DIGITAL AERIAL TRIANGULATION - THE OPERATIONAL COMPARISON

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ABSTRACT:

Although the block adjustment phase of aerial triangulation has been automated to a great extent, point transfer and point mensuration phases have practically remained conventional. The need for near real-time results may be the main reason that photogrammetry techniques have not been fully accepted in non-mapping applications, such as architecture, industrial engineering, and medical disciplines.
Recent progress in digital photogrammetry has opened new possibilities. Digital photogrammetry has been accepted as economical in medium- and small-scale mapping applications, particularly in digital terrain model (DTM) extraction and orthophoto generation. The next advance in digital photogrammetry involves automatic aerial triangulation using image matching techniques to automate point transfer and point mensuration phases. Several methods and computer programs for digital aerial triangulation are being developed. These methods are based on the automatic selection and transfer of tie points using multiple image feature-based and/or least squares matching.
The object of this paper is to compare the operation of a "conventional" and an automatic digital aerial triangulation in terms of accuracy and time. For this purpose, two small blocks of aerial photographs were scanned at 15 µm and 30 µm pixel sizes. Photogrammetric measurements were carried out in a semi-automated mode on an Intergraph InterMap Digital workstation. Image measurements were also performed in an automatic mode using the INPHO MATCH-AT product.
Adjustment results and performance time of both modes of aerial triangulation were compared. Based on this investigation, the estimated precision of the image/object point coordinates obtained by the MATCH-AT program using a 30 µm pixel size data set were very close to theoretical values given by conventional triangulation procedures. It is expected to achieve high accuracy digital triangulation results using 15 µm imagery. The performance time of less than 5 minutes was reached with the MATCH-AT program using these data sets.

1. INTRODUCTION

Aerial triangulation is a complex operation. This operation includes planning photo flight; establishing ground control points; taking and developing aerial photographs based on pre-determined specifications; performing interior orientation; measuring and transferring all tie, check, and control points appearing on all photographs; and performing a least squares block adjustment. This process ultimately provides exterior orientation parameters for all photographs and three-dimensional coordinates for all measured object points.

In the past 30 years, the main progress in aerial triangulation has been in the area of computational techniques for block adjustment. This was due to the advent of fast and powerful computers and the development of sophisticated aerial triangulation computer programs. Self-calibrating bundle and independent model adjustments are examples of such complex computer programs. With the introduction of analytical plotters, the aerial triangulation procedures have reached the present perfected status. Accuracy achieved by these procedures is quite high for photogrammetric point densification such as that obtained in photo-geodesy (Brown, 1976). In spite of achieving such accuracy, point selection, point transfer, and image point measurements of the aerial triangulation process remained unchanged, i.e., were done manually.

Recent progress in digital photogrammetry has opened new possibilities. The impetus for this evolution has been the advancement of computer technologies and image processing techniques. While the principles of photogrammetry have not changed, the tools have. One of the fundamental changes brought on by the digital photogrammetry system is a potential for automated measurement and image matching that simply did not exist in the analytical stereoplotter environment. Today, several commercial digital photogrammetry workstations are available in the market. These digital photogrammetry workstations have been accepted as economical in medium- and small-scale mapping applications, particularly in digital terrain model (DTM) extraction and orthophoto generation. The automatic measurement and image matching techniques are the great value-added components that the new digital technologies bring to photogrammetry (Parker, Madani, 1996).

The next advance in digital photogrammetry involves automatic aerial triangulation using image matching techniques to automate tie point selection and transfer operations. Several methods and computer programs for automatic aerial triangulation are being developed.
Basically, there are two strategies for digital mensuration and triangulation. The first strategy, which is similar to the conventional approach, can be classified

as operator-guided automatic point transfer. The operator selects a suitable tie point on one or more overlapping images using a measuring mark. At this time, image coordinates of the tie point are recorded. Next, this tie point is transferred to other overlapping images either interactively using mono or stereo observations or automatically using image matching techniques. The operator has full control of the operation and produces very accurate results with this approach; however, the approach is time consuming and requires a skilled operator (Ackermann, Tsingas, 1995). A performance time of about 8 minutes per image was achieved on a digital triangulation of 979 aerial photographs using an Intergraph digital photogrammetry system (Beckschafer, 1995).

The second strategy is a fully automated aerial triangulation. The main objective of this strategy is to automate point transfer and tie point measurement operations. Therefore, it minimizes manual work and reduces operator intervention as much as possible.

Up to now, three different methods for automatic point transfer and measurements have been reported. These methods use either feature-based or least squares based matching techniques (Tsingas, 1994; Schenk, 1993; Ackermann, 1995; Krzystek, 1995).

Tsingas (1994) uses feature-based matching in three levels of image pyramids. Feature points are extracted in every digital image, and preliminary pairwise matching is performed by computing correlation coefficients. Then, gross errors are detected and eliminated by using an affine transformation model. Finally, a graph-theoretical model is used to overcome the problems of small matching errors and ambiguities.

Tsingas' approach was tested on OEEPE block FORSSA. Twenty-eight aerial (4 strips of 7 photos) photographs of scale 1:4000 were scanned by PhotoScan at 15 µm and 30 µm resolutions, and three runs were made. Results of these runs were reported by Ackermann and Tsingas (1994). As indicated in this report, a σ_0 value of 6.2 µm corresponding to 0.41 pixel size was obtained. A performance time of achieving bundle adjustment at the highest level of the image pyramid was about 5.3 minutes per photo on a Silicon Graphics IRIS Indigo Workstation (3000 MIPS, 33 MHZ). In a recent test, the same project was triangulated on a Silicon Graphics Indigo 2 workstation (4400 MIPS, 200 MHZ), and a performance time of about 1 minute per image was achieved (Fritsch , 1995).

Schenk (1993) uses a very comprehensive, integrated matching concept including point and edge feature matching. This system consists of three modules. The first module generates a photo mosaic, including DTM points and footprints of all images at a coarse resolution. The second module selects block points at strategic locations using information obtained in the first step. The third module uses a least squares multi-image matching in object space to determine conjugate points as accurately as possible (Toth, 1993).

Krzystek (1995) uses a feature-based matching approach and aims at an operational system leading to very reliable and accurate bundle adjustment results. The intention of the concept is a fully automatic procedure that includes the initialization and the automatic block adjustment. Only at the beginning an initial parameter setup, the interior orientation, and the interactive measurement of control points are needed. If necessary, the results of the automatic block adjustment can be analyzed and post edited. The approach comprises point selection, point measurement, point transfer, and block adjustment ion a single process.

The success of any image matching technique is dependent on the availability of "good" approximate values for exterior orientation parameters. Whereas some of these parameters are known approximately (photo base, average terrain elevation, and average flying height), others are not available with sufficient accuracy. The uncertainty in image matching is due to maintaining a proper sidelap and the amount of terrain relief with respect to flying height. The side lap problem may be solved by careful flight mission planning and by using proper navigational tools (Förstner, 1995). Modern navigational tools, such as Global Positioning System (GPS) and Inertial Navigation System (INS), will be standard in future aerial photography. These tools not only control the flight mission but also provide good approximate values for all exterior orientation parameters. In addition, they will reduce the number of costly ground control points needed in the conventional aerial triangulation. For more information about characteristics of these three automatic digital triangulation strategies, refer to Förstner (1995).

The uncertainty in obtaining good approximate values due to the terrain relief may be solved by increasing the amount of overlaps and by using or creating an approximate DTM. The automatic point transfer techniques use image pyramids and coarse to fine resolution image matching operations. The matched image points, exterior orientation parameters, and object point coordinates resulting in a low level are used as approximate values for the next level in the image pyramids.

In the following sections, brief descriptions about the digital photogrammetry hardware and software used are given. Operational procedures of a semi-automatic and an automatic aerial triangulation are compared using two different photogrammetric data sets. On the basis of this study, some preliminary results and accuracy indicators are reported. Finally, general concluding remarks on the accuracy and performance of an automatic aerial triangulation are provided.

2. MATERIALS, INSTRUMENTS, METHODOLOGIES

Two small blocks of aerial photographs with different photo scales, cameras, and types and numbers of control points were selected from larger projects. The Texas project is a very accurate GPS photogrammetry test field established by the Texas Department of Transportation. Signalized control points were spaced about 90 m apart. Flight design and control point spacing were such that each model had between 15 to 20 control points. Twenty-one diapositives (strips of 7 photos) from the Texas project were selected for this study. The Maryland project is a high-precision GIS project undertaken by Baltimore County. A total of 869 aerial photographs were taken by a Leica RC-30 camera at a scale of 1:6000 utilizing airborne kinematics GPS procedures. Sixty-five diapositives (5 strips of 13 photos) of this project were selected for this study. Characteristics of these two projects are given in Table 1.

Project Description	Texas	Maryland
Camera	Wild RC-20	Leica RC-30
Photo Scale	1:3000	1:6000
Forward/Side Overlap	80 / 60 %	60 / 30 %
Number of Strips	3	5
Number of Photos	21	65
Terrain Relief	75 - 80 m	10 - 110 m

Table 1. Texas and Maryland Project Description

Intergraph PhotoScan was used for scanning aerial photographs, and the InterMap Digital (IMD) workstation with its mensuration software (ISDM) was used for interactive and semi-automatic point transfer and triangulation. Finally, MATCH-AT, developed by Inpho of Germany, was used for a complete automatic aerial triangulation.

2.1 PhotoScan

PhotoScan is a high-resolution, radiometrically and geometrically precise flatbed scanning system that was designed specifically to address the requirements for high-end photogrammetry and image processing film conversion. PhotoScan converts photographic information from black-and-white or color and from positive or negative film sheets into continuous-tone digital image data at a rate of up to 2 million pixels per second (Figure 1).

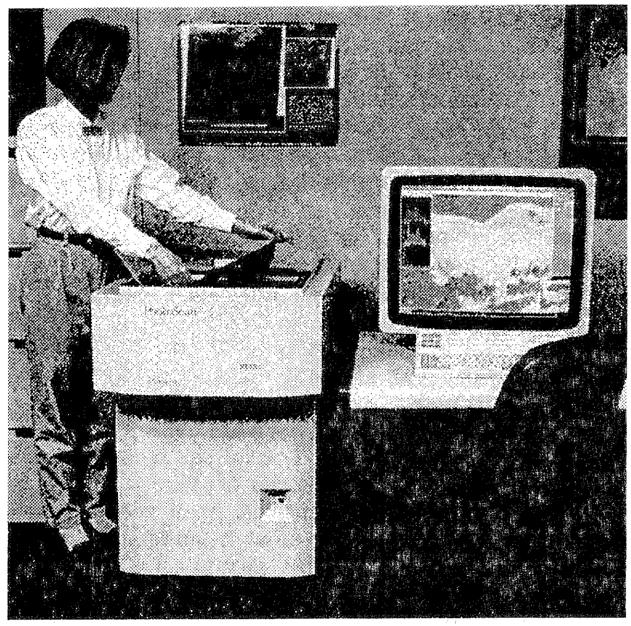

Figure 1. The PhotoScan System

The PhotoScan fixed optics produce a 7.5 μm pixel size camera system which is digitized to a minimum of 10 bits prior to compensation and digital aggregation to the user-specified resolution. Resolution options include the basic 7.5 μm pixel size as well as 15 μm, 22.5 μm, 30 μm, 60 μm and 120 μm sizes (Madani, 1991).

2.2 InterMap 6887 ImageStation

The InterMap 6887 ImageStation digital stereoplotter (IMD) is an analytical stereoplotter designed for users needing photogrammetric functionality for map compilation and revision, engineering mapping and revision, orthophoto production, transportation alignment cross-section collection, digital terrain collection, GIS input and revision, and close-range applications (Figure 2).

IMD provides stereo graphics on a 24-bit true color 27-inch monitor. A JPEG compression/decompression processor allows the use of high-resolution scanned imagery while minimizing the file/storage size of the image. An infrared emitter and liquid crystal glasses provide a high-resolution 3-D image. IMD is also offered with the VI-50 image computer and 64 megabytes of onboard ECC memory as a standard configuration. An ergonomically designed work/digitizer table (34 x 22 inch sensitized area), which includes a 10-button two-handed controller, and a cantilevered monitor table complete the IMD configuration (Madani, 1993).

Figure 2. The InterMap 6887 ImageStation

2.3 ImageStation Digital Mensuration

ImageStation Digital Mensuration (ISDM) software provides a multi-image (up to 6 images at once) multi-sensor point transfer and measurement environment for a photo triangulation workflow.

The high degree of flexibility built into the user interface allows a highly automated mensuration procedure. A flexible window-based image display of multiple images provides the efficient transfer and measurement of points in multi-overlap regions. The use of autocorrelation for this type of mensuration provides a high degree of reliability. While in mensuration, the easy accessibility of the numerous image enhancement and image manipulation functions greatly assist the operator in performing the measuring process. All these factors provide a measurement system that can be used with relative ease (Madani, 1996).

Some of the main features of ISDM are as follows:

- Project, camera, strip, photo, and control creation and editing
- Mono- and multi-cursor measurement
- Interactive/automatic mensuration capability (autocorrelation and least squares refinement)
- Interior, relative, absolute, singe photo resection, and simultaneous bundle adjustment
- Image manipulation and image enhancement tools
- Sophisticated but easy to use image point selection and editing tools
- User selectable statistical indicators and blunder detection methods
- Graphical symbols for points and status of mensuration process for each point

2.4 MATCH-AT (Automatic Aerial Triangulation)

MATCH-AT is a complete automatic aerial triangulation program system (Krzystek, et. al., 1995). MATCH-AT performs hierarchical multi-image matching of cluster tie points in the standard (Gruber) locations.

This program is mainly divided into two parts. In the first part, the user provides geometric information about the block of aerial photographs, such as camera data, flying height, amount of endlap and sidelap, and image sequence in the block. Additional information, such as exterior orientation parameters derived from navigation systems (GPS and INS), a crude DTM data, or a combination of both, can also be used to compute approximate locations of all tie points areas with sufficient accuracy. In the absence of such information, MATCH-AT uses an integrated DTM generation which is applied in the upper levels of the image pyramid (for instance, 960 μm and 480 μm) in combination with the block adjustment. The tie point areas are updated in each image pyramid level using the coarse block DTM. A method which uses an automatic relative orientation for all image pairs is kept in reserve for critical situations that are imprecise initial orientation parameters. The second part uses the approximate locations of tie points to generate feature points using a multi-image technique. Finally, a simultaneous bundle adjustment is carried out on the matched tie points to compute exterior orientation parameters and 3-D coordinates for all ground points.

This new version of the MATCH-AT program was tested on the OEEPE test block FORSSA (4 strips of 7 photographs scanned at 30 μm resolution), and a computational time of about 4 minutes per image and a EINBETTENσ_0 value of 0.33 pixel size were achieved (Heuchel et al., 1996).

3. DIGITAL AERIAL TRIANGULATION RESULTS

The process of digital aerial triangulation (semi-automatic and automatic) may be divided into three steps:

a) Preparation and Project Setup
b) Measurement and Orientations
c) Bundle Block Adjustment

3.1 Preparation and Project Setup

In this step, all photographs of both projects were scanned by PhotoScan using its "Photo Alignment" option at 15 resolution. The Photo Alignment option allows for precision interactive/automatic measurements of fiducials or reseau points prior to the digital image collection. A full set of overviews (6 overviews) for each image was created and then compressed by a JPEG board (available on both the PhotoScan and the IMD systems). Overview creation and image compression were done in a batch mode. The turn-around time for scanning at 15 μm pixel size, for creating a full set of overviews, and for image compression was about 15 minutes per photo.

The Project Management utility of the ISDM product was used to set up the Texas and the Maryland projects. Camera data, control points coordinates, and other parameters relevant to these two projects, such as image refinement flags, orientations, and bundle adjustment tolerances were also entered.

3.2 Measurement and Orientations

Digital triangulation operation by ISDM is done in two steps: Interior Orientation (IO) and Relative Orientation (RO) and Point Transfer.

The fiducial marks of one image from both projects were measured manually. Then, automatic IO was performed on all remaining images. The overall performance time for measuring 8 fiducial marks and applying an affine transformation was about 1 minute per image, including editing and remeasuring observations, if necessary.

Before performing a relative orientation, a suitable tie point pattern can be created using the Project Management utility to generate a well distributed image point configuration. This option was not really necessary due to the fact that the Texas block had at least 12 signalized points on each image, and the Maryland block had 5 to 7 pugged points on every other photograph. Nevertheless, it helped to locate these points very quickly and to measure additional tie points.

The ISDM product has a very flexible procedure for performing a semi-automatic relative orientation and point transfer. The procedure used in this study is as follows:

a) Measuring First Model in a Strip

- Set proper auto-measurement flags on.
- Measure manually center points of the stereo pair.

- Measure manually all remaining tie/control points on one image. Auto-measurement will transfer all points to the other image.
- If auto measurement fails, remeasure manually the point on the second image.

b) Measuring Subsequent Models in a Strip

- Set proper auto-measurement flags on.
- Measure manually center points of stereo pair.
- Transfer automatically points already measured down the center of the left image to the trailing edge of the second image.
- Measure manually all remaining tie/control points on one image. Auto-measurement will transfer all points to the other image.
- If auto measurement fails, remeasure manually the point on the second image.
- Repeat this process for all remaining models in the strip.

Strips were tied together in a 4 or 6 image mode, viewing 2 or 3 images from each strip. On-line bundle adjustment was performed in relative mode to check the quality of the measured tie points. Blunder detection was used for on-line checking of model and strip connections.

3.3 Bundle Block Adjustment

Bundle block adjustment was performed on the Texas project using all photogrammetry measurements and 9 full control points with the assumed standard deviation of 1 cm. Seventy-one signalized check points were used for empirical accuracy estimation. The estimated precision of the image coordinates (σ_0) was 3.4 µm, and the empirical accuracy indicators of the check points were about 1 cm. in XY and 2.9 cm. in Z (Table 2).

The MATCH-AT program was invoked for the automatic triangulation of the Texas project using the same number of control and check points. Necessary parameters and approximate locations for tie point areas were created by the ISDM product. MATCH-AT was run on the Silicon Graphics Indigo R4000 workstation using both 15 µm and 30 µm pixel size imagery. The number of tie points, especially at 30 µm, was quite large. This gave high redundancy and hence improved accuracy and reliability. Most of the tie point areas were located on a runway of the Texas project with a low contrast. Therefore, the feature-based matching technique provided less matched points for the 15 µm data set than the 30 µm imagery (Table 2). MATCH-AT automatically eliminated these erroneous observations which occurred due to poor texture. The estimated precision of the automatic digital triangulation was 8.8 for 30 µm and 6 µm for 15 µm imagery, respectively. These σ_0 values were very close to the theoretical values obtained in the conventional aerial triangulation using natural tie points (Ackermann, Tsingas , 1994).

The theoretical results were excellent, especially for the 30 µm case. The standard deviations of object points were equivalent to 1.1 σ_0 for XY and 2.5 σ_0 for Z. Also, the standard deviations of the exterior orientation parameters were excellent compared to the ISDM triangulation results. The main reason for such a high accuracy is the large redundancy of the feature-based automatic aerial triangulation. The mean standard deviations of the object point coordinates (theoretical values) corresponded quite well with the RMS values at check points.

Very good results for the theoretical accuracy and the empirical accuracy were also obtained with the 15 µm case. It is remarkable that for 15 µm no gain in accuracy is attained, although the σ_0 value is better. The reduced redundancy of the 15 µm case is due to the low texture which causes decrease in matched and transferred points. A least squares matching might improve the precision and the theoretical accuracy. Again, the mean standard deviations corresponded reasonably well with the RMS values.

	MATCH-AT Results		**ISDM Results**
Pixel Size (µm)	30	15	15
Matched Point Area	15.0	10.9	1
No. of Points/Image	490	120	15
σ_0 (µm)	8.76	6.0	3.4
σ_0 (pixel)	0.29	0.4	0.23
	Empirical Accuracy		
No. Of Check Points			
XY	71	71	71
Z	71	71	71
RMS X (cm) RMS Y (cm) RMS Z (cm)	1.2 1.0 5.1	1.3 1.1 2.9	0.8 1.3 2.9
	Theoretical Accuracy		
Sigma X (cm) Sigma Y (cm) Sigma Z (cm)	2.9 2.7 6.5	2.4 2.3 5.1	1.3 1.2 2.4
	Exterior Orientation Parameters		
Sigma X (cm) Sigma Y (cm) Sigma Z (cm) Sigma ω (mgon) Sigma φ (mgon) Sigma κ (mgon)	4.4 2.4 3.2 6.5 7.6 2.4	4.7 4.2 3.0 7.1 6.9 3.0	3.2 3.6 2.2 5.4 3.6 2.2

Table 2. Texas Project Bundle Adjustment Results

Concluding, it is to be stated that the MATCH-AT results for the 30 µm case are better than those which could have been attained with ISDM using only a 30 µm pixel size. In a theoretical scenario, the estimated precision of the semi-automatic digital triangulation using the 30 µm pixel size would be two times larger than the corresponding value of the 15 µm data set. This is, the σ_0 value would amount to about 6.8 µm. Also, the results of ISDM mainly refer to the signalized points. Therefore, it is expected that the ISDM results using non-signalized points would end up in a σ_0 value of about 6 to 8 µm. Thus, from that point of view, the MATCH-AT results of the 30 µm case are equivalent or even better than those obtainable with conventional aerial triangulation using non-signalized points. The main reason that MATCH-AT did not fully reach the excellent results of ISDM with 15 µm pixel size was the drastic loss of the redundancy due to the poor texture. A remedy for such cases is to use a least squares matching method, which gives best measurement precision. This feature will be an option in the MATCH-AT system very soon.

The bundle adjustment was also performed on the Maryland project. In this case, 25 full control points with the standard deviations of 4 cm in XY and 6 cm. in Z were used. These standard deviations were obtained from a previous bundle adjustment using all 869 photographs and GPS data. The results of the ISDM and the MATCH-AT programs using 15 μ m and 30 μm pixel sizes of the Maryland project were not available at the time of this writing. The complete analysis of these digital aerial triangulations will be presented at the ISPRS Congress.

The overall performance time of the semi-automatic digital triangulation of the Texas project was about 7 minutes/ image and of the Maryland project was 9 minutes/image (measuring and correlating many signalized points). The net computation time of the automatic digital triangulation (measuring and matching natural tie points) of the Texas project on the Silicon Graphics Indigo R4000 workstation was 3.9 minutes per image. It is expected to achieve the same or better performance time for the MATCH-AT running on the ImageStation 6887 digital workstation.

4. SUMMARY AND CONCLUDING REMARKS

The accuracy of automatic aerial triangulation depends on the quality and the number of matched points. Feature-based matching delivers high redundant matched points (between 250 to 500 points per image). The reported point accuracy of the feature-based matching was between 0.3 to 0.4 pixel size, which is similar to the theoretical values obtained by the conventional aerial triangulation. The feature-based matching approach provides very accurate and reliable exterior orientation parameters due to its capability of generating many redundant tie points (strong geometry configuration).

This preliminary investigation showed that MATCH-AT is a very powerful automatic digital triangulation program. This program has the potential to improve its efficiency and robustness and to increase its success rate of creating correct matched tie points. Aerial photographs used in this study were taken from "controlled" projects of rather flat terrain with many signalized and pugged control points. Therefore, approximate coordinates of the tie point areas were easily computed with sufficient accuracy. In practical applications, such projects do not exist very often. Thus other procedures such as a crude DTM and/or GPS/INS systems, are required to compute approximate locations of the tie point areas for the photographs taken from undulating terrain with heavy build-up areas and trees.

The current version of the MATCH-AT program can use navigation (GPS/INS) information, a crude DTM data, or a combination of both to determine approximate locations of all tie points areas with sufficient accuracy. In the absence of such information, MATCH-AT uses an integrated DTM generation which is applied in the upper levels of the image pyramid in combination with the block adjustment. The tie point areas are updated in each image pyramid level using the coarse block DTM. This method uses an automatic relative orientation for all image pairs for imprecise initial orientation parameters.

A new phase of development in automatic digital triangulation has just been started, and several computer programs are being developed. The goal of the automatic digital triangulation is to minimize the manual work, such as initial project set up and control point measurement, and to reduce operator intervention. The preliminary results reported in this paper and previously published studies have clearly shown that the automatic digital triangulation has the potential to not only be more accurate than the conventional aerial triangulation, but also to improve productivity very significantly.

5. ACKNOWLEDGMENTS

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