AN AUTOMATED 3D MOTION ANALYSIS SYSTEM FOR DIGITIZED HIGH SPEED FILM

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ABSTRACT

A 3D motion analysis module was developed for an existing 2D high speed system. A high level of automatization is required, as is a user interface for non-specialists in photogrammetry. A short and fast dynamic process is recorded with high speed photographing using two or more film cameras, and the film is digitized in a film scanner. After point identification in the first image the points are automatically tracked, measured and analyzed in the rest of the film sequence. A high flexibility ensures the system to handle different situations concerning target calibration, self calibration using bundle adjustment and point determination depending on the environment and point configuration. A commercial implementation for the car industry is demonstrated.

Key words: 3D, tracking, high speed, motion analysis, calibration, bundle adjustment

1. BACKGROUND

A high speed 2D motion analysis system was to be extended with a 3D module for a more general and accurate evaluation motion in fast dynamic processes. The existing system, TrackEye (Product information), is a general motion analysis system with high flexibility concerning the image input. The 3D module was of special interest for high speed digitized film sequences of car crashes in controlled environments. A typical example is a car crashing against a wall, fig 1, or studies of the effect on the human body, fig 2.

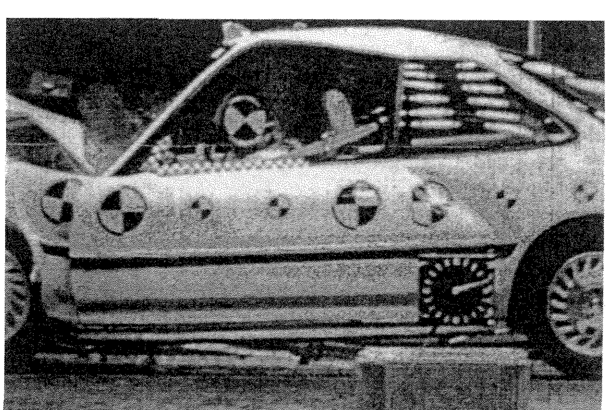

fig 1 Controlled car crash

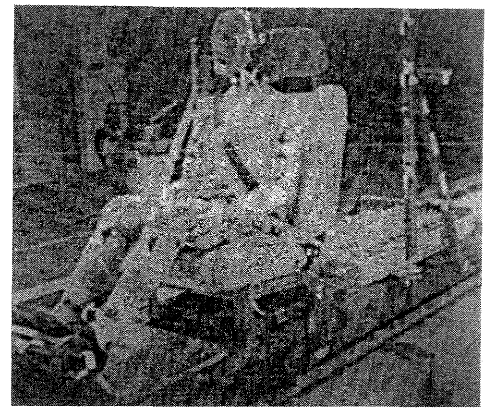

fig 2 Sledge for studies of the effect on the body

A system for 3D calculations from measurements in high speed films will be encountered with several problems not found in more traditional photogrammetry. These problem will be of different types, ranging from a different kind of camera geometry to the large amount of data in movement analysis. The system must also be highly automated to be able to run in an industrial environment with as few as possible interactions with an operator. In the discussed system the automation level is set at a very high level during the whole process, starting with automated measurements in the digitized image, calibration of various types, bundle adjustment with self calibration and 3D calculations of object points.

2. THE EXISTING SYSTEM

The Video and Cine Film Analysis system, TrackEye, is an fully interactive system, menu driven and with a high level of automation of the process if wanted, fig 3. The system is PC controlled with a special hard ware unit for the image handling and processing. A film scanner is used for converting the high speed film to digital images.

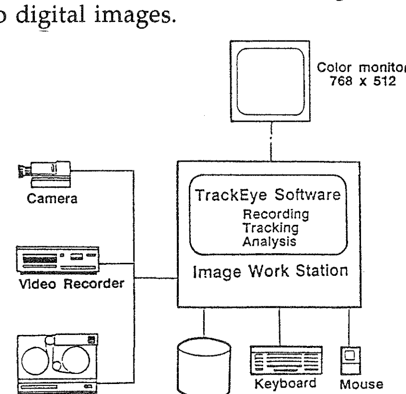

fig 3 TrackEye motion analysis system

The software of the system consists of three main parts:

Recording
Tracking
Analysis

2.1 Recording

The recording transfers a sequence if images from an external source to the internal Video Disc of the TrackEye system. A video disc file can be generated using three different sources:

Standard video sources from a video or a video tape recorder.

Film scanner for 16 mm cine film

Selected copies or sequences from earlier recorded video disc files.

2.2 Tracking

The tracking is automatic with manual supervision and is able to follow 95 objects simultaneously. The points are defined by the user in the first image by positioning a cursor on the point of interest. Interactive tools for zooming, backtracking, motion view survey etc. are provided. The manual supervision can be used in several ways depending on the complexity of the sequence, from manual marking with position proposal to fully automatic tracking with an error list indicating the uncertain areas in the sequence. The tracking algorithm uses a modified correlation technique and

2.3 Analysis

Point positions from the tracking session are used to perform calculations of distance, velocity, acceleration, angles and angular velocities. Other features are:

Result presentation with graphical overlay on the image sequence
Data and result filtering
Comparison with previous evaluations
Image and result data base
Report and documentation generation

The new module for the 3D calculations were to be a part of the analysis software package. Since an existing data structure was present, the module had to fit into that environment. It turned out to be rather complicated to do this, and the time schedule for that part of the work were heavily underestimated.

3. CHOOSING AN APPROACH

The main choice was to decide which type of basic mathematical model to use, either projective geometry, leading to the direct linear solution, DLT, or the collinearity equations, leading to the bundle adjustment solution. The given conditions can be described as:

Accuracy requirements: ± 10 mm
2 - 6 high speed cine film cameras
No fixed camera positions between sequences
No fiducial marks in camera
No fixed focus cameras
Zoom lenses may be used
Unstable inner orientation during a sequence

Several of the above mentioned conditions were pointing toward the DLT solution, but the need of corrections for radial distorsion and scale differences in x and y and the fact that the inner orientation might change during a sequence made the bundle adjustment more attractive. If a change were detected during the sequence, a correction of the inner and outer orientation parameters would require less control points to compute with a self-calibration in the bundle adjustment than using the DLT. As a consequence of this, the bundle adjustment approach was chosen, giving a good structure for a self-diagnosting system with as little operator support as possible. The GENTRI (Larsson) soft-ware was used for the bundle adjustment and self-calibration.

One of the major disadvantages of the chosen appoach is the need of approximate values for the camera orientations.

For a comprehensive comparison between the DLT and bundle approach see (Edgardh, 1992)

4. IMPLEMENTATION

4.1 Overall view

The complete system for the 3D measuring can be divided into two main parts: point measurements and calculations. The point measurements is done automatically by a tracing algorithm from one image to the next. This part of the system will not be discussed here but is well documented in other sources (ref). The mathematical (or photogrammetrical) part must interact with the point measurements with a high flexibility to be able to meet the level of automation. The three main parts of the calculations, calibration, bundle adjustment with self calibration and 3D measurements, must for this reason be able to adjust themselves to the needs at the different stages in the procedure.

Normally a sequence of images, taken with the speed 1000 frames/seconds, is calculated sequentially and the information regarding orientation and calibration is brought along and used if relevant. As can be seen in fig 4 the different actions taken by the system will be guided by the stability and functionality of the calibrated camera parameters. If the inner orientation parameters are stable, then the calculations can be done with a prior calibration of a known test-field and no additional self calibration is necessary. If the outer orientation is stable through the whole sequence, then the bundle adjustment is only done once in the beginning, but if it is unstable it will be recalculated when needed.

The 3D measuring part of the Track Eye system for high speed film consists of two main parts:

- Calibration
- 3D calculation

Both parts have similar interfaces regarding their data-organisation and error handling.

The calibration is done for each camera separately on a known test-field. Since some of the calibration parameters, mainly the principal point, are unstable, these can also be estimated in the 3D calculation part. An eight bit flag controls the different camera status' and the action to be taken by the program and/or operator.

The 3D calculation is done in two steps. In the first image set the orientation of the cameras (and possibly the principal point) is established by bundle adjustment. If the cameras have stable inner and outer orientation the next frames will be calculated directly from these parameters. If the camera is unstable in some manner, which is often the case with high speed film cameras, the bundle adjustment will be redone when needed.

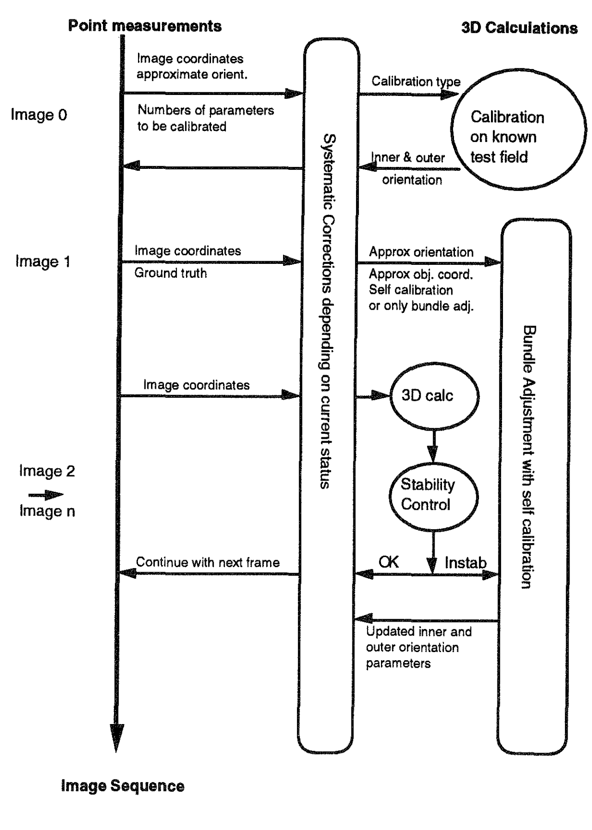

fig 4 3D module for TrackEye

4.2 Digitizing and Tracking

In the TrackEye Film Scanner the approach taken to film digitizing is based on a CCD linear array camera, which builds up an image by continuously moving the film past the CCD array (Källhammer, 1990). The array covers the whole width of the 16 mm cine film in order to be able to collect also timing and reference mark, fig 5. The horizontal resolution is given by the 2592 pixels in the CCD array, giving 6.2 µm for each pixel. The vertical resolution is set up to be the same, giving square pixels. A full frame is approximately 2592 by 1230 pixels, or about 3 Mega-bytes of data.

The digitizing rate is 0.83 seconds/frame on average if a sequence of 100 frames including start-up time. The data is stored on high speed, high capacity discs to faciliate fast and easy access in the coordinate extraction and analysis process. The disc system has a normal storage capacity of 3.1 Giga-bytes, giving the possibility to store at least 1000 full-frame images. The access time for a 3 Mega-byte image is 0.3 seconds.

The tracking process is gray scale based and aided by adaptive filters and path prediction. The tracking can be performed in fully automated, semi-automated or manual mode. A dedicated pipelined two-dimensional processor is used for the computationally heavy tracking, image handling, zoom and filtering operations.

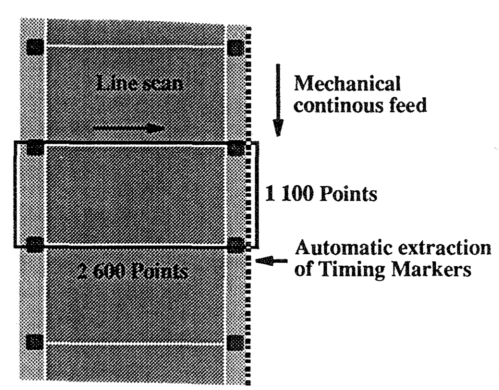

fig 5 Digitizing the film

4.3 Calibration

The calibration of the high speed cameras are done as flexible as possible, since the type and construction of the cameras may vary. The calibration is done either as a single camera calibration with a known test field or as additional parameters in the bundle adjustment (self calibration).

One of the largest problems with most high speed cameras is the lacking ability to produce some sort of fiducial marks. The problem is fundamental since most calculations are based on the collinearity conditions. Instead of using fiducial marks in the camera, stable object points may be used as reference marks through one sequence of images. A requirement for this to work is the stability of the outer orientation during a sequence, a requirement which must be checked continually and corrected for if not achieved. The corrections can be done as a self calibration of the principle point in the bundle adjustment.

The high speed cameras normally used have a rotating prism and a continuously moving film. The errors caused by this type of camera can be modelled as a scale factor between the axis and separate radial distortion coefficients for x and y.

Since the film is digitized with a scanner the calibration must also be able to pick up the errors caused by that procedure. The main type of error is most probably a scaling error between the coordinate axis and will be modelled as such.

In the single camera calibration the type of calibration parameters can be any combination of the following:

- Principle distance
- Principle point
- Radial distortion
  - separate in x and y with a 3 ° polynomial
  - a uniform 5 ° polynomial
- Scale difference between x and y

The cameras can also be calibrated in the bundle adjustment as additional parameters. Since there are as many cameras as there are camera stations the requirements for the ground truth is high even for the self calibration, but since some of the calibration parameters can be regarded as fix from previous calculations the ability is still of use. It is also possible to use other type of additional parameters such as polynomial deformations.

4.3.1 Mathematical Formulation The calculations are based on the central projection model, i.e. all image rays are assumed to pass through one and the same point, the projection centre. This leads to the use of the collinearity equations, which states that the object point, the projection centre and the image point lie on a straight line. If the rotation matrix, the projection centre coordinates and the calibration parameters are unknown the observation equations will look like :

$$vx = (-x' + xpp + corr) \bullet 1 \bullet -c \frac{a11(X-X0) + a12(Y-Y0) + a13(Z-Z0)}{a31(X-X0) + a32(Y-Y0) + a33(Z-Z0)}$$

$$vy = (-y' + ypp + corr) \bullet sc \bullet -c \frac{a21(X-X0) + a22(Y-Y0) + a23(Z-Z0)}{a31(X-X0) + a32(Y-Y0) + a33(Z-Z0)}$$

where

x', y'	the observed image coordinates
x_{pp}, y_{pp}	the principal point
corr	correction terms for the radial distortion
sc	scale difference in x and y
c	the principal distance
X,Y,Z	the object point coordinates
X_0, Y_0, Z_0	the projection centre coordinates in the object point coordinate system
$a_{11} .. a_{33}$	the elements of the rotation matrix of the image

The two equations are not linear in the unknowns. To solve the equation system they are expanded in a Taylor series where only the first degree terms are used. The solution is iterated until stability.

4.3.2 Requirements for the test field The point configuration for the test field is based on the geometrical conditions for determining the unknown parameters with as few points as possible without loosing the quality and security in the estimated parameters. The unknowns are the six orientation´parameters, principal distance, principal point, radial correction terms (2) and a scale factor between x and y giving a total of 12 unknowns.

The *principal distance* needs targets distributed in the outer parts of the image in as large depth difference as possible.

The *principal point* needs points in a similar manner as the principal distance, but is strengthen if 3D information is available in the centre of the image as well.

The *radial distortion* is dependent on the distribution of points over the whole image. It is not dependent on any 3D information.

The *scale difference* have similar requirements as the radial distortion.

The construction of a test field with this properties, which at the same time is stable, foldable and easy to move, is not a trivial matter. A three-folded test field with locking devices to keep the stability is a model which is considered.

4.3.3 Approximate values To be able to run the calibration approximate values must be entered by the operator for

- position (X,Y,Z in object coordinate system)

- rotation (X-axis,Y-axis,Z-axis, positive directions)

- principal distance

An implementation of an algorithm for finding initial values based on the method described in (Haralick et al, 1991) is planned.

4.3.4 The calibrated parameters The result from the calibration phase can be divided in two parts:

- Inner orientation parameters

- Outer orientation parameters

The inner orientation parameters are the principal distance, the principal point, radial distortion coefficients and the scale difference in x and y. In a metric camera with fiducial marks these parameters are defined and constant and indifferent to camera movement. In a high speed camera this is not the case. It is especially the principal point which is unstable due to the lack of fiducial marks. In the present version the principal point is not regarded as constant while the other parameters are.

The outer orientation describes the position and the direction of the camera in the object coordinate system. If the calibration is done with the same set-up of the cameras as the actual test set-up, these outer orientation values can be used as approximate values for the 3D calculations. They are not used for any other purpose.

4.4 3D - Calculations

The actual 3D calculation is done either as a result from the bundle adjustment or as a resection from the known orientation parameters and image coordinates. There are two reasons not to make a new bundle adjustment for each frame: time and stability. The time requirements for the system will probably permit an adjustment for each frame, but if a few hundred frames are measured the time saving is still considerable. Another reason is the stability of the system. If a new adjustment is done for each model, the measuring noise might give a larger instability than using a constant setting for all frames. An error in the constant settings will obviously create an error, but this error will have a uniform structure through the sequence and the local errors between frames might be smaller than with a new bundle adjustment for each frame.

The 3D coordinates are calculated from, at least, two images. The coordinates for the point is measured in the images and the object space coordinates are computed as the intersection of the rays. To be able to do this, the inner and outer orientation of the cameras must be known. The inner parameters are taken from the calibration phase as well as the approximate values for the outer orientation if the calibration is done with the same set-up as the test run. When using high speed film cameras, the inner orientation is normally not stable since there are no reference marks (fiducial marks) to define the principal point. Due to this, the principal point must be re-calibrated during the 3D calculations. If the cameras are fairly stable, i.e. the inner and outer orientation parameters do not change, the 3D calculations are performed without recalculating the outer orientation for each image frame. If the deviations to the known object points are too large the outer orientation parameters will be recalculated.

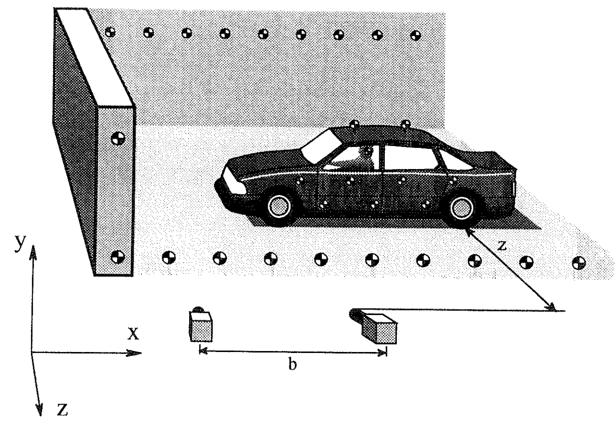

fig 6 Control point configuration

4.4.1 Control point configuration The purpose of the control points in the 3D calculation are to connect the image coordinate systems to the object coordinate system. In the case of additional calibration of the principal point they also serve this purpose. The minimum configuration for the control points are three points, but in order to achieve some redundancy and control of the calculations this number should be increased to at least six points, preferably three behind the test object and three in front of the object. They should be as well distributed as possible under the given practical conditions over the image plane. An example of acceptable control point configuration is shown in fig 6.

4.5 Self Diagnosis and Quality Reports

The philosophy of the system is that an operator should be avle to run through an image sequence with as little interaction as possible. This means that errorneous measurements or changes in the inner or outer orientations must be diagnosed and corrected automatically as fas as possible by the system. Two types of diagnosis is made:

4.5.1 Internal Diagnosis By looking at the residuals for each computed 3D point indicates if an error are present. If more than two cameras are used it will normally be possible to detect the erroneous measurement. In the camera calibration on known test-fields, a re-weighted least squares procedure is used to reduce the effect of the errors.

4.5.2 External Diagnosis In each frame a few stable known coordinates will always be seen. They will be used as a measure of stability during the sequence. When the 3D calculations are done, these points will be compared with their true values and if drifted away beyond a threshold, the bundle adjustment will be re-calculated to establish a new outer orientation.

4.5.3 Quality Report As little as possible of the statistical information is exposed to the operator, but mainly used in the internal self-diagnosis. The information from the various computations are saved in log-files if needed for a deeper analysis.

5. STABILITY TEST OF ANALOGUE HIGH SPEED CAMERAS

In order to get a deeper knowledge of the geometrical properties of a high speed film camera during the exposure phase, a stability test of a camera has been performed. The study was designed out of the following conditions and questions:

- Which parameters are stable during the exposure
- Cameras without fiducial marks will be used
- How should any instability be compensated and handled

5.1 Equipment and Conditions

Two set of cameras were used for the test. Only one of the cameras were possible to process further because of exposure problems with the other. A 3D test field was filmed from two camera stations to achieve a stereo coverage. The film was digitized with the TrackEye film scanner and measured. Approximately 70 points were measured in each frame of which app. 55 were common in both left and right image.

Camera: LOCAM, 500 frames/second

Optics: Smitar 10 mm

Digitizing: 6.2 µm/pixel (square)

5.2 Evaluation of the Measured Film

Three frames in the beginning and three frames in the end were measured by the TrackEye system. Of these six frames, four were selected for the stability test; frames number 1,4,90 and 91.

The stability test was carried out as three separate parts:

i A separate calibration on the data from each image frame

ii A calibration on frame 1
and an outer orientation using bundle adjustment on frame 1 followed by a 3D calculation of frames 1,4,90 and 91 with fixed outer orientation parameters. The mean deviation from the known points were compared.

iii A calibration on frame 1
and an outer orientation using bundle adjustment on each frame with the principal point as unknown. A 3D calculation of each frame with the orientation parameters and the principal point from its outer orientation computation.

5.3 Separate calibration of each camera

The camera were calibrated on a known test field with 55 points in one plane and 30 points in various positions separated from the plane. The purpose of the test was to find out which parameters were stable during a whole image sequence and between sequences.

The calibration parameters were computed as a single point resection in space with the parameters as extra unknowns. The calibrated parameters were

- principal distance [pixels]
- principal point [pixels]
- radial distortion coeff., separated in x and y
- scale difference between x and y

table 1 Calibration Parameters

The result from the calibration shows the following characteristics:

5.3.1 Principal Distance The principal distance seems to be stable during one sequence and fairly stable between to sequences. It is not known if the camera were accidentally moved or re-focused between the two camera positions. The difference is small enough to be regarded as noise. The deviations referres to the first frame.

Principal Distance [pixels]							
Frame	1	4		90		91	
	PD	PD	*dev*	PD	*dev*	PD	*dev*
Pos 1	1639.4	1639.8	*+0.4*	1639.2	*-0.2*	1638.4	*-1.0*
Pos 2	1635.0	1634.4	*-0.6*	1634.1	*-0.9*	1634.8	*-0.2*

table 2 Principal Distance

5.3.2 Principal point The principal point is, as expected, not stable between different frames. This is probably due to the digitizing process, but how large parts that are coming from the optical system is impossible to say. The original idea, to calibrate the principal point for each frame, seems to be necessary. The deviations referres to the first frame.

Principal Point [pixels]							
Frame	1	4		9		91	
	PP	PP	*dev*	PP	*dev*	PP	*dev*
Pos 1 x	-7.7	-8.5	*-0.8*	-6.7	*+1.0*	-8.8	*-1.1*
Pos 1 y	-2.3	+4.2	*+6.5*	9.9	*+12.2*	+11.1	*+13.3*
Pos 2 x	-9.5	-9.9	*-0.4*	-9.5	*0.0*	-10.0	*-0.5*
Pos 2 y	-1.6	0.0	*+1.6*	+7.2	*+8.8*	+9.1	*+10.7*

table 3 Principal Point

5.3.3 Radial distortion coefficients The radial distortion coefficients are stable and does not seem to be effected by the moving principal point. In this test they are calculated separately in x and y. In this camera type, with the film fixed during the exposure and not a rotating prism, it did not improve the result compared to a common parameter in x and y. The deviations referres to the first frame.

Radial Distortion separate in x and y [polynomial]				
Frame	1	4	90	91
	RD	RD	RD	RD
		dev	*dev*	*dev*
Pos 1 x	-.35e-7	0.37e-7	-0.34e-7	-0.35e-7
		-0.2e-9	*+0.1e-9*	*0.0*
Pos 1 y	-.33e-7	-0.31e-7	-0.34e-7	-0.35e-7
		+0.2e-9	*+0.1e-9*	*0.0*
Pos 2 x	-.32e-7	-0.31e-7	-0.32e-7	-0.31e-7
		+0.1e-9	*0.0*	*+0.1e-9*
Pos 2 y	-.32e-7	-0.31e-7	-0.30e-7	-0.32e-7
		+0.1e-9	*+0.2e-9*	*0.0*

table 4 Radial Distortion

5.3.4 Scale difference in x and y The scale difference between the x and y axis is very small, less than 0.3 percent, but might be more significant for other types of cameras.

Scale factor between x and y [x/y]				
Frame	1	4	90	91
	SF	SF	SF	SF
		dev	*dev*	*dev*
Pos 1	0.9986	0.9973	0.9998	0.9999
		-0.0010	*+0.0012*	*+0.0013*
Pos 2	0.9993	0.9997	0.9993	1.0002
		+0.0004	*0.0*	*+0.0009*

table 5 Scale Factor

5.3.5 Position and rotations The position and rotations of the camera are no actual calibration parameters, but is calculated by the program and used as approximate values for the bundle adjustment if the test run is performed with the same set-up as the calibration. In this study they are compared to see if the camera moves during the exposure of the film. The position has only very small deviations, less than 5 mm. The rotations have deviations which may be of more importance, less than 0.1 grade, which may be caused by the rather heavy forces on the camera house during the exposure. This is also supporting the correctness of recalculating the outer orientation and principal point rather often or for every frame.

5.4 One calibration for whole sequence

The cameras were calibrated on frame one and an outer orientation with no free calibration parameters were performed. The orientation parameters were then used to calculate 3D coordinates with fixed orientation on all four frames. The purpose of the test was to find out if it was enough to do one outer orientation with the bindle adjustment in the beginning of the strip and then use these parameters for the rest of the strip.

The comparative measure is the mean radial deviation (MD) from the known points in the test field. The unit for the deviations is in [mm] and the number of points used is 60. The result shows that it is not sufficient to do one outer orientation in the beginning of the sequence and use it for all following frames.

Deviations, one outer orientation [mm]							
Frame	1	4		90		91	
	MD	MD	*dev*	MD	*dev*	MD	*dev*
Pos 1+2	6.8	7.8	*+1.0*	27.1	*+20.3*	25.8	*+19.0*

table 6 One calibration for whole sequence

5.5 New calibration of principal point for each frame

In the third test, a calibration were performed on frame one. For each of the frames, including frame one again, an outer orientation with the principal point as extra unknown were performed. After this, a 3D calculation with the parameters for each frame were done to be able to compare the result with test two. The purpose of the test was to find out if it is necessary to do a new outer orientation for each frame with the principal point as unknown.

The result shows that the mean deviations from the known points are sometimes higher than in test 5.4 It seems however that the including of the principal point as unknown also lowers the accuracy in some cases.

Re-computing the principal point [mm]				
Frame	1	4	F90	91
	MD	MD	MD	MD
Pos 1+2	10.7	15.0	10.5	10.8

table 7 Re-computing the principal point

As a comparison, the same test were performed again but now with fixed principal point. One would expect this to increase the deviations from the known points. Instead it actually lowered the numbers. In some cases very little, while some were lowered considerably. It seems like the small change in the principal point is better picked up in a slightly different outer orientation than in the parameter itself when the control points are limited.

Keeping the principal point fixed [mm]				
Frame	1	F4	90	91
	MD	MD	MD	MD
Pos 1+2	6.8	7.0	9.8	7.5

5.6 Conclusions

The results from the stability test are in some parts easy to interpret while other are more difficult. It seems clear that the inner orientation of the camera is not completely stable. The principal point cannot be defined properly since the digitizing of the film is not accurate enough and, at the same time, there are no fiducial marks in the camera. The principal point may be computed again for each frame if wanted. It is however unsure if this improves the result. The deviations in the principal point is rather small (up to 10 pixels or 60 μm) and it seems that a new outer orientation with fixed parameters is just as good. The other parameters, principal distance, radial distortion and scale factor, seem to be rather stable and should be possible to use for several sequences.

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