DIGITAL AERIAL TRIANGULATION

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ABSTRACT:

Aerial triangulation enjoyed great success during the last 30 years. Highly efficient block adjustment methods are now in widespread use. A more recent development began a few years ago by integrating GPS into the aerial triangulation process. This will significantly change the way control information is used. GPS, together with advances in navigation systems and camera stabilization, highly accurate flight missions are now possible. All this remarkable progress will be equaled by new developments in digital photogrammetry. Several digital aerial triangulation systems are now in various stages of development. Two distinctly different approaches can be observed: interactive systems that require human operator guidance and softcopy workstations; and automatic systems. Automatic aerial triangulation systems attempt to reduce the aerial triangulation problem to a batch process, with little or no help of a human operator. Today's systems are close to meeting this challenge, but the identification and measurement of control points remains an interactive task. The paper focuses on automatic aerial triangulation. Major effort is spent on identifying essential tasks that are independent of existing systems. The tasks, such as selecting suitable tie points, determining accurate approximations, and matching multiple images, are derived from the objectives of digital aerial triangulation considering the potential of image processing and computer vision. The solution of these essential tasks brings a myriad of challenging problems. The concluding remarks comment on the differences between traditional and digital approaches and discuss the consequences.

KURZFASSUNG:

Aerotriangulation erfuhr in den letzten 30 Jahrn einen beispielhaften Aufschwung. Leistungsfähige Blockausgleichungs Programme sind heute im weltweiten Einsatz. Wie viele andere Disziplinen wird GPS auch die Aerotriangulation nachhaltig beeinflussen, z.B. durch die Art und Weise, wie Passpunkte verwendet werden. Die digitale Photogrammetrie wird neue Änderungen bringen. Der Übergang von analytischer zu digitaler Aerotriangulation wird so bedeutend sein wie seinerzeit der Wechsel von analogen zu analytischen Methoden. Heute kann man zwei Arten von digitaler Aerotriangulation unterscheiden: interaktiv und automatisch. Automatische Verfahren zielen darauf ab, den ganzen Prozess ohne Hilfe eines Operateurs abzuwickeln. Dies scheint in der Tat möglich zu sein, mit Ausnahme der Identifikation und Messung von signalisierten Punkten. Der Schwerpunkt dieses Beitrages liegt in der Ausarbeitung von fundamentalen Prozessen, die es in der automatischen Aerotriangulation zu lösen gilt. Zu diesen Prozessen gehören die Auswahl von geeigneten Verknüpfungspunkten, sowie deren Übertragung in angrenzende Bilder mit anschliessender Messung (Mehrfach-Bildzuordnung). In den Schlussfolgerungen werden die wichtigsten Unterschiede zwischen traditioneller und digitaler Aerotriangulation diskutiert. Aus diesen Unterschieden ergeben sich einige wichtige Konsequenzen auf die ebenfalls kurz eingegangen wird.

1 INTRODUCTION

The development of aerial triangulation during the last 25 years is a major success story! Consider, for example, the increase in accuracy from 25 μm to 5 μm, a tenfold increase in performance and reliability, and the widespread use of efficient block adjustment methods. Other than success, is there anything else worth reporting? Apart from incremental improvements, are there any significant changes in sight? The answer is yes, for exciting developments are taking place—aerial triangulation is going digital, a change that is as significant as the transition from analog to analytical aerial triangulation methods a quarter of a century ago. This paper is about the new transition from analytical to digital methods, its challenges and prospects to researchers in and users of digital aerial triangulation methods.

Fig. 1 illustrates the progress in research and the development of aerial triangulation systems. The

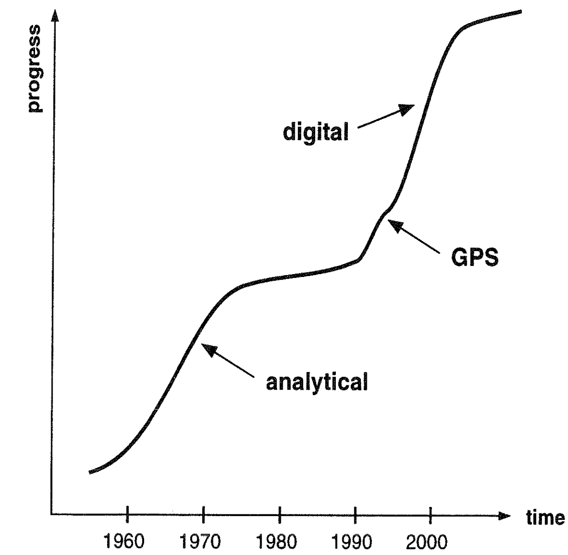

Figure 1: Past and predicted development of aerial triangulation.

use of modern aerial triangulation techniques in photogrammetric practice could be represented by another curve. It would be much flatter and shifted to the right, accounting for the typical time shift that can be observed between inventions, availability of operational systems and their widespread use.

The rapid progress in the late sixties and early seventies was mainly in the areas of block adjustment methods and error propagation analysis. With the availability of analytical plotters some procedural changes took place. For example, one of the most significant results was the great simplification of the point transfer problem. GPS had, and is going to have, a great impact on aerial triangulation. Not only did it spark new research interest, but it also changed significantly the way aerial triangulation projects are carried out. Once a sensitive problem, the determination of good control points is now a snap. Using differential GPS methods during data acquisition greatly reduces the number of control points. Digital photogrammetry and computer vision will bring about new changes that will shape aerial triangulation as dramatically as analytical photogrammetry did during the past 30 years.

Not only is aerial triangulation in an exciting state of change, but the entire field of photogrammetry. It is safe to predict that the majority of papers presented at the XVIII ISPRS Congress will deal in one way or another with digital photogrammetry. As the name suggests, digital photogrammetry deals with digital imagery and the goal is to capture, to store, and to process images automatically. Ever since computers became available, researchers tried to mimic the mental faculty of seeing. It is tempting to endow computers with the information processing capabilities similar to those of human operators. How soon can we expect a machine that produces maps automatically, performs an aerial triangulation, generates DEMs and orthophotos at the touch of a button? The answer almost entirely depends on how well the human processes necessary to solve photogrammetric tasks are understood. There is common agreement in the artificial intelligence, computer vision, and photogrammetry communities that these processes are poorly understood. It appears that the broader the knowledge that is required to solve a problem, the more difficult it is to encapsulate it. For example, to make a map relies on a much broader knowledge base than aerial triangulation. The major difference is in the type of knowledge: the map making process requires common sense, general "world knowledge" and image understanding abilities; aerial triangulation, on the other hand, uses a great deal of very specialized knowledge (block adjustment, error propagation, etc.). This is good news because the knowledge of an aerial triangulation expert is far less difficult to represent explicitly. This warrants the assumption that aerial triangulation can be automated much more readily than, say, making maps. Oddly enough, it is much more difficult to explain aerial triangulation to a layman than how to make a map.

This paper does not review existing digital aerial triangulation systems nor is it a status report. Rather it elaborates on the fundamental problems—called essential tasks here—that are inevitably linked to automatic aerial triangulation. The next section comments on terminology and attempts to classify digital aerial triangulation and to contrast it to existing procedures. The paper focuses on automatic aerial triangulation. Readers familiar with the subject may skip the introductory sections and proceed directly to Section 5, where essential tasks are derived and possible solutions are analyzed. Finally, the paper concludes with some remarks on the consequences digital aerial triangulation will have on photogrammetry. Incidentally, if some opinions and ideas expressed in this paper appear provocative to the reader, then it is purposely in the hope of stimulating interesting discussion.

2 BACKGROUND

Digital aerial triangulation enjoys great interest in digital photogrammetry, both by researchers and users. This is manifest in many publications. The organizers of the Photogrammetric Week '95 devoted one session to the subject, featuring 10 interesting contributions that addressed various aspects of digital aerial triangulation (see References).

2.1 Taxonomy

Whenever new technologies emerge usually no universally accepted terminology exists in the beginning and confusion is great at times. Exactly, what is *digital, interactive, automatic* aerial triangulation? How do they differ from analytical aerial triangulation? The following comments are not intended to propose new definitions, they merely help to classify the different methods in this paper.

The term digital aerial triangulation is now consistently used. It differs from analytical aerial triangulation in that it draws on methods developed in digital photogrammetry, image processing and computer vision. The division into *interactive* and *automatic* aerial triangulation is less straightforward. Interactive methods require a human operator and digital photogrammetry workstations, also called softcopy workstations. This is not the case for automatic methods; here, the goal is to run aerial triangulation as a batch process, with little or no operator involvement.

2.2 Objectives of Digital Aerial Triangulation

It may seem surprising to discuss the objectives here. Isn't it clear that all that we need are the exterior orientation parameters of the imagery involved? This is an extreme view that disregards the object space. Photogrammetric products refer almost exclusively to the object space, for example, maps, surfaces (DEMs), orthophotos, points, profiles. Aerial triangulation is a prerequisite for these processes and it seems justified to request as much information about the object space as possible. Ideally, the result of aerial triangulation should include a completely reconstructed surface, both in terms of geometry (DEM) and radiometry (orthophoto). This is the other extreme view about the objectives. In reality we would request a partial reconstruction, consisting of the adjusted blockpoints or perhaps of reconstructed surface patches.

2.3 Typical Workflow

In a narrower sense aerial triangulation involves the following four phases:

Preparation: on every photograph a suitable number of well distributed points are selected. The location must be chosen such that the same point appears on as many neighboring photographs as possible. Selected points are appropriately annotated.

Point transfer: the points selected in the previous phase must be marked on every photograph, either directly by drilling a hole into the emulsion, or indirectly by the stereovision ability of a human operator.

Point mensuration: all selected points, including control points, are precisely measured on analytical plotters or softcopy workstations, either manually by a skilled operator or automatically by image matching methods.

Block adjustment: is performed by one of the many highly efficient programs.

The success of aerial triangulation depends on highly skilled personnel. With the increased use of GPS technology for determining control points, the point transfer phase is probably the single most critical factor.

Table 1 compares analytical and digital aerial triangulation methods with regards to the way the workflow tasks are solved. Section 5.3 provides a more detailed analysis of an automatic aerial triangulation workflow.

Table 1: Comparison of different aerial triangulation methods.

major tasks	analy-tical	digital inter-active	digital auto-matic
identifying sign. pts.	M	M	M
selecting blockpts	M	I	A
point transfer	M	I	A
measuring			
– sign. points	M	M	M
– blockpoints	M	I	A
block adjustment	A	A	A

A automatic procedure
I interactive procedure
M manual procedure

3 IMAGE MATCHING

One of the most fundamental processes in photogrammetry is to identify and measure conjugate points in two or more overlapping photographs. In analytical aerial triangulation the identification of conjugate points is performed by a human operator; in digital aerial triangulation one attempts to solve the problem automatically—a process known as *image matching*.

Image matching has quite a long history. The first experiments started in the fifties, most notably by Hobrough. The solution was analog in nature; correlators which were realized in hardware compared (correlated) the gray levels of two images. From the early seventies to the mid-eighties research related to image matching focused on digital correlation techniques. Despite considerable effort no general solution was found. Researchers were puzzled because humans find conjugate points easily, without conscious effort.

We know now that the human stereo system does not correlate gray levels, rather it matches edges.

Because of the lack of a unified terminology the following definitions are introduced in this text:

conjugate entity: is a more general term than conjugate point. Conjugate entities are the images of object space features, including points, lines and areas.

matching entity: is the primitive which is compared with primitives in other images to find conjugate entities. Primitives include gray levels, features, and symbolic descriptions. Note that matching entities are not necessarily physical quantities such as gray levels (pixels), but may be abstract quantities (derived from physical quantities), for example, symbolic descriptions.

similarity measure: is a quantitative measure of how well matching entities correspond to each other. The degree of similarity can either be a maximum or minimum criteria. The cross correlation coefficient is an example of a maximum criteria.

matching method: performs the similarity measure of matching entities. The methods are usually named after the matching entity, for example, area-based matching, feature-based matching, and symbolic matching.

matching strategy: refers to the concept or overall scheme of the solution of the image matching problem. Strategies include: hierarchical approach, neural networks approach.

Table 2 shows how these terms are related. The first column lists the three best known matching methods. *Area-based matching* is associated with matching gray levels. That is, the gray level distribution of small areas of two images, called *image patches*, is compared and the similarity is measured by correlation or least-squares techniques. Area-based matching using correlation is often simply called *correlation*. Likewise, area-based matching with a least-squares approach for measuring similarity is referred to as *least-squares matching (LSM)*.

Area-based matching probably renders the highest accuracy. Under good conditions, accuracies of 1/10 of a pixel or better can be expected. Feature-based matching is predominantly used in computer vision. Here, edges or other features derived from the original images are compared. The similarity, for example, the shape, sign, and strength (gradient) of edges, is measured by a cost function. In photogrammetry, feature-based matching refers to the process of finding conjugate interest points.

Table 2: Relationship between matching methods and matching entities.

matching method	**similarity measure**	**matching entities**
area-based	correlation least-squares	gray levels
feature-based	cost function	edges
symbolic	cost function	relational description

The third method, *symbolic matching*, compares symbolic descriptions of images and measures the similarity by a cost function. The symbolic descriptions may refer to gray levels or to derived features. They can be implemented as graphs, trees, or semantic nets. In contrast to the other methods, symbolic matching is not strictly based on geometric similarity properties. Instead of using the shape or location as a similarity criterion, it compares topological properties. Feature-based matching methods are in general more robust and require less stringent approximations.

An important aspect in digital aerial triangulation is the need to match several images simultaneously. We use the term *multiple image matching* when more than two images are involved.

4 INTERACTIVE AERIAL TRIANGULATION

In this paper the term interactive (digital) aerial triangulation refers to methods that require considerable human operator involvement and an interactive workstation, such as a softcopy workstation. Generally, softcopy workstations offer tools for manual or interactive measurement of tie points. The difference between the two terms is not well defined; both are used to describe the interactive process where the operator selects the tie point on one image, and the matching is performed by the computer, allowing the user to accept or reject the results. However, a much higher level of automation is preferable—the subject of the next section.

Interactive methods essentially mimic the way aerial triangulation is performed on analytical plotters. Additional comfort may be offered by displaying more than two images simultaneously for easier identification of tie points. The transfer and the measurement of tie points is greatly facilitated by image matching. Since interactive systems work in a controlled environment, less effort is made to make all processes robust for the operator is called for help whenever the system fails.

A point of confusion is the term "automatic" that is used on softcopy workstations to indicate that the point measurement is performed "automatically" by employing a matching algorithm. In the next section the term is used in a much broader sense: not only are the points measured automatically, but also their selection, their transfer, and the determination of suitable approximations.

A major advantage of interactive aerial triangulation is of a practical nature: users may follow familiar procedures thus reducing the risk of making costly mistakes with new technologies.

Various interactive aerial triangulation systems are in practical use and results about performance and experience haven been reported (e.g., Haumann, 1995; Beckschäfer, 1995).

5 AUTOMATIC AERIAL TRIANGULATION

Automatic aerial triangulation systems are on the verge of entering the marketplace. Several systems have been described (see, e.g. Ackermann, 1995; Krzystek et al., 1995; Schenk, 1995). Tsingas (1995) and Fritsch (1994, 1995) report about experimental results. Some systems evolved from successful solutions of automating the relative orientation (see, e.g., Tang et al., 1994; Mayr, 1995).

With automatic aerial triangulation we mean methods that attempt to solve the task as a batch process, with little or no help from a human operator, except the measurement of control points. In order to achieve this ambitious goal it is imperative to fully exploit the potential of digital photogrammtry, image processing, and computer vision. This, in turn, may suggest taking a fresh look at the problem rather than mimicking existing procedures that are optimal for traditional aerial triangulation but perhaps not ideally suited for an automatic approach. We pursue this view here and derive essential tasks from the objectives of automatic aerial triangulation. These essential tasks must be addressed by every aerial triangulation system in one way or another—they are sort of invariant, independent of the method. Incidentally, the solution of essential tasks determines the level of comfort and performance of automatic aerial triangulation systems. Thus, they may serve as evaluation criteria.

5.1 Essential Tasks

The essential tasks of automatic aerial triangulation are derived in a backward fashion, starting from the objectives which include the determination of the exterior orientation parameters and a partial reconstruction of the object space. We request that the orientation parameters are as accurate and reliable as in analytical aerial triangulation. The adjusted blockpoints form a minimal reconstruction of the object space. With blockpoints, or tie points, we refer to the matching entities. They may comprise points, point features, or line features. More advanced systems would also include regions, ranging from small surface patches with their topography and radiometry to the entire surface of the project area. Obviously, this latter concept would combine aerial triangulation, DEM and orthophoto generation in one process.

5.1.1 Number of Blockpoints: With analytical methods accurate orientation parameters are obtained by measuring relatively few blockpoints, say, 9 to 15 points per photograph, as precisely as possible. For economic reasons the challenge is to work with a minimum number of points that still assure reliable and accurate results. Consequently, the points must be carefully chosen, transferred, and measured.

In automatic aerial triangulation the situation is quite different. First, it really does not increase computing cost significantly if hundreds of points per image are matched. But more important, human operators are far superior in selecting blockpoints than machines. As a result, we are much better off in using many, but less carefully chosen blockpoints. The emphasis shifts from a few points to masses of points. Isn't this neglecting the accuracy aspect? Suppose we have 25 times more blockpoints in automatic aerial triangulation than in the standard case. Since all points contribute to the determination of the exterior orientation parameters, their accuracy will be roughly five times better. This is the same as to say that the accuracy of the orientation parameters remains the same if many but less accurate points are used. The compelling conclusion is that the accuracy of an individual point is much less important than in traditional aerial triangulation. Consider a pixel size of 30 μm and a matching accuracy of 1/3 of a pixel. Even though this measuring accuracy is not outstanding at all we still obtain more accurate orientation parameters. Moreover, the reliability increases.

The claim of higher accuracy and reliability of the exterior orientation parameters is confirmed by experimental results (see, e.g., Fritsch, 1995; Tsingas, 1995; Ackermann, 1995).

5.1.2 Location of Blockpoints: Even though the selection of blockpoints is less critical than in traditional aerial triangulation, their location should not be arbitrarily chosen. This is particularly true if aerial triangulation is viewed as a preprocess to other photogrammetric procedures, such as DEM generation and map compilation. For example, the automatic generation of DEMs would greatly benefit if the blockpoints were selected at interesting locations, such as along breaklines. In any case, the selection should satisfy the following criteria:

multiple overlap object points that appear on as many images as possible increase the stability of the block adjustment.

image function of the image patches to be matched should be well conditioned. This is usually the case for areas with enough texture and contrast. Note that the selection also depends on the matching method. For example area-based matching methods inherently assume flat surfaces; matching windows selected on breaklines are potential problems. Feature-based methods are much less sensitive in that regard. In fact, edges in many cases correspond to breaklines.

topography points in flat areas are a better choice than points on slopes or on tree tops. Tilted surface patches more likely lead to unsuitable image patches due to foreshortening. By the way, the foreshortening problem is much more pronounced in aerial triangulation because the connections of all projection centers involved result in many more critical orientations. In a single model only one critical orientation exists (along the model base).

even distribution of points increases not only the block stability but also render a better partial reconstruction of the surface.

5.1.3 Multiple Image Matching: Most of the blockpoints are imaged on more than two images. Thus, the need arises to find the most probable conjugate location by matching all image patches simultaneously. This possibility does not exist with traditional methods because humans can only see two image patches at a time. Multiple image matching (MIM) alleviates the tie point problem.

5.1.4 Approximations: In order to meet the accuracy expectations matched entities should have subpixel precision. As discussed in Section 3, every matching method needs approximate matching positions. The accuracy of the approximations depends largely on the matching method: area-based methods require two to three pixels, feature-based methods are less demanding but still need good approximations (see, e.g., Förstner, 1995). Suppose we employ LSM on a resolution level of 15 to 30 μm. The challenge is to provide approximate locations that are better than 1/20 mm.

Not only does the pull-in range determine the approximations, but also the size of the matching windows. Fig. 2 depicts three image patches, size $s \times s$. Their centers are only approximately known and the common area is much smaller than one window. Let d be the uncertainty in predicting the matching location. In the worst case the three windows are displaced in one direction by $2 \cdot d$. Suppose now that the same process is repeated with 3 windows of the adjacent strip. Again assuming the worst case situation, the displacement can be in the opposite direction, resulting in an overall displacement of $d_m = 5 \cdot d$. Considering d_m a maximum error we must expect an average displacement of $d_a = 1.7 \cdot d$ in a six overlap situation. Now we still expect a common overlapping area of, say, half of the original window size. From $d_m \leq 0.5 \cdot s$ we conclude that the uncertainty, d, of predicting conjugate points should not exceed 1/10 of the window size to assure that the common area is still large enough.

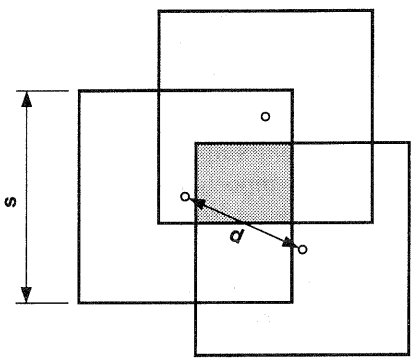

Figure 2: Three partially overlapping matching windows, offset by the uncertainty from predicting their centers.

5.2 Solutions, Assumptions, Constraints

The essential tasks are the result of solving the orientation parameters as well as possible and of partially reconstructing the object space for subsequent photogrammetric processes, such as the automatic generation of DEMs and orthophotos. The tasks must be solved in one way or another by automatic aerial triangulation methods. Their solution entails new problems which are briefly discussed here.

5.2.1 Footprints The request for multiple overlap and even distribution of blockpoints requires the knowledge of footprints. Fig. 3 depicts a realistic overlap situation; it goes without saying that selecting features in the 6-fold overlap area requires more accurate positions of the footprints than is available from the nominal overlap. To determine the footprints, the surface and the exterior orientation must be known. This is a dilemma: what we want to determine in the aerial triangulation is what we wish to know in the very beginning.

5.2.2 Predictions: A fundamental aspect of matching is to predict the matching locations and the matching range. Assume we have selected an interesting location according to Section 5.1.1+2. In order to perform MIM (5.1.3) we need approximate locations on all corresponding images. The matching range (size of search window) depends on the convergence radius of the matching method (pull-in range) and the uncertainty of the prediction process.

Fig. 4 illustrates the concept of a predictor. It works in two modes: the classical mode begins with selecting a matching entity in one image, followed by projecting it into the object space and from there back to the

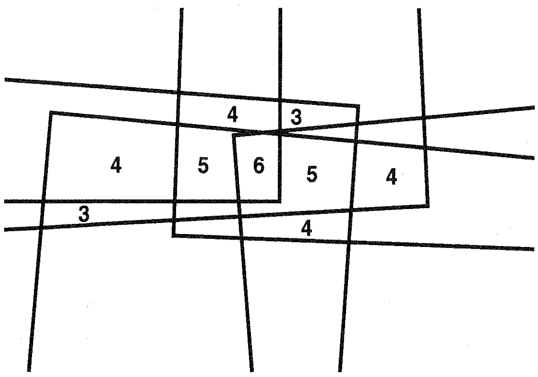

Figure 3: Example of 6 overlapping images.

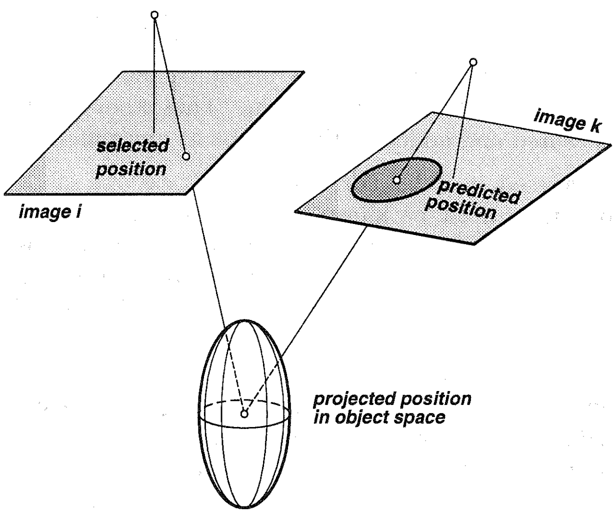

Figure 4: Schematic diagram of predicting conjugate locations.

images that are involved in the matching procedure. The result of the first step is an uncertainty figure in the object space, symbolized in Fig. 4 by an ellipsoid. This figure is a function of uncertain exterior orientation parameters of image i and uncertain elevations—usually the dominating factor. Thus, the figure has an elongated shape in the z-direction. The projection back to the other images results in the predicted position and in the uncertainty figure that determines a plausible search space. The figure is further influenced by the uncertainty of the exterior orientation of image k. The second mode of the predictor begins by selecting an entity in object space followed by predicting it to all images involved. In that case the uncertainty figure in object space is pretty much restricted to a vertical line with the centroid being the estimated elevation and the length being the uncertainty of the estimate.

Because the influence of uncertain elevations on the matching location and size of the search space is often underestimated, we elaborate further on this subject.

Table 3: Uncertainty factors for predicting conjugate locations due to inaccurate exterior orientation and elevations.

errors in EO				errors in	
position		attitude		elevation	
$\frac{\Delta P}{H}$	ε_p	[deg]	ε_a	$\frac{\Delta h}{H}$	ε_h
0.001	0.001	0.01	0.0002	0.01	0.010
0.01	0.01	0.1	0.002	0.1	0.111
0.05	0.05	1.0	0.022	0.2	0.25
0.1	0.1	5.0	0.122	0.33	0.5

Table 3 contains three different coefficients ε which show the influence of an error in position (ε_p), attitude (ε_a), and elevation (ε_a). The errors on the predicted conjugate locations are obtained by multiplying the coefficients by the base. For example, $e_p = b \cdot \varepsilon_p$ gives the error in the predicted location as a function of the uncertainty in the position of the projection centers. Likewise, $e_a = b \cdot \varepsilon_a$ indicates the error as a function of uncertain attitude data. Finally, $e_h = b \cdot \varepsilon_h$ is the error because of uncertain elevations.

The first column expresses the uncertainty in position of the exterior orientation, ΔP, as a ratio to the flying height H. Consider a large-scale aerial triangulation project for a moment, scale 1:2000, and a wide angle camera. Then the first entry means that the position of the projection centers is fairly well known (0.3 m). The first entry of column 3 indicates that the attitude is also well known. The first row reflects the situation where accurate GPS/INS data are available. The fourth row is more representative of flights without additional information. An error of 5^o in attitude leads to an error in the predicted position of $e_a = 88 \cdot 0.122 = 10.8$ mm, assuming the base is $b = 88$ mm.

A closer examination of the coefficients reveals that the uncertainty in elevations has a much higher influence on the predicted position than errors in the exterior orientation. For example, the first entry in column 5 refers to a situation where all elevations are either well known, or where a very flat surface is assumed. The ratio of elevation uncertainty, Δh, to flying height, H, is most likely considerably larger. Mountainous areas may have elevation differences as much as 1/3 of the flying height. In this extreme case, the uncertainty of the predicted conjugate location would reach half of the base. Table 3 also demonstrates that even if the exterior orientation is well known the predicted locations suffer from unknown topography, a fact that is often overlooked.

5.2.3 Multiple Image Matching: The problem of matching more than two images is approached in different ways. A more pragmatic solution is to employ the proven concept of matching two image patches at the same time. In that case, all possible pairs are matched, perhaps even forth and back as a control (see, e.g. Fritsch, 1995). This approach has several disadvantages. Fore one, the pairs are not independent from each other. Moreover, it may happen that the sequential matching procedure comes to an early end, leaving some alternatives unexplored.

The information content in every image patch can only be fully exploited if all patches are simultaneously. Agouris presents a rigorous solution in (Agouris, 1992) that eliminates the problems of sequential approaches. A different approach is proposed in (Krupnik, 1994; Schenk et al., 1996). Here, the matching is performed in object space. The exterior orientation, the topography of the surface patch and its gray levels are the parameters to be determined. Matching in object space has been proposed by other researchers (see, e.g., Ebner et al., Wrobel, 1987; Heipke, 1990). Förstner (1995), elaborates on the differences between these approaches. All these methods use gray levels as matching entities and the matching method is LSM. Tsingas solves the multiple image matching problem in a different fashion (Tsingas, 1994). Instead of gray levels interest points are used as matching entities and the matching method is based on graphs.

5.3 Work Flow

We identified several problems automatic aerial triangulation systems must solve in order to deserve the predicate "automatic." There is considerable flexibility in the solutions, resulting in different levels of comfort and performance.

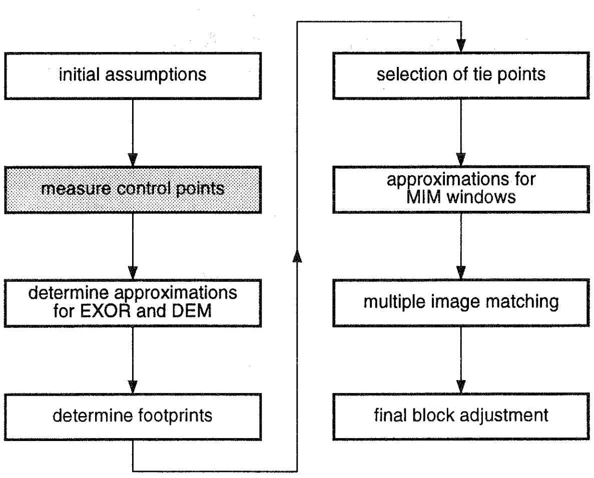

Figure 5: Workflow of automatic aerial triangulation system.

The workflow in Fig. 5 is a schematic diagram that depicts the major steps an automatic aerial triangulation system must take. A real system may omit some of the steps or follow a different sequence. At any rate, every system begins with some initial assumptions. This may involve the topography of the project area (e.g., flat), the availability of exterior orientation elements (e.g., GPS/INS system, flight index map), the block geometry (e.g., overlap configuration, information about cross-flights, holes, delineation of special areas, such as lakes). Furthermore, it is also assumed that the interior orientation is known, the imagery is controlled and perhaps radiometrically preprocessed.

For the immediate future it must be assumed that the control points will be measured by a human operator. Despite encouraging experiments (see, e.g., Gülch, 1995), there is little hope that automatic methods would soon cope with recognizing the diverse shapes of targets in noisy images to an acceptable level of confidence and reliability. One should also bear in mind that with the increasing use of airborne GPS fewer control points are required. A final remark to when the control points must be measured: it is conceivable to perform all steps, including the block adjustment, without control points. Thus, they can be measured and added to the process at any time.

As argued in 5.2.1 fairly accurate locations of the footprints must be known so that tie points can be selected in highly overlapping areas. For this purpose good approximations of the exterior orientation parameters and of the surface are essential. As a rough estimate the exterior orientation should be known to 1–2 mm in image scale. This implies an angular accuracy of about half a degree. For a photo scale of 1:10,000 the positional accuracy amounts to 10 m. Quite often the orientation parameters are not so accurately known at the outset and they must be determined, for example, by a block adjustment with coarse measurements (see, e.g., Schenk, 1995). But even the most precise exterior orientation parameters do not render accurate footprints if the surface is not known. In fact, the surface must be known quite well, otherwise the footprints will be wrong. Moreover, the prediction of conjugate matching locations is inaccurate, perhaps causing the matching procedure to fail (outside pull-in range). In conclusion, the surface should be known to approximately 3 mm.

The selection of tie points should follow the criteria sketched in Section 5.1.2. Incidentally, the reader is reminded that the well-known term "tie point" should not be taken too literally here: it reflects a concept that includes features, such as interest points, edges, and regions. Most automatic aerial triangulation systems work with a regular pattern, say, the classical 9 point locations, and determine a point cluster in these locations (see, e.g., Ackermann, 1995; Tsingas, 1992). However, it must be stressed that these locations must be determined from precise overlap configurations, surface and exterior orientation. Some approaches take a shortcut and assume rather flat surfaces and orientation data from GPS/INS systems. Another important request for tie points may come

Table 4: Minimum and desirable requirements for solving critical tasks.

essential tasks	requirements minimum	desirable
assumptions		
– ext. or.	GPS/INS	no restrictions
– surface	flat	no restrictions
selection		
– number	limited	unlimited
– location	random	planned
prediction	overlap	predictor
matching		
– approx.	image pyramid	image pyramid
	single image	all images
– MIM	pair wise	simultaneous

from processes following aerial triangulation, for example DEM generation. Here, the adjusted tie points (blockpoints) serve as initial seeds. Consequently, they should be in strategically relevant locations, e.g., on breaklines. Working with edges as entities in aerial triangulation would greatly facilitate the DEM process because edges are likely to correspond to breaklines (see, e.g., Schenk, 1992).

The final step of multiple image matching requires very good approximations for the matching windows. This is the purpose of the approximation task. Usually, a hierarchical approach is preferred where the selected matching entities are tracked through the image pyramid. At first sight the task appears trivial, but there are some intricate details that make it a challenge. It is known from scale space theory that features selected on one level of the image pyramid may disappear on higher resolution levels. It is quite unlikely that features to be matched on the high resolution level appear on the coarse level where the hierarchical approach begins. As a consequence, new features must be extracted on every level, and, more important, must be matched. It is during this process that some of the original n-connectivity (object space feature appears on n images) is lost, thus weakening the block stability.

5.4 Summary

Some of the more important aspects of automatic aerial triangulation are summarized in Table 4. The first column contains essential tasks, while the second and third columns indicate minimum and desirable specifications.

To offer the most flexibility it is desirable to have a system that does not depend on GPS/INS information for the initial estimates of the exterior orientation parameters. A more relaxed assumption is the standard aerial case where the attitude may reach 5^o and the base elements may vary as much as 10 percent from ideal overlap conditions. Presumably, the most severe restrictions of automatic aerial triangulation systems are in the surface conditions. As another example to demonstrate the importance of knowing (or computing) the surface, suppose the initial match begins on a 128×128 resolution level, pixel size ≈ 1.8 mm. For a mountainous area with elevation differences up to 1/3 of the flying height, the surface uncertainty amounts to 24 pixels—probably too much for any matching scheme.

As elaborated in Section 5.1.1+2, the selection of blockpoints should be intelligent and unrestricted in number of points. For predicting matching locations it is desirable to have a sophisticated "predictor" that also determines the uncertainty of the estimated conjugate locations based on the uncertainties of all parameters involved, such as exterior orientation and surface. Sometimes, multiple image matching (MIM) is approximated by matching all possible pairs of images. Again, it is desirable to employ a MIM scheme capable of simultaneously matching all entities. Rigorous solutions are described in (Agouris, 1993; Krupnik, 1994; Schenk, 1996).

6 CONCLUSIONS

Digital aerial triangulation is here! It comes in two forms: interactive and automatic. Interactive methods depend on a human operator who makes critical decisions and takes over control should the system fail. Not an absolute necessity, most interactive methods are built around softcopy workstations. The combination of well established and familiar procedures of automatic aerial triangulation with image processing and softcopy workstations results in attractive solutions that successfully compete with traditional methods. Virtually every softcopy workstation now has a digital aerial triangulation component.

Automatic aerial triangulation systems strive for reducing the operator involvement. Such systems run in a batch environment. What began a few years ago as a rather esoteric research subject is now on the verge of entering the marketplace. The first generation systems will offer a high degree of automation; the only manual task is the identification and measurement of targeted points (control points, premarked tie points).

At first sight automatic aerial triangulation resembles traditional methods. For example, the major tasks of selecting, transferring, and measuring tie points remain as well does the block adjustment. However, their solution is quite different, except for the block adjustment. Transferring tie points means predicting conjugate matching locations, measuring means matching. Since selected features appear on more than two images, multiple image matching is needed.

There are some distinct differences between automatic and analytical aerial triangulation worth mentioning. In the wake of these differences are some consequences which need to be discussed further among users and developers.

concept of a point: a point is an abstract quantity which does not exist in reality. A tie point or control point, for example, is the result of a sophisticated analysis by a human operator, employing image understanding and reasoning abilities far exceeding those available on machines. Automatic methods cannot compete and the rescue is extracting features, ranging from interest points to edges and to regions. A "point" then represents a feature, for example, an edge can be represented by characteristic points, a region by its centroid. It follows that it would be better to deal with the extracted feature as an entity, rather than emulating it by points. So the quest is to extend block adjustment methods to include features as entities.

number of points: for economical reasons traditional aerial triangulation works with as few points as possible. Such considerations do not apply for automatic methods. The disadvantage that automatically determined "points" are less carefully selected is compensated for by increasing the number. It turns out that hundreds of tie points per image with a lower accuracy compared to manually measured points still render better exterior orientation, both in accuracy and reliability. The motto is: "from quality to quantity."

features vs. points: in general, features are more tangible quantities than points. Apart from increasing the robustness of aerial triangulation, using features is also desirable in subsequent processes, such as DEM generation or map compilation. For DEM generation it is advantgeous to begin with as much information about the surface as possible. It may be possible to include useful features (e.g., breaklines) in the aerial triangulation process to aid DEM programs.

A final note on the differences of the various automatic aerial triangulation systems that have been described in proceedings and journals. They all must solve the essential tasks on which this paper elaborated intensively.

initial assumptions: about the exterior orientation and the surface of the project area. These assumptions range from expecting accurate exterior orientation elements (e.g., from GPS/INS) to less demanding assumptions (e.g., "aerial case"). The initial assumptions include the camera model. Apart from central projection, automatic aerial triangulation is also successfully applied to other applications (see, e.g., Ebner et al., 1994). Presumably more severe are the assumptions about the surface topography: they may range from flat to mountainous (e.g., 1/3 of the flying height). It should be noted that these assumptions are sometimes not explicitly labeled as such, rather they are a consequence of the selected methods.

selection of tie points: solutions span a wide range, from random to planned selection (e.g., analyzing location, topography, image content, etc.).

transfer of tie points: some authors combine the two processes of transferring and measuring tie points though these are two separate processes. The transfer entails predicting conjugate image locations. As simple as it may appear, it is an intricate process that involves error propagation from an image into object space and back to the target images. Moreover, it should include a check whether the feature indeed appears on the target image.

matching tie points: solutions range from pairwise matching to true multiple image matching.

We conclude this paper by a quote from (Ackermann, 1995) "...every effort should be made to develop automatic digital aerial triangulation. It will be of great practical and economic benefit to photogrammetry and—in combination with GPS camera positioning—will revolutionize the orientation problem."

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REFERENCES

Ackermann, F., 1995. Automation of Digital Aerial Triangulation. Proceedings 2nd Course in Digital Photogrammetry, Bonn.

Ackermann, F. and V. Tsingas, 1994. Automatic Digital Aerial Triangulation. Proc. ASPRS/ACSM Annual Convention, Vol. 1, pp. 1–12, Reno.

Agouris, P., 1992. Multiple Image Multipoint Matching for Automatic Aerotriangulation. PhD Dissertation, Deptm. of Geodetic Science, OSU, Columbus, Ohio.

Beckschäfer, M., 1995. Digitale Photogrammetrie im Einsatz. Proceedings Photogrammetric Week '95, pp. 243–251. Wichmann Verlag.

Cho, W., 1995. Relational Matching for Automatic Orientation. PhD Dissertation, Deptm. of Geodetic Science, OSU, Columbus, Ohio.

Ebner, H., W. Kornus and T. Ohlhof, 1994. A simulation study on point determination for the MOMS - 02/D2 Space project using an extended functional model. GIS, Vol. 7, No. 1, pp. 11–16.

Ebner, H., D. Fritsch, W. Gillesen and C. Heipke, 1987. Integration von Bildzuordnung und Objektrekonstruktion innerhalb der digitalen Photogrammetrie. BuL (55), 5, pp. 194–203.

Förstner, W., 1995. Matching Strategies for Point Transfer. Proceedings Photogrammetric Week '95, pp. 173–183. Wichmann Verlag.

Fritsch, D., 1995. Introduction into Digital Aerotriangulation. Proceedings Photogrammetric Week '95, pp. 165–171. Wichmann Verlag.

Fritsch, D., V. Tsingas and W. Schneider, 1994. Von der Blockausgleichung zur automatischen Aerotriangulation. ZPF, 62, pp. 214–223.

Gülch, E., 1995. Automatic Control Point Measurement. Proceedings Photogrammetric Week '95, pp. 185–196. Wichmann Verlag.

Haumann, D., 1995. Practical Experience with Digital Aerotriangulation. Proc. Photogrammetric Week '95, pp. 235–241. Wichmann Verlag.

Heipke, C, 1990. Integration von digitaler Bildzuordnung, Punktbestimmung, Oberflächenrekonstruktion und Orthoprojektion in der digitalen Photogrammetry. DGK, Reihe C, No. 366.

Krupnik, A., 1994. Multiple-Patch Matching in the Object Space for Aerotriangulation. PhD Dissertation, Deptm. of Geodetic Science, OSU, Columbus, Ohio.

Krzystek, P., T. Heuchel, U. Hirt and F. Petran, 1995. A New Concept for Automatic Digital Aerial Triangulation. Proceedings Photogrammetric Week '95, pp. 215–223. Wichmann Verlag.

Mayr, W., 1995. Aspects of Automatic Aerotriangulation. Proceedings Photogrammetric Week '95, pp. 225–234. Wichmann Verlag.

Schenk, T. and A. Krupnik, 1996. Ein Verfahren zur Hierarchischen Mehrfachbildzuordnung im Objektraum. ZPF 64, pp. 2–11.

Schenk, T., 1995. Zur Automatischen Aerotriangulation. ZPF 63, pp. 137–144.

Schenk, T. and C. Toth, 1991. Reconstructing visible surfaces. SPIE Vol. 1526, pp. 78–89.

Tang, L. and C. Heipke, 1994. An Approach for Automatic Relative Orientation. Proc. Optical 3-D Measurement Techniques II, pp. 347–354. Wichmann Verlag.

Tsingas, V., 1995. Operational Use and Empirical Results of Automatic Aerial Triangulation. Proceedings Photogrammetric Week '95, pp. 207–214. Wichmann Verlag.

Tsingas, V., 1994. A graph-theoretical approach for multiple feature matching and its application on digital point transfer. International Archives of Photogrammetry and Remote Sensing, Washington, D.C., Vol. 30, Part 3/2, pp. 865–869.

Wrobel, B., 1987. Digitale Bildzuordnung durch Facetten mit Hilfe von Objektraummodellen, BuL 55, pp. 93–101.