Three-Dimensional Absolute Orientation of Stereo Models Using Digital Elevation Models

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ABSTRACT: A method for using digital elevation models (DEMs) as exclusive information for absolute orientation of stereo models is investigated. The discrete first derivatives of the DEMs (the slopes) are used in the observation equations. DEMs from three different areas used in a previous ISPRS comparative DEM test were used in the experiments. The method gave an accuracy comparable to or better than traditional absolute orientation with natural or signalized control points. Some possible areas of application are in satellite photogrammetry, in small scale topographic mapping with aerial photogrammetry, and in close-range photogrammetry in real-time, for instance, in quality control.

INTRODUCTION

THE ESTABLISHMENT of ground control points for absolute orientation is often costly. A photogrammetric stereo model is usually absolutely oriented on pretargeted control points or on points computed by block triangulation, which in turn is also based on pretargeted control points. It can be an advantage, in some applications, if the costly establishment of ground control can be avoided. In this paper a method for absolute orientation using digital elevation models (DEMs), or other three-dimensional models of the object, is formulated and investigated. The method can be used when elevation information, which can be transformed into a DEM, is available in the entire area or in parts of the area to be absolutely oriented. Results from the use of DEMs for absolute orientation in connection with three line imagery have been reported by Ebner (1986).

FORMULATION

We have the known DEM, $Z = f(X,Y)$, where Z is the ground elevation of a point with plane coordinates X, Y in the ground coordinate system (DEMs are usually stored in regular grids, but this is not necessary for solving our problem). We also have the measured model coordinates $(x_{ij}, y_{ij}, z_{ij})_p$, where x, y, z are the coordinates of the point in the ith column (the x-direction) and the jth row (the y-direction) of the DEM grid of the pth model. Again, the measured model coordinates do not have to be distributed regularly. In order to simplify the following formulation, the indices will not further be used.

The absolute orientation of a stereo model can be expressed as

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} X_0 \\ Y_0 \\ Z_0 \end{bmatrix} + m\,\mathbf{R} \begin{bmatrix} x \\ y \\ z \end{bmatrix} \tag{1}$$

where X_0, Y_0, and Z_0 are translations, m is the scale factor, and the orthonormal rotation matrix is

$$\mathbf{R} = \begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{bmatrix}.$$

The rotation elements are here chosen to be

$$\begin{aligned}
r_{11} &= \cos(\eta)\cos(\alpha) \\
r_{21} &= \cos(\xi)\sin(\alpha) + \sin(\xi)\sin(\eta)\cos(\alpha) \\
r_{31} &= \sin(\xi)\sin(;\alpha) - \cos(\xi)\sin(\eta)\cos(\alpha) \\
r_{12} &= -\cos(\eta)\sin(\alpha) \\
r_{22} &= \cos(\xi)\cos(\alpha) - \sin(\xi)\sin(\eta)\sin(\alpha) \\
r_{32} &= \sin(\xi)\cos(\alpha) + \cos(\xi)\sin(\eta)\sin(\alpha) \\
r_{13} &= \sin(\eta) \\
r_{23} &= -\sin(\xi)\cos(\eta) \\
r_{33} &= \cos(\xi)\cos(\eta)
\end{aligned}$$

where ξ, η, and α are rotations around the X, Y, and Z axes, respectively. Linearization around $\xi = \eta = \alpha = 0$ and $m = 1$, a special case of Equation 1, will give the following differential equation system for absolute orientation:

$$\begin{aligned}
\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} + \begin{bmatrix} \Delta X \\ \Delta Y \\ \Delta Z \end{bmatrix} &= \begin{bmatrix} \bar{X}_0 \\ \bar{Y}_0 \\ \bar{Z}_0 \end{bmatrix} + \bar{m}\,\bar{\mathbf{R}} \begin{bmatrix} x \\ y \\ z \end{bmatrix} \\
&+ \begin{bmatrix} \Delta X_0 \\ \Delta Y_0 \\ \Delta Z_0 \end{bmatrix} + \begin{bmatrix} \Delta m & -\Delta\alpha & \Delta\eta \\ \Delta\alpha & \Delta m & -\Delta\xi \\ -\Delta\eta & \Delta\xi & \Delta m \end{bmatrix} \begin{bmatrix} x \\ y \\ z \end{bmatrix}
\end{aligned} \tag{2}$$

This formulation describes how differential changes in the orientation parameters affect the ground coordinates. The Z portion of Equation 2 can explicitly be expressed as

$$\begin{aligned} Z + \Delta Z &= \bar{Z}_0 + \bar{m}\,(\bar{r}_{31}\,x + \bar{r}_{32}\,y + \bar{r}_{33}\,z) \\ &\quad + \Delta Z_0 - x\,\Delta\eta + y\,\Delta\xi + z\,\Delta m \end{aligned} \tag{3}$$

where ΔZ is introduced as a differential function of the plane coordinates in the DEM: $Z = f(X,Y)$

$$\Delta Z = \frac{df}{dX}\,\Delta X + \frac{df}{dY}\,\Delta Y \tag{4}$$

The X and Y portions of equation 1 give, when linearized around $\xi = \eta = \alpha = 0$ and $m = 1$,

$$\begin{aligned} \Delta X &= dX_0 + x\,dm - y\,d\alpha + z\,d\eta \\ \Delta Y &= dY_0 + x\,d\alpha + y\,dm - z\,d\xi \end{aligned} \tag{5}$$

From Equations 3, 4, and 5 we obtain the following observation equation for a corresponding point in the two coordinate systems, i.e., the DEM and the stereo model:

$$\begin{aligned} \lambda &= Z - \bar{z}_0 - \bar{m}\,(\bar{r}_{31}\,x + \bar{r}_{32}\,y + \bar{r}_{33}\,z) \\ &= dZ_0 - x\,d\eta + y\,d\xi + z\,dm \\ &\quad - \frac{df}{dX}\,(dX_0 + x\,dm - y\,d\alpha + z\,d\eta) \\ &\quad - \frac{df}{dY}\,(dY_0 + x\,d\alpha + y\,dm - z\,d\xi) \end{aligned} \tag{6}$$

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where λ is the discrepency between the height of the DEM and the height of the stereomodel (the observation) when approximate values of the transformation are used.

This is close to the solution. We just have to make clear how the partial first derivatives (df/dx) and df/dy) are computed. The derivatives are the change in Z in the DEM corresponding to a unit change in X and Y, respectively, or, in other words, the slope at the point X, Y in the ground DEM. However, we have in this investigation instead chosen to use the stereo model for the computation of the first derivatives. This is done mainly for one reason, that is, by doing so we do not have to recompute the coefficients in the design matrix between iterations, which makes it unnecessary to update the normal matrix. Seen from a practical point of view, the most important consideration is which of the two systems has data of higher quality, as errors in the elevation model used for the computation of the first derivatives will give errors in the design matrix. The discrete first derivative in x is thus in this investigation computed as

$$\frac{df}{dX} \approx (z_{i+1,j} - z_{i-1,j}) / 2d \tag{7}$$

where d is the grid distance. The computation is analogous in the y-direction. In cases where the DEM is not a regular grid, the derivatives have to be found by the proper calculations depending on the actual DEM structure.

The seven unknown transformation parameters in Equation 6 are solved for by the least-squares method. The rotation parameters ξ, η, and α; the scale m; and the translations X_0, Y_0, Z_0 are updated with the results and the computation is iterated until convergence. After each iteration, all points in the stereo model are transformed to the ground coordinate system. For each point, new heights are interpolated (bilinearily) in the ground DEM. The iterations are interrupted when the translation parameters are changed by less than 0.01 of the grid distance, the scale factor by less than 0.05 percent, and the rotations by less than 0.5 mrad. An alternative method would be to use a statistical test of the joint significance of the unknowns in the adjustment.

From the standard error of unit weight, the variances of the transformation parameters or of other functions of the observations can be computed by classical error propagation.

WHAT SLOPE AND ELEVATION INFORMATION ARE NEEDED?

When absolute orientation is performed in a traditional way, at least three ground control points (which are not on a straight line) with known elevations and at least two ground control points with known plane coordinates are needed. Analogously, we are able to specify the demands on a DEM used for absolute orientation. In Figure 1 the discussion is illustrated. In all seven marked points, accurate elevations are needed. Each arrow in the figure shows the need for a known relatively large and accurate first derivative (slope) at the point. The actual element that will be determined is shown for each point.

First, one accurate elevation point is needed for the determination of dZ_0. The rotations around the X- and the Y-axes ($d\xi$ and $d\eta$) are determined by two more elevation points. These three points should not be on a straight line. The scale dm is, together with a translation in plane (say dY_0), determined by two points with slopes (first derivatives) in the same or opposite directions. The next translation in plane (dX_0) needs one further point with a slope, this time perpendicular to the last two. Finally one point with a slope in a direction making rotation around the z-axis impossible is needed ($d\alpha$).

However, it should be noticed that the first derivatives (the slopes) are by necessity inaccurate; they are just discrete approximations of the real slopes. If the slope is small, then the propagation of a height error to the plane parameters is unfavorable. This means that each point in this example should be replaced with a group of points, with the same properties concerning slope as indicated in Figure 1.

THE INVESTIGATION METHODS

Working Group III/3 of ISPRS 1980–1984, dealing with "Mathematical Aspects of Digital Terrain Models," carried out a comparative test during the first half of the 1980s (Torlegård *et al.*, 1987). The data and results are quite well known in the photogrammetric world. The original data are available at the Department of Photogrammetry of the Royal Institute of Technology in Stockholm, where the work reported in this paper was performed. Three of the six areas used in the comparative test were selected to be used in this investigation, the Bohuslän area (Figure 2) the Stockholm area (Figure 3), and the Söhnstetten area (Figure 4). For each test area three models measured by the participants of the test were chosen, one with as good accuracy as possible (given the numbers "1" in the tables), one with moderate accuracy (given the numbers "2"), and one with as poor accuracy as possible (given the numbers "3").

The elevation data from the participants were received in specified square grids, with uneven grid spacing and rotations of the coordinate system. In the following part of the paper the models will be treated as if they were in an ordinary x,y coordinate system. The elevation values were obtained from interpolation in DEMs established by the participants. The three different test areas also had different numbers of grid points (Table 1).

The calculations in this investigation were performed as absolute orientations of the DEMs measured by the participants

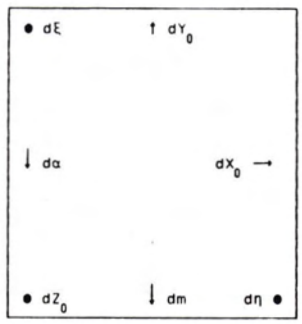

FIG. .1. An example of the necessary elevation and slope information in the DEM.

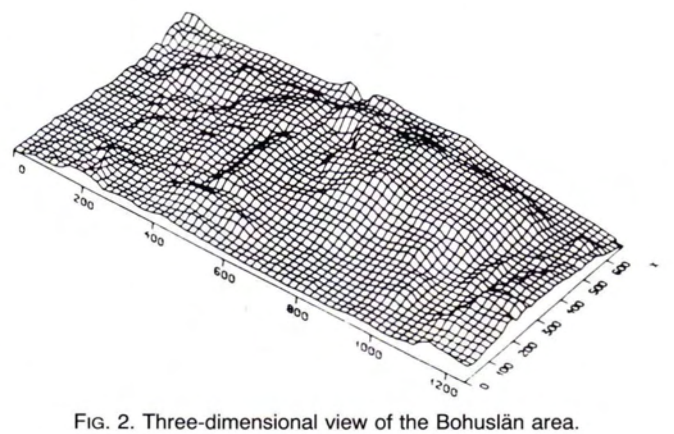

FIG. 2. Three-dimensional view of the Bohuslän area.

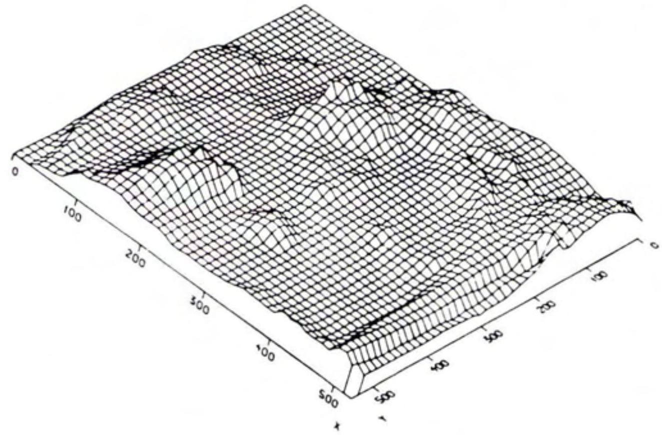

FIG. 3. Three-dimensional view of the Stockholm area.

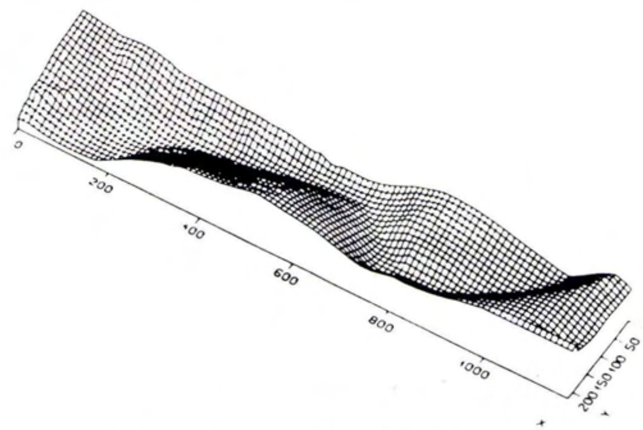

FIG. 4. Three-dimensional view of the Söhnstetten area.

TABLE 1. SOME DATA ABOUT THE TEST AREAS. NUMBER OF GRID POINTS IN x AND y, THE GRID SPACING, THE TOTAL AREA SIZE, AND THE APPROXIMATE MEAN SLOPES IN x and y.

	# Grid Points		Grid	Area Size		Slope %	
Test Area	in x	in y	Spacing	in x	in y	in x	in y
Bohuslän	64	35	19.81 m	1248 m	674 m	6.3	6.6
Stockholm	46	45	11.98 m	539 m	527 m	5.6	7.4
Söhnstetten	104	20	11.38 m	1172 m	216 m	14.5	25.7

(treated as the "stereo models") to the ground truth DEMs (regarded as given control).

As initial values no translations ($X_0 = Y_0 = Z_0$), no rotations ($\xi = \eta = \alpha = 0$), and the scale factor 1 were chosen. This means that all computed transformations are to be considered as errors either in the data received from the participants or as errors in the absolute orientation performed using the described method. It also means that the sensibility of the method to bad initial values is not investigated.

Observation equations were computed for those points where the elevations were known in the ground DEM and where both of the partial discrete first derivatives could be computed in the "stereo model." For the computations of the Bohuslän area, between 1,638 and 1,653 observations were used. Between 1,341 and 1,387 observations were used for the computations of the Söhnstetten area and, for the "Stockholm1" and "Stockholm3" areas, 1,341 and 1,453 observations were used, respectively. In all cases the observations points were rather symmetrically distributed, except for the area "Stockholm2" with 963 observations, which had a large area in the south-west part without any height information (Rosenholm and Torlegård, 1987).

RESULTS AND DISCUSSION

The changes of the transformation parameters after orientation with DEMs are partly improvements of the participants absolute orientation and partly errors caused by the method. Much of the following discussion is for the purpose of separating these two components in order to study the accuracy of the investigated method in comparison with traditional methods.

A COMPARISON TO THE RESULTS OF THE ISPRS-TEST

In Table 2 the RMS difference before the adjustment and the standard error of unit weight after convergency, are shown. In the ISPRS-test and in this investigation, exactly the same elevation points were not used. The initial RMS and the σ_0 after absolute orientation in this investigation are compared with the RMS before and after elimination of gross and systematic errors (leveling) in the ISPRS-test.

There is a similarity between σ_0 after the absolute orientation with RMSs and the RMS after leveling of the participants results. This points towards the fact that absolute orientation with DEMs gives a better accuracy, at least in height, than traditional absolute orientation with control points. The same systematic errors seem to be eliminated by the absolute orientation with DEMs as by the leveling done in the ISPRS-test.

SIGNIFICANCE OF THE TRANSFORMATION PARAMETERS

The changed absolute orientation parameters, after absolute orientation with DEMs, are given in Table 3. The leveling made in the comparative test corresponds to Z_0, ξ, and η, while X_0,

TABLE 2. THE INITIAL RMS AND THE STANDARD ERROR OF UNIT WEIGHT, IN METRES, AFTER ABSOLUTE ORIENTATION. ONE COMPUTATION DID NOT CONVERGE. IT IS MARKED WITH "D)". FOR COMPARISON, SOME RESULTS FROM THE ISPRS-TEST ARE GIVEN.

	This Investigation		The ISPRS-test (RMS)		
Computation	Initial RMS	σ_0	Initial	Gross E. Exclus.	Level
Bohuslän1	1.32	0.83	1.31	1.30	1.03
Bohuslän2	1.62	1.48	1.62	1.50	1.43
Bohuslän3	2.44	2.18	2.35	2.25	2.15
Stockholm1	0.59	0.50	0.64	0.54	0.52
Stockholm2	1.29	0.95	1.32	1.25	1.11
Stockholm3	3.19	d)	3.23	3.23	3.12
Söhnstetten1	0.38	0.21	0.38	0.38	0.24
Söhnstetten2	0.48	0.41	0.48	0.42	0.38
Söhnstetten3	1.22	1.15	1.19	1.10	1.08

TABLE 3. THE COMPUTED PARAMETERS AFTER ABSOLUTE ORIENTATION.

Computation	X_0 metre	Y_0 metre	Z_0 metre	m	ξ mrad	η mrad	α mrad
Bohuslän1	1.8	2.8	0.7	1.0017	0.6	−0.1	−3.0
Bohuslän2	0.2	−2.8	0.3	0.9992	0.4	0.7	−0.1
Bohuslän3	3.7	−3.3	0.8	0.9977	0.1	1.0	2.5
Stockholm1	1.4	0.5	0.0	1.0021	−0.5	0.7	−3.0
Stockholm2	−1.0	1.1	0.3	1.0169	−0.1	−0.3	−10.9
Söhnstetten1	−0.3	0.5	−0.4	1.0007	0.3	0.8	−0.7
Söhnstetten2	0.0	−0.2	0.4	1.0025	−0.1	−0.1	−1.1
Söhnstetten3	−0.1	0.7	0.0	0.9979	−0.4	−1.9	−0.5

Y_0, m, and α are the new parameters introduced in this investigation compared to the ISPRS-test.

In Table 4 the propagated standard deviations of the computed parameters are shown.

The standard deviations are significantly smaller than the estimated variables. With the large number of degrees of freedom (redundancy) in this study, all ratios between the computed transformation parameters and their standard deviations larger than 1.96 are significant at the 95 percent level. Thus, most of the transformation parameters are statistically significant, assuming normally distributed errors, which points towards the fact that this new absolute orientation by DEM is a significant improvement over the old absolute orientations made by the participants in the test.

A Comparison with Ordinary Absolute Orientation

Another way of comparing the results obtained from ordinary absolute orientation, and absolute orientation with DEMs is to compare the propagated standard deviations of the unknown transformation parameters. In Table 5, the standard deviations, of ξ, η, X_0, Y_0, and Z_0 from an absolute orientation in a Kern DSR11 are listed. The absolute orientation was made with the existing software (a seven-parameter solution) and according to the data and instructions given to the participants in the test. The measurements were carefully performed by an experienced operator. In Table 6 the corresponding standard deviations from the absolute orientation with DEMs are pooled for each area.

Absolute orientation with DEMs gives a higher precision of the joint height parameters (Z_0, η, ξ). The difference is highly significant concerning the Z_0 parameter, which in this case dominates the height error. In planimetry, however, the precision is not correspondingly high but still fully comparable to the accuracy obtained from classical orientation on control points.

Table 4. The Standard Error and the Standard Deviations of the Absolute Orientation Parameters after Absolute Orientation with DEMs.

Computation	σ_0	σ_{X_0} metre	σ_{Y_0} metre	σ_{Z_0} metre	σ_m	σ_ξ mrad	σ_η mrad	σ_α mrad
Bohuslän1	0.83	0.32	0.31	0.03	0.0009	0.2	0.1	1.0
Bohuslän2	1.48	0.48	0.47	0.05	0.0012	0.2	0.1	1.3
Bohuslän3	2.18	0.67	0.68	0.07	0.0017	0.3	0.2	2.0
Stockholm1	0.50	0.18	0.14	0.02	0.0008	0.1	0.1	0.8
Stockholm2	0.95	0.58	0.57	0.05	0.0030	0.3	0.2	2.9
Söhnstettent1	0.21	0.04	0.05	0.02	0.0002	0.0	0.1	0.2
Söhnsteten2	0.41	0.07	0.09	0.04	0.0004	0.0	0.2	0.3
Söhnstetten3	1.15	0.20	0.26	0.10	0.0010	0.1	0.7	0.7

Table 5. The Standard Error and the Standard Deviations of the Absolute Orientation Parameters after Traditional Absolute Orientation on Control Points with a Kern DSR11.

Computation	σ_0 metre	σ_{X_0} metre	σ_{Y_0} metre	σ_{Z_0} metre	σ_ξ mrad	σ_η mrad
Bohuslän	0.7	0.6	0.4	0.8	0.27	0.31
Stockholm	0.3	0.2	0.2	0.4	0.09	0.16
Söhnstetten	0.1	0.1	0.1	0.1	0.06	0.10

Table 6. The Pooled Standard Error and the Pooled Standard Deviations of the Same Absolute Orientation Parameters as in Table 2 after Absolute Orientation with DEMs.

Computation	σ_0 metre	$\sigma_{X_{00}}$ metre	σ_{Y_0} metre	σ_{Z_0} metre	σ_ξ mrad	σ_η mrad
Bohuslän	1.60	0.51	0.51	0.05	0.2	0.1
Stockholm	0.76	0.42	0.42	0.04	0.2	0.2
Söhnstetten	0.72	0.12	0.16	0.06	0.1	0.4

Model Fidelity

In a similar application of the least-squares method—automatic parallax measurements with the least-squares matching method—the standard deviation of the parallaxes is smaller than the obtained RMS error of the parallaxes (Rosenholm 1986a; Hartfiel, 1986). What discrepencies are there between reality and the adjustment model? One discrepancy from the correct model is that we treat a nonlinear estimation problem as linear. This fact does not necessarily mean that we get a bad result as long as the problems behave linearily when the correct solution is close. How do nonlinearities affect the adjustment in this case?

We have errors in the design matrix because of two reasons. First, the first derivatives (the slopes) are discrete approximations over a length of two grid distances, and second, the elevations from which the first derivatives are computed usually have errors. The observations (the right hand side) are also affected. The interpolations in the DEM, performed between each iteration, are not made in a ground surface but in a mathematical (in this case bilinear) surface. In reality, there is one additional deviation from the estimation model that is very important.

In our application of the least-squares method, we have assumed the observations to be independent. We can be sure that they are not independent, although we have not introduced any *a priori* covariance matrix in the least-squares estimation. In the ISPRS-test, from which we have taken the data, it was shown that the errors in elevation were correlated over very long distances, many hundreds of metres actually (Östman, 1987; Torlegård *et al.*, 1987). Disregarding the covariances is probably the largest deviation from the correct statistical model in this investigation.

CONCLUSIONS

The method for absolute orientation formulated in this report gives a sufficient accuracy for many purposes. The accuracy is dependent on the quality of the ground DEM, the stereo model, and the slope characteristics of the object.

In most cases very high accuracy, better than with conventional methods, is obtained for the absolute orientation in elevation. The accuracy in planimetry is highly dependent on the slope and the geometry of the object but is of the same magnitude as traditional absolute orientation on ground control. The type of terrain, and particularly the derivative of the terrain, will influence the accuracy of the solution.

The method does not require a regular grid DEM, but local regular grids in either the ground DEM or in the stereo model data are an advantage for simplifying the computation of the derivatives and of the interpolation in the DEM.

A consequence of the very high redundancy and the fairly high regularity of the observations makes the method well suited for data snooping. The cofactor matrix of the residuals can usually be approximated by the unit matrix, making the computations very simple.

The method can be applied in topographic mapping as soon as a DEM is available, and when the establishment of classical control points is more expensive. Examples are satellite photogrammetry with imagery from the Large Format Camera (LFC), ESAs Metric Camera, and the French SPOT satellite. Old topographic information can thus be used for absolute orientation. It is possible that the accuracy requirements for the ground data do not need to be very high in these applications due to the advantageous propagation (small effect) of the height errors to the transformation parameters, an advantage caused by the high redundancy.

Another similar application example is photogrammetric map revision, e.g., super high and high altitude photography at scales between 1:60,000 and 1:150,000 for the revision of topographic maps at a scale of 1:50,000. In practice, the given DEM may be selected from a national elevation data bank. In Sweden, for instance, there is such a DEM with a 50-m grid. A typical stereo model to be oriented may be measured from aerial photographs at a scale of 1:30,000, covering an area of 3 by 6 km. All given DEM points provide some 60 by 120 = 7200 points for the absolute orientation.

Application areas can also be found in close-range photogrammetry, where often very large first derivatives of the three-dimensional models are at hand. The method can, for instance, be used for shape control in the manufacturing industry without any need for control points. It would be possible to locate errors in the shape of manufactured objects by the data snooping technique after adjustment to the ideal design shape.

A combination of automatic parallax measurements of gridded data, for instance, multi-point matching (Rosenholm, 1986a, 1986b, 1987) and the method for absolute orientation shown in this paper, may have great advantages for the total automation of photogrammetry and for robot vision.

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