DO IT ON THE GROUND: INCREASING RELIABILITY AND ACCURACY OF AUTOMATIC AEROTRIANGULATION BY MATCHING IN THE OBJECT SPACE

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ABSTRACT

Automatic aerotriangulation is one of the major topics currently studied by the photogrammetric research community. Its motivations are the potential increase in efficiency, accuracy and reliability of the aerotriangulation task. The work described here is concerned with the last step of automatic aerotriangulation, which is automatically matching conjugate points from more than two images. The matching strategy proposed in the paper is *multiple-patch matching in the object space*. It is based on iterative reconstruction of small object surfaces around tie points, and matching multiple image patches simultaneously. In this paper, the idea is described, and experimental results are shown and discussed.

1 INTRODUCTION

Aerotriangulation has been a common photogrammetric technique for obtaining exterior (and possibly interior) orientation parameters for a set of aerial photographs. Its main purpose is to reduce the number of ground control points required for orienting these photographs. Rather than a few ground control points for each stereo model (minimum three), such points are required less often, which reduces the cost of a photogrammetric mapping project considerably.

One of the major tasks in aerotriangulation is the measurement of conjugate points on two or more partially overlapping photographs. These points tie the photographs to each other. With the current trend towards digital photogrammetry, and the use of softcopy photogrammetric workstations, there is a growing interest in automating the aerotriangulation task [Ackermann (1995)], and particularly the measurement of tie points. This interest is motivated by three key factors:

- **Efficiency:** Manual aerotriangulation, carried out by a human operator, is a time consuming procedure. Conducting it automatically in a batch mode, or even in a semi-interactive environment will save many human working hours.
- **Accuracy:** Hardcopy photographs are usually superior to digital images in terms of resolution. Automatic measurement using sub-pixel algorithms, compensates for the inferiority of the digital images, and also allows simultaneous measurement on more than two images, which is not possible for a human operator.
- **Reliability:** Compared to a human operator, an automated system is capable of finding a large number of tie points during relatively short time. This in turn leads to more reliable results since the redundancy is large and blunders are detected easily.

Research studies describing ways for automating the aerotriangulation procedure were presented in [Helava (1988), Ackermann and Tsingas (1994), Agouris (1992)] (see [Krupnik (1994)] for a more detailed description). "The most comprehensive and sophisticated concept for fully automatic aerial triangulation..." [Ackermann (1995)] is the *Automatic AeroTriangulation System* (AATS), presented in [Schenk and Toth (1993), Toth and Krupnik (1996)]. The last phase of AATS, accurate, multiple-patch matching is the main concern of this paper.

Although accurate matching has been the subject of numerous research studies in the fields of photogrammetry and computer vision (see e.g., Baltsavias (1991), Dhond and Aggarwal (1989), Lemmens (1988), Wrobel (1988) for reviews), its application for aerotriangulation adds some new aspects that have not been fully addressed:

- The exterior orientation parameters are not known. Therefore, constraining the search space for the matching by geometric conditions, e.g., the epipolar line, is not possible.
- The accuracy requirements are more demanding than in other applications (e.g., automatic generation of DEM).
- Only a single point is matched in each area. Therefore the matching should be sufficiently reliable, and not dependent upon the surrounding surface for determining wrong solutions.
- More than two overlapping image patches are used at each matching location. In order to obtain consistency, a simultaneous matching of more than two image patches is required.

These aspects are addressed and considered in the *multiple-patch matching in the object space*, presented in this paper. The method is based on hierarchically reconstructing the elevations of small surface patches, centered around each matched tie point. Having these surface patches, image patches (two or more) are warped and simultaneously matched. Each iteration of the algorithm improves both the calculated orientation parameters and the surface patches around each point.

In the following sections, the motivations for the proposed algorithm are explained, the algorithm is shown, and experimental results are presented and discussed.

2 MOTIVATIONS AND BASIC CONCEPTS

Three main goals motivated the design of the matching approach presented in this paper. These goals are emerged from the aspects described in the previous section and the lack of sufficient solutions for them.

1. **Reliable matching with single points:**
   Failures in area-based matching are usually rooted in insufficient information within the matching windows. In DEM generation applications for example, constraints are used for obtaining reliable results. The object surface is assumed to be smooth, or at least smooth between discontinuities. If the disparity at a certain point is considerably different from its surroundings (i.e., the matching procedure converged to a wrong location), or if a solution cannot be obtained, an elevation is calculated by interpolation from the neighboring points. When only a single point is required at each location, which is the case in automatic aerotriangulation, it is not possible to use the smoothness constraint to check the reliability of the results.

   A possible solution is to use large matching windows, which are more likely to contain sufficient information. This however, leads to inaccuracies if conventional area-based matching techniques are used. In these techniques, the shape of the object surface is assumed to be a horizontal plane (in straightforward cross-correlation without shaping) or a tilted plane (in least-squares matching using an affine transformation).

   The idea in the proposed matching method is to reconstruct a small surface patch around each point to be matched, via a hierarchical iterative procedure. The purpose of this reconstruction is to have a better representation of the ground within the matching window. Using the reconstructed ground surface the image patches are warped and the matching is performed between the warped patches. Since the geometric differences are minimized, patches which are significantly larger than those used by traditional methods are accurately matched by a least-squares procedure, using a rather simple transformation.

2. **Avoiding numerical problems and correlation among parameters:**
   Theoretically, the mathematical model of least-squares matching may include the surface elevations and the exterior orientation parameters (see e.g., Ebner *et al.* (1993)). However, when these parameters are introduced as unknowns in the LSM, numerical problems may lead to a weak solution. The cause for these problems are dependencies between the parameters. For example, such dependencies exist between the elevations and some of the exterior orientation parameters.

   A possible solution is to alternate alternating two groups of unknowns within adjustment procedure. The image patches at each tie point are warped and matched as describe earlier. Then, the entire set of tie points is used for determining the orientation parameters of all the photographs in the block by a standard block adjustment. By alternating these two steps while refining the resolution of the images, the process is converged to the correct location.

3. **Avoiding correlation among observations:**
   When more than two images are used for matching, a mathematical model based on simultaneous adjustment should be used to take advantage of the additional information. One possibility is to use differences between gray values from each possible combination of a pair of images as observations [Agouris (1992)]. With this approach, there are correlations among the observations. For example, if three image patches are considered, and the differences between the first and the second images, and between the first and the third are involved, the differences between the second and third images do not contribute any new information to the solution.

   The proposed matching method uses gray values as observations, rather than gray-value differences. The "true" intensities of the surface (referred to as the *gray values of the surface elements*) are introduced as unknowns in the adjustment.

Two key concepts are used in the multiple-patch matching in the object space, which was derived as a consequence of the motivations described above: matching more than two image patches simultaneously matching warped images (or matching in the object space). The former is described in detail in [Krupnik (1996). The second concept and its use are described here.

When the surface around a certain tie point is known, it is possible to rectify the image patches that cover this area to obtain an orthophotograph. Since in the case described here the surface is approximated but not known, the result of the rectification process are "warped" image patches that are not real orthophotographs. However, geometric differences between warped image patches of the same area are significantly smaller than those of the original image patches. The rationale of matching warped patches is described below.

For the sake of simplicity, the idea is explained here for the one dimensional case with two images only. The extension to the two dimensional case with more than two images is obvious.

Figure 1 shows a schematic description of the geometric situation. For a given point p_ℓ on the left image, the conjugate point p_r' on the right image is sought. If point p_r is an approximation for p_r', an object point P, which does not lie on the true surface, is obtained. Using the available surface elevations (which are not necessarily known a priori, but are approximated and modified during the iterative procedure), the image patches, centered on p_ℓ and p_r are warped. The corrected location found by the matching of the warped images ($\overline{P}$) is then projected back to the image (based, again, on the available surface elevations), and a better approximation is obtained for the matched point. Note that as the differences between the approximate and the true surfaces become smaller, the correction will bring the location found by the matching closer to the true location.

3 OUTLINE OF THE PROPOSED STRATEGY

Figure 2 shows a schematic description of the iterative procedure. Each iteration contains three main phases:

Warping and Matching Phase (Figure 3): Image patches, centered on each tie point, are warped according to the

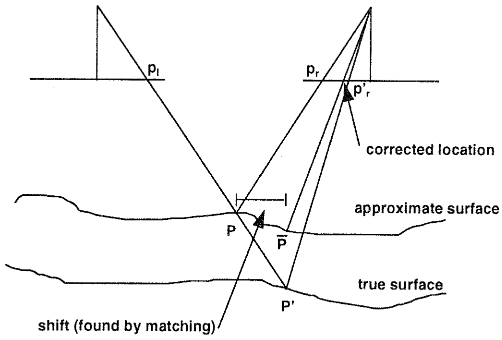

Figure 1: Schematic description of the concept of matching warped images.

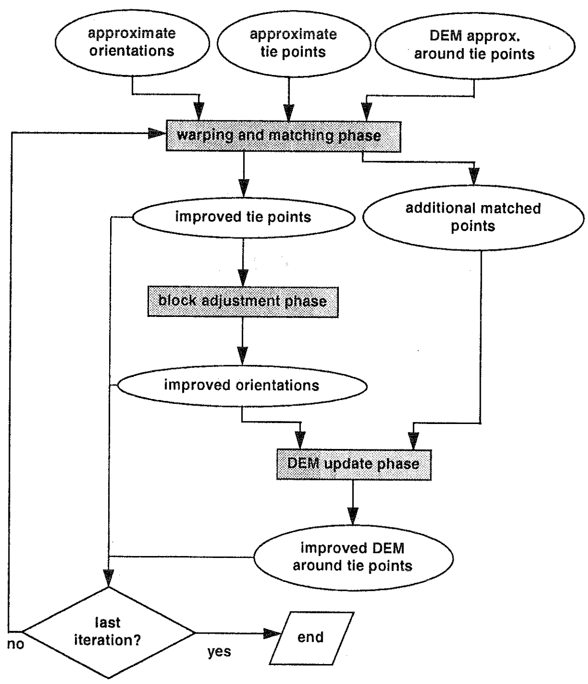

Figure 2: Outline of the proposed matching scheme.

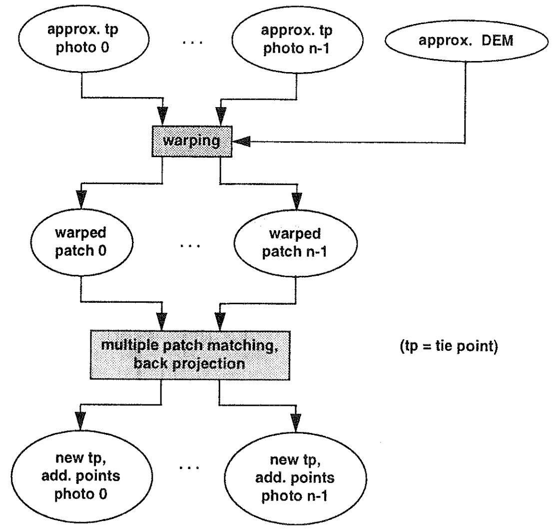

Figure 3: Warping and Matching Phase.

available approximations of the orientation parameters and the surface around the point. When no surface approximation is available, a horizontal plane is assumed. During the final iteration, a multiple-patch matching is performed with these warped image patches to determine the exact image coordinates of the tie point. In all iterations but the last one, a grid is formed in the object space, centered on the approximate tie point. Multiple-patch matching is used (in the same manner as in the last iteration) to match each point on this grid. Each matched grid point is projected back, through the available surface, to the image space. As explained earlier, the resulted photo coordinates are more accurate than those from the previous iteration. The obtained photo-coordinates are used for the "Block Adjustment Phase."

Block Adjustment Phase (Figure 4): The photo-coordinates of the center of the grid found in the "Warping and Matching Phase" constitute the input for a bundle block adjustment. The results of the block adjustment are new (improved) orientation parameters.

DEM Update Phase (Figure 5): Using the new orientation parameters estimated in the "Block Adjustment Phase," a surface is reconstructed around each tie point intersecting the photo-points (from the "Warping and Matching Phase") back to the object space and interpolating them into regular grids. The grid interval is half the interval that was used in the former iteration.

Since each "Warping and Matching" phase yields better locations for the conjugate photo-points, the results of the block adjustment render improved orientation parameters. These orientation parameters, together with the improved conjugate points, lead to better approximations for the object surfaces around each tie point. The process converges iteratively to the desired solution.

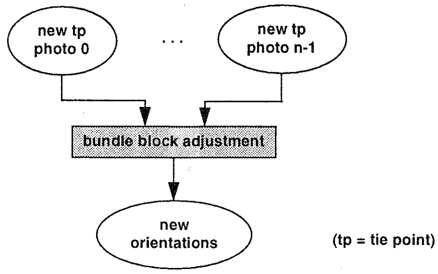

Figure 4: Block Adjustment Phase.

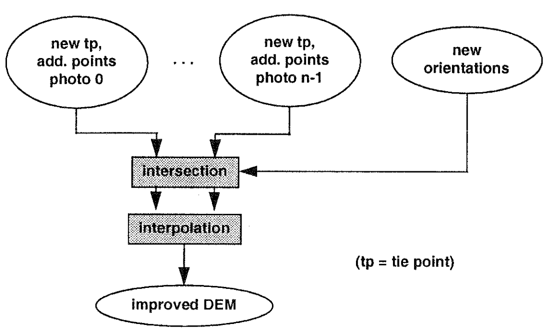

Figure 5: DEM Update Phase.

4 EXPERIMENTS AND RESULTS

The concept of *Multiple-Patch Matching in the Object Space for Aerotriangulation* has been implemented on an Intergraph workstation. The purpose of this implementation is to check the feasibility and effectiveness of the proposed ideas. This section presents the experiments that were performed and discusses the results.

4.1 Data Sets and Reference Measurements

Six data-sets were used for the experiments (see Table 1)*. Each of the first three data sets, OSU, SWISS-2 and WY contains only one stereo model. Using such sets is important in order to check the effect of the object space approach, without involving multiple-patch matching. The other three data-sets, SWISS-3, TEXAS and OEEPE contain areas that are covered by more than two images, and therefore multiple-patch matching must be employed. Images from all data-sets are of relatively large scale. At such a scale, most matching procedures face problems because of foreshortening and surface discontinuities. These problems are less acute with small scale images where a solution is obtained more easily. The scenes described in the images vary: OSU and SWISS show heavily structured urban areas; OEEPE shows rural areas and suburbs; TEXAS shows an air-field (runways, no airplanes or vehicles); and WY shows a rural mountain area.

*SWISS-2 is a subset of SWISS-3. When "SWISS" is mentioned, it refers to both SWISS-2 and SWISS-3.

Table 1: Image configuration of the data-sets.

	# of photos	# of strips	% overlap	Image scale
OSU	2	1	60	1:4000
SWISS-2	2	1	60	1:2500
WY	2	1	60	1:6000
SWISS-3	3	1	60	1:2500
TEXAS	6	2	60/25	1:4000
OEEPE	8	2	60/50	1:4000

Table 2: Point configuration of the data-sets.

	# of	Coverage (images)					$\pm\sigma_0$	Rsd.
	pnts	2	2	4	5	6	[μm]	
OSU	24	24	—	—	—	—	2	2
SWISS-2	24	24	—	—	—	—	3	4
WY	24	24	—	—	—	—	2	3
SWISS-3	36	25	11	—	—	—	4	7
TEXAS	68	39	13	12	1	3	5	12
OEEPE	109	42	22	24	5	16	12	40

In order to obtain both reference (a "ground truth") and approximate coordinates, conjugate points were measured manually for each of the data-sets. In most cases, the locations of the points were selected at the von-Gruber locations. Around each location, a few points were measured in order to facilitate the detection of incorrect matching results. In Table 2, the first column shows the total number of points that were measured in each data-set. The next five columns show the number of points that appear on 2,3,4,5 and 6 photographs, respectively.

The reference points of the OSU and SWISS data-sets were measured on a Zeiss P1 analytical plotter, using the original diapositives. For the WY, TEXAS and OEEPE sets, only digital images were available. Therefore, measurements were performed with an Intergraph softcopy station. The available resolution for the images of the OSU, SWISS and WY sets was 15μm, for the TEXAS set–22.5μm and for OEEPE–30μm.

Quality and consistency of the measurements were checked by a bundle block adjustment. Since no control points were involved (as it would be virtually impossible to distinguish between matching and control errors), seven parameters of the block were fixed. This involved the identification of the block coordinate system with the coordinate system of the first photograph, and setting the scale of the block system to be approximately the scale of the photographs. The results of the bundle adjustment are summarized in the last two columns of Table 2. The accuracy (σ_0), and the maximum residual for each data set are shown.

As noticed from Table 2, the accuracies of the TEXAS and OEEPE data sets are somewhat worse than those of the other sets. There are two possible explanations for this. First, measuring points across strips without marking them on the images is difficult. An attempt was made to measure the points across strips as accurately as possible by creating

Table 3: Parameter setting for the iterative procedure.

Iteration	1	2	3
Pixel size [μm]	240/180	120/90	60/45
Window size	13 × 13	23 × 23	45 × 45
# of matched points	5 × 5	3 × 3	1
Grid interval [μm]	1920/1440	960/720	480/360

Table 4: Results of the matching procedure.

	σ_0	rsd.	# of	# rjctd
OSU	5	6	96	12
SWISS-2	6	9	96	12
WY	6	8	96	0
SWISS-3	6	11	166	18
TEXAS	4	13	376	22
OEEPE	12	46	734	102

Table 5: Comparison between object-space and image-space approaches.

	Object-space			Image-space		
	σ_0	rsd.	rjct.	σ_0	rsd.	rjct.
OSU	5	6	12	7	13	20
SWISS-2	6	9	12	9	11	16
WY	5	8	0	5	6	12

Table 6: Comparison between the matching results and reference measurements.

	Matching results		Ref. measur.	
	σ_0	rsd.	σ_0	rsd.
OSU	5	6	2	2
SWISS-2	6	9	3	4
WY	6	8	5	3
SWISS-3	6	11	4	7
TEXAS	4	14	5	12
OEEPE	12	40	11	31

"models" with images from different strips. However, measuring exactly the same point on more than two images is not possible. The second reason is the relatively low resolution levels (22.5 μm and 30 μm, respectively) that were available for the images of these sets. Nevertheless, an overall accuracy of one fifth of a pixel was obtained for the TEXAS set, and approximately one third of a pixel for OEEPE.

4.2 Results

The manually measured reference points provided approximations for the matching procedure. Normally, approximations that are obtained through an automated procedure (like AATS) are not as good as those considered here. However, preliminary experiments (see Krupnik (1994)) showed that adding errors of up to 2 pixels to the coordinates obtained from the reference data hardly changed the results. Furthermore, the main idea of the object-space approach is to improve the accuracy of the results by improving the mathematical model of the matching, assuming that the reliability problem has been solved by increasing the size of the matching window. Therefore, it was decided not to add errors to the reference image coordinates.

For the iterative procedure, three levels were chosen. The pixel size, the size of the matching windows, the number of matched points and the grid interval for each iteration are shown in Table 3. In the entries of the table that contain two values, the first value refers to the OSU, WY, SWISS and OEEPE data-sets, and the second value refer to the TEXAS data-set. As can by observed, the resolution of the final level is lower than the available resolution. This enabled a comparison with the results obtained by the manual measurements.

Table 4 shows the results of the matching in the object space. For each data-set, the overall accuracy, the maximum residual, the total number of observations and the number of rejected observations are shown. It should be noted that in order to simplify the testing procedure, for each point where a blunder was detected (i.e., the matching diverged or converged to a wrong location), all the observations were not considered.

In the case of only two images, the results can be easily compared to results of a traditional matching procedure. A standard least-square matching was applied to the OSU, WY and SWISS-2 data-sets. The same approximations and window size (45 pixels) as in the object-space case were used. The results are compared in Table 5. Since not the same points were rejected in both cases, only points that were considered in both cases were used in the comparison.

The comparison shows a clear advantage of the object-space approach on the image space approach for the first two data sets. Both σ_0 and the maximum residual are smaller in the results of the object space approach. For the WY data set, there is no significant difference between the results of the two methods. Recalling the image contents of the data sets, these results are expected. The WY data set covers a smooth rural area. Although there are elevation differences, no significant discontinuities and gradient changes exist within a matching window. Therefore, the mathematical model of the image-space matching, i.e., approximating the object surface as a plane, still leads to satisfactory results. On the other hand, the two other data sets, OSU and SWISS-2, contain many man-made features which cause discontinuities and gradient changes in the surface within the matching window. Obtaining a better approximation of the surface and matching in the object space lead to much better results.

The matching results of all the data sets were also compared to those of the manual measurements. As was done in the previous comparison, points that were rejected by the matching, were also removed from the adjustment of the manual measurements, in order to allow an objective comparison. The comparison is shown in Table 6.

For the OSU, SWISS-2 and WY data sets, the results of the manual measurements are better than the matching results. Nevertheless, the matching was performed with 60 μm resolution images, while the manual measurements were done on analog photographs (for the OSU and SWISS-2 data-sets) and 15 μm resolution images (for the WY set). For the SWISS-3, TEXAS and OEEPE data-sets, the results of the matching procedure are comparable to the manual measurements, despite the inferiority of the images that were used for the matching. These results point to the advantage of the matching procedure on the manual measurements. Points that appear on more than two images are matched simultaneously, while during the manual procedure they are measured in pairs. The matching procedure therefore contributes to the consistency in identifying exactly the same point on more than two images. Overall accuracy of the matching was between 1/5 and 1/12 of a pixel.

5 SUMMARY

A method for accurate and reliable image matching of points for aerotriangulation was developed and tested. In order to increase reliability, large image patches that are more likely to contain significant information are necessary. Most matching methods use small image patches because the object surface around the matching area is assumed planar. In the method presented here, the matching is performed in the object space which minimizes the geometric differences between the matched patches. Consequently, much larger image patches are used and the accuracy and the reliability are increased.

The method has been derived theoretically and then implemented in order to show its effects on aerotriangulation. The experimental results described earlier are summarized in the following determinations:

- The accuracy of the matching results is 1/12-1/5 of a pixel. Although images of relatively coarse resolution were used (30–60 μm), the results compare favorably with manual aerotriangulation. If higher resolution images were used for the matching, better results would have been expected.
- The proposed matching scheme performs better than traditional matching methods in areas that include surface discontinuities. The results are similar to image-space matching when smooth surfaces are involved.
- Since multiple images are simultaneously matched, the method is superior to manual measurements because a human operator cannot measure on more than two images simultaneously.

These results are very encouraging. They show that by employing multiple-patch matching in the object space, conjugate points for aerotriangulation with accuracy that exceeds manual measurements may be obtained. Together with the increase in efficiency by an automated procedure, these results lead to a new era of automated, accurate and reliable digital aerotriangulation.

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