HIGH PRECISION CALIBRATION OF CLOSE RANGE PHOTOGRAMMETRY SYSTEMS

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ABSTRACT

This paper deals with investigations on test field calibration of close range photogrammetric systems for high precision industrial applications, with emphasize on the use of stereo vision systems of 2 or 3 cameras. The initial investigations are based on simulation studies: The influence of different parameters on the accuracy of the calibration are investigated i.e. the number and configuration of signalized object points, the object control of given points or given distances, the number and configuration of exposure stations, and the type of camera parameters. Finally, the result of a practical investigation on the calibration of a digital photogrammetric system on the basis of given distances in object space is reported.

KEY WORDS: Accuracy. Calibration. Close-range. Photogrammetry.

1. INTRODUCTION

Traditionally, the objective of calibration is to estimate those parameters in the photogrammetric system which can be considered as "constants" in later photogrammetric measurement tasks. The parameters of the photogrammetric system (the functional relationhip between image points (x,y) and object points (X,Y,Z)) are primarily those of inner and outer orientation describing the fundamental model: the central perspective, and secondly additional parameters which describe the deviations from this model. These deviations (model errors) can conveniently be mathematically formulated as systematic image errors, on the basis of a physical approach or a numerical/statistical approach. The systematic image errors are often considered as belonging to the concept of "inner orientation" in a wider definition of this concept. It should be mentioned that when using analog cameras the inner orientation has to be restored for every picture, on the basis of fiducial marks. Such a restoration is not necessary when using digital cameras, as it can be assumed that the position of the pixels in the image system retain their positions from exposure to exposure. In some cases the calibration may also include the outer orientation, as for instance when a permanently mounted unit of cameras is used for a consecutive dimensional control of constructions in a workshop hall. Considering a stereo vision system as a unit of cameras which have a fixed relative orientation (relative camera rotations and positions), this orientation is also subject to calibration.

The simulation approach has generally become very popular to guide the surveyer in network design. Within close-range photogrammetry simulation studies of the factors influencing the accuracy and reliability are reported, together with results of verifying the conclusions on applications. (Fraser, 1989 and Schlögenhofer, 1989).

The primary objective of this paper is on the basis of simulation to investigate some factors which influence the accuracy of test field calibration. Such factors may be the configuration of object points and camera orientations, inner orientation including systematic errors (local or global), and the object control (given points and distances). As a measure on the accuracy of the calibration the relative accuracy of estimated unknown distances in representative positions and directions within the test field is given. (The variance/ covariances of the etimated calibration parameters might also have been used). The simulated cases are rather restricted; further investigations are therefor highly desirable. At the end real results of calibrating a high precision digital photogrammetric system are reported. However, first some aspects of precalibration are discussed.

2. PRECALIBRATION METHODS

There are two main approaches to precalibration: Optical calibration and Test field calibration. (Freyer, 1989). As the simulation in this paper deals mainly with test field calibration, the optical calibration is briefly discussed.

2.1 Optical calibration

Optical calibration uses optical means for a thorough laboratory test of the physical and mechanical function of the camera and its geometrical quality, including a high precision estimation of the inner orientation parameters, radial lens distortion (often in the 4 diagonal directions) and sometimes also decentering. (See e.g. Burner, 1990). For analog cameras, the calibrated coordinates of fiducial marks serve as a means for restoring the calibration image system (where the principle point is defined) in later photogrammetric measurment tasks. In principle a transformation on the fiducial marks by translation and rotatation should suffice. A more sophisticated transfomation may, however, model physical sources of errors (like film shrinkage) which have been active between the exposure and the measurement of the image.

2.2 Test field calibration

The actual calibration parameters are estimated on the basis of measuring pictures taken of a test field. The dependence of principle distance, radial distortion and decentering on the focussing (which in turn is dependent on the distance between the object and the exposure station) may also be subject to calibration, (Freyer, 1989). The calibration conditions (temperature, illumination, ..) should be as possible similar to those expected in later photogrammetric tasks. The disadvantage of test field calibration is the large quantity of work involved: A stable 3-dimemsional steel frame with e.g. retro-reflex targets must be built, and next a control must be established. The control may be given points (X,Y,Z) in some chosen object system and/or given distances between some of the targeted points. Given distances may also be introduced by placing bars with targeted points (which are the endpoints of the given distances) in favourable positions and directions within the actual object space. The control may be established by high precision geodetic methods. The control of a test field for calibrating digital cameras of moderate accuracy may, however, be photogrammetrically established using high precision metric analog cameras (Åmdal et al, 1990). Equivalent to the use of a 3-dimensional frame is the use of a 2-dimensional frame which can be positioned paralell to itself (Beyer, 1987).

Because test field calibration involves much work, and also because unwanted instabilty in the calibration parameters may occur, one may rather prefer the approach of self-calibration i.e introducing the calibration parameters as unknowns in the system of the actual photogrammetric measurement task. However, this approach may require some particular care in deciding upon the optimal number and type of additional parameters, and statistical tests of their estimates should be used to avoid overparameterization (Grün, 1978). The following simulation may be relevant also to the self-calibration approach, as the test field can rather be considered as an actual object to be measured.

One may differentiate between two main forms of object control: a) given object points only, and b) given distances only. In practice it may be more relevant to use a combination of a) and b).

2.2.1 Test field with given points only With all the signalized object points given, a single-image-calibration of the camera is possible. It is, however, advisable to take several pictures, preferably with different κ-rotations, to obtain a better accuracy in estimating the calibration parameters. At least two exposure stations at different distances to the test field are required if the influence of the focussing is to be calibrated.

It is important to obtain an even distribution of the imaged points in the image plane so that the calibration result becomes representative for the whole image. Uneven distribution may give rise to strong correlation between calibrated parameters. For instance, a clustering of image points outside the central part of the picture area may introduce a strong correlation between estimated radial distortion and the estimated principle point. Correlation may also reflect the algebraic formulation of systematic image errors. (For example, the correlation coefficient between the radial distortion parameters f_1 and f_2 in eq.s (A1) in the Appendix is about -0.97). Strong correlation between the estimated parameters may give rise to slow convergence of the numerical solution and complicate the statistical testing of additional parameters. For the determination of the inner orientation (x_0,y_0,c) a favorable space distribution of the object points is of importance.

2.2.2 Testfield with given distances only The configuration of the exposure stations and the direction of the camera axes must be carefully considered to obtain favourable intersections of rays in the measured unknown object points and a favourable distribution of the imaged points in the image planes. For instance, one may use 3 exposure stations in a triangle configuration with convergent camera axes directed towards the centre of the test field. A practical problem might be to mount the targets in such a way that they are well visible from all the exposure stations. Another problem might be the establishment of the control of given distances. Those distances have to be measured with sufficient precision (i.e. with standard error in the order of 0.01 mm) and distributed within the actual object space in a favourable configuration regarding both position and direction. It might be an advantage if the distances could be measured between targets mounted on suitable reference bars which may be freely placed anywhere in the object space.

It might be a further advantage if one could use only these bars and thus avoid entirely the use of any rigid frame. The unknown targeted bar points (which provide intersection conditions), and the given distances (which provide additional constraints) may namely provide a sufficient basis for estimating the calibration parameters with the required precision. This approach may be easily adapted to the calibration of a stereo vision system of digital cameras: A single bar with targeted endpoints of given distances is placed in different prescribed positions and directions, and exposed in one and the same set of stereo pictures.

When a stereo vision system generates several sets of synchronized pictures of the test field, it may be assumed that the relative orientation of the cameras is retained from set to set. The additional constraints based on this assumption are given by eq.s (A2) in the Appendix). Free bundle adjustment may be used (Haggren, 1990).

A stereo vision system may consist of cameras with individually different sets of camera parameters. The assumption of local (instead of global) camera parameters requires carefully planning of the geometry, in particular when using the approach of given distances only, to avoid ill-conditioning. The following simulation may illustrate this.

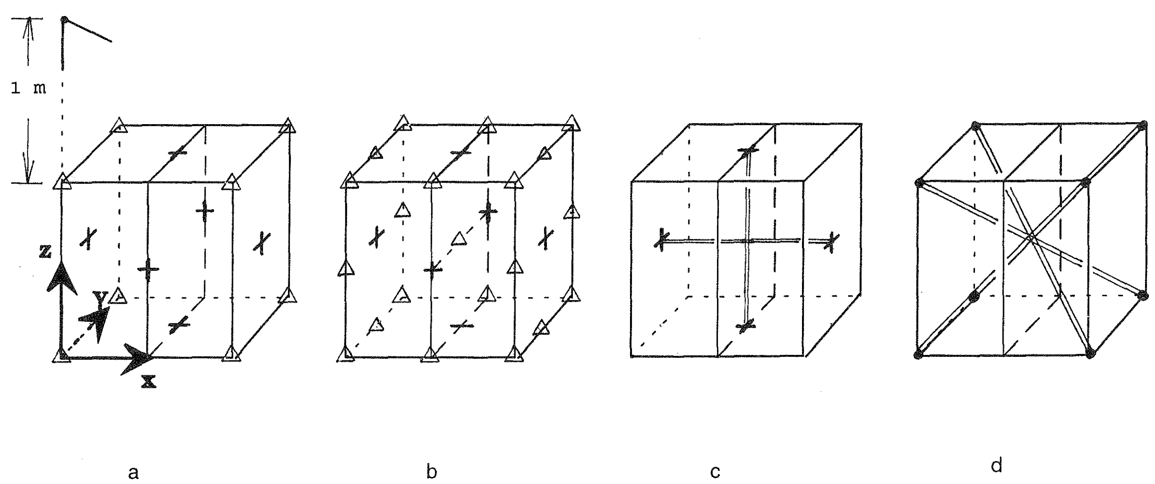

Fig. 1 a: test field of 14 points; b: test field of 27 points; c: distances to be estimated; d: 4 space diagonal distances which may be given.
△: object points which may be given
+: object points which are unknowns in all cases.

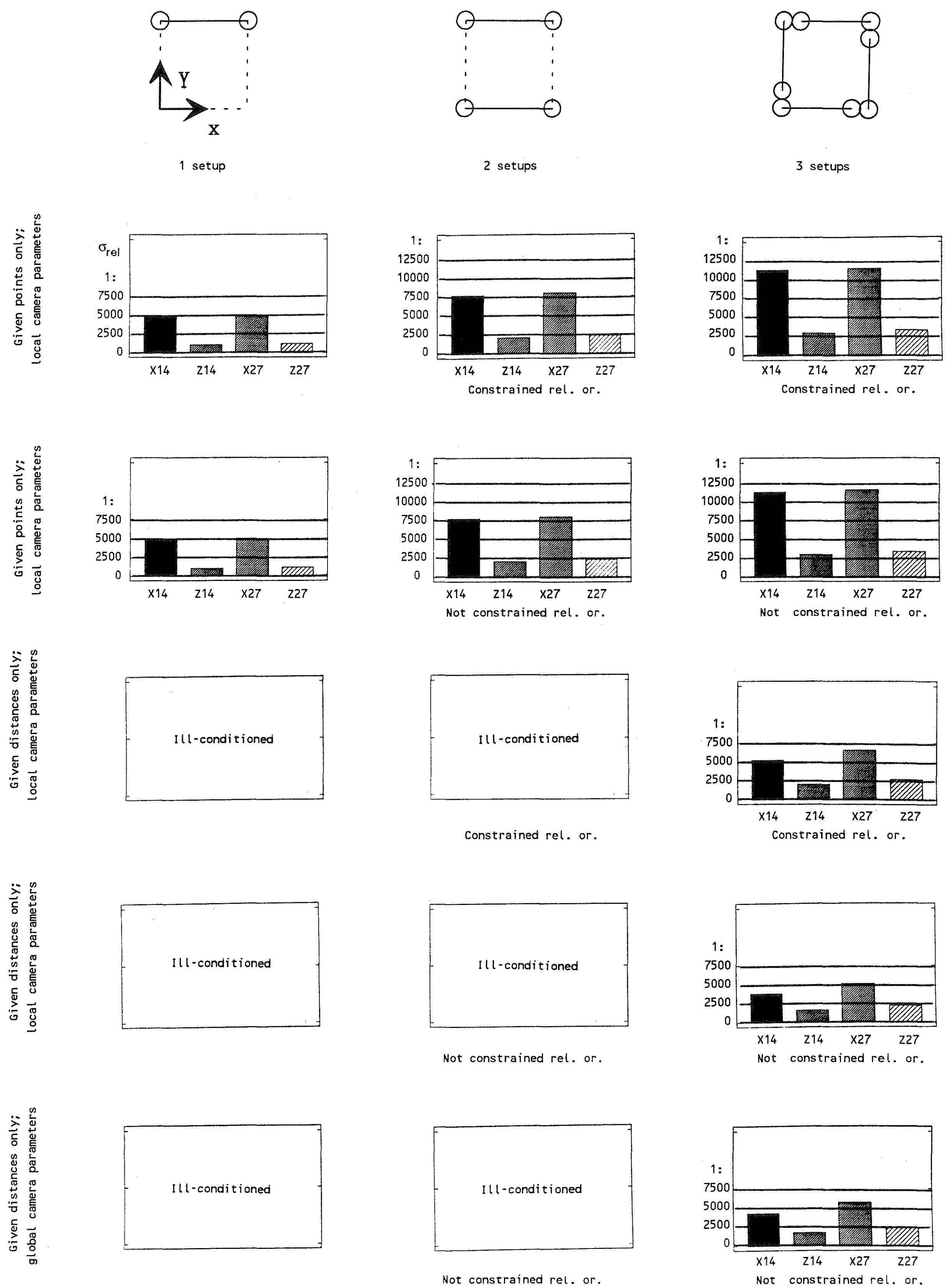

Fig. 2 2-camera setups. Each graph shows for 14 and 27 points' testfields (fig.s 1a and 1b) the relative standard error σ_{rel} for estimated distances (fig. 1c) in X- (or Y-) and Z-direction (bars X14,Z14,X27,Z27). $\sigma_{0\ (image\ coordinate)}$ = 0.1 pixel is assumed.

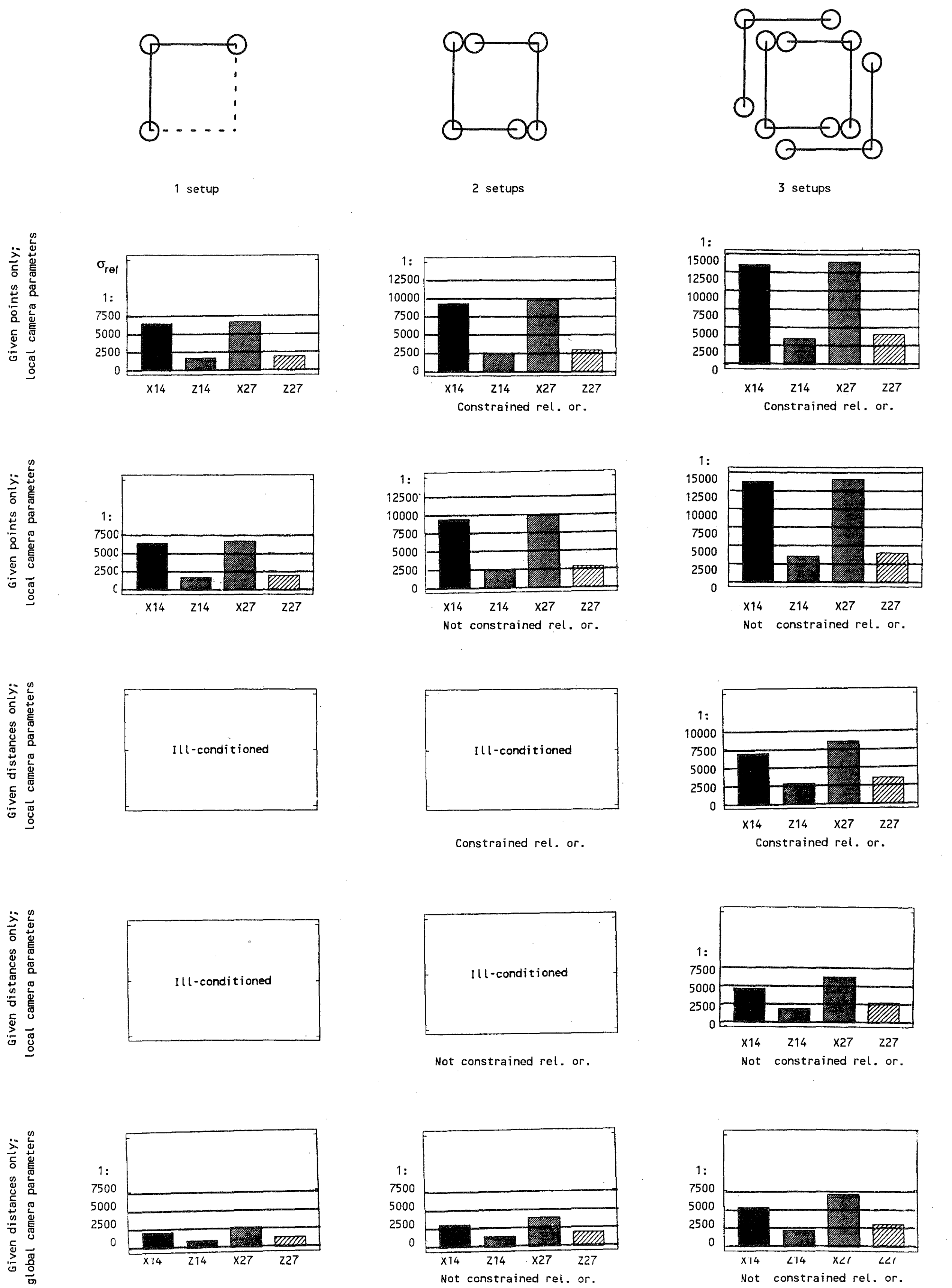

Fig. 3 3-camera setups. Each graph shows for 14 and 27 points' testfields (fig.s 1a and 1b) the relative standard error σ_{rel} for estimated distances (fig. 1c) in X- (or Y-) and Z-direction (bars X14,Z14,X27,Z27). $\sigma_{0\ (image\ coordinate)}$ = 0.1 pixel is assumed.

3 SIMULATION

3.1 Assumptions

The simulation assumes that a setup of 2, alternatively 3 cameras is placed in alternatively 1, 2 and 4 positions 1m above a test field (volume: 1x1x1 m^3) with camera axes directed towards the centre of the field, see fig. 1. (Principle distance =1800 pixels, image format: 1000x1000 pixels). Thus a near normal configuration is the case. The result is derived by bundle adjustment (Hådem, 1989) and shown in fig.s 2 and 3.

Two alternative configurations of object points are assumed, as illustrated by fig.s 1a and 1b.

Two alternatives of object control are assumed:

- "given points only": the object points are given except the 6 endpoints of distances fig.1c (i.e. the testfields fig.s 1a and 1b get 8 and 21 given points, respectively);
- "given distances only": the distances fig.1d are given (i.e. all the object points are unknowns).

Two alternatives mentioned as constrained and not constrained relative orientation, are assumed (for those cases where the setup of cameras have been placed in several positions):

- constrained relative orientation: It is assumed that the 2 (3) cameras of a setup retain their relative orientation when the setup is moved to another position to taking a new set of pictures;
- not constrained relative orientation: No such assumption.

5 unknown camera parameters are assumed: those of inner orientation (x_0,y_0,c), affinity and lack of orthogonality (see eq.s (A1) in the Appendix). In fig.s 2 and 3, these parameters are assumed to be different from camera to camera, except for the lower row where it is assumed that they are global.

3.2 Summary and conclusions

On the basis of the graphs in fig.s 2 and 3, a summary and some concluding comments will be given. In the following, $\sigma_{rel}(..)$ indicates the mean of actual σ_{rel} taken from the graphs. The results 1) - 5) assume local camera parameters.

1) The ratio $\sigma_{rel\ (in\ X-\ or\ Y-direction)}/\sigma_{rel\ (in\ Z-direction)}$ is:
0.27 in the "given points only" cases,
0.42 in the "given distances only" cases
showing that the accuracy of distances in different directions is rather inhomogenous.

2) The ratio $\sigma_{rel\ (given\ points\ only)}/\sigma_{rel\ (given\ distances\ only)}$ is:
0.55
showing that the geometry in the "given distances only" cases is far from being optimal.

3) The ratio $\sigma_{rel\ (27\ object\ points)}/\sigma_{rel\ (14\ object\ points)}$ is:
0.76 in the "given points only" cases
0.92 in the "given distances only" cases

4) The ratio $\sigma_{rel\ (constr.\ rel.\ or.)}/\sigma_{rel\ (not\ constr.\ rel.\ or.)}$ is:
0.99 in the "given points only" cases,
0.74 in the "given distances only" cases.
The effect of constraints is more significant in the "given distances only" cases, recalling that these cases have a less optimal geometry.

5) The ratio $\sigma_{rel\ (setup\ of\ 3\ cameras)}/\sigma_{rel\ (setup\ of\ 2\ cameras)}$ is:
0.81

6) The ratio $\sigma_{rel\ (global\ camera\ par.)}/\sigma_{rel\ (local\ camera\ par.)}$ is:
0.87 in the "given distances only" cases.

7) When global (instead of local) camera parameters are assumed, there is less frequent ill-conditioning.

The main conclusions are:

1) The use of a) constrained relative orientation, b) more than 2 cameras in a setup, and c) different positions and rotations of the setup strengthens the geometry.
2) The use of given distances (in stead of given points) requires careful geometrical considerations of their placement in object space.
3) The assumption of local (in stead of global) camera parameters weakens the geometry and decreases the relative accuracy.
4) "The near normal case" gives inhomogenous relative accuracy.

Although many interesting simulation results have been obtained so far, there are still many questions left. Thus, it is desirable to perform further investigations on the use of:

- other camera orientations (position and convergence) to get better intersection conditions,
- other configurations of given distances (position and direction),
- a larger number of object points for different cases of type of control (points and distances),
- other types of additional parameters (like global or local radial distortion and decentering).
- constraining precalibrated relative positions of targeted points on reference bar,
- constraining geometrical information (e.g. linearity, see Zielinski, 1992); geometrical figures may be placed in different positions in the object space.

Such investigations should be followed up by real experiments.

4 EXPERIMENTAL ACCURACY RESULTS FOR A PHOTOGRAMMETRIC STATION.

To indicate the accuracy potential of a high precision calibrated photogrammetry system, some of the results from an accuracy test of the Metrology Norway System (MNS see Pettersen, 1992a and 1992b, Åmdal, 1992, and Axelsson, 1992) is reported. The MNS is an on-line photogrammetry system based on high resolution CCD cameras (Kodak Megaplus with 12.5 mm lens) interfaced to a VME computer, measuring coordinates of laser spots or Light Emitting Diodes (LEDs). Using the Light Pen (see Pettersen, 1992b) turns the system into a "Hand-Held Coordinate Measuring Machine" (CMM), allowing the use of standard CMM accuracy tests for evaluating the accuracy of the MNS. The CCD cameras in the MNS are laboratory calibrated by Metronor AS, employing an optical calibration method which differs from the test field approach studied in the simulations. This one time calibration process, which involves measuring more than 10 million calibration points for each camera, turns the high resolution CCD camera into a photogrammetric camera.

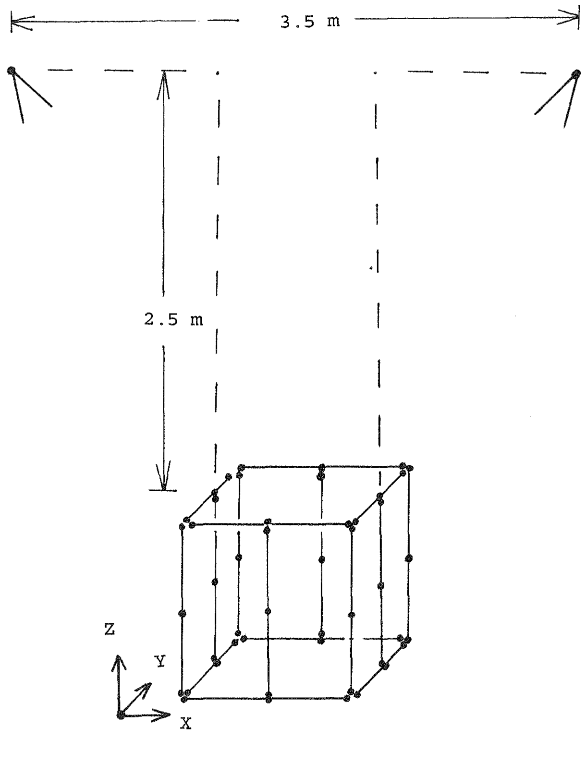

Fig. 4 Placements of reference bar on test volume; camera setup
• : targeted points.

4.1 Calibration of the relative orientation and scale for distance measurements

When the system is set up, a moveable (hand-held) reference bar equipped with 3 LEDs is placed in 16 predetermined positions and orientations, enclosing the test measurement volume of 1x1x1 m^3 (see fig. 4). The distances between the target points (LEDs) are precalibrated with an accuracy of better than 5.0 microns (2 x sigma level). For each reference bar position, the observed sensor coordinates of the targets are recorded for each camera. Sensor coordinate observations are subsequently put into the setup adjustment, which is a free network bundle adjustment only constraining the given distances on the reference bar.

A simple accuracy check follows the setup adjustment. For each reference bar position of the setup measurements, the 3D coordinates of the target points on the reference bar are calculated by intersection, employing the orientation parameters found in the setup adjustment. The distances between the intersected target points are compared with their nominal values. Based on the found differences (errors), a distance measurement accuracy can be estimated as RMSqE. For the test measurement volume (1x1x1 m^3), this distance measurement accuracy is found to be better than 0.10 mm (2 x sigma level).

4.2 Volvo/Renalult test

In April 1991 and March 1992, extensive accuracy evaluations were carried out by Volvo Car Corporation. The test procedure conforms to the relevant parts of the German VDI-VDE norm, (see GMA, 1986) for accuracy evaluation of CMM's. In the tests, a dual-camera system was set up to give a measurement volume of 1x1x1 m^3 with a camera configuration approximately as showed in fig. 4. The most important results were (given as U95 i.e. 2 x sigma level):

- Repeatability of Light Pen measurements better than:
  In the depth direction, Z : 0.08 mm
  In the X or Y direction : 0.02 mm

- Diagonal bar length measurement. Distances along all 4 spatial diagonals are compared to nominal values using a high precision step block gauge (see GMA, 1986). The Light Pen is used for the length measurements. Total bar length is 1000 mm:
  Uncertainty of measurement (GMA, 1986) : 0.12 mm

The repeatability numbers are mean values for the total measurement volume. Uncertainty of measurement is defined in (GMA, 1986), and includes both statistical spread of single measurements at both ends of the bar, as well as systematic errors. Early experiments with a modified Light Pen having more optimal geometry, indicates even better repeatability. The standard deviations on estimated distances that is found in the simulation studies, can not be directly compared to the experimental U95 uncertainty of measurements. The accuracy characteristics of MNS is described in more detail in (Pettersen, 1992).

APPENDIX. Constrained relative orientation

We will give the formulas for bundle adjustment assuming that the cameras of the stereo vision system retain their relative orientation when taking several sets of pictures.

The collinearity conditions are (see e.g. Freyer, 1989):

$$x - x_o + dx = -c \frac{(X-X_0)a_{11}+(Y-Y_0)a_{12}+(Z-Z_0)a_{13}}{(X-X_0)a_{31}+(Y-Y_0)a_{32}+(Z-Z_0)a_{33}}$$

$$y - y_o + dy = -c \frac{(X-X_0)a_{21}+(Y-Y_0)a_{22}+(Z-Z_0)a_{23}}{(X-X_0)a_{31}+(Y-Y_0)a_{32}+(Z-Z_0)a_{33}} \qquad A(1)$$

c, x_o, y_o: principle distance and principle image point
X,Y,Z: object point
X_0, Y_0, Y_0: exposure station
x,y: image point
a_{ij}: element of a rotation matrix R
$dx = -x'b_1+y'b_2+x'dr/r+p_1(r^2+2x'^2)+2p_2x'y'$
$dy = y'b_1+x'b_2+y'dr/r+p_2(r^2+2y'^2)+2p_1x'y'$
$dr/r = f_1(r^2-r_o^2)+f_2(r^4-r_o^4)+f_3(r^6-r_o^6)$
$r^2 = x'^2+y'^2$
$x' = x-x_o$
$y' = y-y_o$
r_o: zero-radius
b_1, b_2: affinity and lack of orthogonality
f_1, f_2, f_3: radial distortion
p_1, p_2: decentering

Let us consider a vision system of n cameras by which k sets of pictures are taken, and denote the rotations and exposure stations of those pictures in the global system (X,Y,Z) as:

$$(R_{\alpha\beta\gamma}, X_0, Y_0, Z_0)_{ij}; \quad i=1..\,n; \quad j=1..\,k$$

Let us further introduce a local object system (X',Y',Z') identical to the image system of one camera (say camera number 1), and denote the rotations and exposure stations of the n-1 residual cameras in this local system as:

$$(R_{\alpha'\beta'\gamma'}, X'_0, Y'_0, Z'_0)_i; \quad i = 2..\,n$$

The additional constraints are then:

$$\left.\begin{array}{l}(R_{\alpha'\beta'\gamma'})_i = (R_{\alpha\beta\gamma})^T_{1J} \cdot (R_{\alpha\beta\gamma})_{iJ} \\ (X_0', Y_0', Z_0')_i^T = (R_{\alpha\beta\gamma})_{1j} \cdot (X_{0i}-X_{01}, Y_{0i}-Y_{01}, Z_{0i}-Z_{01})^T_J\end{array}\right\} i=2..n;\ j=1..k \quad (A2)$$

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