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DEFORMATION MEASUREMENTS BY HIGH-FREQUENCY PHOTOGRAPHY DURING CRASH TESTS OF STEEL CONCRETE PLATES

Abstract:

Monitoring the metric deformations of steel concrete plates during crash tests from the first touch of the plates to its final destruction is a problem of high-frequency photography and of photogrammetry as well. The paper describes a new evaluation procedure on the strict basis of analytical photogrammetry (functional and stochastical model, the structure of the evaluation procedure and of software, geometric properties of the Hycam-filmcamera used).
Finally some results of the evaluation of an experiment are presented.

1. Introduction

Nowadays, quick-motion or high-frequency photography is applied in many areas of industry and science.Very fast processes thus are at first registered photographically in very short intervals and then made perceptible for the human eye and accessible for analysis. The simple methods of visual examination and interpretation of the projected films are often sufficient for the analysis. Besides, there are often merely photographic evaluations such as enlargements, possibly reading off dimensions and the like.

In photogrammetry the metric derivation of deformations from films has frequently been taken up, partly because of concrete tasks, partly because of a theoretic interest in the solution of the single-image problem which normally represents the basis of the evaluations, see e. g. /1/, /3/, /4/, /7/ and the literature given there.

The present contribution reports on the conception and application of an evaluation process of film pictures which is as general and, at the same time, as strict as possible for the purpose of two-dimensional deformation determinations. Conditions for the camera installation, e. g. the adjustment of the picture plane parallel to an object-coordinate-plane - often required still nowadays - were purposely overcome. The model formation is at first based on existing ideas, but then runs its own road. Particularly a complete process of evaluation of film pictures, applicable for data processing from data control up to the computer plot of deformations, has been created. Concrete photographs could be made because of the obliging cooperation of the Institute for Reactor Technology, University of Bochum, and the Rheinisch-Westfälische Elektrizitätswerk AG., Abtl. Bau/Vermessung. A HYCAM high-frequency camera was used, a high-class camera working on the principle of continous film motion. An octogonal prism, rotating simultaneously to the film, provides for motion compensation and a static corrector behind the prism for an extensive compensation of aberrations. The achievable quality of the pictures is said to be above the average /2/. With a series of interchangeable objectives of Messrs. KERN and a large variety of film velocities the camera can be adapted to many tasks /12/.

2. A configuration for the determination of deformations during tests of carrying capacity

During the tests for this paper (carrying capacity tests with concrete plates) a steel concrete plate lying horizontally on four supports was deformed by a vertically working force (kinetic energy of a falling weight, "Fallbär"). This very fast process of deformation had to be registered by the HYCAM camera and then evaluated by the help of measuring technique. A suitable arrangement is given in figure 1 in vertical and horizontal projection.

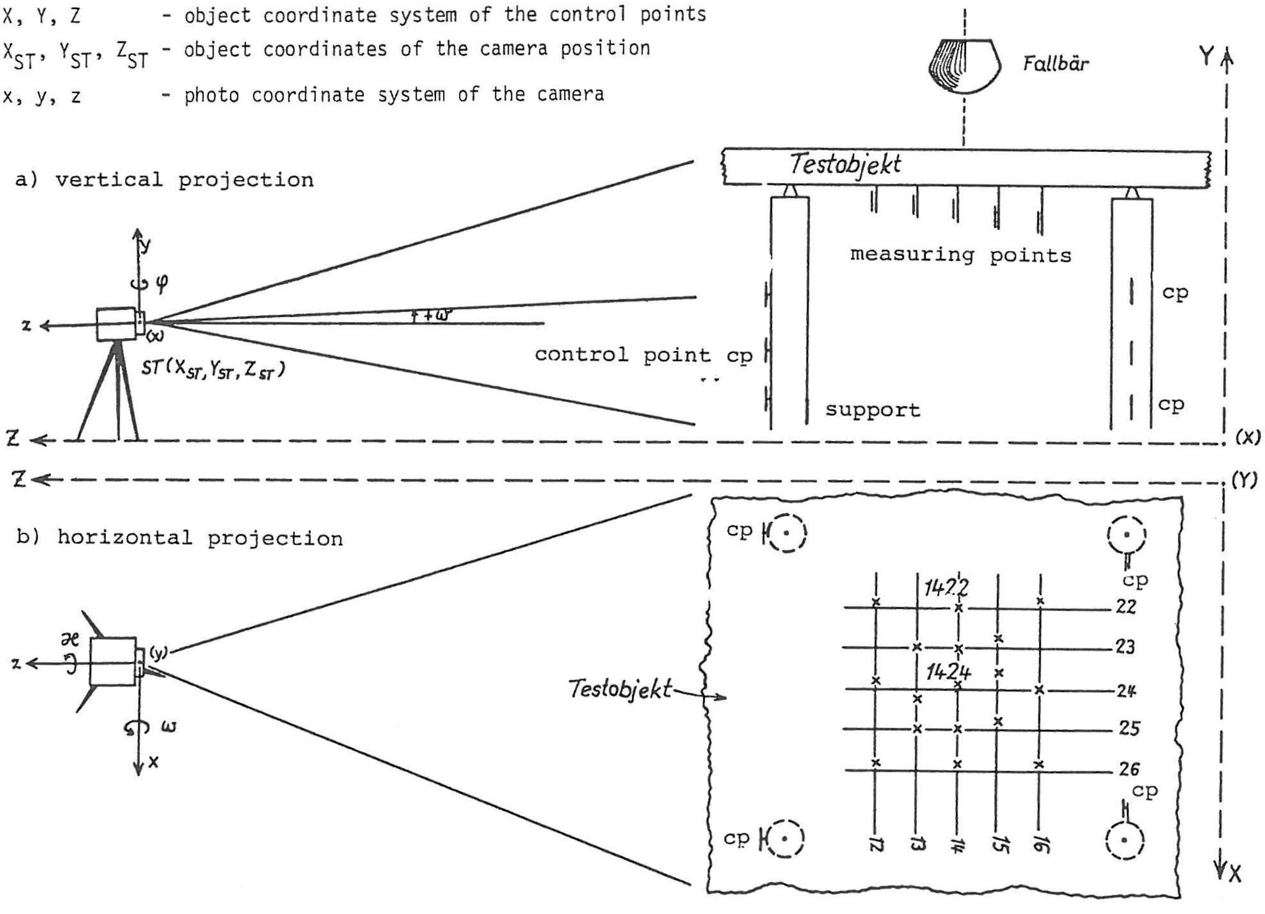
The main deformations will occur in Y-direction, much smaller ones in direction of X and Z. According to the single-image concept only the deformations Y and X are determined under the hypothesis that Z = constant, a calculabe uncertainty of Z in the error budget being taken into account and thus controlled.

Fig. 1: Typical photographing arrangement for the determination of two-dimensional deformations according to the single-image procedure

X, Y, Z - object coordinate system of the control points

X_{ST}, Y_{ST}, Z_{ST} - object coordinates of the camera position

x, y, z - photo coordinate system of the camera



Departing from the consideration that the deformation will occur inside the level stretched by four supports, the test area was marked with a screen of black and white signals. A mutual covering of the marks in the picture must be avoided. This was obtained by fixing the marks on small stalks under the plate; besides they vary in their vertical (fig. 1 a) as well as in the horizontal (fig. 1 b) arrangement.

A covering can also be avoided if the camera photographs the test plate obliquely from below ($\omega > o$). This is no hindrance for the following concept of evaluation, because all degrees of freedom of a camera are taken into account there. Nevertheless, an excessive camera inclination must be avoided. During the deformation small components in direction of Z will certainly appear which will remain without any perceptible influence on the looked for amounts Y and X as long as the projection rays hit the deformation level Z = constant nearly vertically.

The measurement informations necessary in this photographing configuration for a single-image evaluation including their standard errors are:

a) control-points in the object system (X, Y, Z)
b) Z-coordinates in the object system for the measuring points
c) image coordinates x, y of all points
d) interior orientation

Generally, the measurement information can be determined in the following way:

for a) and b) by geodetic measurements or from pictures of stereometric cameras
for c) by comparator measurements
for d) from factory statements or by calibrations of one's own.

In the present paper a) and b) were achieved by geodetic measurements, c) by measurements at the ZEISS PK 1, and d) by calibrations of our own.

3. A general conception for photograph evaluation

Normally the cameras of high speed cinematography must be characterized as non-metric cameras from a photogrammetric point of view: the interior orientation is only approximately known in most cases and during a series of photographs not necessarily constant. Besides, technical devices are often missing for a steady geometrical relation between what is in the photograph and the photographing optics with the help of fiducial marks or the like. This is valid even more for the data of exterior orientation. Actually, in many applications of cinematography, could these data easily be defined at the same time, but not made use of as long as the technical relation with the photo coordinate system is missing. At the other hand, these photogrammetric deficiencies could be removed or at least reduced by comparatively small instrumental manipulations and calibrations. The quality of the evaluation would be improved by this in any case. Altogether, a conception for photograph evaluation should be capable of evaluating photographs taken by any non-metric camera as well as by pricise survey cameras, including measured values of the elements of orientation.

With this one aspect of model formation has been discussed. As we already said, we are not talking about stereoscopic pairs photographed simultaneously, but about the case of single image evaluation. In spite of this, it must be made clear now if the independent or simultaneous evaluation of a series of photographs is necessary. This question depends very much on the photographic arrangement and the conditions during the experiment.

In an arrangement as in fig. 1 a, 1 b the illustrated events will at least be related with each other over the same control points and with a strict numeric evaluation in a process of adjustment algebraically correlated. Even more: The camera firmly installed the exterior orientation ought to remain strictly identcal for all the photographs of a series. For this reason, a strong connection could be obtained by identity conditions between the six data of orientation of two successive photographs. By this, the accuracy and compatability could be increased. How these equations must be put up has already been exposed in /10/. The same statement can also be made about the interior orientation if it is cleared up that the constancy of these data in a series of photos really exists. As a result of these considerations one must require a simultanieous adjustment for a general conception of photograph evaluation in which all the photographs of a series are included with a few conditions of connection and the common control points. In this way, most favourable preconditions for the definition of metric informations from the photographs would be created.

Nevertheless, there are processes of photographing in which - as in this case - an independent evaluation of the photographs seems necessary. As explained before, it is the question of an analysis of "falling bear" experiments here. The striking of the "falling bear" on a steel concrete slab which is to be tested produces very strong percussions in the surroundings during the time of photographing: a constancy of exterior orientation had to be doubted therefore. Besides it must be mentioned that there was no interest in absolute metric information, but only in the changes in time, in the deformations during the short deformation-phase of a slab. Although certain approximations in the stochastic and the functional models prevent an unbiased estimation of absolute information, it does not prevent the one of deformations, see e. g. PELZER 1980, NIEMEIER 1979. For this case the photograph evaluation was finally modelled as independent single image photogrammetry and laid down in very comfortable software (Standard FORTRAN).

Related to the coordinate system in Fig. 1 a, 1 b to begin with we depart from the known analytic projection equation between object space and image space:

$$\begin{bmatrix} X_i \\ Y_i \\ Z_i \end{bmatrix} = \begin{bmatrix} X_o \\ Y_o \\ Z_o \end{bmatrix} + \lambda_i \underline{D} \begin{bmatrix} x_i - x_o \\ y_i - y_o \\ c \end{bmatrix} \quad ; \underline{D} = \begin{bmatrix} d_{11} & d_{12} & d_{13} \\ d_{21} & d_{22} & d_{23} \\ d_{31} & d_{32} & d_{33} \end{bmatrix} \tag{3.1}$$

or

$$X_i = X_o + (Z_i - Z_o) \frac{(x_i - x_o)\, d_{11} + (y_i - y_o)\, d_{12} + c\, d_{13}}{(x_i - x_o)\, d_{31} + (y_i - y_o)\, d_{32} + c\, d_{33}} \tag{3.2}$$

$$Y_i = Y_o + (Z_i - Z_o) \frac{(x_i - x_o)\, d_{21} + (y_i - y_o)\, d_{22} + c\, d_{33}}{(x_i - x_o)\, d_{31} + (y_i - y_o)\, d_{32} + c\, d_{33}}$$

in which

X_i, Y_i, Z_i (3.3) X_o, Y_o, Z_o (3.4) – cartesian coordinates of a point P_1 respectively of the centre of projection in the object space

$\underline{D} = \{d_{ij}\}$ $d_{ij} = d_{ij}(\phi, \omega, \kappa)$ (3.5) – orthogonal matrix $\underline{D}$ as a function of three independent angles ϕ, ω, κ

x_i, y_i (3.6) – coordinates of the image point P_1' in any system of the image space

c, x_o, y_o (3.7) – interior orientation: camera constant c, coordinates of the principal point of image in the image space

The equations (3.2) contain the usual 9 parameters of a calibrated survey camera, that is the data of interior orientation (3.7) and of exterior orientation (3.4), (3.5). Normally, (3.7) is known; (3.4) and (3.5) are derivated from control points or other information.
In order to obtain a representation free of orientation data for non-survey cameras the terms of numerator and denominator in (3.2) are multiplied and all constant quantities are summed up to new projection parameters L. We obtain:

$$X_i = X_o + (Z_i - Z_o)\,\frac{x_i L_1 + y_i L_2 + L_3}{x_i L_7 + y_i L_8 + L_9}$$
$$Y_i = Y_o + (Z_i - Z_o)\,\frac{x_i L_4 + y_i L_5 + L_6}{x_i L_7 + y_i L_8 + L_9} \qquad (3.8)$$

in which

$X_o, Y_o, Z_o, L_1 \ldots L_9$ – projection parameter for the points of a picture

The rest of the quantities remain valid. Between the new parameters L and the orientation data the relation (3.9) originates from the transition of (3.2) to (3.8):

$$L_3 = -(x_o L_1 + y_o L_2 - cd_{13})$$
$$L_6 = -(x_o L_4 + y_o L_5 - cd_{23}) \qquad (3.9)$$
$$L_9 = -(x_o L_7 + y_o L_8 - cd_{33})$$

The remaining L are identical with elements of $\underline{D}$:

$$\underline{D} = \begin{bmatrix} L_1 & L_2 & d_{13} \\ L_4 & L_5 & d_{23} \\ L_7 & L_8 & d_{33} \end{bmatrix} = \underline{L} \qquad (3.10)$$

For later on we need the inner products from L:

$$L_1^2 + L_4^2 + L_7^2 = N_x^2 \tag{3.11}$$

$$L_2^2 + L_5^2 + L_8^2 = N_y^2 \tag{3.12}$$

$$L_1 L_2 + L_4 L_5 + L_7 + L_8 = N_o \tag{3.13}$$

Approach (3.8) has - as directly evident - with its 12 parameters 3 more than the projection equations stated for the survey cameras (3.2). With the additional parameters a certain part of systematic image deformations can already be recorded without having to fall back on the known approaches of self-calibration. Obviously, the parameters L are linearly dependent on each other: one could dispose - as usual up to now - of one of the parameters arbitrarily, for example assign to L_9 a constant value $L_9 = 1$. In this paper we proceed in another way to be able to react on image deformations flexibly with the two utilizable degrees of freedom; later on we are going to come back to this.

If, however, the projection of the object space into the image space is to represent an exact perspective, the parameters L in (3.10) must, as is well known, fulfill the following relations of normalization and orthogonality:

$$N_x^2 = 1 \tag{3.14}$$

$$N_y^2 = 1 \tag{3.15}$$

$$N_o = 0 \tag{3.16}$$

One must always fulfill one of the conditions because of the dependence of the L; for reasons of a strong numerical condition one has to prefer (3.14) or ((3.15). The strict consideration of the three conditions leads from approach (3.8) back to the law of projection with 9 parameters (3.2).

If it is possible to use a "photogrammetric" cinê camera or even one of the known survey cameras for single image tasks, it is often possible and very useful to employ measurement information about the orientation data in the evaluation process /10/. Universal conceptions of evaluation should therefore always be designed to this. As not all the orientation data occur directly as parameters in the general approach (3.8), the functions between the parameters L and the data of inner and outer orientation must be established. First of all we make a reasonable precondition: Let us suppose the orthogonality of the axes in the image space and with that, necessarily, the condition (3.16). Except the normalizations (3.14), (3.15) matrix $\underline{L}$ (3.10) represents a genuine orthogonal matrix. Thus, in the following formulae only a normalization must be made before rotations can be derived from matrix $\underline{L}$ or measured values of the camera position can be related to the projection centre in the usual way. The formulae for the inclusion of measured outer orientation data for general camera types are found in /10/ and /11/. We restrict ourselves to formulae for measurement data of interior orientation.

In order to calculate explicit expressions for the elements of interior orientation we depart from system (3.9). It contains the 9 linearly dependent quantities L as it were as coefficients and the 5 looked-for quantities x_o, y_o, as well as cd_{13}, cd_{23} and cd_{33} as unknown quantities. From (3.9) only it would not be possible to obtain a unique solution. Therefore it is necessary to make use of further independent information: 2 equations originate from the orthogonality of the first two columsn of $\underline{L}$ to the third column; a further information could be taken from the conditions (3.14) - (3.16), but it is complicated to insert them into (3.9). Instead of this we use the statement that the distance c between the projection centre and the image plane assumes a given value invariant in case of rotation. This very strong condition can substitute one of the before introduced or complete it in the case of adjustment. In detail the following relations result. Departing from (3.9) we form the sum:

$$\begin{aligned} L_1 L_3 + L_4 L_6 + L_7 L_9 = & - x_o L_1^2 - y_o L_1 L_2 + c L_1 d_{13} - \\ & - x_o L_4^2 - y_o L_4 L_5 + c L_4 d_{23} - \\ & - x_o L_7^2 - y_o L_7 L_8 + c L_7 d_{33}, \end{aligned}$$

from which, because of the required orthogonality of the columns $\underline{L}$ and with (3.11), follows immediately

$$x_o = -(L_1 L_3 + L_4 L_6 + L_7 L_9) / N_x^2 \tag{3.17}$$

and in the same way

$$y_o = -(L_2 L_3 + L_5 L_6 + L_8 L_9) / N_y^2 \tag{3.18}$$

$$L_3^2 + L_6^2 + L_9^2 = x_o^2 (L_1^2 + L_4^2 + L_7^2) + y_o^2 (L_2^2 + L_5^2 + L_8^2) + c^2 (d_{13}^2 + d_{23}^2 + d_{33}^2)$$

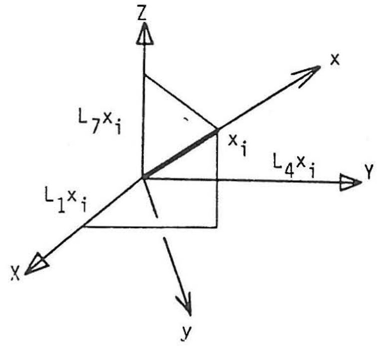
from which, with rotation invariance of the camera constant c and with (3.11), (3.12):

$$c^2 = L_3^2 + L_6^2 + L_9^2 - (L_1 L_3 + L_4 L_6 + L_7 L_9)^2 / N_x^2$$
$$- (L_2 L_3 + L_5 L_6 + L_8 L_9) / N_y^2 \tag{3.19}$$

Possibilities of application of the general single image method

The equations (3.8), (3.14) - (3.16), (3.17) - (3.19) as well as the relations for measured values of exterior orientation /10/, /11/ here not rendered represent, as a whole, the general method with spatial point accumulations. According to the combination of the equations the result is the spatial projective resection with the highest number of 11 independent parameters up to the spatial resection with the lowest number of only 6 parameters. Thus, the whole of the formulae covers, as we see, all degrees of freedom of a camera and the possibilities of putting it up.
In a special case also the transformation from plane point accumulations actually with 8 parameters, can be solved. It is only necessary to stop the information gap increased to 4 linearly dependent parameters by the corresponding data. For example, the 3 elements of inner orientation x_o, y_o and c can be introduced (as usually is employed in rectification instruments) and as a fourth element one of the normalization conditions (3.14), (3.15).

We must particularly stress the performance potentialities of the general method for the registration of simple image deformations. The capacity for this is , with the full number of parameters 12, given with only 1 additional condition. In order to show this, an interpretation of the conditions (3.14) - (3.16) is useful. We put the question what changes the image coordinates x, y of a point will undergo in statement (3.8). As we know, the column vectors of the transformation matrix $\underline{L}$ (3.10) inform us about this completely, as to x, y columns 1 and 2. The sketch beside the text shows the x component before and after its transformation. Only fulfilling condition (3.14), the new axis segments $L_j\ x_i$ can be interpreted by vertical projection of x_i on X, Y, Z and the L_j can be considered as direction cosine in consequence. Hence, the norms N_x and N_y of the columns prove changes of the scale of the x axis respectively the y axis when $N_x \neq 1$, $N_y \neq 1$, and the inner product of both columns N_o indicates that x and y form an oblique angle when $N_o \neq 0$. The two additional and independent degrees of freedom (related to statement (3.2)) existing in the L can therefore be used for the registration of image deformations in the shape of an individual scale factor for x or y a special affine transformation. In the following summary combinations strong in numerical condition are found, including the equations (3.17) - (3.19). An extension of the approach for the registration of further image deformations must take account of it.



Equations	Registration of image deformations
approach (3.8) plus condition $N_x = 1$	- right angle mistake - free scale factor for y
approach (3.8) plus condition $N_y = 1$	- right angle mistake - free scale factor for x
approach (3.8) plus conditions (3.16) (3.19)	- common free scale factor for x and y

Stochastic model, evaluation process of the measuring data

On the basis of independent single images an evaluation process according to the Gauß-Marcow-model of independent observations has been developed and programmed with the mentioned equations. The process considers the 12 transformation parameters X_0, Y_0, Z_0 and L_1 to L_9 as unknowns and the quantities (3.5) to (3.7) as well as the data not mentioned here for the camera position as stochastic measuring data, each one with individual standard deviation a priori. The conditions (3.14) - (3.16) are enforced with high weights. All equations lead to an adjustment according to observation equations, except system (3.8). But this one, too, can easily be transformed into an adjustment quasi-according to observation equations and programmed, because only a series of two-dimensional matrices must be inverted. A complete calculation of the corrections of all the measuring data and an error propagation of the transformation parameters and the orientation elements concludes the adjustment process.

Following up the adjustment, metric information are actually drawn from the images: from all image points P'_i with the image coordinates x_i, y_i, the object coordinates X_i, Y_i can directly be calculated from equation (3.8) with the parameters known by now. Nevertheless, as unevitable in single image tasks, the object coordinate Z_i of the point P_i must be known beforehand and taken into account in (3.8). Also for the object coordinates X_i, Y_i the standard deviations are found out in a strict way, considering

1. the variance-covariance matrix of the parameters as well as
2. the standard deviations of x_i, y_i and
3. also - as hardly before - of Z_i.

In this way the influence of point movements in direction to Z during the loads on the results in X_i, Y_i can be defined.

The data flow and the structure of software result from the following synopsis. Details are found in /11/.

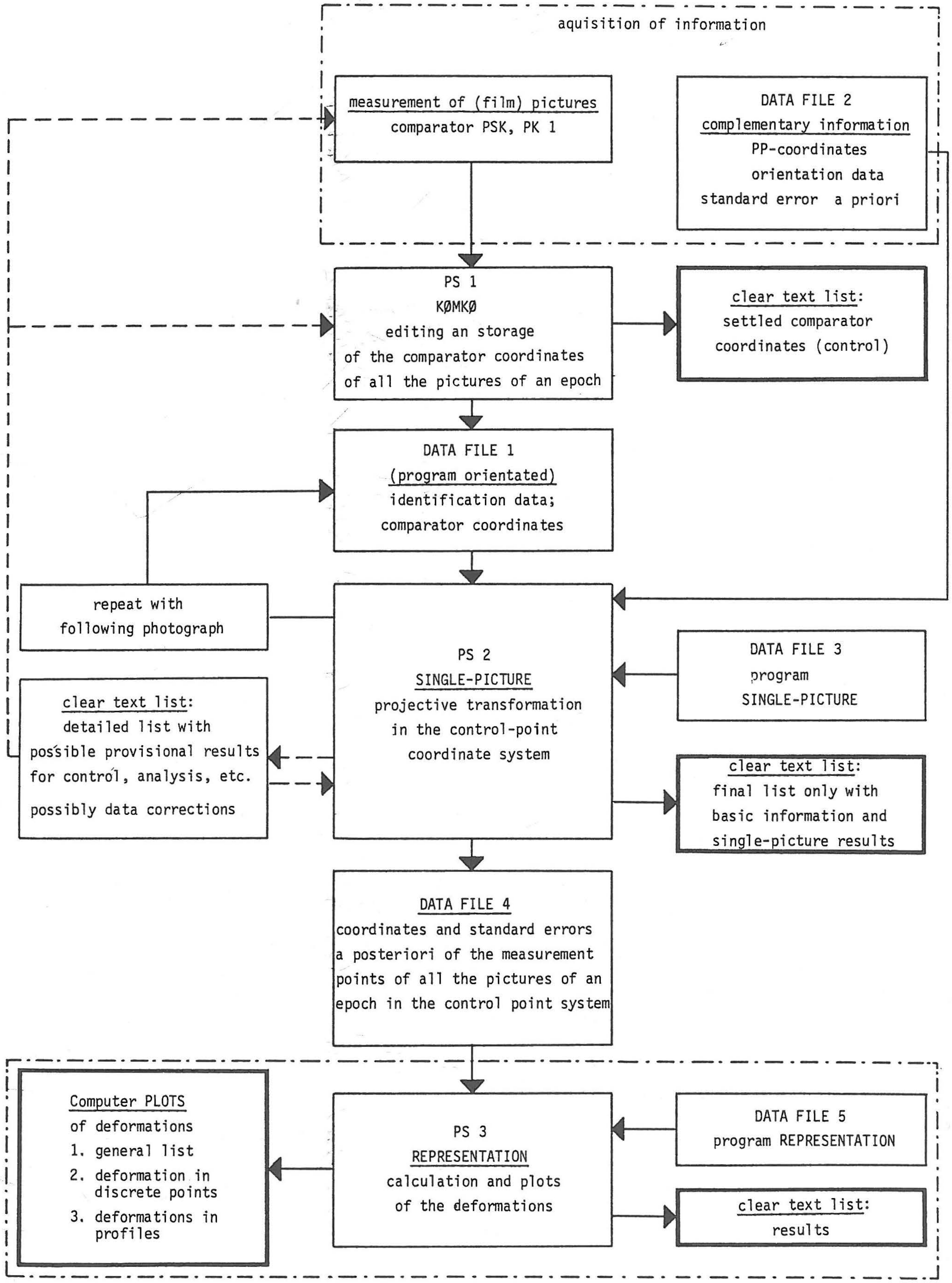
4. Examination of the photogrammetric qualities of the HYCAM-camera

As object for the test a plain field of control points of highest precision, stretched by three vertically installed precise levelling laths, was used. From this test film various successive pictures had then to be evaluated, each one with approximately 140 measured control points, in order to obtain statements concerning constancy.
The HYCAM, which works on the priciple of optical film compensation, has for this purpose an octagonal rotation prism in its ray path, from which result together with the other optically effective elements, "eight projecting systems". As only for this reason up to eight different distortions can appear sucessively at least eight successive pictures had to be examined.
Both evaluated films ("falling bear" experiment, test field photographs) were taken by the same highly sensitive panchromatic KODAK RAR film 2479 (ESTAR-AH BASE). In spite of its 27 DIN and only 1/1000 sec exposure time (400 pictures per second, 2,5 factor of a sectorial stop) there were problems of illumination which could only be solved by various 1,5 kW halide flood light reflectors. As the HYCAM is no survey camera it has us fiducial marks which define a picture coordinate system and fix the interior orientation according to this. In order to get any picture coordinate system the corner points of the picture were estimated. Fig. 3 shows as an example an amplification of a single picture from the HYCAM film of the "falling bear" experiment. Nevertheless it is abvious that the corner points fall on the holes of the transporting perforation. This is why it was necessary to form the point of intersection of the two collateral lines as corner point of the picture and to move the measuring mark to this spot. This was rather easy; for independent repetitions of measurements the deviations from the average amounted to about $\pm$ 10 µm.
The data flow in the evaluation of the test film took place according to the software structure (compare fig. 2) up to data file 4, on which the remaining errors VXB, VYB of the control points in picture coordinate system were now stored in order to represent them graphically by a simple plot routine afterwards.

Results:

1. The yet very small format of the perforated 16 mm narrow-gauge film of about 10,6 x 7,4 mm^2 in gross can be used photogremmetrically only to an extent of 75 %, because of which the net format amounts to only

Fig. 2: Data flow and software structure of the evaluation process:
from the picture to the computer plot of deformations
$PS_i \hat{=}$ program segment No i
- - - manual data corrections



about 8,0 x 5,6 mm^2. Inside this surface, though a surprisingly high point precision of $s_0 = \pm 6$ µm was achieved, with an average standard setting error of $s_E = \pm 1,5$ µm at the ZEISS PK 1.

2. The results for the data of interior orientation from the single-image compensation of the test film were examined with respect to constancy. Only for y_0 of the principle point significant differences were stated. The reason is obviously the inexact definition of the fiducial marks and underlines the necessity of an instrumental modification of the camera before it can be called a photogrammetric camera.

3. Plots of the remaining errors for all eight prisms show a nearly common sinusoidal, i. e. non-linear change in direction of the film movement ($\hat{=}$ y), which, admittedly, especially in the central region of the picture, is disturbed by irregulatities. Most frequent are remaining amounts less than $2 \cdot s_0$.

4. All calculations can be made up without distortion corrections because the distribution of the remaining errors in the test calculation cannot be explained by the distortion data from the data sheet of Messrs. Kern.

5. In this case it is better to register the systematic image errors recognized in 3. - as usual in photogrammetry - by selfcalibration. As a first step to this a particular scale factor in direction of the film movement y and a right angle error were taken into account:
The approach (3.8) of this work does so if only the first of the orthogonality relations (3.14) is enforced.

   The compensation system has now a bigger freedom which led to the improvement of the standard error s_0 by 3 % and made the norms N^2_y change from 1 to 1,0003 for the scale factor in y and the right angle condition N_0 from 0 to 0,0015. Apart from some extreme remaining errors which diminished by 1 - 2 µm the linear approach practised here has brought no decisive improvement: the remaining errors show a non-linear behaviour by nature!

6. From the before said we can sum up that a further refinement of the compensation approach is not necessary any longer, because

   6.1 it would be without interest for the determination of deformation because of the difference formation,

   6.2 the photogrammetric process limit for HYCAM photographs seems to be reached at $\pm$ 5 µm.

5. Example for application: Temporal and metric resolution of a "falling bear" experiment

At first, the event (deformation) was registered photographically by the HYCAM according to the photographing configuration from passage 2, and the first 17 photos (one before the occurrence and 16 afterwards) were evaluated; compare Fig. 3. As the "falling bear" rebounded twice after hitting the plate for the first time until it finally remained there, 15 photos more were evaluated at the end of the whole event.

The measurement turned out to be difficult not only because of the bad picture contrast (large grain film, partly underexposed etc.), but also because three point marks were hard to identify in the depth. With two points this led to a confusion which was only noticed in the plots of the profiles. Further on, some marks got separated from their stalks because of the strong acceleration. The points in question could be purposed only with difficulties.

The analytic evaluation of the "falling bear" experiment as single-image task has had the following results:

1. The measurement accuracy at the comparator PK 1 was, like in the test film, $s_= = \pm 1,5$ µm.

2. The standard errors for image points because of the single-picture compensations, though, were $s_0 = \pm 3$ bis $\pm$ 6 µm. This photogrammetric process accuracy is surprisingly high under the given circumstances.
For the derived heights YN of measuring points the following values were attained:

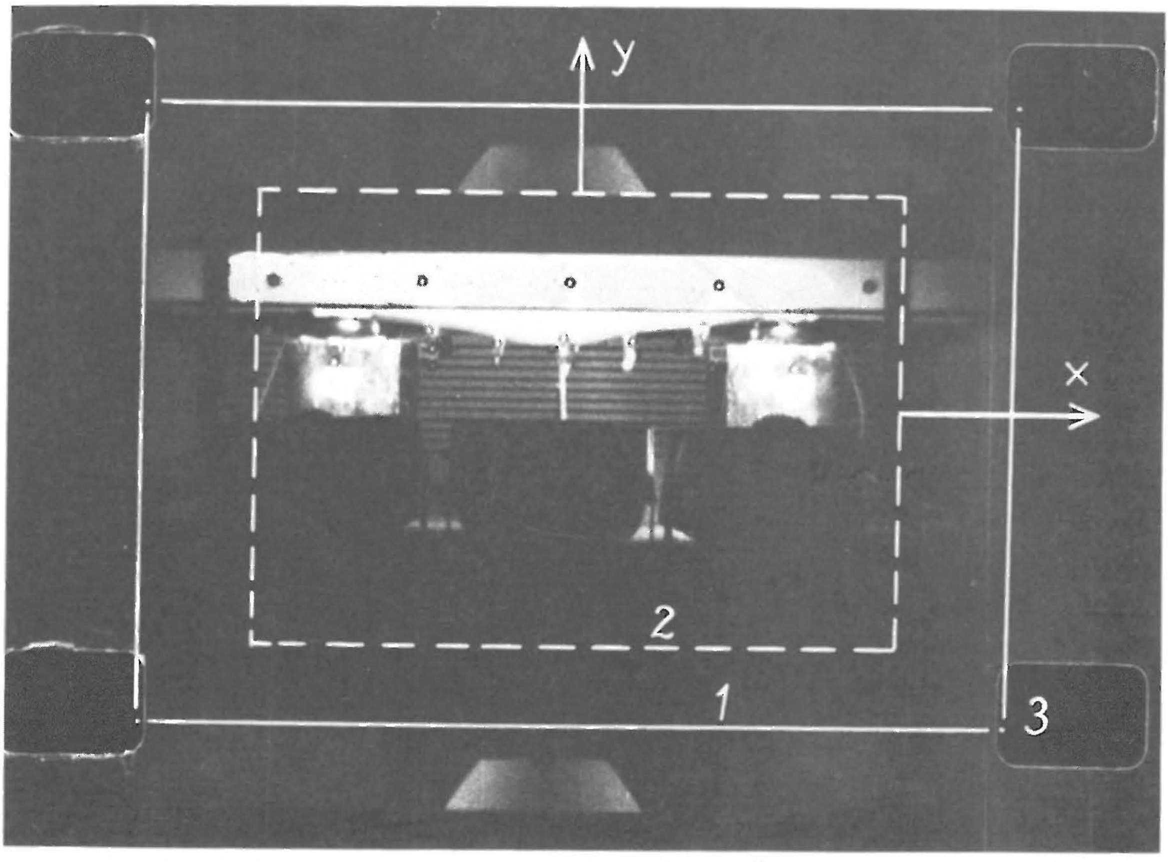


Fig. 3.: Steel concrete plate in the "falling bear" experiment at the moment of maximum deformation (enlargement of a picture with supplements in white)

1 limits of the gros format

2 limits of the net format

3 corner points estimated in the measuring process as "fiducial marks"

x, y axes of photo coordinates related to the centre of gravity of the fiducial marks

Standard error s_{YN} of heights YN under consideration of the influence of:			
Point No	bundelorientation measurement accuracy of the photo coordinates $s_x = s_y = \pm 4$ µm	bundelorientation measurement accuracy of the photo coordinates $s_x = s_y = \pm 4$ µm and the object coordinate ZN:	
	(i. e. $s_{ZN} = 0$)	$s_{ZN} = \pm 20$ mm	$s_{ZN} = \pm 50$ mm
1422	± 1,64 mm	± 1,65 mm	± 1,66 mm
1424	± 1,53 mm	± 1,53 mm	± 1,55 mm

The main error component results from the photo coordinate accuracy because the quotient from $s_{YN} : s_y \sim m_b$, produces rather well the picture scale number: 382, respectively 415 as against $m_b = 307$.

3. The standard errors s_{YN} are only litte dependent on the variances s^2_{ZN} of the ZN-coordinates because of the telephoto lens which was used. That is why the changes in ZN may be neglected because of the stalks and the deformations.

4. Fig. 6 shows as a result of the temporal and metric resolution of a "falling bear" experiment the deformation of a steel concrete plate in the X, Y-level in profile 14 (comp. Fig. 1 b) in eight equidistant

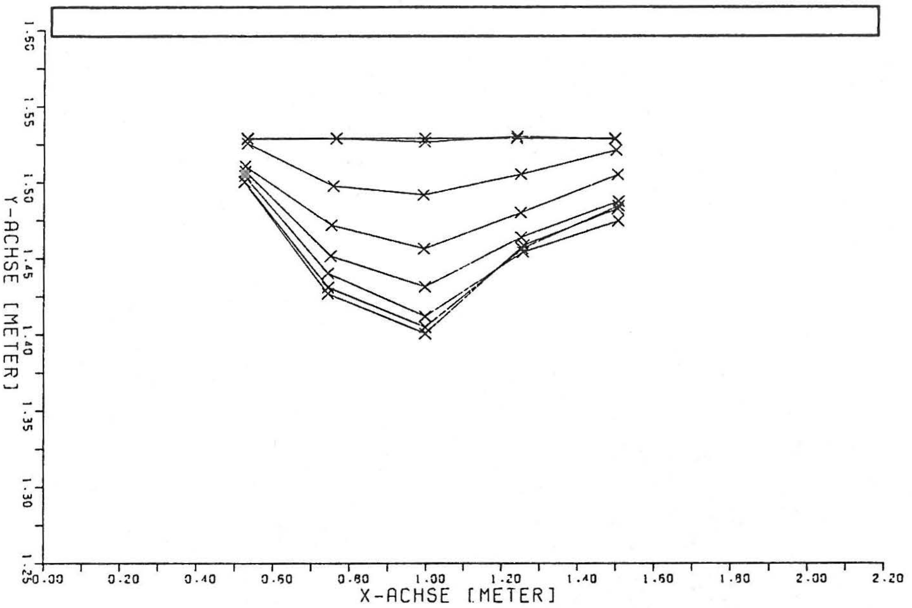


Fig. 4: Deformation of a steel concrete plate in the X-Y-plane at eight equidistant moments t with Δt = 0.025 seconds, comp. profile 14, Fig. 1 b

equidistant moments t with Δt = 0.0025 sec. It is evident that at the moment of the pictures 1 and 2 the event hat not yet occured, whereas between the pictures 2 and 6 the main part of the deformation takes place. Between the pictures 6 and 8 this process slows down more and more, and in the points 1425 and 1426 (at the right hand in the profile) the process takes already place inversely, which is shown by the pictures 9 to 17 not represented here for reasons of clearness.

5. Fig. 5 shows the temporal change of the object height YN of the points 1422 and 1424 over all measured pictures. Here a deformation phase (picture 2 to picture 13) and vibration phases (picture 13 to picture 17 and picture 80 to picture 93) as well as the maximum deformation at the moment of picture 8 can clearly be seen.

   It is interesting to see that the "falling bear", when hitting the plate for the first time, causes a deformation reversible to 75 %, whereas the lasting deformation, even if the "falling bear" hits the plate once again, does not increase but only vibrates slightly.

6. Outlook

Using a film camera for the temporal and metric resolution of fast processes has had surprisingly good results in this case. Above all the evaluations on a test field of high precision has clearly proved this. One reason is certainly to be seen in the fact that the HYCAM camera which was used bases on the principle of continuous film motion. Besides it turned out that for the evaluation of pictures a general formulation and programming of analytic-photogrammetric equations are necessary, e. g. in order to be able to correspond flexibly to all photographing situations or in order to reach reliable, reproducible accuracy statements.

A photogrammetric process accuracy of about $\pm$ 4 - 6 µm (in the picture plane) has already been reached by the projective approach which includes a two-parametric registration of linear systematic image errors. Because of the remaining errors in the camera calibration a different behaviour of the eight compensation prisms can be excluded. Nevertheless a common, non-linear systematic deformation superposed by a certain noise, is clearly to be noticed. With corresponding approaches of self-calibration the process accuracy could perhaps be increased to about $\pm$ 2 - 3 µm. Such a step would above all be important for the determination of absolute metric informations, hardly for deformation measurements.

The elements of interior orientation proved surprisingly stable in the HYCAM camera for a long series of pictures. But this quality remains photogrammetrically hardly useful as long as no fiducial marks or something like that are represented in addition to this. This would be very recommendable for all photogrammetric applications - especially in experiemnts with only a small number of control points - and would only increase the value of such a camera.

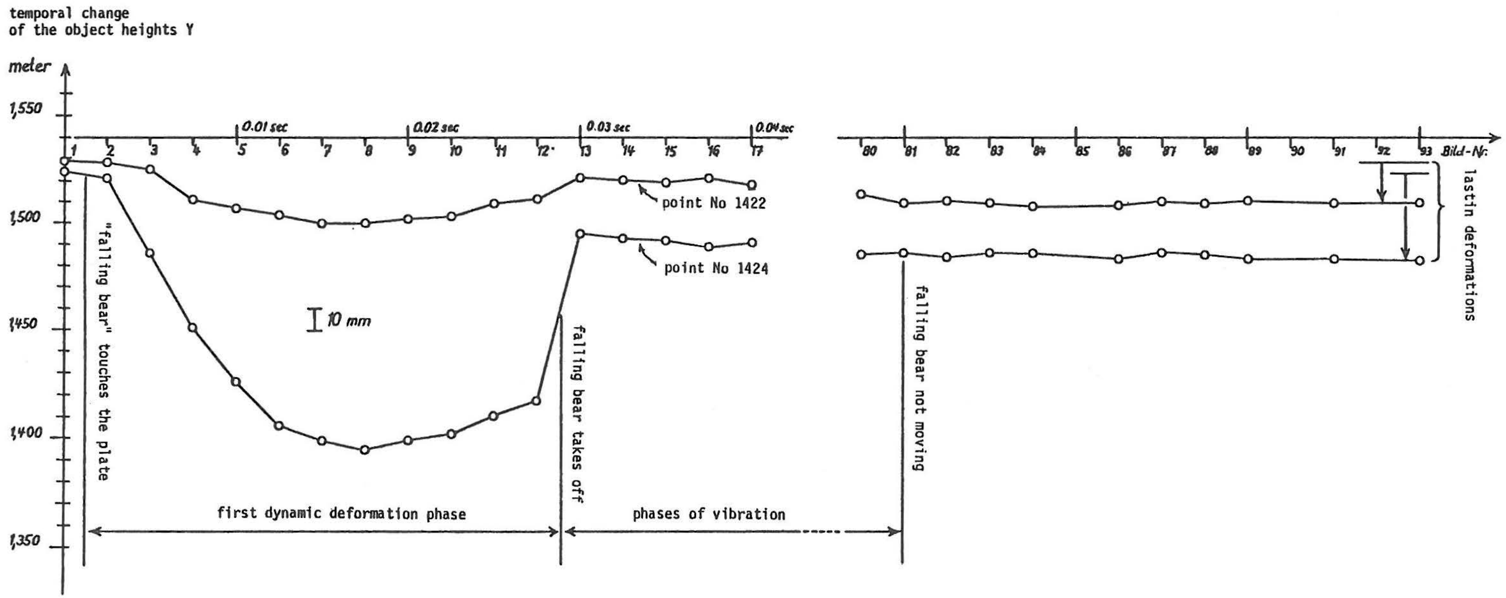


Fig. 5:
Deformation as a function
of time in two selected points
1422 and 1424 from profile.14
fig. 1 b)

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