DEFORMATION ANALYSIS OF THREE-DIMENSIONAL PHOTOGRAMMETRIC POINT FIELDS

H. Borutta and J. Peipe
Universität der Bundeswehr München

ABSTRACT

Multistation bundle adjustment yields precise and reliable point determination in close-range photogrammetry. Simultaneous calibration of the used camera is possible if an appropriate configuration of photographs is applied. The comparison of three-dimensional point fields of an object at different times allows a deformation analysis to be verified by statistical means. The procedure is illustrated by an example related to the construction of automobiles.

INTRODUCTION

Applications of close-range photogrammetry in industry have increased over the last years (e.g. Fraser and Brown 1986). Photogrammetry as a procedure for determining position, shape and size of objects related to a spatial coordinate system has to compete with conventional techniques such as 3D-coordinate-measuring-machines or sensor robots. Of special interest are the geodetic industrial measuring systems developed recently, for instance KERN ECDSI, ZEISS IMS, WILD RMS 2000 (Bill 1985). In comparison with these methods the well-known advantages of photogrammetry (see e.g. Torlegård 1981) have to be considered. In particular, a photograph is quickly obtainable and represents a high density data storage that documents the object situation at the instant of exposure. A decision on the number of photographs to be evaluated and on the extent of the measurement is possible at any time. On the other hand some time elapses between taking the photographs and receiving the results of the evaluation. The development of on-line and real-time recording systems is very advantageous when applying photogrammetry effectively to industry.

If at a certain moment an object can be represented by a selected number of discrete points the comparison of two or more sets of spatial coordinates obtained at different times allows a deformation analysis. The significance of calculated movements belonging to a reference system has to be verified by statistical means. This investigation is of major importance if the magnitude of deformation corresponds with the magnitude of the accuracy of point coordinates. In comparison with other techniques such as time parallax method, controlled stereomodels and resection-intersection procedures, the bundle adjustment approach is highly recommended for deformation measurements (Buck 1977, Cooper 1984, Fraser and Gründig 1985, Wester-Ebbinghaus and Wezel 1985, Zinndorf 1985). The self-calibrating "combined" bundle adjustment offers the best possible solution for determining three-dimensional point fields including all information available in image space and object space (e.g. Ebner 1984). The multi-station approach yields precision and reliability due to the increased number of intersecting rays for each object point. Thus photogrammetry meets the resolution of the geodetic measuring systems as mentioned before.

In the following an automobile has been used as an example for the industrial application of photogrammetric deformation measurement and the analysis of movements.

SKETCH OF THE DEFORMATION PROBLEM

During production an automobile usually moves along an assembly line. The car-body itself is painted and subsequently completed by mounting electric devices, motor, axles, wheels etc. The production cycle takes about 20 hours. The chassis is first

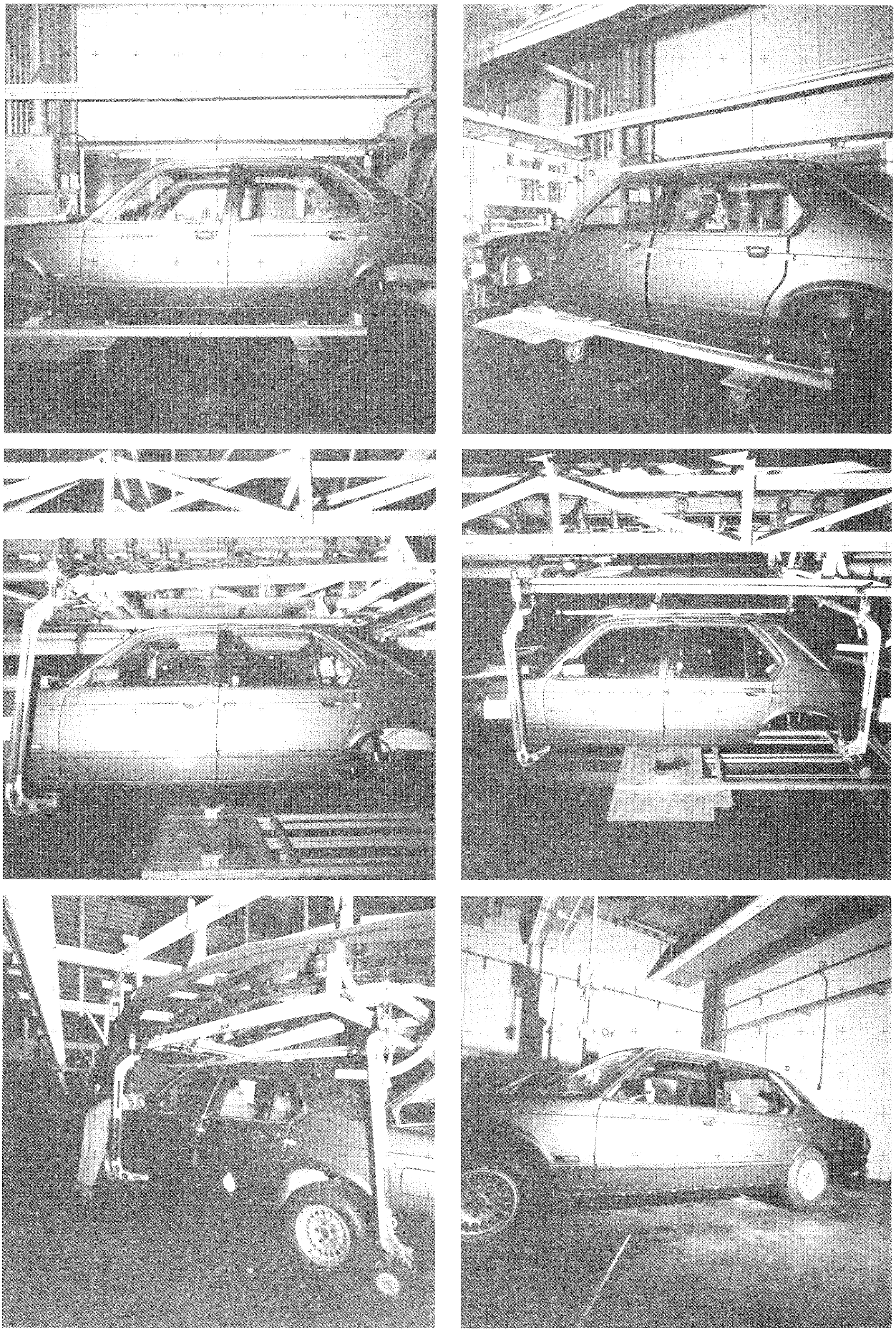


Fig. 1 Photographs of the four stations (epochs) along the assembly line

jacked up on a mobile mounting platform and subsequently hanged on a rigid suspension. Finally the car stands on the ground (Fig. 1). The points for picking up the load change during the assembling procedure. For this reason and due to the heavy weight of the components installed step by step the car-body is being deformed. The magnitude of movements should be determined with a standard deviation of $\sigma_{X,Y} < \pm\ 0.3$ mm and $\sigma_Z < \pm\ 0.5$ mm (Z-axis perpendicular to the investigated side of the car). Photogrammetry in this case is the best suitable method since a set of more than 50 targets has to be recorded simultaneously and the workers are not allowed to be disturbed under any circumstances. Four typical situations representing different deformation epochs during the mounting of one selected automobile (Fig. 1) are chosen for an investigation.

DATA ACQUISITION

While photographing in the assembly hall some difficulties occur, viz. the light conditions are unfavourable, the assembling of the automobile is carried out without any interruption, and the time for taking photographs from different exposure stations is limited. A camera system is required that presents simple operating facilities, light weight and a fast succession of photographs. A suitable metric camera covering the entire field of these specifications is not available. To fulfil all demands, the partial metric camera Rolleiflex SLX RESEAU (Wester-Ebbinghaus 1983) was used for the recording. This professional 60×60 mm^2 camera system had been modified for photogrammetric purposes by the installation of a rêseau-plate in front of the film (Fig. 2). The photo information can be transformed with the known coordinates of the 11×11 rêseau crosses in order to avoid systematic image errors due to film deformations.

The photogrammetric network design of an epoch is shown schematically in Fig. 4. According to the multi-station conception of bundle triangulation several convergent photographs are included. In addition, oblique images were taken at the central position required for camera calibration (Wester-Ebbinghaus 1986). The number of photographs varies (see Table 1) due to the specific conditions at the four selected stations along the assembly line. Because of the limited camera-to-object distances between two and four meters and the dimension of the car, the wide-angle lens Zeiss DISTAGON of 40 mm focal length was used in connection with the Rolleiflex SLX (Fig. 3). As an example, photographs of the four epochs obtained from different exposure stations and directions are presented in Fig. 1. More than 50 object points signalized by simple adhesive marks of eight or ten millimeters in diameter can be seen on the images.

As the car is moving constantly, a control field applicable for the different epochs cannot be established. The scale of the four photogrammetric networks is determined by a two meter subtense bar attached to the car roof shortly before photography. The absolute length of the subtense bar was calibrated with a standard deviation of ± 0.01 mm. According to the specifications of the car-manufacturer there are three of the signalized object points situated on the frame (Fig. 5) which can be considered as rather "stable". The deformation analysis has to check this assumption referring to the achieved precision.

Image coordinates were measured monoscopically in an analytical plotter Zeiss Planicomp C 100 and transformed meshwise (Kotowski 1984) into the rêseau plane.

DATA REDUCTION

The combined adjustment of photogrammetric and non-photogrammetric observations, i.e. in this case the image coordinates and the length of the subtense bar, was calculated with the program MOR (Wester-Ebbinghaus 1985). Gross error detection according to Baarda's data snooping is included. Due to the multi-station approach a minimum of five rays intersect, thus resulting in a precise and reliable point determination. Blunder detection has been performed with the error probabilities $\alpha = 0.001$

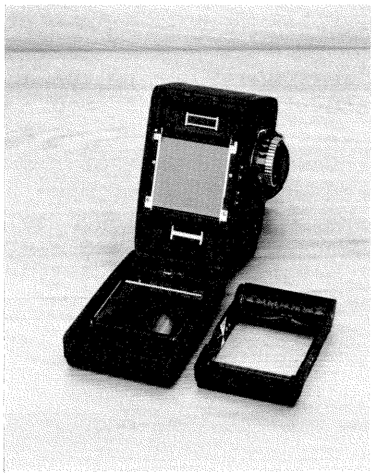


Fig. 2 Réseau-plate of the Rolleiflex SLX

Fig. 3 Rolleiflex SLX with 40 mm lens DISTAGON

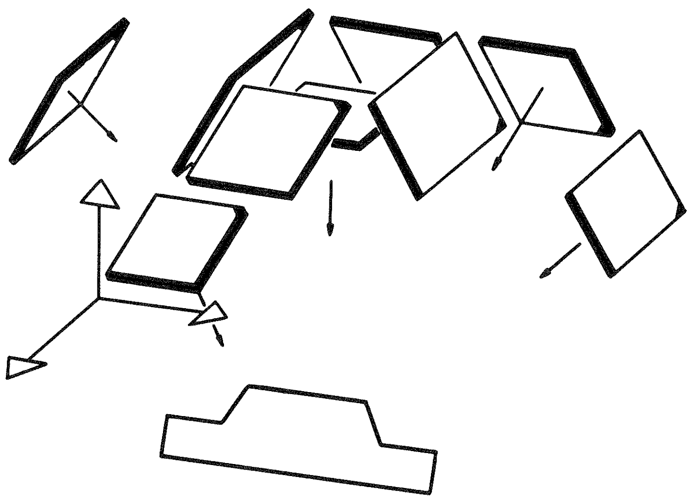


Fig. 4 Multi-station configuration for bundle adjustment

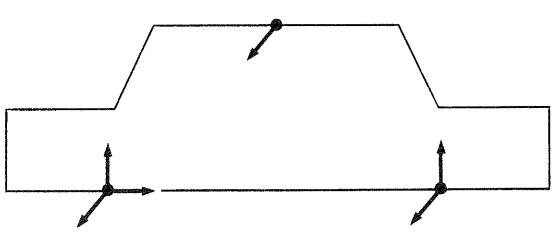


Fig. 5 Datum definition

and $\beta = 0.80$. Then the largest non-detectable gross error of the image coordinate measurement is of about 18 µm (internal reliability). This causes object point displacements of $\Delta X = 0.2$ mm, $\Delta Y = 0.1$ mm and $\Delta Z = 0.4$ mm (external reliability).

An accurate reconstruction of the photogrammetric bundles is only possible if the elements of the interior orientation of the camera are known. In order to define the object very precisely the pre-determined position of the perspective centre in image space is not sufficient. On-the-job calibration simultaneously with the calculation of the object point coordinates and the exterior orientation of the photographs yields the best possible solution. Hereby the self-calibration operates solely by means of photogrammetric information without any additional control point information. Using a partial metric camera the elements of interior orientation are "photo-invariant" for a series of images taken with a fixed camera body-lens-combination. Applied to this study the principal distance c, the coordinates x_0, y_0 of the principal point and the radial-symmetric distortion were computed (Peipe 1985). The comparison between the calibration results of the four epochs adjusted separately (Table 1) shows good agreement. This is a sign for the stability of the partial metric camera used.

Epoch/Station	1	2	3	4
Number of photographs	8	8	6	9
s_0 a post.	± 2.3 µm	± 2.5 µm	± 2.3 µm	± 2.4 µm
$c \pm s_c$	40.973 mm ± 0.009 mm	40.959 mm ± 0.008 mm	41.009 mm ± 0.013 mm	40.951 mm ± 0.008 mm
$x_0 \pm s_{x_0}$	-0.024 mm ± 0.007 mm	-0.028 mm ± 0.006 mm	-0.034 mm -	-0.034 mm ± 0.005 mm
$y_0 \pm s_{y_0}$	0.201 mm ± 0.008 mm	0.236 mm ± 0.007 mm	0.198 mm -	0.198 mm ± 0.006 mm

Table 1 Calibration parameters of the epochs (stations) 1-4 and their standard deviations

Epoch 3: x_0 and y_0 cannot be determined sufficiently accurate due to the lack of oblique photographs taken at the central exposure station. Hence the x_0, y_0 of Epoch 4 have been introduced in the adjustment of Epoch 3 as fixed.

The radial-symmetric distortion not mentioned in the table shows as good as the same values for the four calculations. The maximum difference amounts to 3 µm.

As explained, all object points are suspected to show deformations, and a control field could not be established in the assembly hall. In order to eliminate the rank defect of seven, the scale of the network is determined by the length of the subtense bar and in addition, six coordinates are introduced as fixed in the adjustment (Fig. 5). Thus a minimum constraints solution is performed. The chosen coordinates belong to the three points assumed "stable" by the car-manufacturer. The datum defined in this way remains the same for all epochs.

Finally, for each epoch a set of three-dimensional object point coordinates exists resulting from the independent bundle adjustments. The mean standard errors are $s_X = \pm 0.2$ mm, $s_Y = \pm 0.1$ mm and $s_Z = \pm 0.2$ mm . Thereby the required precision is achieved. The estimated object point coordinates, the cofactor matrix, the standard deviation of the weight unit and the degrees of freedom are transferred to the program DAPHNE for the deformation analysis.

DEFORMATION ANALYSIS

The main goal in deformation analysis is the separation of significant point displacements from those caused by measurement errors. Based on distributional assumptions on the observations (Gaussian Distribution) statistical methods are applied. The analysis is usually carried out as a set of two-epoch comparisons. The method used in this paper had been developed by Pelzer (1971 and 1974) and Niemeier (1976) based on variance-analytic methods using uni-variate test statistics. The procedure is adapted for the three-dimensional analysis and has been slightly modified concerning the treatment of the datum problem.

Data Preparation

The starting point of the analysis is as follows. The cluster of points under investigation had been determined in several epochs separately. The number of points and the design of point determination may differ in each epoch. The coordinates are estimated in a Gauss-Markov model as a minimum constraints solution as described in the previous chapter. Besides the parameter vector x_i , the cofactor matrix Q_{x_i} and the standard deviation of weight unit s_{0_i} are estimated with f_i degrees of freedom.

As a first step of analysis the variances of weight unit are to be checked for equality. The basis hypothesis for the following procedure

$$H_0 : E(s_{0_1}) = E(s_{0_2}) = \dots = E(s_{0_n}) = \sigma \tag{1}$$

is to be tested for example with Barlett's test (Sachs 1978). If H_0 is to be rejected the stochastic models of the epoch adjustments are to be modified and the adjustment procedure is to be repeated until the basis hypothesis cannot be rejected any more.

The set of points is devided in two groups. The first group contains all points which are assumed to keep stable during all epochs and the second group includes the points assumed to change their positions. For further preparation all estimated parameter vectors x_i are transformed in the same datum, which is defined by the approximate coordinates of the points in the first group using S-transformations

$$\bar{x}_i = S_i x_i \; ; \quad \bar{Q}_x = S_i Q_x S_i^T \tag{2}$$

with the transformation matrices

$$S = I - G(B_i^T G)^{-1} B_i^T \tag{3}$$

where G contains for each point a submatrix G_j such as

$$G_j = \begin{vmatrix} 1 & 0 & 0 & 0 & z & -y \\ 0 & 1 & 0 & -z & 0 & x \\ 0 & 0 & 1 & y & -x & 0 \end{vmatrix} \tag{4a}$$

if the rank deficiency of Q_x is six.

$$B_i = E_i G \tag{4b}$$

E_i is a pick-up matrix containing the number "one" in the correspondent diagonal element, if the parameter contributes to the datum, and "zero" else. For further details on S-transformations see van Mierlo (1980) and Illner (1983).

Global Congruency Test

In the following the procedure for a two epoch comparison is described. From the adjustments' results a difference vector d is computed from the S-transformed parameter vectors together with the corresponding cofactor matrix.

$$d = \bar{x}_2 - \bar{x}_1 \quad ; \quad Q_d = \bar{Q}_{x_1} + \bar{Q}_{x_2} \tag{5}$$

The variances of weight unit of both epochs are comprised if equàtion (1) is true

$$\bar{s}_0^2 = \frac{f_1\, s_{0_1} + f_2\, s_{0_2}}{f_1 + f_2} \quad ; \quad f_g = f_1 + f_2 \quad . \tag{6}$$

The difference vector is splitted up according to the two groups of points (assumed stable and remaining points).

$$d = \left[\begin{array}{c} d_F \\ \hline d_0 \end{array}\right] \qquad Q = \left[\begin{array}{c:c} Q_{FF} & Q_{F0} \\ \hline Q_{0F} & Q_{00} \end{array}\right] \tag{7}$$

In the next step of the analysis the hypothesis, that the points in the first group kept fixed, is tested. For this purpose the null hypothesis

$$H_0 \; : \; E(d_F) = 0 \tag{8}$$

is set up. Because of the stochastic independence of d_F and $\bar{s}_0^2$ an independent measure for the precision of the weight unit can be estimated from

$$\Theta^2 = \frac{d_F^T\, \bar{Q}_{FF}\, d_F}{h} \tag{9}$$

where h represents the rank of Q_{FF} . If H_0 is true the test statistic (Pelzer 1971)

$$F = \frac{\Theta^2}{\bar{s}_0^2} \tag{10}$$

follows a central Fisher distribution with h and f_g degrees of freedom which results in the relation

$$P\,\{F > F_{h,f,1-\alpha} | H_0\} = 1 - \alpha \tag{11}$$

where α denotes the chosen error probability of first kind. If the critical value of the F-distribution with h and f degrees of freedom is smaller than the test statistic F , the first group of points is congruent in both epochs with error probability α . The analysis is to be continued with the computation of the final displacements. Otherwise the set of points is not congruent and a localization procedure is required in order to detect those points which caused the failure of the global test.

Localization Procedure

In the case that the global congruency test indicates point displacements in the point group, which is assumed to keep stable, further investigations are necessary to isolate those points, which did not remain stable. The difference vector d_F is again splitted up together with the corresponding cofactor matrix in two subvectors

$$d_F = \begin{bmatrix} d_S \\ \hline d_B \end{bmatrix} \quad ; \qquad P_{FF} = \left[\begin{array}{c|c} P_{SS} & P_{SB} \\ \hline P_{BS} & P_{BB} \end{array}\right] = Q_{FF}^{-} \tag{12}$$

where d_B contains the elements of point j . The quadratic form $d_F^T\, P\, d_F$ is separated into two independent subforms

$$d_F^T\, P\, d_F = d_S^T\, \bar{P}_{SS}\, d_{SS} + \bar{d}_B^T\, P_{BB}\, \bar{d}_B^T \tag{13}$$

applying the transformations

$$\begin{aligned} \bar{d}_B &= d_B + P_{BB}^{-1}\, P_{BS}\, d_S \\ \bar{P}_{SS} &= P_{SS} - P_{SB}\, P_{BB}^{-1}\, P_{BS} \end{aligned} \tag{14}$$

where the second term of (13) represents the contribution of point j to the quadratic form $d_F^T\, P_{FF}\, d_F$. The decomposition of the quadratic form is carried out for each point. The point which corresponds to the greatest contribution of $d_F^T\, P_{FF}\, d_F$ is regarded as non stable and excluded for the further localization by replacing d_F by d_S and P_{FF} by $\bar{P}_{SS}$. A new global congruency test is carried out based on

$$\Theta^2 = \frac{d_S^T\, \bar{P}_{SS}\, d_S}{h - m} \tag{15}$$

where m denotes the number of coordinates per point. If the test fails again a new localization step is required. The procedure is to be repeated until no further displacements are indicated.

Treatment of Object Points

Now the whole set of points is finally separated in a set of stable points and a set of remaining points.

$$d = \begin{bmatrix} d_F \\ \hline d_0 \end{bmatrix} \quad ; \qquad Q_d = \left[\begin{array}{c|c} Q_{FF} & Q_{F0} \\ \hline Q_{0F} & Q_{00} \end{array}\right] \quad ; \qquad P_d = Q_d^{-} \tag{16}$$

The difference vector is to be transformed in a new datum, which is defined by the stable points only. The final displacements are then obtained by

$$\bar{d}_0 = d_0 + Q_{00}\, P_{0F}\, d_F \tag{17}$$

with cofactor matrix Q_{00} . The vector $\bar{d}_0$ is called deformation vector and the result of the analysis. Finally the components of this vector are to be tested for significance. The components are pointwise splitted up in subvectors d_j with the corresponding cofactor matrices Q_j . The quadratic forms

$$\Theta_j^2 = \frac{d_j^T\, Q_j^{-1}\, d_j}{m} \tag{18}$$

are again measures for the precision of weight unit if the corresponding point did not change its position, i.e. if

$$H_0 : E(d_j) = 0 \tag{19}$$

is true. The test statistics

$$F_j = \frac{\Theta_j^2}{\bar{s}_0^2} \tag{20}$$

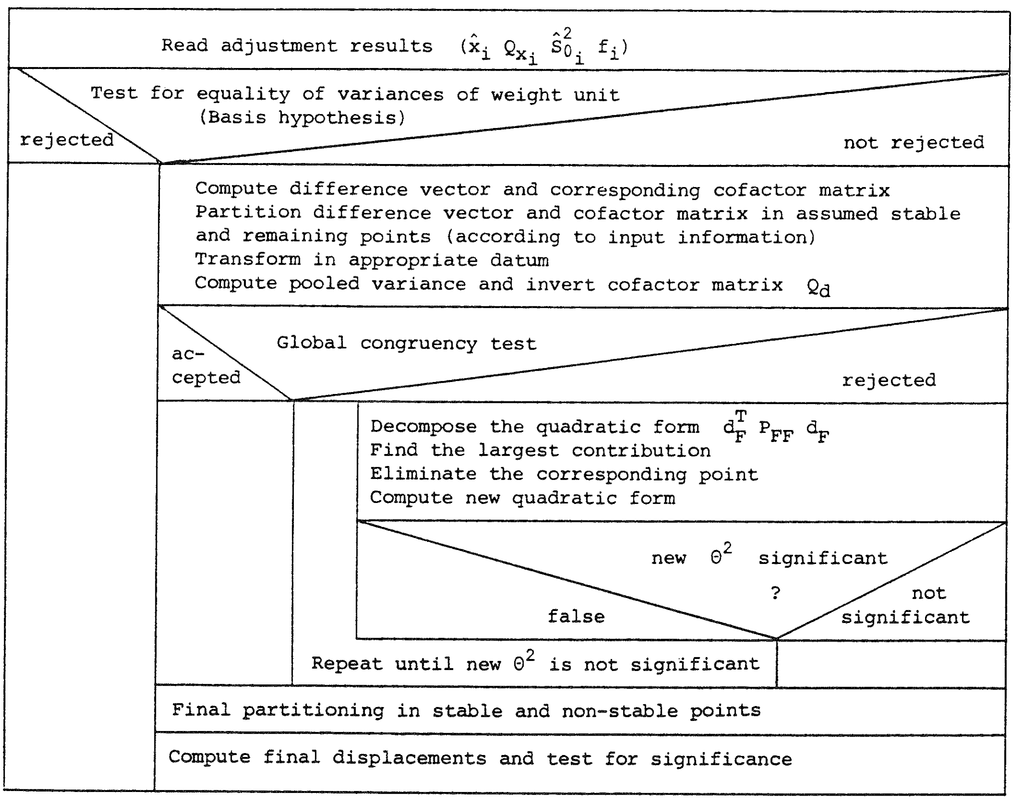
follows a central F-distribution with m and f_g degrees of freedom. The probability relation

$$P\{F_j > F_{m,f_g,1-\bar{\alpha}} | H_0\} = 1 - \alpha \qquad \bar{\alpha} \approx \frac{\alpha}{n} \tag{21}$$

holds exactly if no correlations between the points occur. Of course, this assumption is not satisfied in most cases. Therefore, this strategy is not strong but a quite good approximation.

THE PROGRAM DAPHNE

In order to perform practical analyses the software package DAPHNE (Deformation Analysis for Photogrammetric Networks) has been developed and tested. The program has been implemented on the Burroughs B 7800 machine of the computing centre of the University FAF Munich. In the present state DAPHNE enables the strong three-dimensional deformation analysis of networks up to 50 - 70 points. Input data are, for example, the results of a bundle adjustment. The program transforms the estimated parameter vectors and the corresponding cofactor-matrices in an appropriate datum and realizes the testing procedure according to the following graph.



CONCLUSIONS

Close-range photogrammetry is a very useful tool for high-quality deformation measurements. The combination of the partial metric camera technique, the multi-station configuration of photographs and the self-calibrating bundle adjustment including all available photogrammetric and non-photogrammetric information results in a precise and reliable point determination. The calculation of spatial coordinates of signalized points on an automobile served as an example to demonstrate the efficiency of the procedure even under unfavourable conditions during the assembly of the car. Deformation monitoring is possible by comparing the estimated coordinates of different epochs. The developed program package DAPHNE allows a rigorous deformation analysis based on variance-analytic methods. The procedure results in a verified set of points which kept stable. This set is used as the basis for the computation of the deformations of all other points, which are finally tested for significance.

REFERENCES

Bill, R., 1985: Automatische Meß- und Berechnungssysteme für den Industriebereich. Allgemeine Vermessungs-Nachrichten 92, 205-210.

Buck, U., 1977: Numerische Auswertung und statistische Analyse von ingenieur-photogrammetrischen Deformationsmessungen. Dissertation Hannover.

Cooper, M.A.R., 1984: Deformation Measurement by Photogrammetry. Phot. Record 11(63), 291-301.

Ebner, H., 1984: Combined Adjustment of Photogrammetric and Non-Photogrammetric Information. XV. ISPRS-Congress, Commission III, Rio de Janeiro.

Fraser, C.S., Brown, D.C., 1986: Industrial Photogrammetry: New Developments and Recent Applications. Phot. Record (in press).

Fraser, C.S., Gründig, L., 1985: The Analysis of Photogrammetric Deformation Measurements on Turtle Mountain. Phot. Engineering & Remote Sensing 51, 207-216.

Illner, I., 1983: Freie Netze und S-Transformation. Allgemeine Vermessungs-Nachrichten 90, 157-170.

Kotowski, R., 1984: Zur Rêseaukorrektur von systematischen Bildfehlern. Bildmessung und Luftbildwesen 52, 96-101.

van Mierlo, J., 1980: Free Network Adjustment and S-Transformation. Deutsche Geod. Kommission, Reihe B, Nr. 252, 41-54, München.

Niemeier, W., 1976: Grundprinzip und Rechenformeln einer strengen Analyse geodätischer Deformationsmessungen. VII. Int. Kurs für Ingenieurvermessungen hoher Präzision, Band II, 465-482, Darmstadt.

Peipe, J., 1985: Simultankalibrierung einer Teil-Meßkammer - Ein Anwendungsbeispiel aus dem Fahrzeugbau. Deutsche Geod. Kommission, Reihe B, Nr. 275, 152-158, München.

Pelzer, H., 1971: Zur Analyse geodätischer Deformationsmessungen. Deutsche Geod. Kommission, Reihe C, Nr. 164, München.

Pelzer, H., 1974: Neuere Ergebnisse bei der statistischen Analyse von Deformationsmessungen. XIV Int. Kongreß der Vermessungsingenieure, Invited Paper No. 608.3.

Sachs, L., 1978: Angewandte Statistik. Springer-Verlag Berlin-Heidelberg-New York.

Torlegård, K., 1981: Development of Non-Topographic Photogrammetry and its Future. Finnish Society of Photogrammetry 1931-1981, Anniversary Publication.

Wester-Ebbinghaus, W., 1983: Ein photogrammetrisches System für Sonderanwendungen. Bildmessung und Luftbildwesen 51, 118-128.

Wester-Ebbinghaus, W., 1985: Bündeltriangulation mit gemeinsamer Ausgleichung photogrammetrischer und geodätischer Beobachtungen. Zeitschrift für Vermessungswesen 110, 101-111.

Wester-Ebbinghaus, W., 1986 : Analytische Kammerkalibrierung. ISPRS-Symposium, Commission V, Ottawa.

Wester-Ebbinghaus, W., Wezel, U.E., 1985: Photogrammetrische Vermessung von Crashfahrzeugen. Automobil-Industrie 30, 49-53.

Zinndorf, S., 1985: Kalibrierung eines terrestrischen Meßkammer-Systems am Beispiel der Aufnahme einer Kirche im Bergsenkungsgebiet. Deutsche Geod. Kommission, Reihe B, Nr. 275, 142-146, München.