AUTOMATIC RELATIVE ORIENTATION - REALIZATION AND OPERATIONAL TESTS

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ABSTRACT

An automatic procedure for relative orientation (ARO) of aerial images was developed and implemented in the digital photogrammetric workstation PHODIS ST from Carl Zeiss. The algorithm is designed and realized based on practical conditions with respect to available prior knowledge, speed of computation, and obtainable accuracy. A coarse-to-fine strategy using image pyramids is incorporated into the algorithm. A feature-based image matching is first carried out to determine conjugate points in the image pair on higher pyramid levels. Then, a fine measurement of image coordinates of conjugate points is done by a least squares image matching through the rest of pyramid levels down to the original images. In order to prove the practical applicability of ARO, a large number of stereopairs of aerial images was investigated. The selected stereopairs show different terrain types and ground cover. They are of various scales ranging from 1:3,200 to 1:820,000 and scanned with different pixel sizes. About 100 well-distributed conjugate points per stereopair were selected for the final computation of the relative orientation parameters. The obtained root-mean-square standard deviations of the image coordinates generally lie between 0.2 and 0.4 pixel. Stereo models were found to be free of y-parallaxes by skilled human operators. The elapsed computing time was about 75 sec per stereopair scanned with 30 µm pixel size and in between 2 and 3 min for a 15 µm stereo pair on a Silicon Graphics Indy with R4400 processor (150 MHz). The paper deals with the realization of the algorithm and reports on the results of the intensive operational tests. It could be proven that ARO is ready for photogrammetric practice.

KURZFASSUNG

Eine automatische Prozedur für die relative Orientierung von Luftbildern wurde für die digitale photogrammetrische Arbeitsstation PHODIS ST von Carl Zeiss entwickelt und im PHODIS-System implementiert. Die Konzeption des Algorithmus' setzt praktische Anforderungen bezüglich vorhandenen Vorwissens, der Rechengeschwindigkeit und erreichbarer Genauigkeit voraus. Im Algorithmus wird eine auf Bildpyramiden beruhende grob-zu-fein Strategie eingesetzt. Zunächst findet eine merkmalsgestützte Bildzuordnung auf einer höheren Pyramidenebenen statt, um homologe Punkte in dem Bildpaar zu bestimmen. Danach folgt eine flächenhafte Bildzuordnung nach der Methode der kleinsten Quadrate. Dabei wird jedes vorher bestimmte Punktepaar durch die restlichen Pyramidenebenen bis auf die originale Bildauflösung verfolgt. Um die praktische Einsetzbarkeit der automatischen Prozedur nachzuweisen, wurde eine Reihe von Luftbildpaaren bearbeitet. Die ausgewählten Luftbilder zeigen verschiedene Geländetypen und Bodenbedeckungen, variieren im Maßstab von 1:3,200 bis zu 1:820,000 und haben unterschiedliche Pixelgrößen. Zur endgültigen Berechnung der relativen Orientierungsparameter wurden in der Regel etwa 100 regelmäßig verteilte homologe Punkte pro Bildpaar verwendet. Die erreichten Standardabweichungen der Bildkoordinaten liegen durchschnittlich im Bereich zwischen 0.2 und 0.4 Pixel. Die mit Hilfe der Orientierungsparameter erstellten Stereomodelle erwiesen sich alle als parallaxenfrei. Die Rechenzeit betrug je nach der Bildauflösung ca. 75 Sekunden für ein mit 30 µm gescanntes und zwischen 2 und 3 Minuten für ein mit 15 µm gescanntes Stereopaar. Der vorliegende Beitrag beschreibt die Realisierung des Algorithmus und berichtet über die Ergebnisse der intensiven operationellen Untersuchungen. Es zeigt sich, daß die automatische relative Orientierungsprozedur einsatzreif für die photogrammetrische Praxis ist.

1. INTRODUCTION

Relative orientation is a prerequisite to provide users from photogrammetry and other disciplines with parallax-free stereo viewing for photogrammetric data collection, interpretation purposes and other tasks. In digital stereo photogrammetry, parameters of relative orientation are necessary for epipolar resampling of digital images. Since the beginning of the nineties, research on algorithms for automating the procedure of relative orientation of aerial images has been carried out in several institutions. Reports on these developments can be found in (eg. Hannah, 1989; Schenk et al., 1991; Haala et al., 1993; Wang, 1995).

In order to meet the demand from the photogrammetric practice, a joint project for developing an automatic procedure for relative orientation of digital aerial images was initiated between the Chair for Photogrammetry and Remote Sensing, Technical University Munich and the Carl Zeiss company in early 1993. Reports on preliminary versions of the algorithm can be found in (Tang, Heipke, 1993, 1994), and detailed descriptions of the algorithm and the achieved results of the first implemented version of the end of 1994 were given in (Tang, Heipke, 1996). Since early 1995, the developed automatic relative orientation procedure ARO has been integrated into the digital photogrammetric workstation PHODIS ST from Carl Zeiss (Dörstel 1995). It is also the core matching routine for the software package PHODIS AT for automatic aerial triangulation (Braun et al. 1996). In order to prove the practical applicability of ARO, 53 stereopairs of aerial images were used for intensive operational tests, which were finished in early 1996.

The paper reports on ARO updates, discusses some implementation aspects and presents the test results.

2. ALGORITHM

The concept and the implementation are based on practical conditions with respect to available prior knowledge, speed of computation and obtainable accuracy. In addition to image data, some readily available input information must be provided:

- the interior orientation parameters of the camera,
- the relationship between image and pixel coordinate system, and
- the order of images (eg. left or right).

A coarse-to-fine strategy based on image pyramids is incorporated into the algorithm. ARO starts from the highest pyramid level with the smallest image size and the lowest resolution, and ends at the lowest level with the original size and resolution. The whole procedure is subdivided into two parts. The first one, called point matching, runs from the highest pyramid level until a so-called intermediate one. The second part is called point tracking and runs through the remaining levels. The criterion for defining the intermediate level is to arrive at an optimal combination of the use of the available amount of information and the computation time.

During point matching, a feature-based matching is performed to determine conjugate points. For each level, point features are first extracted separately in each image using an interest operator. They are then matched according to certain geometric and radiometric criteria, resulting in a list of candidates for conjugate points. These candidate point pairs are further introduced into a robust bundle adjustment procedure, which determines both the relative orientation parameters of the image pair and the three-dimensional coordinates of the conjugate points. Outliers are also detected and eliminated during the robust bundle adjustment and by a further consistency check. The orientation parameters and the three-dimensional coordinates obtained are finally forwarded to the next lower pyramid level, supporting the feature-based matching there. The point matching stops at the intermediate level. The final results of the point matching are the relative orientation parameters of the image pair and the three-dimensional coordinates of the conjugate points determined at the intermediate level.

In the second step, called point tracking, a fine measurement of the image coordinates of the conjugate points determined at the intermediate level is conducted by least squares matching (LSM, Ackermann, 1983) through the remaining pyramid levels. Around a given point pair at the intermediate level, a reference and a search window are defined. Six affine parameters and two radiometric ones are calculated between the two windows in an iterative way. For each matched pair, the cross correlation coefficient between the two surrounding windows is then computed. If the coefficient is larger than a threshold, the match is declared successful. The interest operator is used again in the reference window to find a proper point for transfer to the next lower pyramid level. This point is then transformed to the search window via the affine parameters, defining the corresponding point there. These two points are mapped onto the next lower pyramid level and the LSM is repeated. At the end of point tracking, conjugate points successfully tracked to the original images are entered into the robust bundle adjustment again for computing the final relative orientation parameters of the images and the three-dimensional coordinates of the conjugate points. The point tracking is of great advantage to speed up the whole procedure without suffering any loss in accuracy and reliability of the results. It ensures that the search for conjugate points is done only in areas in which well-defined features can be expected.

3. IMPLEMENTATION

In addition to speeding up the algorithm while maintaining the reliability of the result, special attention was paid during the implementation of ARO in PHODIS ST to

- restrict user input parameters to a very limit, and
- keep the number of conjugate points in the image pair to a reasonable number.

For point matching a number of control parameters such as window sizes and threshold values exists. Their optimal setting changes with different kinds of image texture, scale and terrain types. In order to avoid the parameter setting by users, a number of different sets of control parameters is used for point matching on every pyramid level. This has the advantage that the control parameters can be adapted to the image material. However, the computation time increases if runs with multiple parameter sets are performed one after the other. Therefore, all the different parameter sets are used in a one-pass operation in the current implementation. This leads to a decrease of the computing time while maintaining the reliability of the results.

Approximate overlap values of an image pair were optional parameters in the early algorithm. The current implementation includes a function that determines the overlaps automatically, so that a user input is no more necessary. First, the feature-based matching is performed assuming the overlaps to be 80% end overlap and 100% side overlap, however with a large tolerance. Using the matched point pairs, a robust least squares adjustment of the x- and y-parallaxes is then conducted. In this way, outliers in the matches are also eliminated to some extent. The adjusted parallaxes approximately represent the base components in image space and overlap values can directly be derived from these values.

Usually, the number of conjugate points determined by the automatic procedure from an image pair can be unnecessarily large for the computation of the relative orientation parameters. Therefore, the current implementation tracks conjugate points only selectively. A grid is used in the overlapping area to control the point selection. This also speeds up ARO considerably, since point tracking needs a lot of I/O operations and is thus very time-consuming.

In summary, the current implementation of ARO in PHODIS ST requires no user input parameters except the order of images, because the camera data and the pixel-image coordinate relationship belong to the standard PHODIS image. The preparation steps of ARO are:

- define the left and the right image,
- check whether the image information is complete, eg. camera, interior orientation and pyramid,
- if not complete, call corresponding tools to accomplish it,
- if complete, start the procedure.

4. OPERATIONAL TESTS

In order to assess ARO for the photogrammetric practice, the algorithm was tested with 53 image pairs. The image pairs differ in pixel size (12.5-30 μm), ground cover (rural, forested, urban, glacial, desert), and terrain type (flat, rolling, mountainous). Image scales range from 1:3,200 to 1:54,000.

Table 1 contains a classification of 47 image pairs into 9 groups according to image scale and ground cover/terrain type. Moreover, 6 special cases have been investigated in order to find out the limits of the developed approach. These are characterized in Table 2.

In the following the test procedure is described. First the analogue images were scanned, mostly with a pixel size of either 15μm or 30μm and 8 bits per pixel. In the next step image pyramids were generated. Then, the interior orientation of the images was determined using either the automatic module AIO (Automatic Interior Orientation) of PHODIS ST, or interactive measurements. Then, ARO was started. No parameters whatsoever had to be provided for ARO. For verification purposes, epipolar images were computed using the orientation parameters from ARO. Finally, the epipolar images were checked for remaining y-parallaxes by stereoscopic viewing in the PHODIS ST environment.

In the sequel the results of the successful ARO runs are discussed with regard to remaining y-parallaxes in the stereomodel, accuracy, reliability and computing time. The main focus is to analyze the accuracy, represented by the variance factor σ_0 a posteriori, as a function of image scale, ground cover, terrain type, pixel size, overlap, number of conjugate pairs and image quality. While ARO was successful for all stereo pairs of Table 1, the procedure failed in three of the special cases of Table 2. These are discussed towards the end of the chapter.

The following observations can be made from the obtained results of the successful ARO runs:

- The models checked on the PHODIS ST stereoplotter were all found to be free of y-parallaxes.
- The σ_0 as a measure of the overall accuracy ranges approximately between 0.2 and 0.4 pixel.
- 70-190 well distributed conjugate pairs provide a high reliability for the five estimated orientation parameters.
- The elapsed computing time amounts to 75 sec (30μm pixel size) and 2-3 min (15μm pixel size) for an stereo pair on a Silicon Graphics Indy with R4400 processor (150 MHz).

Tables 3-6 show the σ_0 for different image scales, terrain types, pixel sizes, overlap and number of conjugate pairs. It can be seen from Table 3 that the terrain type has no significant influence on the accuracy of the results, and that the accuracy is getting only slightly poorer as the image scale decreases. The accuracy, however, is highly dependent on the pixel size of the scanned images. Table 4 shows that σ_0 for images with a large pixel size (mostly 30μm) is about half of the value for images with a small (mostly 15μm) pixel size. This result is in contradiction to the assumption that the accuracy of image matching mainly depends on the pixel size. At this stage we have no explanation for these findings, and further theoretical and empirical investigations will be conducted to clarify this point.

As represented in Table 5 an end overlap of 80% or more provides a significantly better accuracy than 60 %. This finding is not surprising, because the larger the overlap the more similar are the images. The influence of the number of conjugate points on σ_0 is clearly visible in Table 6. σ_0 decreases with increasing number of conjugate points.

As a typical example the results of the stereo pair Lohja are depicted in Figure 1. The two images are superimposed with the extracted conjugate points at level 0 of the image pyramid.

In three of the special cases ARO failed to produce correct results. The reason is that these cases violate at least one of the assumptions incorporated into the algorithm. It should be noted, however, that these extreme cases do not occur in usual aerial photogrammetry.

- Homburg: the image scale of the two images differs too much,
- Istanbul: the overlap is too small,
- Burghausen: the rotation difference is too large.

The other three of the special cases from Table 2 could be processed successfully. This was not much of a surprise for the spaceborne example depicted in Figure 2. Interesting is the fact that the problems with the dangerous cylinder in the example Schelingen could be overcome. The algorithm extracted less conjugate points as compared to the other cases, and the accuracy was not excellent either, but the subsequently computed epipolar imagery was free of y-parallaxes. This is in contrast to an unsuccessful attempt to manually orient the stereo pair on an analytical plotter. Perhaps surprisingly, ARO also performed well for the close range example Felsendom. The results are shown in Figure 3. This example should, however, not be interpreted as a statement, according to which ARO can handel close range imagery. More experiments need to be performed in order to assess the potential of our algorithm for such applications.

5. CONCLUSIONS AND OUTLOOK

The paper reports on the results of an investigation of automatic relative orientation. Concept, algorithm and realization are described. Test strategies and runs with 53 different stereo pairs are presented. About 100 well distributed point pairs were selected for each model, except for three extreme cases. Many more point pairs could be made available. The obtained root-mean-square standard deviations of image coordinates generally lie between 0.2 and 0.4 pixel. Stereo models were found to be free of y-parallaxes by skilled human operators. The elapsed computing time was about 75 sec per stereopair scanned with 30 μm pixel size and in between 2 and 3 min for a 15 μm stereo pair on a Silicon Graphics Indy with R4400 processor (150 MHz). It could be proven that the automatic relative orientation procedure is ready for photogrammetric practice.

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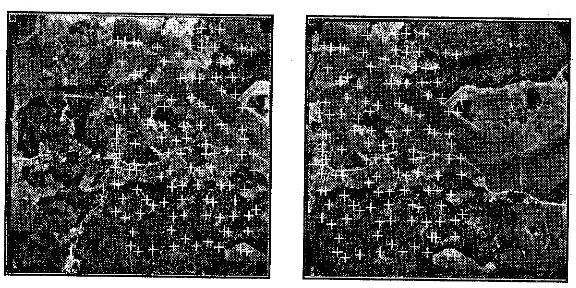

Figure 1: Conjugate points in stereo image pair (level 0) of model Lohja

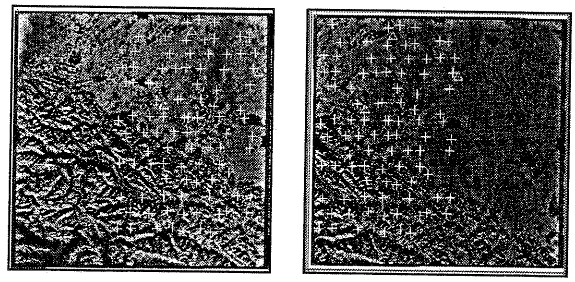

Figure 2: Conjugate points in stereo image pair (level 0) of model Spacelab (Images courtesy of the European Space Agency)

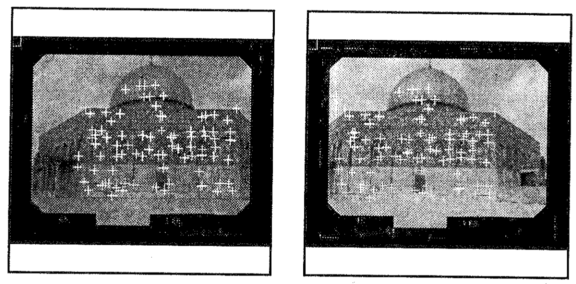

Figure 3: Conjugate points in stereo image pair (level 0) of model Felsendom

	rural, forested cover, flat and rolling terrain	urban terrain	glacial cover, mountainous terrain
M > 1:6,000	4	10	-
1:6,000 < M < 1:15,000	7	2	2
M < 1:15,000	5	3	14

Table 1: Tested image pairs, classified depending on image scale and ground cover/terrain type

project	image scale	description
Homburg	1:1,000,1:1,800	scale factor difference 1.8
Istanbul	1:4,000	overlap 40 %
Burghausen	1:15,000	rotation difference 40 deg
Schelingen	1:6,000	dangerous cylinder
Spacelab	1:820,000	spaceborne imagery
Felsendom	1:300	close range imagery

Table 2: Tested image pairs - special cases

	flat, rolling terrain	urban terrain	mountainous terrain
M > 1:6,000	0.24	0.35	-
1:6,000 < M < 1:15,000	0.26	0.38	0.25
M < 1:15,000	0.44	0.44	0.28

Table 3: σ_0 [pixel] as depending on image scale M and terrain type

pixel size [μm]	number of image pairs	σ_0 [pixel]
small (mostly 15μm)	18	0.40
large (mostly 30 μm)	29	0.26

Table 4: σ_0 as depending on the pixel size

end overlap	number of image pairs	σ_0 [pixel]
approximately 60 %	32	0.37
approximately 80 %	15	0.22

Table 5: σ_0 as depending on the end overlap

number of conjugate points	number of image pairs	σ_0 [pixel]
< 80	12	0.45
80 - 160	29	0.29
> 160	6	0.18

Table 6: σ_0 as depending on the number of conjugate pairs