COMPLETE AUTOMATION OF THE RELATIVE ORIENTATION OF A STEREOPAIR

AVTOMATIZACIJA CELOTNEGA POSTOPKA RELATIVNE ORIENTACIJE STEREOPARA

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ABSTRACT

In the paper the results of the research on the complete automation of the relative orientation of a stereo pair is presented. The theoretical background needed for understanding this topic is described and the results of testing the algorithms with real data are presented. In general, the relative orientation procedure consists of three phases: input data acquisition, computation of relative orientation parameters and estimation of observation errors. In the process of the complete relative orientation automation, the key step is the automation of homologous points acquisition in the stereo area. In the tests presented, the homologous points were acquired with different methods: manually, semi-automatically and fully automatically. The results of the computed relative orientation parameters have been compared. It has been concluded that the automation of the relative orientation procedure is successful and reliable if the control of the observation errors estimation is built into the procedure, and, especially, we get the results faster than with the manual or semi-automated method.

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POVZETEK

V članku so predstavljeni rezultati raziskave avtomatizacije celotnega postopka relativne orientacije stereopara. Opisana so teoretična izhodišča, ki so potrebna za razumevanje problematike, predstavljeni so rezultati testiranja algoritmov na realnih primerih. Postopek relativne orientacije je v splošnem sestavljen iz treh faz: zajema vhodnih podatkov, izračuna parametrov relativne orientacije in ocene pogreškov opazovanj. V procesu popolne avtomatizacije relativne orientacije je ključnega pomena avtomatizacija zajema homolognih točk na stereoobmočju. V testu smo homologne točke zajeli z različnimi metodami: ročno, polavtomatsko in avtomatsko, nato smo rezultate izračuna parametrov relativne orientacije med seboj primerjali. Ugotovili smo, da avtomatizacija postopka relativne orientacije deluje uspešno in zanesljivo, če v postopek vgradimo nadzor nad oceno pogreškov opazovanj, predvsem pa do rezultatov pridemo hitreje kot z ročno ali polavtomatsko metodo.

KEY WORDS

relative orientation, automation, image matching, robust estimation of errors

KLJUČNE BESEDE

relativna orientacija, avtomatizacija, slikovno ujemanje, robustna ocena pogreškov

1 INTRODUCTION

This paper presents the results of a research into the automation of the complete relative orientation of a stereo pair, performed within the research project »Development of methods and systems for terrain image capture, detection and target recognition« (Kogoj et al., 2006).

Relative orientation (RO) is one of the central methods in photogrammetry dating back to the age of analogue technology. It is the first stage in the orientation of a stereo pair enabling us to establish the correct position between stereo images, therewith creating a stereo model. The second stage is absolute orientation (AO), which puts the stereo model into its correct position in the space of reference. Both stages are represented in Figure 1.

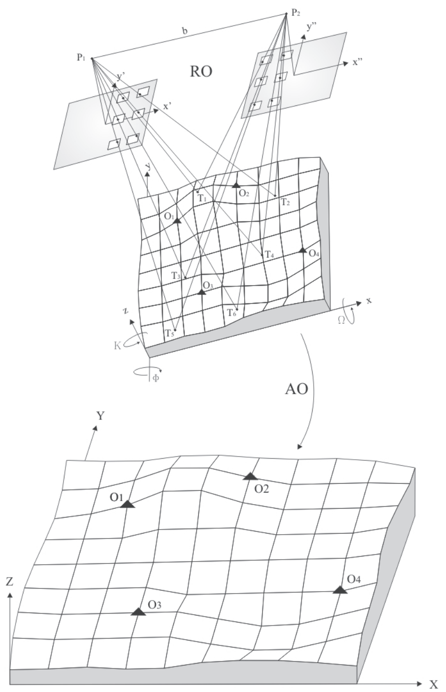

Figure 1: *Illustration of the relative (RO) and absolute (AO) orientations of a stereo pair.*

The position of a stereo pair in space is defined by 12 parameters (three translations and three rotations per each image), 5 of which are solved by using relative orientation and 7 by absolute orientation. The absolute orientation is mathematically expressed as a 7-parameter spatial similarity transformation, which is solved based on the known co-ordinates of at least three (in practice, however, of at least four or more) control points in both co-ordinate systems (reference and model ones); in Figure 1 the control points are marked as $O_1 \dots O_4$. In geodesy, this transformation is well known and used when the transformation between two different 3-D co-ordinate systems is performed.

Relative orientation is conceptually fairly different from the absolute orientation and it is more demanding in terms of performance. The correct relative mutual position of both images, forming a stereo pair, is achieved when in at least five points of the model the homologous pairs of rays intersect (a model is a spatial object, which has been moved, rotated and typically reduced in size; a ray is a straight line running through the projection centre of the image and the image point). The five parameters of the relative orientation are calculated on the basis of the measured parallax y (that is, the difference of image coordinates y of homologous points), therefore image measurements are sufficient for their solving.

The main input for the calculation of parameters of relative orientation are the measurements of image co-ordinates of homologous points, which in the past could be measured manually only. Only with the emergence of digital images (in the beginning of 1980s) was a broader automatisation of photogrammetric processes made possible. The automatic relative orientation was introduced by different authors, especially in the program modules for digital photogrammetric workstations (Tang and Heipke, 1993). Notably, the procedures of image matching are highly efficient in this respect, enabling us to recognize the patterns and measure image co-ordinates of homologous points.

When considering the complete automation we stumble upon a rather complex problem of selecting good feature (characteristic) points or patterns. However, since in comparison to human selection the automated search of feature points is not reliable, we have to introduce a mechanism for control of errors after the adjustment, which could identify and remove the potential gross errors in input data.

In our study the following procedures for complete automation of relative orientation were employed:

- numerical calculation of parameters of relative orientation,
- Förstner algorithm for selection of feature points extraction,
- area-based image matching, and
- method of robust estimation of observation errors.

2 NUMERICAL CALCULATION OF PARAMETERS OF RELATIVE ORIENTATION

A photograph is taken by the rules of central perspective mapping. At the moment of exposure the light from spatial point (T) is mapped through the projection centre (O_1 or O_2) onto a film or digital sensor (T' or T'') (Figure 2, left). In the phase of measurement (Figure 2, right) quite the opposite is true – our departure point is the image point (T' for the left image and T'' for the right image) and through the projection centre (O_1 or O_2) the ray is mathematically expressed. The

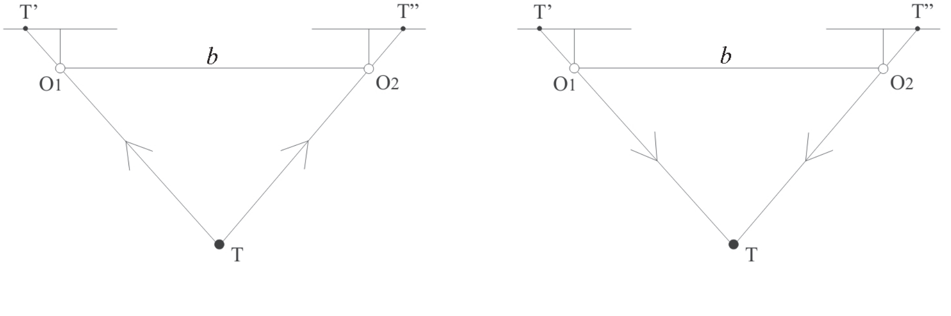

Figure 2: *Exposure phase (left) and the procedure of measurement (right) (Vezočnik, 2006).*

spatial point is determined by the intersection of homologous image rays, where the spatial position has to be the same as the one during exposure. The establishment of the original position of images can be achieved by different methods, one of them being the two-stage method.

As mentioned in the Introduction, in the first stage we establish the correct mutual position of stereo images. We define the mathematical model represented by the parallax equation (1).

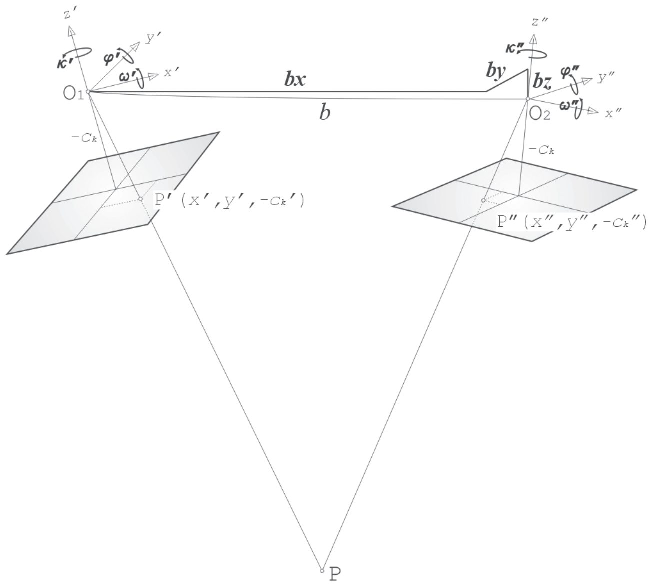

Figure 3: *Mathematical model of relative orientation (Vezočnik, 2006).*

The parallax equation takes the form:

$$py = A \cdot dby + B \cdot dbz + C \cdot d\varphi' - D \cdot d\omega' - E \cdot d\kappa' - F \cdot d\varphi'' + G \cdot d\omega'' + H \cdot d\kappa'' \qquad (1)$$

The vector from the left (O_1) to the right projection centre (O_2) is called the stereo pair baseline (*b*) (Figure 3). The image co-ordinate system of the left image has its origin in O_1 and co-ordinate axes *x'*, *y'*, *z'*, while the image co-ordinate system of the right image has its origin in O_2 and co-ordinate axes *x''*, *y''*, *z''*. In both co-ordinate systems the rotations around the co-ordinate axes are defined (ω', φ', κ' for the left image and ω'', φ'', κ'' for the right image). We also define the components of the baseline vector b_x, b_y and b_z, representing the shift of the projection origin O_2 with regard to the image co-ordinate system of the left image. Altogether there are six rotation angles and three baseline components. Baseline component b_x can be selected arbitrarily, since it only influences the scale of the model, which is correctly determined in absolute orientation. The inter-position of the images is thus described by eight parameters (six rotations, b_y and b_z) expressed in the parallax equation p_y (1). Figure 3 shows that the homologous rays intersect exactly when the three vectors (b, O_1P, O_2P) are in a plane, which is called the coplanarity condition (Schenk, 1999). The parallax p_y is the difference of the image co-ordinates y of homologous points and must equal zero in order to fulfil the coplanarity condition. A further detailed analysis shows that only five parameters out of eight mentioned earlier are linearly independent, so they can be considered as real parameters, and the other three as constants. The selection of the five parameters can be random, however the following two selections are mostly used:

- image rotations (independent RO): $d\kappa'$, $d\kappa''$, $d\varphi'$, $d\varphi''$, $d\omega''$;
- conjunction of successive photographs (dependent RO): dby, dbz, $d\omega''$, $d\varphi''$, $d\kappa''$.

For the calculation of the five parameters in the parallax equation we therefore need measurements of image co-ordinates of at least five homologous points. The best results are achieved if the homologous points in the area of the stereo pair are chosen in six von Gruber locations, as shown in Figure 4 (points in location six are for control). In each location at least one homologous pair of points is selected and measured, however, for higher reliability and control it is recommended that the number of these points is higher.

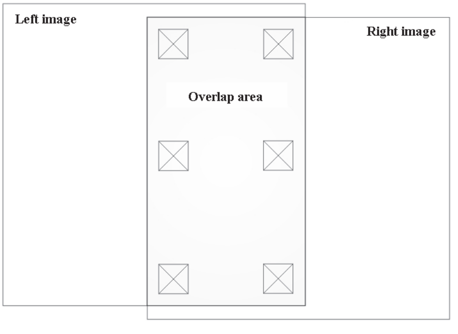

Figure 4: *Areas appropriate for selection of homologous points.*

The calculation of parameters of relative orientation is performed using least-squares adjustment. In the literature, the expression digital relative orientation (DRO) is often used for the numerical calculation of parameters of relative orientation.

3 FÖRSTNER ALGORITHM FOR SELECTION OF FEATURE POINTS

The pairs of homologous image points (points P' and P'' in Figure 3), which, beside the parameters of inner orientation of the camera (principal point, camera constant, lens distortion), represent the input for determination of orientation parameters of relative orientation, can be determined and measured in three ways using:

- the manual method: the points are chosen and measured manually,
- semi-automated method: in one image the point is chosen manually, in the second one, the homologous point is selected and measured automatically,
- automated method: the selection and measuring of points are fully automated.

The goal of our study was to elaborate an automated method and compare it to the results of the semi-automated and manual methods, respectively. For the selection of feature points in the primary image we used the Förstner operator (after W. Förstner).

The algorithm for feature point extraction has to fulfil the following conditions (Förstner and Gülch, 1987):

- distinctness: the detected points should stand out against the immediate neighbouring feature points,
- invariance: the selection and chosen position should be independent of the geometrical and radiometrical distortions – meaning that the change in image orientation and its radiometrical features does not influence the selection and location of the feature points,
- stability: the determination of feature points should be robust to noise,
- seldomness: the distinctiveness fulfils the condition of local uniqueness, and rarity the condition of global distinctness of points, which helps to improve the distinction of repetitive patterns,
- interpretability: the selection should be well founded, e.g., one needs to detect edges, corners and other significant image patterns.

There are many algorithms for automated detection of image points, proposed by several authors (Kraus, 2004; Fritch et al., 1993). In terms of the procedure, the algorithms differ, however, in an actual situation some are more appropriate than the others. In our study, we used the Förstner operator of feature points, which fulfils all the criteria given above and ensures good results in a relatively short time of processing. The algorithm operates so that it first looks for the optimum size of the window, within which the optimum point is detected, following the criteria mentioned above. Based on the algorithm, published in Förstner and Gülch (1987), we worked out a program module, and its operation was verified using different data. The case in Figure 5 shows us the results of the algorithm in extracting feature points.

Figure 5: *Feature points as extracted by the Förstner operator.*

4 AREA-BASED IMAGE MATCHING

In detection and measuring of homologous points in a stereo pair we used the method of area-based image matching. After selecting a point in one image of a stereo pair (primary image), it is then detected in another image using the procedures of image matching. There are several different methods of image matching. In our study we opted for the area-based method, which uses the correlation coefficient as the similarity criterion. The reason of our selection lies in the high efficiency and reliability (Baltsavias et al., 1990; Kraus, 2004; Vollmerhaus, 1987; Vovk, 1998).

The method is based on the determination of similarity of two surfaces, which are represented by an extraction in the primary image and the extraction in its stereo pair. In the mathematical sense, the extraction of the area represents a part of the image matrix. In the primary image, the selected point is in the centre of the matrix, while the matrix size should be appropriate related to the point significance and its neighbourhood. Such a matrix is called a pattern or a reference matrix. A larger search window is determined in the stereo pair (part of the image), where it is expected that the homologous point is to be found. The "pattern" is laid over the search window (Figure 6) and in each possible position (the window is shifted in lines and columns) the correlation coefficient is calculated.

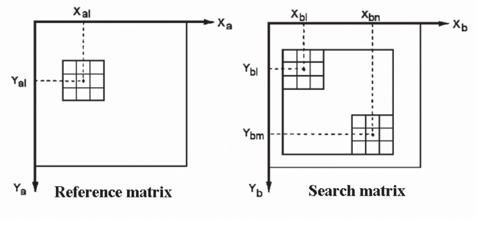

Figure 6: *The principle of area-based image matching (Albertz and Kreiling, 1989).*

The correlation coefficient is the relationship between the covariance of radiometrical values of the pattern and the matrix in the search window (σ_{12}) and of the product of standard deviations of both matrices (σ_1 is the standard deviation of radiometric values in the pattern, σ_2 is the standard deviation of radiometric values in the matrix of the search window) (Kraus, 2004):

$$r = \frac{\sigma_{12}}{\sigma_1 \cdot \sigma_2} \tag{2}$$

Coefficient *r* has values between *r* = -1(one matrix is the negative of the other) and *r* = 1 (absolute match – the matrices are completely identical). If *r* equals zero, there is no similarity between the pattern and the matrix in the search window. For the most probable position of the homologous point we therefore choose the central pixel of such position in the search window, where the correlation coefficient assumes the highest value (e.g. if the highest *r* = 0.85, it means that the match between the pattern and the matrix in the search window is 85%). We can also define the threshold defining which minimum value of *r* is still acceptable.

5 METHOD OF ROBUST ESTIMATION OF OBSERVATION ERRORS

For successful automation of the complete relative orientation one needs to introduce a mechanism, which will automatically control the errors of calculation of relative orientation parameters. The algorithm used for calculation of parameters of relative orientation is based on the Gauβ -Markov model of least-squares adjustment. This model was upgraded by including the robust estimation of errors of observations, where the observations are represented by single photo measurements of homologous points. The expression "robust" refers especially to the feature of statistical estimators and it ensures that such estimators are as insensitive to large deviations in the data as possible. The deviations represent the difference between the measured and estimated or adjusted data values.

In the techniques of robust estimation of observations there is great attention given to a proper designation of weights per single observations, which are included into the adjustment process. The weights are assigned according to the chosen weight function, which is for our case represented in Figure 7.

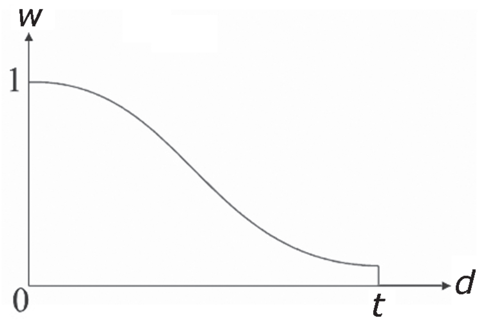

Figure 7: *Weight function (d – observation error, w – weight, t – tolerance threshold).*

Weight function equation:

$$w(d_i) = \begin{cases} \dfrac{1}{1+(a\cdot|d_i|)^b} & \text{za } d \le t \\ 0 & \text{za } d > t \end{cases} \qquad (3)$$

Parameters a and b in the weight function determine the shape of the curve, where $a > 0$ and $b > 0$.

Since observations are always subject to errors, the estimated values of parameters or unknowns are under their direct influence. In order to stop the transfer of large and gross errors to the parameters needed, and deterioration of their quality, we determine the proportion of influence of single observations to the unknowns proportionately to the size of their error and the weight is assigned accordingly. The weight is, therefore, the value adjusting the observation influences, also eliminating the gross errors from the adjustment procedure.

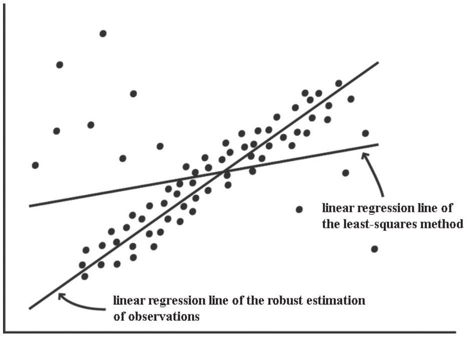

Figure 8: *Illustration of comparison of the least-squares method and the robust estimation technique.*

It is interesting to compare the robust estimation technique with the least-squares method, which is highly applied in geodesy. Graphically, the difference between the methods is shown on a simple case in Figure 8. In case of the least-squares method, the parameters (in the figure the parameters are coefficients *a* and *b* of linear regression) are highly influenced by gross error observations, while in the case of the robust estimation the determination of unknown parameters is not influenced by gross error observations. Since the reliability of automated determination and measurement of homologous points is, as expected, poorer than that obtained by the manual techniques, the application of the robust estimation techniques is essential.

6 PERFORMANCE AND RESULTS OF AUTOMATED RELATIVE ORIENTATION

The practical part of the study included the making of computer programs in the form of modules (in the environment Visual C++ 6.0). A particular module solves a particular phase of the process, however, through their relatedness a full automatisation of calculation of parameters of relative orientation is achieved. The modular structure is acceptable based on several aspects, the main reason being the easier testing of single phases and determination of their successful operation; besides, the particular modules can be used in other photogrammetric tasks.

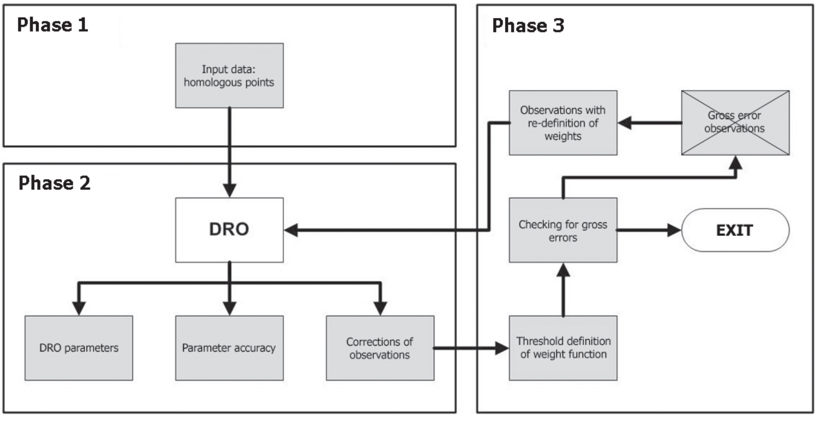

Figure 9: *Diagram of implementation of automated relative orientation (DRO – digital relative orientation).*

The procedure was divided into three phases: acquisition of input data (phase 1), calculation of parameters of relative orientation (numerical and digital relative orientation – DRO; phase 2) and error estimation of observations (phase 3). The making of computer programs was rather demanding, since it involved complex mathematical algorithms, which had to be linked into a coherent whole. Figure 9 shows the making and connectedness of single parts of the phases mentioned.

The correctness of operation of each phase was checked against aerial images, where the photo imaging and parameters of orientation (inner, relative and absolute) were already at hand. The numerical results obtained by automated relative orientation coincided with those gained using the standard aerial triangulation procedure (Kogoj et al., 2006).

The practical operation was then tested in terrestrial imaging, where the procedure will finally be applied. The recording was performed with a pair of regular digital cameras Canon XM1, which were fixed to a metal mount at a fixed distance of approximately 1 m (Figure 10). The cameras were pre-calibrated, meaning that their parameters of inner orientation (focal length, principal point and lens distortion) were known.

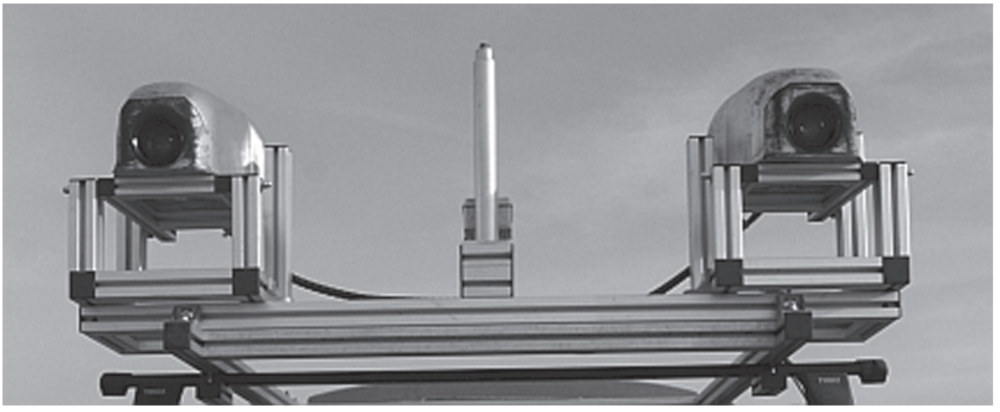

Figure 10: *A pair of digital cameras Canon XM1, fixed on a metal mount.*

The aim of the test was to test the operation of the developed system under real conditions that included field imaging with two video cameras of medium resolution.

The input data (homologous points) were captured in different ways: manually, semi-automatically and automatically, then the parameters of relative orientation were calculated in both ways (independent RO, dependent RO) and the results were compared. The manual and semi-automated measurements were performed in DOG program (developed and owned by: DFG CONSULTING d.o.o.). The details of the performed tests are published in Kogoj et al. (2006). The collected results of the calculation of parameters of relative orientation are represented in Table 1, and that both for the independent and dependent methods of relative orientation.

To understand Table 1 we must clarify the contents of stereo pairs marked 1–5. Stereo pair 1 is the image of the façade, stereo pair 2 has the same content, but it was recorded at a different moment of time. In the case of stereo pair 3 we used a special metal frame which was fitted with targets, which ensure a good distribution and recognition of input points for relative orientation (Figure 11).

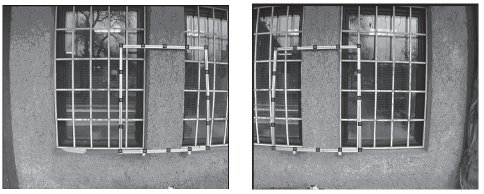

Figure 11: *Case of stereo pair 3 with targets fitted to the frame. Stereo pairs 1 and 2 have the same content, although without the frame.*

Stereo pair 4 was recorded so that the frame with the targets was moved in the area of the stereo overlap. In practice, in terrestrial images it often occurs that a part of the image is represented by the sky, when one is unable to extract points in certain locations. By moving the frame (time synchronisation of both images is necessary) we can ensure appropriate points in the entire area of overlap. Stereo pair 5, where we performed an almost fully automated calculation of relative orientation, is in its contents the same as stereo pair 4 (moving of the frame). In such imaging configuration which is, as said before, the closest to the real situation (sky in the background, as opposed to stereo pairs 1, 2 and 3), it was sensible to test the robustness of the algorithm of the fully automated relative orientation.

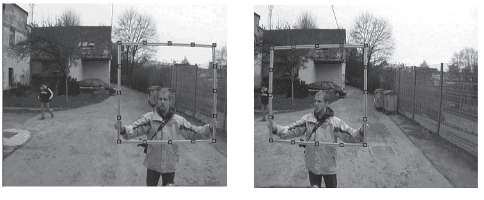

Figure 12: *Case of stereo pairs 4 and 5 by shifting of the frame.*

The results of independent and dependent relative orientation for the stereo pairs 1–5 are collected in Table 1.

Independent RO		ω' [gon]	φ' [gon]	κ' [gon]	φ'' [gon]	κ'' [gon]
Manual / semi-automated extraction of input data	Stereo pair 1	1.126	-1.936	-1.332	-0.067	-1.614
	Stereo pair 2	0.890	-1.716	-0.788	0.249	-1.078
	Stereo pair 3	1.162	-1.620	-1.288	0.149	-1.581
	Stereo pair 4	1.151	-1.840	-1.369	-0.006	-1.620
ARO	Stereo pair 5	0.874	-1.808	-0.694	-0.410	-0.867
Average value of a parameter		1.007	-1.783	-1.028	0.045	-1.293
Highest deviation		0.155	0.163	-0.341	-0.455	0.426

Dependent RO		by [m]	bz [m]	ω [gon]	φ [gon]	κ [gon]
Manual / semi-automated extraction of input data	Stereo pair 1	-0.021	0.030	-1.118	1.873	-0.249
	Stereo pair 2	-0.022	0.028	-1.145	1.837	-0.216
	Stereo pair 3	-0.013	0.027	-0.882	1.969	-0.263
	Stereo pair 4	-0.021	0.025	-1.155	1.774	-0.261
ARO	Stereo pair 5	-0.011	0.028	-0.844	1.486	-0.167
Average value of a parameter		-0.017	0.028	-0.996	1.845	-0.239
Highest deviation		-0.006	-0.003	-0.159	0.287	0.072

Table 1: *Results of independent and dependent relative orientation.*

On the left side of Table 1 the results of independent relative orientation, and on the right side the results of dependent relative orientation. In the upper part of both tables the results of relative orientation of manual or semi-automated extraction of input data (DRO – digital relative orientation; stereo pairs 1, 2, 3 and 4) are shown, followed by the results of the automated extraction (ARO; stereo pair 5). The last two lines show the average value of each parameter and the highest deviation, which is the highest absolute difference between the parameter value for a stereo pair and its mean. The differences between the calculated parameters are at a first glance rather large, however, in our opinion, this is due to the poor technical characteristics of the system and not the result of incorrectness of the algorithms used. The recording system used is intended primarily for recording of spatial structures from a distance of up to 50 m, with the recording angle of 75° and the size of digital images of 720 x 576 pixels. Under such conditions, the angle deviation in the size between 0.4 and 0.5 gon in an image represents a difference of 2–3 pixels only. The results might have been better if the calibration of the cameras was repeated prior to the recording; this, however, was not done due to time restraints.

In analysing the results of dependent relative orientation we have also seen that the differences between the stereo pairs are rather large, however, considering all aspects, they are considerably smaller when compared to the independent method. The deviations of baseline components *by* and *bz*, which include the mechanical instability of the cameras fixed to a mount, are especially small (maximum deviation from the arithmetic mean is smaller than 1 cm).

7 CONCLUSION

The research project »»Development of methods and systems for terrain image capture, detection and target recognition« (Kogoj et al., 2006), which provided the frame for this study, was too extensive. The following topics were covered within the project: 1) detection of structures based on movement, 2) recognition of structures based on features (e.g. colours, shapes), 3) determination of the position of a structure based on stereo pairs and definition of direction and velocity of moving objects. Since we were primarily interested in dynamic field systems, a preliminary relative orientation of stereo pairs, taken with a digital (video) camera is necessary for the determination of the position of a structure (or in the broadest sense of the target, that is, the subject matter of our interest).

Within the study, we proposed a methodology and computer algorithms that fully automate the relative orientation procedure, which helped to solve on of the key problems of the project. Much time was needed for the selection and detailed study of different algorithms, producing the methodology and making of the computer programs. Different tests helped us to establish the correctness of operation of the programs and applicability under real circumstances of image recordings. We found that the computer modules operated in a correct manner, however, some of them should be optimized; the recording system of the digital cameras used, however, had certain disadvantages (smaller sensor resolution and camera stability). Practical testing showed that the automatisation of relative orientation was successful and reliable, if the procedure was introduced by control of error estimate. And above all, the results were acquired in a faster way than when using the manual or semi-automated methods, respectively. The saving in time depends primarily on the number of input measurements (image points).

The end goal is the making of a terrain imaging system, by making the use of digital photographic and video cameras, which would ensure the spatial position of objects in real time. Within the research described, we produced the corner stones needed for the realization of such a system.

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