vectors, and their mean values were input in the AC1 as ancillary distortion points (INP program module).

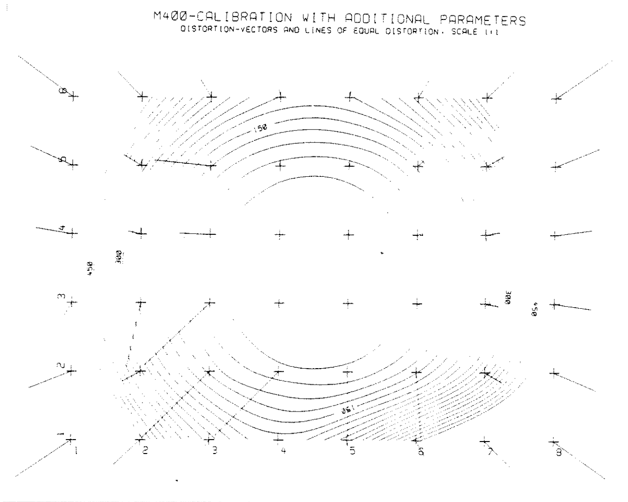

Fig. 6 Distortion vectors and lines of equal distortion for M400 photographs (reduced)

5 Restitution

Only the M400 photographs were plotted. This decision was made due to the fact that for the calibration of the M7A photographs, the geometry of the optical path could not be readily determined and the calibrated camera constant proved to vary substantially from the data provided by the camera manufacturer. Further, the absence of a computer-controlled zoom on the AC1 would have made restitution from convergent photographs extremely laborious.

Restitution of the portion of the specimen chosen for study (fig. 2) was carried out both graphically (on-line and off-line) and digitally.

The following modules of the AC1 system software were used:
INP (input), OUT (output), PLI (plot initialization) and PMO (plotting mode), (Kreiling, 1982).

In INP, the parameters for inner and outer orientation of the photographs as computed by ORIENT were input and stored in so-called camera and orientation files. The object coordinates of the centre points of the crosses were also stored in this module in a control-point file.

The manuscript sheet can be prepared in PLI. In this, the control points, coordinate grids and annotations are plotted and initialization of the graphic parameters required for later restitution is carried out.

With the OUT module, various input or acquired digital and graphic data can be transferred to the plotting table, hard-disk, magnetic-tape unit etc. Type and means of this transfer can be freely selected by the user, e.g. format, shift etc for digital data and the form of graphic representation, and scale, projection plane etc in the case of graphic data.

Restitution as such is carried out in PMO.

5.1 Model orientation

Following initialization of the various parameters, the photographs are placed on the picture carrier. Up to ten small-format photographs can be inserted, oriented and plotted simultaneously. Following this, inner orientation is carried out, based on the following formulae:

$$x = a_0 + a_1x' + a_2y'$$

$$y = b_0 + b_1x' + b_2y'$$

where:

x,y	transformed image coordinates of the fiducial marks into their theoretical coordinates
x',y'	measured image coordinates of fiducial marks
a_i,b_i $(i=0,1,2)$	transformation parameters determined by adjustment

A choice can be made between a similarity transformation ($b_2=a_1$, $b_1=-a_2$) or an affine transformation. The theoretical points of intersection of the straight lines along the sides as used for the calibration measurements are also used here.

Following epipolar orientation (elimination of the κ angles of the photographs by stereoscopic measurement of the principal points) outer orientation is carried out.

There are two alternatives available for the outer orientation of the model:

a: Adoption of the parameters X_0, Y_0, Z_0, ω, φ, κ obtained from ORIENT in the orientation files

b: Measurement of orientation and control points

It was decided to use method (b), since in (a) the measurements were carried out binocularly but only monoscopically and the coplanarity condition in bundle adjustment was disregarded, whilst in (b) accuracy of the orientation parameters can be increased by greater redundancy.

For outer orientation, four orientation points were measured in addition to the eight control points and the six Gruber's points.

Each point measured produces four equations (2 photographs x 2 coordinates) in accordance with formulae (1), and three unknowns. Each control point with three known coordinates produces three equations. The total number of equations is thus 96 (18 measured points x 4 = 72, plus 8 control points x 3 coordinates = 24), the number of unknowns being 66 (2 photographs x 6 orientation parameters = 12, plus 18 measured points x 3 object coordinates = 54). As a result,it was possible to obtain a redundancy of 30 in setting up the system equations.

5.2 Results

In the present project, the numerous possible alternatives available for direct graphic plotting provided by the AC1 were not fully utilized. Here, the object of the direct graphic plot was to obtain a simple graphic representation of pitting in the sample and of the control points at a given scale, together with figured depths of relevant points (fig. 7a).

In this particular case it was more important to obtain a graphic plot of various types of digital data, such as profiles, sections etc. These data were recorded in PMO and output on the plotting table by using OUT (fig. 7b). Data acquisition was carried out by time, distance, and manual release used alternately for the points. For off-line interpolation and plotting the isolines of equal depth, points arranged in a regular grid were also recorded.

The mean square error for the observations(image coordinates) obtained from the orientation adjustment was found to be 0.010mm at image scale. The maximum difference at control points was 0.014mm at the object.

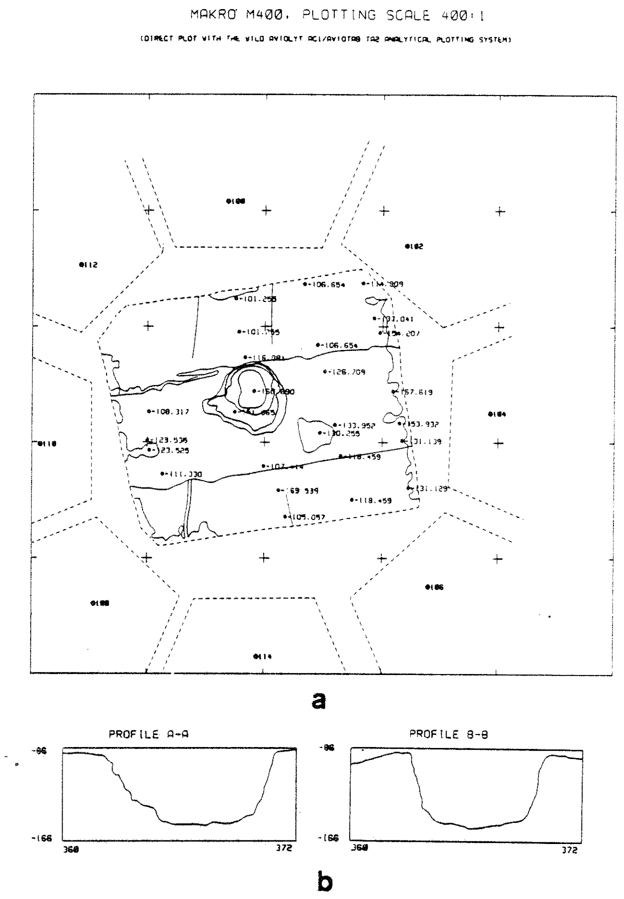

Fig. 7 a: Reduction of a direct graphic plot of sample, based on stereo-macrographs as shown in fig. 4a

b: Off-line graphic plot of profiles A-A', B-B'

Introduction of additional parameters in determining the inner orientation produced an increase in accuracy. Figure 8 shows the effect of introducing the additional parameters for the right-hand photograph of grid G100. Figure 8a shows the isolines of equal distortion before introducing the additional parameters, figure 8b shows them after their introduction.

Since in the AC1, photographs of any camera constant can be restituted, any possible additional model deformation which may occur in analog plotters is eliminated (e.g. affine deformation when a false camera constant is introduced).

Further processing of the data obtained in this way did not form part of the object of this exercise. The project was designed in such a way, that data processing will be carried out at the Imperial College London.

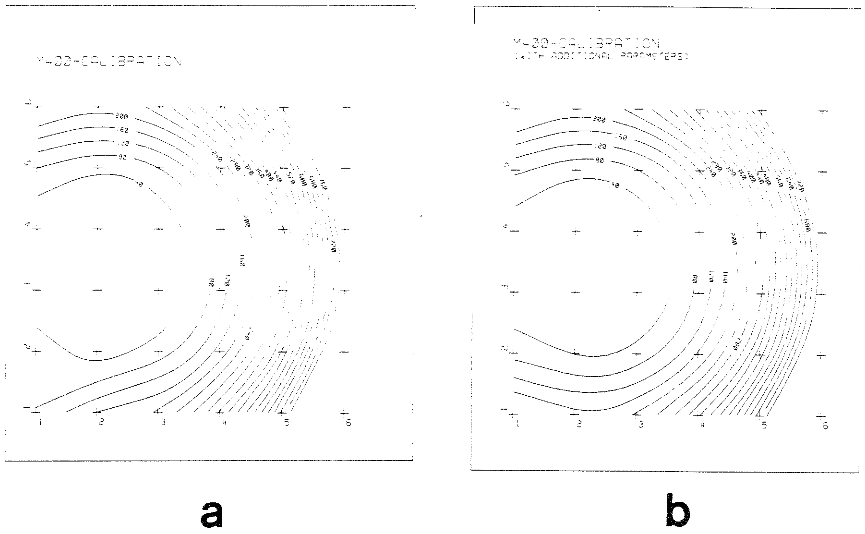

Fig. 8: Reduced plot of interpolated isolines of identical residual errors for the control grid G100, computed from ORIENT by resection for the right-hand stereophotograph (fig. 4b).

a: Before introducing additional parameters
b: After introducing additional parameters

6 Conclusions

By reference to a practical example, this paper offers proof that photogrammetric techniques of photography and restitution can be used successfully for applications in the field of microscopy.

The availability of analytical plotters and special software provides new possibilities for using standard photogrammetric methods in microstereophotogrammetry.

The accurate definition of the geometry of the optical path from object to image plane is still something of a problem. However, one of the ways in which the accuracy of the results can be increased to some extent is the possibility provided for computing systematic errors that occur on exposure and for taking these into account in restitution.

To exploit the capabilities offered by photogrammetry more fully in the field of microscopy, the installation of a universal calibration program in the computer used for the analytical plotting system is essential.

However, before microstereophotogrammetry can be used efficiently for quantitative analysis in daily commercial applications, a large number of still open questions must first be clarified.

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