An Integral Approach to Automatic Aerial Triangulation and Automatic DEM Generation

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Commision III, Working Group III/2

KEY WORDS: Automatic aerial triangulation, automatic DEM generation, multiple image matching

ABSTRACT:

Automatic aerial triangulation will push the economical efficiency of digital photogrammetry to a new level since the time consuming block preparation is avoided and costly interactive input is substantially reduced. Automatic aerial triangulation appears as a turnkey method if it is combined with an integrated DEM generation process, which takes full advantage of the multiple image overlap instead of the standard stereo overlap.

The paper presents a new approach to automatic aerial triangulation that comprises the automatic derivation of tie point areas (= Gruber point positions) and a hierarchical matching of tie point clusters as well. The kernel of the system is an integrated bundle solution which robustly matches feature points in multiple images and estimates orientation parameters simultaneously. The approach comprises point selection, point measurement, point transfer and block adjustment in one process. DEMs are generated either locally in the tie point areas or for the entire block rigorously using the multiple image overlap wherever possible.

The paper outlines the approach for automatic aerial triangulation and reports on practical results assessed in several controlled tests. The examples given include the initialization part of the system and the automatic block adjustment as well. The results for 30 µm pixel size indicate that the approach leads to excellent results in the block adjustment, which meet at least the accuracy requirements of a standard aerial triangulation. The computation time of the entire automatic block adjustment is better than 6 minutes per image. The benefit of the integrated DEM generation is demonstrated with the OEEPE FORSSA test block by comparing the results of the block DEM against the theoretical results of the automatic block adjustment. Preliminary results indicate a DEM accuracy of 0.1 ‰ of the flying height.

1. Introduction

Digital photogrammetry is on the way to reach a new level of economical efficiency because of an ongoing improvement of digital systems towards a higher level of automation, accuracy and product quality. System providers make great efforts to embed fully automatic procedures on their digital systems in combination with powerful editing and visualization techniques. Automatic DEM generation, orthophoto production, and the automation of the interior and the relative orientation have meanwhile become a kind of a standard of today's digital systems. Automatic aerial triangulation in particular is subject to rapid practical development, since it is one of the keys to the economical breakthrough of digital photogrammetry. It is undoubted, once the aerial triangulation has successfully reached an automatic level in a digital production environment, that project costs will be significantly reduced.

Several approaches have been suggested from the scientific community and from some system providers as well. We have to mention the important developments of Toni Schenk's group at the Ohio State University (Schenk, Toth, 1993; Toth, Krupnik, 1994;Schenk, 1995) and the solutions of the Stuttgart University (Ackermann, Tsingas, 1994; Fritsch, 1995). Mayr (1995) and DeVenecia et. al. (1996) are reporting about commercial systems with high automation level. The related approaches differ quite significantly in detail, mainly with respect to the matching strategy. However, they all have in common, that they are intended to operate fully automatically.

The subject of this paper is an approach to automatic aerial triangulation which is currently carried out at INPHO company as a software development (MATCH-AT). It was presented in its key ideas in Krzystek et. al. (1995). Heuchel et. al. (1996) reports very recently about first practical results. The approach provides tie point clusters by means of the feature-based matching technique. The images of a block are orientated simultaneously with the help of an integrated bundle adjustment that robustly gets rid of mismatches. The geometric matching criterion becomes the ray intersection at homologous points instead of the widely used affine transformation. The approach comprises the point selection, point measurement, point transfer and the block adjustment in one single process.

In addition, a DEM is created either locally at the tie point areas or for the entire block area. The concept of an integrated DEM generation is particularly important. As far as the automation of the aerial triangulation is concerned, it helps to principally overcome the problem of relief displacement in the initialization part in case of large scales and hilly or mountainous terrain. Furthermore, the matching of image patches is more effective, if the terrain surface is considered by an appropriate resampling. Once a DEM generation has been integrated in such a system, it is very easy to derive a DEM for the entire block. Such a DEM has the benefit of high quality and accuracy since the multiple image overlap is rigorously used wherever possible. It should be recalled that in a normal block with 60 % end lap and 20 % side lap only about 25 % of the image area is covered by no more than two images. Thus, such a concept of surface reconstruction takes full advantage of the multiple image overlap and uncouples the DEM generation from the classical stereo model. Also, the integral approach has the prospect to automate the aerial triangulation, the DEM generation and the orthophoto production in one batch process.

This paper reports in general on the current status of the ongoing system development. It shortly reviews the approach to the automatic aerial triangulation with special attention to the DEM aspect. Practical results are given for the initialization part of the system based on an integrated DEM generation at a coarse pixel resolution of 480 μm. Main attention is paid to the controlled tests of the automatic aerial triangulation of two blocks with 45 images and 21 images, resp. At the end of the paper, preliminary results of an integrated DEM generation are presented, indicating the advantage of the multiple image matching approach.

2. Concept of automatic aerial triangulation

2.1 General remarks

Two basic key techniques play an essential role in our concept. Firstly, it takes into account that the GPS technology is well established in aerial triangulation. It is well-known that GPS navigation systems provide regular block forms and GPS positioning techniques pre-determine the projection centers with an absolute accuracy of at least 30 m. Thus, the initialization is considerably simplified, since a sufficient overlap of the homologous image patches is guaranteed, except for large scale photography in mountainous terrain and camera attitudes larger than 2 degrees. Secondly, we use predominantly the feature-based matching method as the matching strategy. This means that point clusters are measured and transferred by means of image processing techniques instead of single points. The implied measurement philosophy aims at a high redundancy which is one of the preconditions for highly accurate and reliable results.

Basically, the approach is intended as a fully automatic process which can start from scratch by using only little initial block information. The key idea of the approach is to use an integrated block adjustment in the matching strategy in combination with robust statistics. Thus, the AT process provides as main results both orientation parameters and adjusted object coordinates. The entire procedure is characterized by two main steps. It starts with the initialization which determines accurately enough the tie point areas at the Gruber point positions. The kernel system then applies the matching strategy in the homologous image patches through the image pyramid (Figure 1).

The possible input data are manifold and comprise very crude initial block data like the flight index map, the strip azimuths and a mean terrain height, as well as GPS/INS sensor data eventually in combination with a DEM. The digital images are given at appropriate resolutions (e.g. 15 μm or 30 μm), eventually with a coarse overview image and the associated interior orientation. Also, sufficient ground control is assumed. The number and distribution of ground control follows the same known rules as for a conventional aerial triangulation. Precise airborne GPS antenna positions can be introduced additionally as control information to reduce the number of ground control points.

The preparation part of the AT system defines some program parameters. If the interior orientation has not been applied so far, the fiducials are semi-automatically measured. Also, the ground control points have to be measured interactively. In the exceptional case of signalized points semi-automatic matching tools can also be applied. Note that only the preparation is an interactive part of the system. All the other process steps can be invoked in batch.

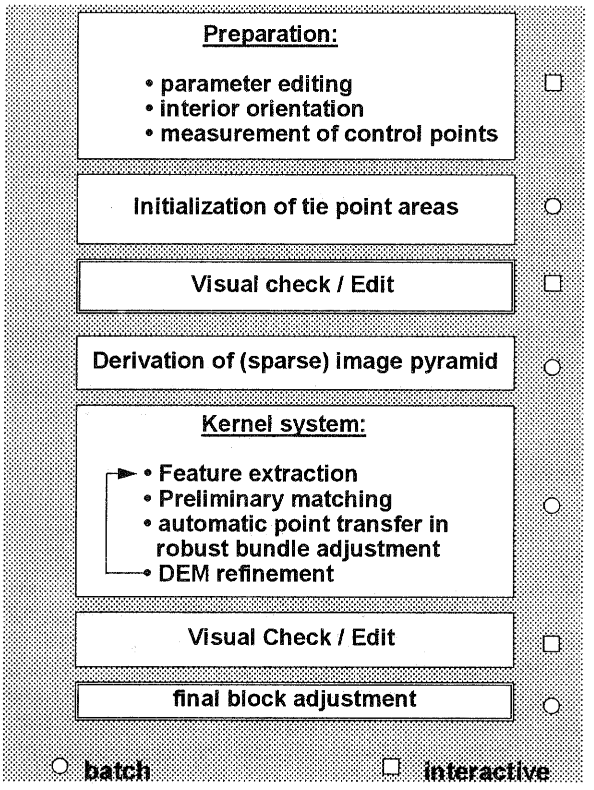

Figure 1: General workflow in MATCH-AT

2.2 Initialization

The initialization has to provide the Gruber positions in the images accurately enough for the pull-in range of the subsequently invoked kernel system. Assuming a pull-in range of 10 pixels for the feature-based matching technique, which is predominantly used in the kernel system, the image patches to be matched should not be shifted against their homologous position by more than 1 cm at a coarse pixel resolution of say 1 mm.

The initialization can use the mentioned input data in various combinations. For instance, if GPS/INS data are given with today's accuracy of 30 m and 0.2 - 0.5 degrees respectively, it is very easy to directly derive the tie point areas with an accuracy of at least 1 cm in the image. In case of large height undulations, a DEM is advantageous to compensate for the critical relief displacement. Although GPS has almost become a standard, low cost INS is going to become attractive and

DEMs are available in highly industrialized countries, we also have to envisage a method which operates mainly with the images and uses the additional data mentioned above, wherever possible. The key idea is to derive a crude block DEM at a coarse pixel resolution. If the projection centers are known with an accuracy of 1 cm in the images, we simply apply a DEM generation after the automatic block adjustment based on the kernel system. This is accomplished hierarchically in several coarse pixel resolutions, typically in the image pyramid levels of 1mm and 0.5 mm pixel size. Eventually, the block adjustment and the subsequent DEM generation is applied iteratively at the same pixel resolution, until a convergence of the Gruber positions is reached. This method works well in any image scale provided that GPS observations for the projection centers are given. Even in small image scales a flight index map, which provides the projection centers usually with an accuracy of 100 - 200 m, may be used. The only critical case remains at large image scales with height undulations of up to 20% and more of the flying height. In such cases we envisage also a method doing an automatic relative orientation at the pyramid levels of 1mm and 0.5 mm pixel size. This method is very similar to Schenk (1995) and is applied to all image pairs with some constraints for small overlap. It aims at an accuracy (=sigma naught) in the final block adjustment of 1 pixel, which means about 0.5 mm. It remains to be seen how flexible the integrated DEM generation approach really works if the image overlap is known rather inaccurately for some reasons. It should be recalled, once more, that the GPS technique has today already reached the status of a standard, and hence only a minority of triangulation projects will not have GPS observations for the exposure centers in future.

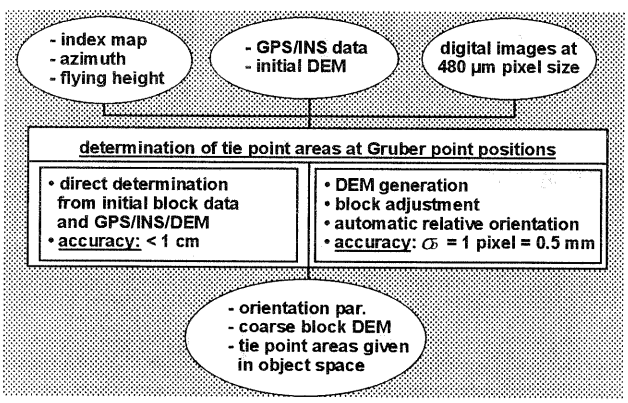

Figure 2: Initialization of MATCH-AT

The main result of the initialization are the tie point areas with an accuracy of at least 1 cm in the image. Furthermore, a crude block DEM and image orientations are calculated (Figure 2). The result of the initialization can optionally be checked and edited in critical cases. However, this interactive step is not mandatory at all and should be reserved if the initialization reports unacceptable results.

2.4 Kernel system

Once the initialization has completed, the kernel system is subsequently invoked using the initialized data. Additionally, the GPS observations for the exposure centers are used with appropriate standard deviations. The image pyramid is optionally derived only at the tie point areas in advance. This sparse image pyramid structure reduces the amount of image data to some extent, although an image compression like JPEG is certainly more effective.

The workflow and matching scheme of the kernel system shown in figures 3 and 5 is applied in all tie point areas. Firstly, a preliminary matching in all image patch combinations yields a list of image point pairs. Those points represent only two-fold points and are tied up to many-fold points by means of a heuristic search procedure. Since especially in the coarser image pyramid levels the percentage of erroneous preliminarily matched points is considerably high, the result of the heuristic search has to be considered error-prone. The subsequent bundle solution, however, eliminates iteratively the mismatches by using robust statistics and estimates simultaneously orientation parameters for all images. This is a remarkable feature of the kernel system compared to other approaches. It uses rigorously the ray intersection as a geometrical constraint in the matching of multiple points. Thus, the approach is not limited by a geometrical assumption about the local matching area (e.g. plane), but provides also matched points on corners of houses, for instance.

After the block adjustment the DEM is updated either at the tie point areas or for the entire block. The local DEMs at the Gruber positions are useful to resample the image patches, which are to be matched, with respect to the terrain surface. The area of the local DEM is slightly larger than the matched image patch in order to overcome edge effects. The knowledge of the terrain surface is advantageous especially in hilly or mountainous terrain and permits the use of larger image patches, as long as the DEM fits accurately enough the terrain. We use the same surface reconstruction technique as in MATCH-T which operates with a robust finite element technique (Krzystek, Wild, 1992). The grid width corresponds to approximately 30 pixels. The DEM generation process takes full advantage of the multiple image overlap. If compared to a conventional automatic DEM generation with two images the multiple image DEM approach creates more terrain points per grid mesh (= square of 4 DEM posts). Additionally, the terrain points are intersected by more than two rays, thus, increasing accuracy and reliability of the DEM.

After the DEM generation, which is practically an option of the system, the tie point areas are updated, using the terrain surface, if it was determined. The described scheme of the kernel system is applied straightforward through the entire image pyramid and results in adjusted object coordinates and image orientations parameters.

2.5 Summary

The approach integrates the point selection, the point measurement, the point transfer and the block adjustment in one single process. Instead of single tie points clusters of points are created. Those clusters are tracked through the entire image pyramid (Figure 4). Thus, we do not track hierarchically single features through the image pyramid which might get lost. Instead,

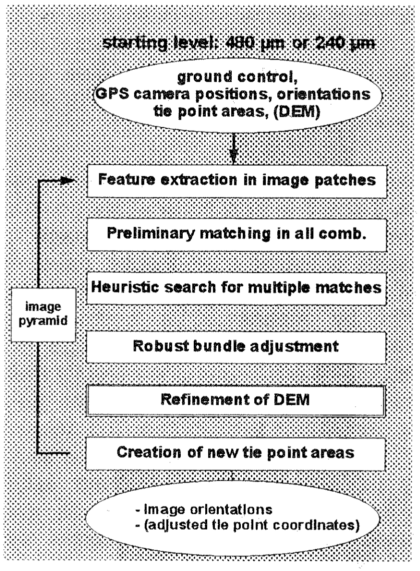

Figure 3: Kernel system of MATCH-AT

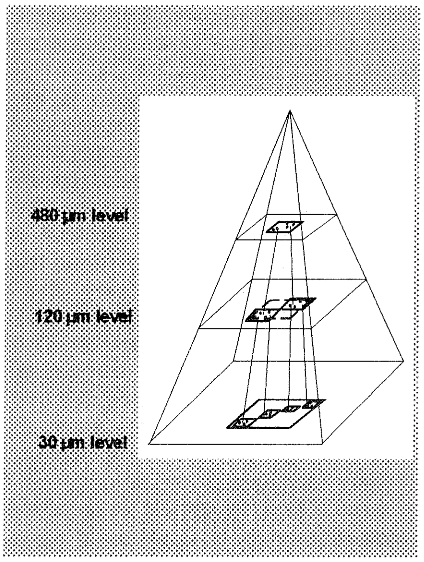

Figure 4: Tie point cluster tracking

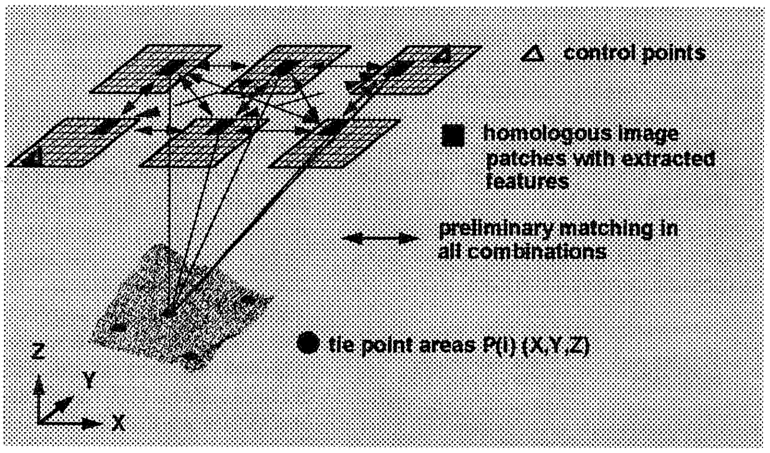

Figure 5: Matching scheme in kernel system

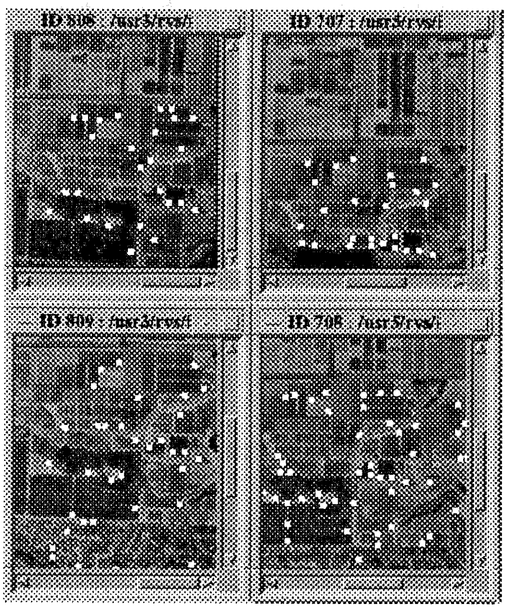

Figure 6: Extracted features in image patches

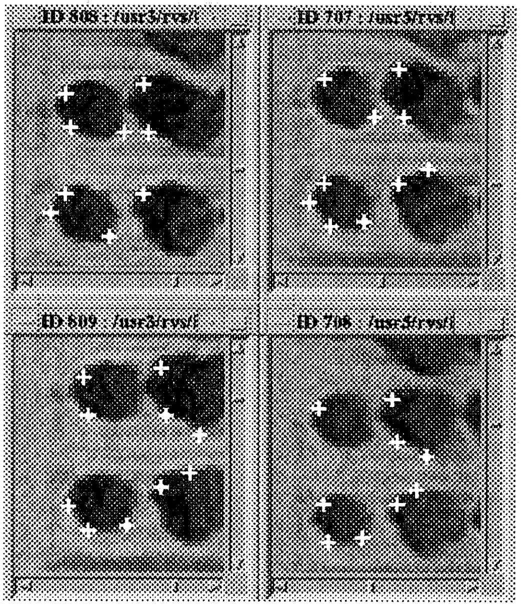

Figure 7: Matched tie point clusters

the algorithm tries to locally detect areas where a large number of points can be matched.

Basically, the accuracy and the reliability of the block adjustment depends on the block geometry, the number and distribution of the transferred tie points and their associated measurement precision (see details Ackermann, 1996b). Typical numbers for our approach are 100 - 200 or even more points per image. In order to keep the number of matched and transferred points at a certain level, the system automatically creates new tie point centers in the case of too few points being initially matched. Thus, the approach is focused in first instance on the feature-based matching technique. The simple key idea behind is to attain highly accurate results in the block adjustment by high redundancy. However, some circumstances like poor texture, for instance, might cause a drastical decrease of the number of matched points. In such cases the least squares matching method appears as a remedy to obtain a maximum measuring precision.

The matched points do not have the same meaning as the points which are usually measured by an operator. The automatically measured point is located, for instance, on house corners or in the neighborhood of natural features (Figure 6 and 7). As long as the result of the automatic aerial triangulation is used within a digital system, the adjusted points are not of interest any more. However, they are important if the digital aerial triangulation is to be used with analytical plotters.

3. Controlled tests

3.1 Initialization

The initialization of the MATCH-AT system based on an integrated DEM generation was tested with a small block of 16 images arranged in 4 strips with 60% side lap and 60% end lap. The photographs scanned with 30 µm pixel size had a photo scale of 1:11500. The block area of approximately 3.2 km by 3.2 km was slightly hilly with height differences of 150 m.

In order to simulate a flight index map we derived the exposure centers from a given aerial triangulation and randomly varied them with a standard deviation of 100 m. A first crude initialization of the tie point areas was then derived solely from the strip azimuths, the approximate exposure centers and an average terrain height. Thus, this "zero" initialization represents the coarsest alternative being possible in the concept of chapter 2.3. After this first initialization some of the tie point areas were significantly shifted against their homologous position by more than 1 cm (Figure 8). The reasons were mainly camera attitude angles of more than 4 degrees and in second instance slight height undulations. If one would apply the kernel system with those initial tie point areas, it could happen in some areas that only few or even no points would be matched. Thus, we applied the initialization of the MATCH-AT system starting at a pixel resolution of 960 µm. The system applied the matching scheme of the kernel system in combination with a subsequent DEM generation at the pyramid levels of 960 µm and 480 µm. After each DEM generation new tie point areas were created using the updated image orientations and the terrain surface. At the 960 µm pixel level the system iterated the algorithm twice to obtain a sufficient convergence of the tie point locations. Table 1 shows the results of the two pixel resolution levels.

Pixel size	σ_0 (Block)	σ_{DEM}
960 µm	230 µm = 2.6 m	3.4 m (1.3 σ_0)
480 µm	113 µm = 1.3 m	1.7 m (1.3 σ_0)

Table 1: Initialization with block adjustment and DEM generation

The sigma naught of the block adjustment (= σ_0 (Block)), which represents the precision of the automatic point identification, was in both pyramid levels approximately 0.24 pixel. Those values are equivalent to 230 µm and 113 µm, resp. The system reported also a theoretical accuracy of the block DEM posts (=σ_{DEM}) of 3.4 m and 1.7 m. Those values are - as expected - by the factor 1.3 larger than the sigma naught of the block adjustment. After this initialization the new tie point areas covered excellently homologous image patches (Figure 9). The locations of those tie point areas were accurate enough for a successful image matching in the kernel system, whose result of the block adjustment is not reported here. Although those preliminary results of the initialization part of MATCH-AT refer to a block with a side lap of 60 %, the method seems to be suited to cope with standard side laps of 20% or 30 %, even if the photo scale is quite large and height undulations cause relief displacements. The critical case is given if only a coarse flight index map is provided with large-scale photography. However, this is going to be more and more a minor issue because of the GPS technology. Altogether, these first results are very promising and future work will be focused on optimizing this integrated DEM approach towards an efficient and flexible initialization of the kernel system.

3.2 Block adjustment results

The MATCH-AT system was applied to two blocks comprising 43 and 21 images, resp. The overall goal of the controlled tests was in first instance to assess the accuracy potential of the automatic aerial triangulation under practical conditions, especially with respect to the number of block images to be processed. Also, the system performance in terms of computation time was another important item of interest. Interactive work was necessary in both test scenarios for an initial parameter setup, the interior orientation, and the manual measurement of control and check points. The imagery was scanned on a PS1 scanner with 15 µm pixel size and a standard JPEG image compression.

3.2.1 Block "Vaihingen/Enz"

This block of photo scale 1:15000 was formed by 45 images arranged in 5 forward strips (6 images) and 5 side strips (3 images) with 60 % end lap and 60 % side lap. The block area was slightly hilly with height differences of about 140 m covering an area of approximately of 9.5 km by 4.5 km. Two of the forward strips were almost identical with two other forward strips. Thus, the block geometry was considerably strong

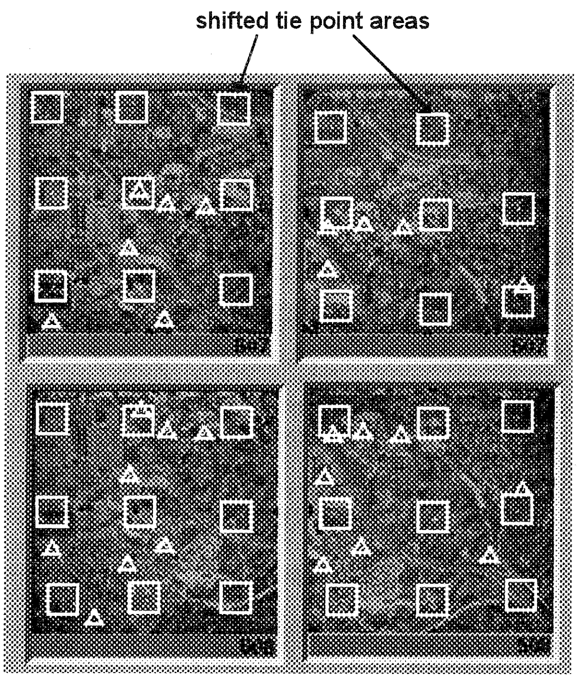

Figure 8: Tie point areas before initialization

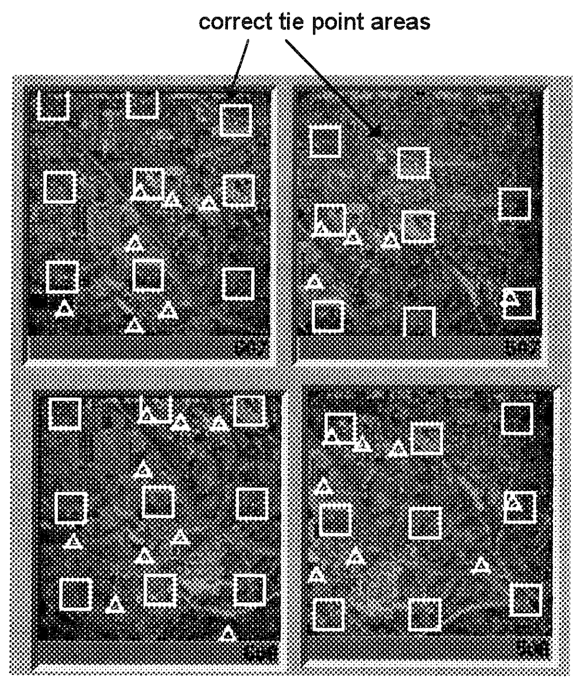

Figure 9: Tie point areas after initialization

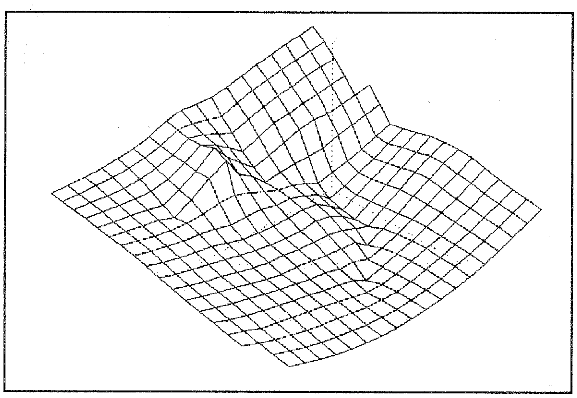

Figure 10: Block DEM for 960 μm pixel size

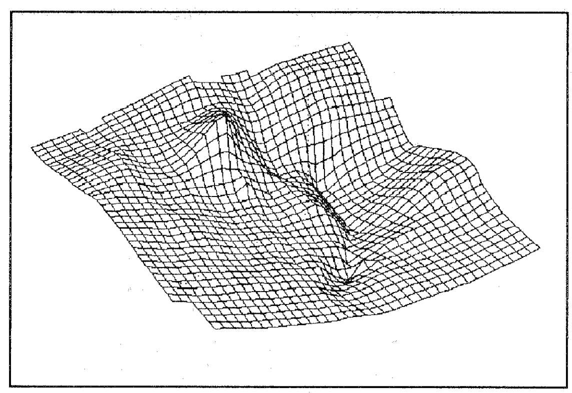

Figure 11: Block DEM for 480 μm pixel size

with a multiple image overlap of up to 15 images. Ground control points (# 16) as well as check points (# 16) were signalized as circular targets which had a size of 3 - 4 pixels in the image. The block served in first instance to test the practical applicability of GPS OTF-ambiguity solutions (Ackermann, 1996a). GPS observations were hence available for the exposure centers which were derived by the software package SKIP (Friess, Heuchel, 1992).

Initial parameters for the kernel system were determined from the strip azimuths, the GPS antenna observations, and an average terrain height. The system created a large number of tie point areas per image because of the large multiple-image overlap. After the initialization the automatic block adjustment was carried out with the kernel system in self calibration mode, whose results are summarized in table 2.

Let us firstly focus on the terms indicating the redundancy effect of the MATCH-AT approach. Especially in the 30 μm level, a huge number of 590 points per image was matched and transferred. The corresponding value for 15 μm pixel size amounts to 490 points per image which is practically the same order of magnitude. Such numbers are in general very characteristic for automatic aerial triangulation which are based on image processing techniques. They are the key to highly accurate and reliable results and can by far not be attained with conventional aerial triangulation. The next parameter to be discussed is the sigma naught value which represents the measuring precision of the feature-based matching technique. Its value of 0.3 pixel, for 30 μm pixel size, is very close to the theoretical expectation, whereas for 15 μm pixel size it ends up at 0.5 pixel. The corresponding values in terms of image units are 9.4 μm and 7.5 μm. Those values compare well with many cases of conventional aerial triangulation with non-signalized points. However, we have to keep in mind the large redundancy and the number of transferred tie points per tie point area, resp. Since the system provided on average 18.7 points per tie point area in the 30 μm pyramid level, the sigma naught is - under the assumption of a unchanged block geometry - equivalent to 9.4 µm / $\sqrt{18.7}$ = 2.1 µm of a conventional aerial triangulation (see details Ackermann, 1996b). Applying the same rule to the 15 µm case we obtain an equivalent sigma naught of 7.5 µm / $\sqrt{5.3}$ = 3.4 µm. Thus, from that point of view the block adjustment results are excellent in terms of a conventional sigma naught for both pixel sizes and meet even the accuracy characteristics of a high precision triangulation with signalized points. This propagation is clearly visible in the theoretical accuracy values of the orientation parameter which are quoted in table 2. In particular, the standard deviations of the photo tilts amount, in the 30 µm case, to about 3 mgrd for omega and phi, and to about 1 mgrd for kappa. The corresponding values for 15 µm pixel size are slightly better, however practically the same. Also, the theoretical coordinate accuracy for the check points confirms those excellent results. It amounts to 9.6 cm = 0.65 σ_o in X and Y, and to 23.5 cm = 1.6 σ_o = 0.1 ‰ h in Z for 30 µm pixel size. For 15 µm pixel size the values are again slightly better, in detail 8.2 cm = 0.65 σ_o in X and Y, and 20.1 cm = 1.6 σ_o = 0.09 ‰ h in Z is attained. The empirical accuracy is very close to those theoretical values, although a slight discrepancy in Z is to be stated.

It can be concluded in general that the digital aerial triangulation provided highly accurate results even for 30 µm pixel size which are very close or even equivalent to results obtained so far with signalized points. However, it is to be stated that the results derived at 15 µm pixel size are not better, as might be expected, and are practically the same as at 30 µm pixel size. The main reason is a reduced redundancy due to a decrease of transferred points per Gruber area. At this point the least squares matching method comes into play which could significantly improve the measuring precision. Future work will be focused on that aspect.

3.2.2 Block "Texas DOT"

This block comprised 21 images which were arranged in 3 strips with 60 % end lap and 60 % side lap. The photo scale was about 1:3300. Ground control points (# 12) and check points (# 68) were provided as signalized points. Since this block was also used as a test block for GPS investigations, the exposure centers were given by GPS antenna observations (Madani, 1996).

The initialization was carried out with MATCH-AT's initialization using the GPS observations for the exposure centers, the strip azimuths, and an average height as starting parameters. The automatic block adjustment was applied with self-calibration, whose results are summarized in table 3.

As far as the redundancy aspect is concerned, the numbers indicate for 30 µm pixel size a large mean number of 490 points per image and about 22 tie points per Gruber area. The corresponding values for the 15 µm case are significantly smaller, roughly by the factor 4. This decrease in redundancy is compensated by a sigma naught of 6 µm which is very close to the theoretical value of 0.29 pixel = 5µm. The sigma naught for 30 µm pixel size meets the theoretical value of 0.31 pixel, resp. 8.8 µm. If we reduce again the sigma naught values by the numbers of tie points per tie point area we end up in equivalent sigma naughts of 8.8 µm / $\sqrt{21.7}$ = 1.9 µm (30 µm pixel size) and 6.5 µm / $\sqrt{5.4}$ = 2.8 µm (15 µm pixel size). They indicate excellent results of the block adjustment which are also reflected in the theoretical and empirical accuracy. In detail, the theoretical accuracy of the photo tilts for 30 µm pixel size is about 7 mgrd for omega and phi, and 2.4 mgrd for kappa. For 15 µm pixel size the values for omega and kappa are slightly better with 5.2 mgrd, and for kappa a value of 2.6 mgrd is attained. The standard deviations for the check points amount to 2.8 cm = 0.95 σ_o in X and Y, and 6.8 cm = 2.3 σ_o = 0.13 ‰ h in the 30 µm case. Those values are in the same order of magnitude as those for 15 µm, which are in detail 2.35 cm = 1.17 σ_o in X and Y, and 5.0 cm = 2.4 σ_o = 0.11 ‰ h. The numbers for the coordinate accuracy represent both for 30 µm and 15 µm excellent results and are in the same order of magnitude as the best results of the OEEPE test block FORRSA (1:4000 photo scale) obtained digitally for 15 µm pixel size and conventionally with signalized points (Ackermann, Tsingas, 1994). Let us finally mention the numbers for the empirical accuracy which were assessed at the 68 check points. The values are especially for X any Y better than the theoretical expectations, and they confirm in general the theoretical standard deviations.

Summarizing the results of this block it can be concluded that the automatic digital aerial triangulation gave best results even for 30 µm pixel size. The comparison with the OEEPE test block FORRSA, which has almost the same photo scale, confirms that the automatic block adjustment with 30 µm pixel size is very close to the accuracy potential of a conventional triangulation with signalized points. However, it is remarkable that very little accuracy gain was attained with 15 µm pixel size. Thus, the implementation of the least squares matching method seems to be a remedy to reach the ultimate goal of a most accurate aerial triangulation, which could reach sigma naught values of about 2 - 3 µm.

3.2.3 Concluding remarks

We have not touched so far the important aspect of system performance. Since our main interest was the accuracy analysis we did not pay much attention on a comprehensive check of the system performance. However, it remains a very important question, as the overall time performance of any automatic digital system - in particular the aerial triangulation - is the key to the economical breakthrough of digital photogrammetry. The preparatory part was in general as expected. The interior orientation took on average 1 - 2 minutes per image. The identification of the necessary control points was simplified since approximate orientation parameters were available by the GPS antenna observations. Assuming, for instance, a minimum ground control configuration for the block "Vaihingen/Enz" of 4 control points it can be estimated that the measurement of control points took roughly 0.5 hour for all images containing the points. If we count the net computation time of about 6 minutes per image (SGI Indigo 2 with R4000/100 MHz) and assume additionally 2 minutes per image for preparation time and post editing, we end up

pixel size	30 µm	15 µm
# matched points / photo	15.0	10.9
# image points / photo	590	490
# block points	5022	5557
# points / Gruber area	18.7	5.2
σ_o [µm]	9.4	7.5
σ_o [pixel]	0.31	0.5
σ_o [cm]	14.5	12.3
Empirical results:		
# check points	16	16
μ_x [cm] ([σ_o])	5.4 (0.4)	4.0 (0.3)
μ_y [cm] ([σ_o])	7.4 (0.5)	7.2 (0.6)
μ_z [cm] ([σ_o])	11.8 (0.8)	16.0 (1.3)
Theoretical accuracy:		
Check points:		
σ_x [cm] ([σ_o])	8.8 (0.6)	7.6 (0.6)
σ_y [cm] ([σ_o])	10.5 (0.7)	8.8 (0.7)
σ_z [cm] ([σ_o])	23.5 (1.6)	20.1 (1.6)
Orientation parameters:		
σ_ω[mgrd]	3.2	2.9
σ_ϕ[mgrd]	3.2	3.0
σ_k[mgrd]	1.3	1.2
σ_x[cm] ([σ_o])	11.5 (0.8)	10.7 (0.6)
σ_y[cm] ([σ_o])	12.7 (0.7)	11.4 (0.7)
σ_z[cm] ([σ_o])	6.3 (1.6)	5.9 (1.6)
net comp. time / image	5.7 min	

Table 2: Block "Vaihingen/Enz" (photo scale : 1:16000)

pixel size	30 µm	15 µm
# matched points / photo	15.0	10.9
# image points / photo	490	120
# block points	4168	1034
# points / Gruber area	21.7	5.4
σ_o [µm]	8.8	6.5
σ_o [pixel]	0.31	0.43
σ_o [cm]	2.9	2.1
Empirical results:		
# check points	68	68
μ_x [cm] ([σ_o])	0.9 (0.3)	0.9 (0.4)
μ_y [cm] ([σ_o])	0.8 (0.3)	1.0 (0.5)
μ_z [cm] ([σ_o])	5.1 (1.7)	2.9 (1.4)
Theoretical accuracy:		
Check points:		
σ_x [cm] ([σ_o])	2.9 (1.0)	2.4 (1.15)
σ_y [cm] ([σ_o])	2.7 (0.9)	2.3 (1.1)
σ_z [cm] ([σ_o])	6.8 (2.3)	5.0 (2.4)
Orientation parameters:		
σ_ω[mgrd]	6.5	5.3
σ_ϕ[mgrd]	7.6	5.1
σ_k[mgrd]	2.4	2.6
σ_x[cm] ([σ_o])	4.4 (1.5)	3.2 (1.5)
σ_y[cm] ([σ_o])	3.4 (1.2)	3.3 (1.6)
σ_z[cm] ([σ_o])	3.2 (1.1)	1.9 (0.9)
net comp. time / image	3.9 min	

Table 3: Block "Texas DOT" (photo scale : 1:3300)

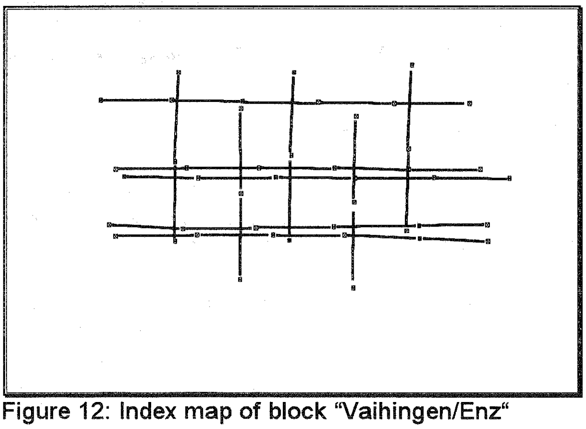

Figure 12: Index map of block "Vaihingen/Enz"

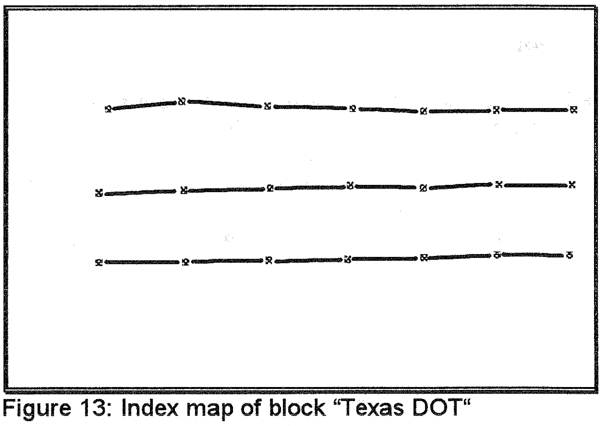

Figure 13: Index map of block "Texas DOT"

at approximately 9 - 10 minutes per image. It is to be kept in mind that the net computation time refers to a rather old processor which has been practically replaced by the R4400 with 250 MHz. That processor gives at least 2 times better performance, Also, the net computation time for the block "Vaihingen/Enz" is high because of the 5 side strips and the related large number of tie point areas. Note that the net computation time for the block "Texas DOT" is in the order of 4 minutes per image. Thus, we can expect an overall time performance of say 5 - 6 minutes per image presuming the power of today's workstations and a fully automatic procedure in the batch processes of the system. Since computer performance is steadily improved in remarkably short time cycles, such numbers can be reduced quite easily. In general, the estimate of the overall time performance per image represents an order of magnitude, but it is very promising for the economical benefit of automatic digital aerial triangulation being implemented in MATCH-AT.

3.3 DEM generation

Finally, we want to mention preliminary results which were attained with MATCH-AT in DEM generation mode. We selected the OEEPE block FORSSA as a test block (photo scale 1:4000; 28 images at 30 µm pixel size; 60 % forward lap; 20 - 40 % side lap). A DEM area was defined in the center of the block covering approximately the area of 2 neighboring stereo models (Figure 14). The block adjustment ran through the entire image pyramid creating in each level a DEM with a post spacing being equivalent to about 30 pixel. Figure 15 shows the block DEM obtained for 120 µm pixel size. The block adjustment gave the same results for σ_0 and the theoretical z-coordinate accuracy σ_z as recently reported by Heuchel et al. (1996). Table 4 quotes also the theoretical DEM accuracy σ_{DEM} which was derived by the surface reconstruction part of MATCH-AT by using the inverse of the normal equation system and the residuals of the automatically matched 3D points (see details Krzystek, Wild, 1992). Those values are better almost by a factor of 2 than the standard deviation σ_z for the z-coordinate of the block adjustment. In detail, a standard deviation σ_{DEM} of 8 cm = 0.13 ‰ h was obtained for 60 µm pixel size. For the 30 µm case the corresponding value amounts to 5.2 cm = 0.08 ‰ h. The improvement against the σ_z of the block adjustment is influenced by the redundancy effect, since a large number of points per grid mesh are filtered in the surface reconstruction process. Those results are very promising in every aspect.

Figure 14: Block DEM of OEEPE Block "FORSSA"

In general, it is to be expected that DEMs derived from more than two images by multiple-image matching techniques will be more accurate and more reliable than DEMs conventionally derived from two images. Especially, in the case of a 60 % side lap this benefit would be fully visible (Thorpe, Schickler, 1996). Future work will be focused on optimizing that special DEM generation approach. Also, ground truths will be used for empirical accuracy checks to independently confirm the theoretical expectations.

4. Conclusions

We have presented an integral approach to automatic aerial triangulation which incorporates a DEM generation process. This strategy helps the system to initialize accurately enough homologous image patches in the presence of large height undulations. Also, the matching of image patches becomes more effective and an entire block DEM can be determined using consequently the multiple image overlap. The practical results of the automatic aerial triangulation indicate that even with 30 µm pixel size excellent results can be achieved which are very close to those with a high precision triangulation. Furthermore it is to mentioned that the system was successfully applied to a block of complex form with many side strips The preliminary results of the DEM generation for a block DEM are promising and indicated an expected height accuracy of 0.1 ‰ h. Future work will be focused on the system development and, especially, on optimized matching strategies to take advantage of the accuracy potential of the 15 µm pixel size.

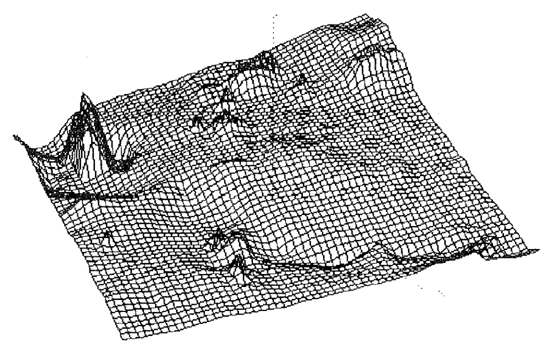

Figure 15: Block DEM

pel [µm]	σ_0 [µm] ([pel])([cm])	σ_z [cm]	σ_{DEM} [cm]	σ_{DEM} [‰ h]
60	19.1(0.31)(7.6)	13.6	8.0	0.13
30	13.5(0.35)(4.1)	9.1	5.2	0.08

Table 4: Theoretical DEM accuracy of block DEM

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