Concept, Implementation, and Results of an Automatic Aerotriangulation System*

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Abstract
During the last two decades, aerotriangulation has enjoyed great success. Block adjustment programs and analytical plotters have contributed the most to reliable and accurate triangulation procedures. Digital photogrammetry and softcopy workstations have added a new dimension to aerotriangulation, and some of the previously manual procedures can now be automated. In this paper, we describe a softcopy-based automatic aerotriangulation system that generates the block configuration, selects block points (tie points), and matches them to sub-pixel accuracy. A key element is the 3D block system which contains information about the coverage of photographs.

Introduction
Digital photogrammetry is rapidly emerging from a predominantly research and development environment to the marketplace. The most obvious sign of this transition is the increased use of softcopy workstations, which signals the replacement of analog and analytical plotters. Other digital photogrammetry products that are being successfully used include the automatic generation of digital elevation models (DEMs) and the production of digital orthophotos.

One of the major advantages of digital photogrammetry is the potential to automate photogrammetric procedures, thus substantially improving the price/performance ratio. A good example is aerotriangulation. Even though today aerotriangulation is a well-established process, its performance and reliability can be considerably improved.

Traditionally, aerotriangulation begins with preparing and annotating photographs, whereby a suitable number of well distributed points is carefully selected such that they appear on as many photographs as possible. Once the preparation is complete, the points must be transferred to all photographs. This latter phase, particularly the transfer of strip tie points, is quite crucial. In fact, the success of an aerotriangulation project depends largely on the quality of the point transfer. Only after the points are transferred or clearly identified can the measuring process begin.

We have designed the automatic aerotriangulation system (AATS) and are currently implementing it into Intergraph's softcopy workstation. The purpose of this paper is to describe the concept (design) of AATS, its implementation, and the results obtained so far. The system was designed without having any special environment in mind. We use the name *concept* for this system-independent, top-down approach. In the implementation section we explain what components of the concept are realized and how they interact with the system environment. Finally, experimental results are reported.

Concept

Design Goals and System Overview
The main objectives of the automatic aerotriangulation system AATS are to

- Automate the preparation phase of an aerotriangulation project, including the automatic selection of block points;
- Automate the point transfer phase: that is, the exact corresponding locations of the block points in all images involved must be found;
- Improve the reliability of the block adjustment by increasing the number of block points[1]; and
- Provide additional products, such as photo mosaics.

These objectives are realized by the tasks depicted in Figure 1. Except for the two highlighted interactive tasks, they are designed as batch processes. After a batch process is executed, control is returned to the operator, who can analyze the results, modify parameters, or edit data if necessary.

Inputs to the system include digitized images with known interior orientation, a list with the sequence of images per strip and block, the camera parameter file, and the control points. No attempt is made to measure the control points automatically, at least not in the present stage. The manual measurements should be available before the block formation. This is not mandatory, however.

The first task generates a coarse block using low resolution images. The coarse block includes the outline of photographs, here referred to as footprints, the exterior orientation parameters, and a coarse DEM of the project area. This information is used in the second task, where suitable block points are selected. The results of the two tasks are displayed and block points can be edited. Tasks one through three correspond to the preparation phase.

This procedure is in contrast to traditional approaches,

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*This paper was originally prepared in 1993-1994 when the authors were engaged in automated aerotriangulation research at the Department of Geodetic Science and Surveying, The Ohio State University, 1958 Neil Avenue, Columbus, OH 43210. The development described represents an important point in the historical evolution of automated aerotriangulation.

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[1] Reliability depends a great deal on the number and distribution of block points. The more points that are measured, the higher the redundancy and the more reliable the error analysis.

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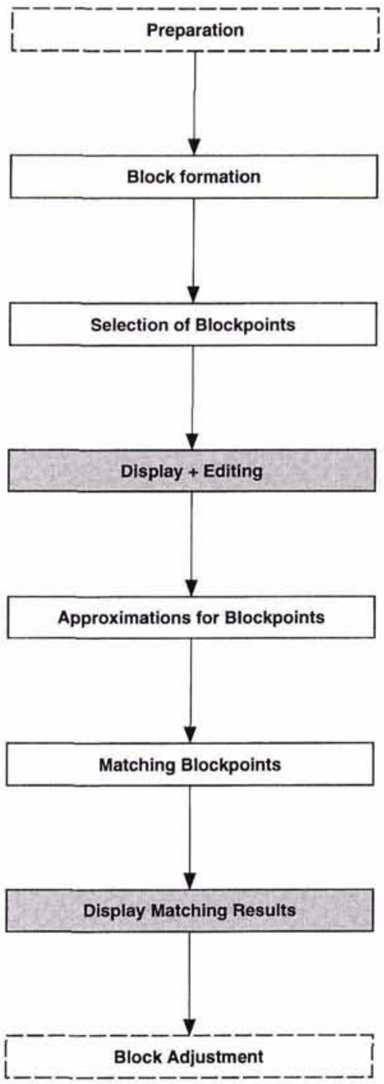

Figure 1. Schematic diagram of the automatic aerotriangulation system AATS.

where the nominal overlap configuration serves as the initial approximation for the locations of blockpoints (see, for example, Helava (1988) and Tsingas (1991)).

The point transfer and the measuring phase are approached in two steps. First, better approximations for the block points must be computed before the precise matching procedure in the next task begins. The last step is, again, an interactive task, allowing the user to analyze the results and specify the output format of the measured points.

Block Formation

The purpose of block formation is to generate a reference system for all images of an aerotriangulation project. In turn, this reference system is used for selecting the block points automatically. They are projected to high resolution images where they serve as centers of image patches. For a sufficient overlap of the image patches, the accuracy of the selected block points should be approximately ±1 mm at image scale. Figure 2 shows a schematic diagram of the strip- and block-formation phase of AATS.

To satisfy the accuracy requirement of 1 mm, it is not sufficient to apply a 2D similarity transformation of the photographs into the block system. Instead, a block is formed, as well as a rough DEM. The ground coverage of an image is found by projecting its corners onto the surface.

Strip Formation

The strip formation is a three-step process (see Figure 2) where first a model is computed, then scaled and translated into the strip coordinate system. The origin and orientation of the strip coordinate system is identical to the photo-coordinate system[2].

Dependent Relative Orientation

We have had positive experiences with the automatic relative orientation system which we developed earlier. As described in Schenk *et al.* (1991), a hierarchical approach with feature-based matching is used in the beginning to compute good approximations, followed by area-based matching at the finest resolution to compute precise locations of the corresponding points.

For the strip formation we only use the first part of the relative orientation scheme, that is, feature-based matching. Because we have described elsewhere the process of determining and matching edges (for example, in Schenk *et al.* (1991) and Li and Schenk (1990)), we will skip the details here. Typically, several hundred points are found with this matching procedure. The large number of points renders very accurate orientation elements, which makes it easy to detect wrongly matched points in subsequent processes.

Scaling the Model

Using a dependent relative orientation assures that the rotation angles of the new image are determined with respect to the previous model (or the strip-coordinate system). The scale of the new model is the only parameter not yet determined. This is an easy problem if model tie points are available. We do not determine model tie points, however. The scale is estimated by comparing points which are close together. Suppose model i is the new model, involving images k and $k + 1$. Then the previous model $i - 1$ involved images

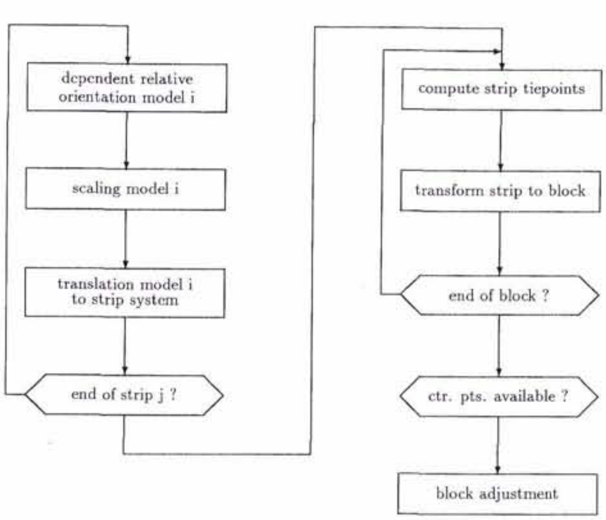

Figure 2. Block diagram of the block formation phase.

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[2] We use the term photo-coordinate system to indicate that all computations are performed in the coordinate system of the diapositive and not in the pixel system of the digital image.

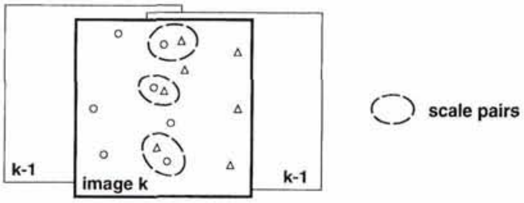

Figure 3. Identifying scale points. Triangles represent points found in the current model, while circles denote points from the previous model.

$k-1$ and k. Because image k is used for both models, it serves as a suitable reference to find neighboring model points.

Figure 3 illustrates this concept. The task is to find points, shown as circles in Figure 3, which are close to points represented by triangles. The latter are points determined in the current model while the former refers to model $i-1$. With all point pairs that passed a maximum distance criterion, the scale s is computed as the weighted average, where the distance d_j between the points is used as the reciprocal weight. We have

$$s = \sum_{j=1}^{n} \frac{p_{i-1,j}}{p_{i,j}} \, \frac{1}{d_j}, \qquad (1)$$

where $p_{i-1,j}$ and $p_{i,j}$ are the distances from the projection centers in model $i-1$ and i to the respective model points of pair j.

Strip Connection

We now turn to a short description of forming a block. The process begins with determining tie points between strips. The same edge detection and matching schema that has been proven successful for the relative orientation is applied. Matching pairs are formed with adjacent images from neighboring strips.

Even though images only overlap by 20 percent sidewise, dozens of tie points are usually detected. The dependent relative orientation performed across strips renders a second set of projection centers for the new strip. The first set is generated during strip formation. Because the overlap is only 20 percent, the ω rotation (actually the rotation about the longitudinal strip axis) must be controlled. If it exceeds a tolerance[3], then we set it to zero. Now, the current strip is transformed to the previous strip by a polynomial adjustment, using the two sets of projection centers as control points.

If control points are available, then a block adjustment using polynomials is performed. AATS cannot identify and measure control points automatically. This procedure is still left to the operator and becomes less significant because, with the increasing use of airborne GPS, fewer control points (on the ground) are required.

Blocksystem

One of the key features of AATS is the 3D blocksystem. The *X,Y*-plane of the 3D blocksystem is tesselated to a one-millimetre grid spacing. Consequently, all geometrical information, such as the corners of images or image points, is rasterized and stored in this 2D *block-coverage system*. Its main purpose is to provide information about the ground coverage of the images (footprints). The ground coverage of all images is then analyzed for selecting areas with a high degree of overlap because that is where block points should be selected and measured.

Figure 4 depicts the 3D block system. The tesselated *X,Y*-plane, the block coverage system, stores the footprints of all images of an aerotriangulation project in raster format. Assuming standard overlap configurations[4] and 1-mm tesselation, the size of the block coverage system is

$$L = \text{Length} = 230(0.4n + 0.6) \text{ pixels}$$
$$W = \text{Width} = 230(0.8s + 0.2) \text{ pixels}$$

where n is the number of photographs per strip and s is the number of strips. For a block with ten strips and 20 photographs per strip, the size of the block coverage system amounts to 1978 by 1886 pixels. Even for a very large project with 30 strips and 40 photographs per strip, the size of 3818 by 5566 is not excessive compared to the amount of storage required if all images were stored on line (one image requires ≈ 100 MB).

Selection of Block Points

The purpose of this task is to automatically determine suitable block points, the precise locations of which are computed in the mensuration task. The block system with its resolution of 1 mm serves as a basis to select block points.

There are a number of selection criteria, including image quality and the location in object space (e.g., flat surface). Probably the most decisive factor is the number of images on which a block point appears. Also, the density of block points contributes to the robustness of the block adjustment. For economic reasons, the number of block points is kept to a minimum in traditional aerotriangulation, because the cost increases proportionally with the number of points measured. This is not the case when using an automatic system.

The block system contains all necessary information to select block points in areas of high overlap. In regular blocks

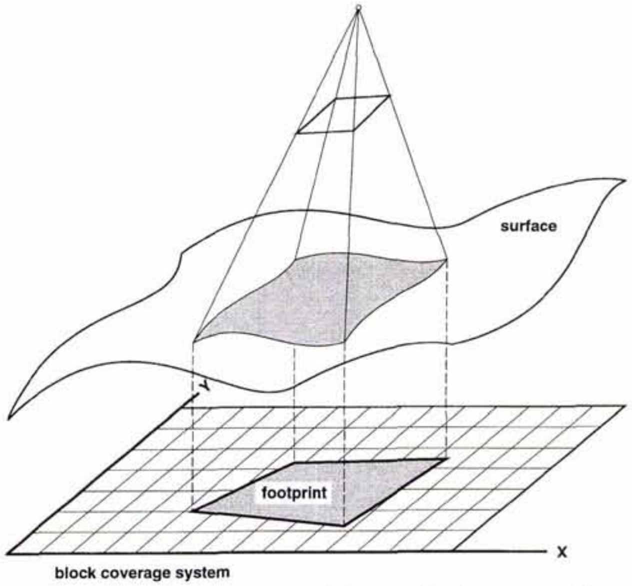

Figure 4. Schematic diagram of the 3D block system. The tesselated *X,Y*-plane is the block coverage system whose primary function is to store the footprints of all images of a block.

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[3] Currently set to ±3°.

[4] 60 percent overlap, 20 percent sidelap.

with 60 percent forward overlap and 20 percent sidelap, block points are first selected in areas that are covered by six photographs. If the area is too small, as may be the case in shifted strips, neighboring areas are checked.

Approximations for Block Points

There is widespread agreement that least-squares matching requires approximate locations of corresponding points of about two to three pixels (see, e.g., Heipke (1990)). The pixel size for aerotriangulation projects is usually smaller than 20 µm. In order to achieve sub-pixel accuracy for the matched points, the approximations must be better than 50 µm, preferably about 30 µm. To compute approximate locations with this accuracy requirement is a challenging task.

The most common approach to solving the approximation problem is to trace initial, coarse locations through the image pyramid (see, e.g., Tsingas (1991)). Let us assume that the multiple image matching is performed at the 15-µm pixel level. In that case, the approximations must be as good as 30 µm. Suppose now that we match at intermediate levels to an accuracy of one pixel, for example, by a simple correlation procedure. A conservative strategy would require that the matching be repeated at levels with half the pixel size.

In contrast to this traditional approach, a direct method is employed in AATS. By direct, we mean that the coarse approximations of the block points (± 1 mm) are projected directly onto the highest resolution level[5]. The accuracy of the block points corresponds approximately to 70 pixels at the matching level — far too much for the multiple image patch matcher to start. We approach the problem of improving the accuracy in several steps, summarized in the block diagram of Figure 5.

After projecting the block points onto the high resolution level, a window is centered around the approximate location of the block points in every image. In order to find corresponding points in all windows, they must sufficiently overlap. An accuracy of 1 mm at the block points ensures an overlap of 80 percent. Obviously, the task is now to align these image patches, a process which we call image patch registration. It is important to realize the difference from multiple image patch matching. Image patch registration delivers the required approximation for the latter process. Once all image patches are aligned, features that appear on all patches must be identified. These identical features (e.g., interest points) are then finally matched as precisely as possible.

Matching Block Points

The objective of multiple image matching is to determine the precise locations of corresponding points from n images ($n \geq 2$). All images should contribute simultaneously to the solution in order to exploit a major advantage that digital photogrammetry offers. In traditional photogrammetry, a human operator can only view (match) two images at the same time. Matching several images simultaneously is usually approached by a least-squares matching scheme. Because we have previously reported about our investigations (e.g., Agouris (1992) and Schenk and Toth (1993)), we skip the details here.

Implementation Aspects

In order to build a working system, the conceptual design discussed in the previous sections must be implemented in a suitable environment. Intergraph's softcopy workstation is such an environment. In the following sections, we discuss some general implementation issues followed by a description of the the workflow of our automated aerotriangulation system AATS and its interaction with Intergraph's aerotriangulation environment.

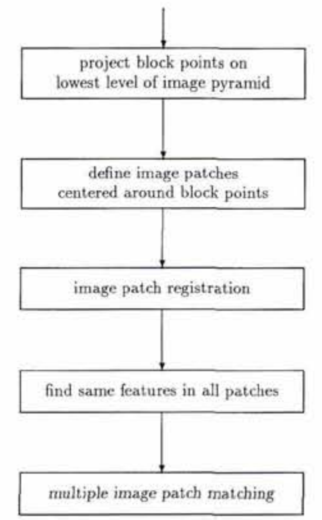

Figure 5. Block diagram of multiple image patch registration and matching in AATS.

The procedure to perform an aerotriangulation project with Intergraph's existing aerotriangulation system closely resembles the traditional way of using analytical plotters. Of course, using a softcopy workstation provides additional comfort and increases the throughput considerably. Also, the mensuration task is automated, using correlation and least-squares matching algorithms. The resulting sub-pixel accuracy compensates for the coarser resolution of digital images compared to aerial photography.

The main goal of implementing AATS is to replace manually executed tasks by automated procedures to further increase the throughput as well as the reliability of aerotriangulation projects.

General Considerations

Two major implementation aspects are discussed briefly here: first, the connection between automated and interactive procedures, and second, the storage and computing demands of the system. The first aspect will likely remain important for a longer time because full automation cannot be expected in the near future. However, the second issue is less crucial because of the continuous progress in the computer industry.

The use of softcopy stations for implementing automatic aerotriangulation systems provides an excellent environment for user intervention. For example, all relevant images or image patches can be displayed at any time, and the user can support the automated process by measuring points manually. The measurements may be performed either monoscopically or stereoscopically on selected pairs of image patches. Moreover, automated and manual procedures can be performed in a sequential or parallel fashion. How the procedures communicate and interact with each other is strictly a software engineering issue.

Computer processing power and storage capacity are the primary requirements for implementing an automated aerotriangulation system. Clearly, storage requirements are currently more crucial than processing power. For example, a compressed image with 15-µm pixel size[6] requires approxi-

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[5] Or the level where multiple image matching takes place.

[6] Scanning standard aerial imagery at 15 µm results in approximately 16K by 16K image size.

mately 80 MB of disk space[7]. A moderate size project consisting of 100 photographs will, therefore, require approximately 8 GB of storage. Although not impossible to handle, this requirement is still beyond the capabilities of most computers available today. Therefore, the data structure design must optimize access performance. Because several resolution levels are required, image pyramids are suggested. Full or partial pyramids are possible. Intermediate levels are called overviews in Intergraph's terminology.

The processing power determines the time required for executing a process. Although processing time may be long, running automated procedures in an unattended batch mode is far more economical than performing manual measurements. Usually, a large project is divided into smaller subblocks. Substantial reduction in processing time can be achieved with multiprocessor systems. In such an environment, a user can easily deal with several processes executed concurrently.

Proposed Workflow

Figure 6 depicts a schematic diagram of AATS workflow as it is implemented in Intergraph's existing aerotriangulation environment. The workflow comprises the three tasks of preparation, block formation, and mensuration.

Preparation

The preparation task is concerned with determining approximate footprints of the photographs. This involves, for example, information about the block configuration (e.g., flight plan), including approximate forward and side overlap. In case the position of the exposure stations is known, e.g., from GPS, the preparation task can be performed semi-automatically. Otherwise, the block configuration must be determined by an operator.

Additionally, the parameters of interior orientation and the photo coordinates of the ground control points (manually measured) are determined in the preparation phase. It is desirable to measure the ground control points during the preparation phase. However, this is not a firm requirement because the block reference system does not need to be identical to the control point coordinate system.

Block Formation

The block formation task is implemented as a batch process. It begins with matching neighboring images, using a feature-based approach. It is essentially the same algorithm we have developed for the automated relative orientation system (e.g., Schenk *et al.* (1991)). Typically, hundreds of corresponding points are obtained, allowing a much more robust determination of the orientation parameters than in the standard case, where usually only a few manually measured points are available. The accuracy of the matched points depends on the pixel size of the images used for matching. We have obtained an accuracy of ±1 pixel at this stage.

The matched points are stored in the photo file. After all images are matched, the operator examines the results, including the message file which lists problems encountered during the matching process. A careful analysis is important because automatic matching is not without problems. The analysis is supported in AATS by displaying the overlapping image patches and providing the possibility to measure points manually. In addition, disabling matching for certain models by a user request is allowed. This is particularly useful if one anticipates problems which may cause the matching procedure to fail.

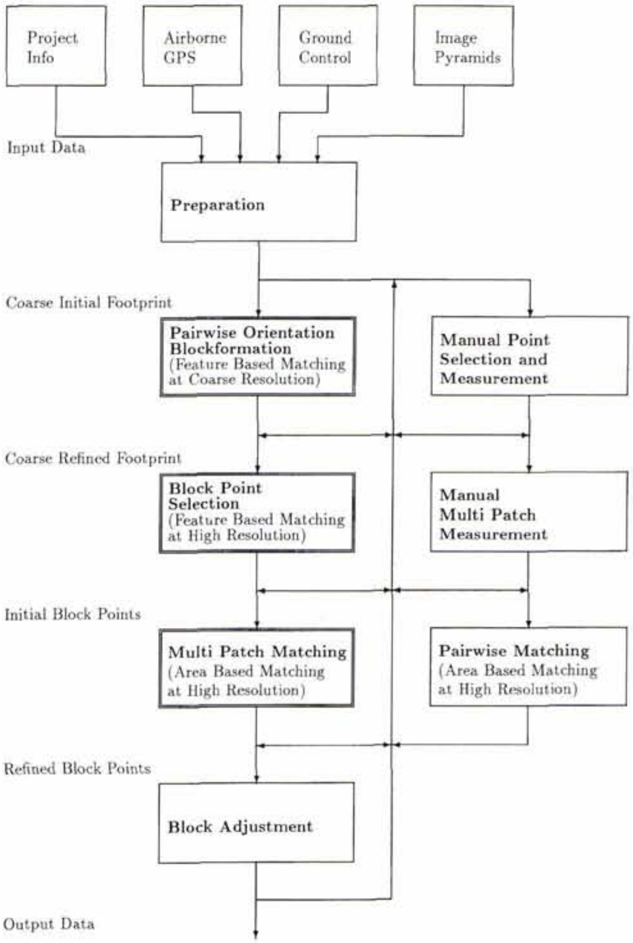

Figure 6. Schematic diagram of AATS' workflow as implemented in Intergraph's aerotriangulation environment.

The next sub-task is the registration of the photographs in a common coordinate system. It consists of three steps: strip formation, strip connection, and block adjustment. These are executed sequentially, unless a fatal error condition terminates the process and returns the control to the operator. The strip formation is implemented as a dependent relative orientation with scale estimation (see section about design). Matching across strips renders strip tie points which are then used to join neighboring strips to a block. If control points are available, a block adjustment by polynomials is performed.

The output of the strip and block formation is a set of approximate orientation parameters for all photographs involved. Additionally, approximate ground (or block) coordinates of the matched points are computed during the block adjustment. By forming a rough DEM of the entire block, improved footprints of the photographs are calculated. Points in areas that have a high degree of overlap[8] are selected for the next task. These block points are displayed and overlayed on the footprints of the photographs for operator inspection and editing (add, delete, or move block points manually).

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[7] This value is based on our experience with urban aerial images, a photo scale of 1:4000, and JPEG compression with a Q-Factor of 25. It may vary, though usually not significantly, for other cases.

[8] Usually ≥ 3, except for the block boundaries.

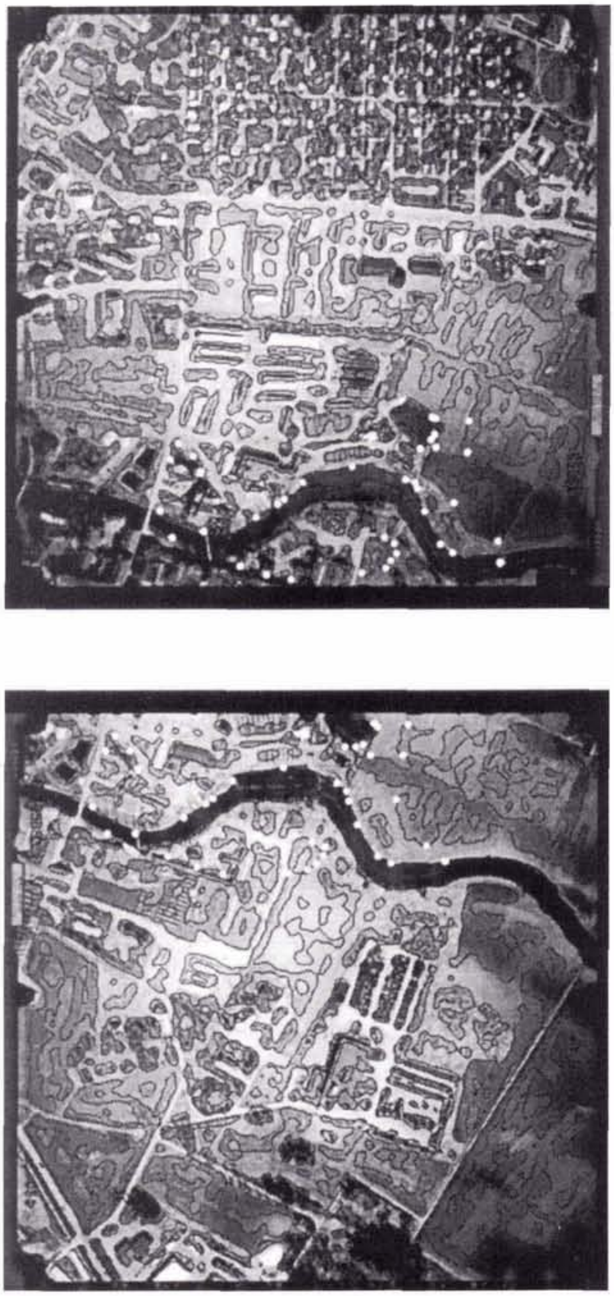

Figure 7. Two images of neighboring strips were matched. Despite a shift between the two strips and the marginal sidelap, many correct matches were found.

Mensuration Task

The goal of the mensuration task is to determine corresponding points as precisely as possible. It is currently implemented as a least-squares matching procedure using high resolution images. This method requires very good approximations. The photo coordinates of the selected block points, computed in the block formation task, are not accurate enough to serve as approximations. For example, an accuracy of ±1 pixel on the 1-mm resolution overviews translates to 70 pixels on the 15-µm resolution image.

The first step of the mensuration task is concerned with computing suitable approximations. As outlined in the design section, an image registration procedure is employed to solve the approximation problem. It is based on the same matching scheme used for the block formation, now applied to the overlapping image patches. User intervention is required in cases where the image patch registration fails. The overlapping image patches are displayed, and the user can measure the points manually.

Experimental Results

The most important aspects of the AATS concept were tested with a prototype installation on Intergraph's ImageStation. We comment here on the results obtained from two different projects. The first project concerns the European Organization for Experimental Photogrammetric Research (OEEPE) test, "Aerotriangulation using Digital Images." The test block, comprised of four strips with seven images per strip, was flown over an urban area in southern Finland. Aerial photography (positive color) was obtained with an RC20 wide angle camera flown at 600 m above ground. The forward overlap is 60 percent, and the sidelap varies between 24 and 49 percent. The color photography was scanned with a PS1 scanner as gray scale images.

Project "CAMPUS" is a sub-block of a larger mapping project that we have performed for the Physical Facility Department at The Ohio State University. It covers an area with many tall buildings, parks, and trees. The diapositives were scanned by Intergraph Corporation with a PS1 scanner. The interior orientation for all images was performed manually on the ImageStation. The diapositives had been measured earlier on a Planicomp analytical plotter. A classical aerotriangulation was then performed. We have used the manual measurements of the control points in AATS.

The matching procedure was performed on every pair of neighboring images, including those from adjacent strips. Overview images with pixel sizes of 1 mm and 0.5 mm were used, without significant differences in the results, except, of course, for the accuracy. For images with good contrast and lots of features, the lower resolution is adequate. Figure 7 shows the results of matching two images from neighboring strips. Apart from the marginal sidelap of 20 percent, there is also a shift between the strips, thus further reducing the overlap area. Nevertheless, a considerable number of correct matches were found. As explained in the previous sections, these tie points are used in the block formation task to join strips.

The most important results are summarized in Table 1. The pixel size refers to the overview images with which all computations were performed. The number of model points is an average value. The numbers range from 198 to 363 in the OEEPE project and from 276 to 423 for the CAMPUS project. The next line with σ_{py} refers to the average standard deviation of the y-parallax in image scale. Note that the values

TABLE 1. RESULTS OF STRIP- AND BLOCK-FORMATION FROM TWO AEROTRIANGULATION PROJECTS

	OEEPE	CAMPUS
photo scale	1:4000	1:4000
pixel size [mm]	0.5	0.95
photos per strip	7	4
number of strips	4	3
points per model	286	338
σ_{py} [mm]	0.43	0.81
blunders per model	35	28
scale points per model	18	22
σ_{scale} [%]	1.4	2.3
X,Y control points	14	8
Z control points	18	12
residual error X,Y [mm]	0.8	1.1
residual error Z [mm]	1.2	1.5

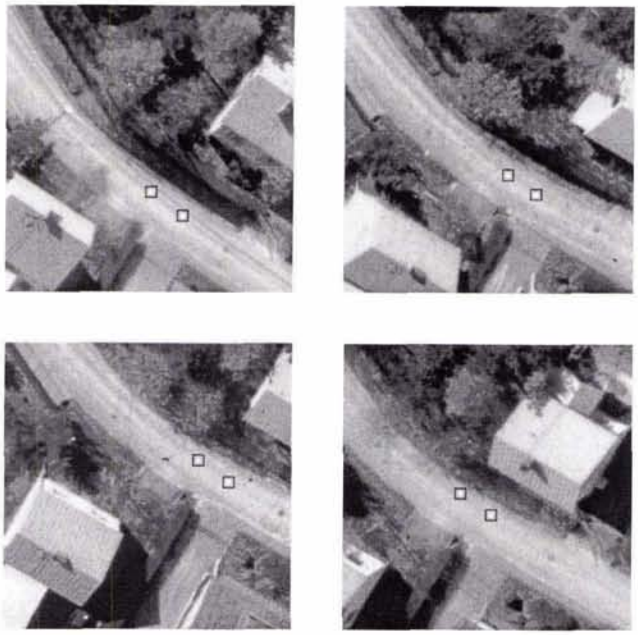

Figure 8. The four image patches are centered around block points which were found automatically. The patch size is 512 by 512. The highlighted points were found on patches. They serve as approximations for the precise point matching.

are slightly smaller than one pixel. As described in the previous section, we employ a rigorous blunder detection schema. The next entry in Table 1 shows the number of blunders, averaged from all models. The number of scale points refers to the point pairs which have been used to determine the scale factor of the model after the dependent relative orientation (see *Scaling the Model* section). The accuracy of the scale factor is expressed in percentage of the base. The average value of 1.4 percent, in the case of the OEEPE project, translates to an error of the base of approximately 1.2 mm. One may argue that this exceeds the accuracy expectations of ± 1 mm; however, this error will be partially compensated for by the block adjustment.

The results of the block adjustment, performed using polynomials, is summarized by the residual error in planimetry and elevation. By residual error, we mean the residuals on the control points as well as the differences on check points. A number of points determined by AATS was measured manually on an ImageStation using high resolution images. Therefore, the check points can be considered true. For the "CAMPUS" project, the check points were measured on an analytical plotter. The residual errors are expressed at image scale. For both projects, they indicate an accuracy of about 1 mm for the matched points.

Figure 8 illustrates the problem of computing approximations for the precise point matching. The four image patches are centered around the block points determined in the coarse block system. The accuracy is approximately 1 mm. This uncertainty is magnified by the ratio of low to high resolution which is, in our example, 1.0 mm to 0.015 mm. In terms of pixels at the finest resolution, it translates into 67 pixels. In order to have an 80 percent overlap of the image patches, a size of 512 by 512 is adequate.

The results of this direct approach are encouraging. Even with a conservative strategy of accepting matches, a few points are found on more than two patches. Note that the highlighted points in Figure 8 were found in all four patches.

Conclusions

The process of aerotriangulation is amenable to automation using digital photogrammetry. In this paper, we have shown that the preparation, point transfer, and measuring phases can be successfully automated. The benefit of automatic aerotriangulation systems, such as AATS, is a substantial increase in efficiency. A number of factors account for an increase in reliability. For example, there is virtually no limit to the number of points per image (or per model for that matter) that are determined automatically by AATS. With, say, 100 points per image (instead of the usual nine-point pattern), it is much easier, and a lot more meaningful too, to identify blunders. Moreover, additional parameters for compensating systematic image errors (e.g., those related to the camera, film, and scanning device) can be more reliably computed during the block adjustment. Finally, the accuracy of the exterior orientation parameters increases proportionally with the number of points.

In this paper, we have described the concept of AATS and its implementation in Intergraph's ImageStation. Block formation is a preparatory step for selecting suitable block points and for providing good approximations. The latter is important in the subsequent process of determining exact corresponding positions.

Results achieved with the block formation module indicate that an accuracy of one to two pixels can be expected, or approximately 1 mm when using coarse overview images. With this accuracy, we generate footprints and photo mosaics that are far better than manual processes can deliver.

Acknowledgments

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