AUTOMATION OF INTERIOR, RELATIVE AND ABSOLUTE ORIENTATION

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ABSTRACT

Considerable progress has been achieved in the automation of image orientation for photogrammetry and remote sensing over the last few years. Today, autonomous software modules for interior and relative orientation are commercially available in digital photogrammetric workstations (DPWS), and so is automatic aerial triangulation. The absolute orientation has been successfully automated for a number of applications. In this paper recent developments and the state of the art in automatic image orientation are presented.

KURZFASSUNG

In den letzten Jahren sind bei der Automatisierung der Bildorientierung innerhalb von Photogrammetrie und Fernerkundung beachtliche Fortschritte erzielt worden. Heute existieren autonome, kommerzielle Softwaremodule für die innere und die relative Orientierung als Teil digitaler photogrammetrischer Arbeitsstationen, dasselbe gilt für die automatische Aerotriangulation. Die absolute Orientierung ist für eine Reihe von Spezialanwendungen ebenfalls automatisiert worden. In diesem Beitrag werden neuere Entwicklungen sowie der Stand der Technik der automatischen Bildorientierung dargestellt.

1 INTRODUCTION

Image orientation is a prerequisite for any task involving the computation of three-dimensional coordinates such as the generation of a digital terrain model (DTM), the computation of orthophotos, and the acquisition of data for geographic information systems (GIS). Image orientation refers to the determination of parameters describing specific photogrammetric models for mapping geometric primitives such as points, lines, and areas from one coordinate system to another one. Thus, image orientation belongs to the class of coordinate transformation problems. Coordinate systems relevant to photogrammetry are the object, the model, the image, and the pixel or stage coordinate system. Their definition can be found in any textbook on photogrammetry and will not be repeated here.

Due to its decisive importance image orientation has always been a focus of attention in photogrammetry. Digital photogrammetry holds the promise of completely automating the process of image orientation using image processing and image analysis techniques. At least from the point of view of users without formal training in photogrammetry, image orientation is regarded as rather complicated and time consuming. Therefore, it is clear that an automatic image orientation module will add to a wider use of photogrammetry and remote sensing. If such a module is available, image orientation can be considered as a preprocessing step in the photogrammetric processing chain, somewhat similar to the geometric and radiometric calibration of the imaging sensor. It is interesting to note in this context that in the computer vision terminology 'image calibration' sometimes already includes image orientation.

In order to become operational for practical applications an automatic orientation module has to meet various requirements. Ideally it should be

- autonomous (as opposed to the term 'automatic', 'autonomous' implies that no user interaction whatsoever is acceptable),
- faster than manual image orientation,
- more accurate than manual image orientation,
- flexible with respect to image and camera type (close range, aerial, satellite images),
- flexible with respect to different types of control information (points, lines, areas, DTM, etc.),
- robust: the module should also work with images of poor quality,
- reliable: the module should have a self diagnosis procedure by which success and failure of the computations can be assessed.

This papers reviews existing algorithms, strategies, and systems for automatic image orientation in digital photogrammetry. What is new in the digital domain is the automatic extraction and matching of the image primitives. The actual computation of the orientation parameters is similar, if not identical to the corresponding step in analytical photogrammetry. Therefore, the emphasise of this paper is on the automatic primitive extraction and matching. The discussion is focused on aerial applications. In the next chapter some background will be given on the central task of image matching. Then, interior and exterior orientation are discussed, the latter split up into relative and absolute orientation. Throughout the discussions, examples from the literature illustrate the state of the art in the field. The paper concludes with some remarks on the future of automatic image orientation.

2 MATCHING FOR IMAGE ORIENTATION

Matching plays a basic role in the automation of image orientation. Therefore, some background on this important topic will be given in this chapter (see also Heipke 1996).

In digital photogrammetry and remote sensing, matching can be defined as the establishment of the correspondence between various data sets. The matching problem is also referred to as the correspondence problem. The data sets can represent images, but also maps, or object models and GIS data. Many steps of the photogrammetric processing chain are linked to matching in one way or another. Examples include

- the reestablishment of the interior orientation: the image of a fiducial is matched with a two-dimensional model of the fiducial,
- relative orientation and point transfer in aerial triangulation: parts of one image are matched with parts of other images in order to generate tie points,
- absolute orientation: parts of the image are matched with a description of control features
- generation of DTM: parts of an image are matched with parts of another image in order to generate a three-dimensional object description,
- the interpretation step: features extracted from the image are matched with object models in order to identify and localize the depicted scene objects.

Except in the case of interior orientation, in image matching we try to reconstruct three-dimensional object information from two-dimensional projections. During image acquisition information was lost. This is most evident in the case of occlusions. Image matching belongs to the class of so-called inverse problems, which are known to be ill-posed. A problem is ill-posed, if no guarantee can be given that a solution exists, is unique, and/or is stable with respect to small variations in the input data. Image matching is ill-posed for various reasons. For instance, for a given point in one image, a corresponding point may not exist due to occlusion, there may be more than one possible match due to repetitive patterns or a semi-transparent object surface, and the solution may be unstable with respect to noise due to poor texture.

In order to find a solution of an ill-posed problem one usually has to deal with an optimisation function exhibiting many local extrema and thus a small pull-in range. Therefore, stringent requirements may exist for initial values of the unknown parameters to be determined. Moreover, usually there is a large search space for these parameters, and numerical instabilities may arise during the computations. Ill-posed problems can be converted to well-posed problems by introducing additional knowledge. Fortunately, a whole range of assumptions usually holds true when dealing with photogrammetric imagery:

- information about the sensor, e.g. in form of a calibration protocol is available,

- the grey values of the various images have been acquired using one and the same or at least similar spectral band(s),
- the illumination (possibly altered by atmospheric effects) is constant throughout the time interval for image acquisition,
- the scene depicted in the images is rigid, i.e. it is not deformable; this implies that objects in the scene are rigid, too, and do not move,
- the object surface is piecewise smooth,
- the object surface is opaque,
- the object surface exhibits a more or less diffuse reflection function,
- initial values such as the approximate overlap between the images or an average object height are known.

Depending on the actual problem at hand additional assumptions may be introduced, and some points of the list may be violated. It is this mixture of assumptions which makes the design of a good image matching algorithm difficult, and has led to the development of different algorithms in the past.

Most matching algorithms proposed in the literature implicitly or explicitly contain a combination of assumptions about the depicted scene and the image acquisition. In order to assess matching algorithms it is useful to decompose them into smaller modules (see also Gülch 1994a). Distinctions can be made on the basis of

- the primitives selected for matching:
  Possibilities include grey value windows in area based matching, image features with descriptive attributes in feature based matching, and structures (a relational description of the image content) in relational matching.
- the models used for defining the geometric and radiometric mapping between the primitives of the various images:
  Geometric models in common use are the central perspective projection for image acquisition and object surface models with varying degree of smoothness. Modelling in the radiometric domain depends on the selected primitives.
- the similarity measure between primitives from different images:
  For area based matching common similarity measures include the cross correlation coefficient and the sum of the squares of grey value differences of conjugate grey value windows. Feature based and relational matching have to rely on cost functions on the basis of differences in the attributes.
- the computation of the optimal match:
  Least squares adjustment (only applicable for area based matching) and different search methods (tree search, graph matching, relaxation, simulated annealing, dynamic programming etc.) are available.
- the strategy employed in order to control the matching algorithm:
  In the matching strategy the individual steps carried out within a matching algorithm are determined.

In a comprehensive comparison between different image matching algorithms for photogrammetric applications Gülch (1994a) showed that while under good conditions accurate matching results can be achieved with a large variety of algorithms, a good matching strategy is decisive for a successful solution in more complicated situations. Faugeras et al. (1992) obtained a similar result for algorithms popular in computer vision. Important points in terms of the matching strategy are:

- Hierarchy:
  Hierarchical methods are used in many matching algorithms in order to reduce the ambiguity problem and to extend the pull-in range. They are employed from coarse to fine, and results achieved on one resolution are considered as approximations for the next finer level. For this task images are represented in a variety of resolutions, leading to so-called image pyramids (see figure 1). It should be noted that the primitives to be matched can vary from level to level according to the application. For instance, a coarse matching can be obtained using a relational description, and the results can subsequently be refined using point primitives.

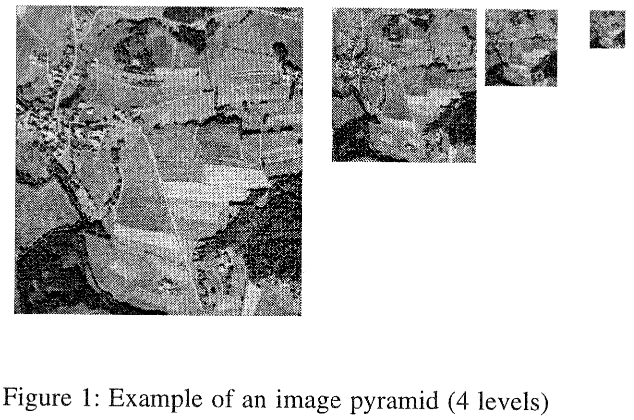

Figure 1: Example of an image pyramid (4 levels)

- Redundancy:
  It is not known how much intelligence the human operator uses when measuring the coordinates of a specific point, but he or she uses certainly more than any available matching algorithm. Thus, the blunder rate for individually matched primitives can be rather high. Efficient blunder detection is only possible if a large redundancy exists in the system. In a recent discussion on matching Ackermann (1996) coined the phrase 'replace intelligence by redundancy'.
- Integration of geometry and radiometry:
  Since in digital photogrammetry the original observations are radiometric grey values, and the geometric concepts of analytical photogrammetry are still valid, an integration between the two fields is mandatory for a good matching algorithm.
- Self diagnosis of each module:
  Each of the modules within a matching algorithm produces intermediate results which should be checked separately in order to avoid an accumulation of errors. In particular checks should be of both, geometric and radiometric nature. Examples include the epipolar constraint and the cross correlation coefficient.

After this short excursion to the principles of matching we will return to the main subject of this paper, namely the automatic orientation of photogrammetric imagery. In the next chapter, the interior and the exterior orientation, the latter split up into relative and absolute orientation, are discussed in detail.

3 AUTOMATIC INTERIOR ORIENTATION

In this chapter we are interested in reestablishing the relationship between the pixel and the image coordinate system. This task is usually referred to as 'interior orientation'. Note, that this term is somewhat misleading, since the actual parameters of interior orientation, namely the calibrated focal length, the image coordinates of the principal point and the lens distortion parameters are not to be determined. They are the result of the camera calibration procedure which is carried out for each camera prior to image acquisition. Instead, we are concerned with the determination of a set of (usually six affine) parameters for the transformation from pixel to image coordinates.

For digital cameras the relationship between pixel and image coordinates is constant and is determined during the calibration procedure in addition to the parameters of interior orientation of the camera. Only if film images are scanned in a separate step (which is the case in aerial photogrammetry today) the sought relationship must be (re-)established for each digital image individually.

The pixel coordinate system of the digital image is explicitly given through the matrix of grey values. The image coordinate system, however, is only implicitly given via the fiducial marks (in some cameras réseau crosses are available instead of fiducials). Therefore, the transformation between pixel and image coordinates can only be accomplished via the fiducials as identical points. The automatic reestablishment of the interior orientation is thus a semantic pattern recognition problem: one has to find the centre of the pattern representing the fiducials and ascribe each found pattern the correct fiducial number. Fiducials of different cameras are depicted in figure 2. Since the approximate location of the fiducials in the image, their size, shape and brightness distribution are known it is possible to design an operational, autonomous interior orientation procedure. Besides being fast, accurate, robust, and reliable (see chapter 1) it should work with (see also Schickler 1995b)
- imagery from different cameras,
- imagery from different scanners,

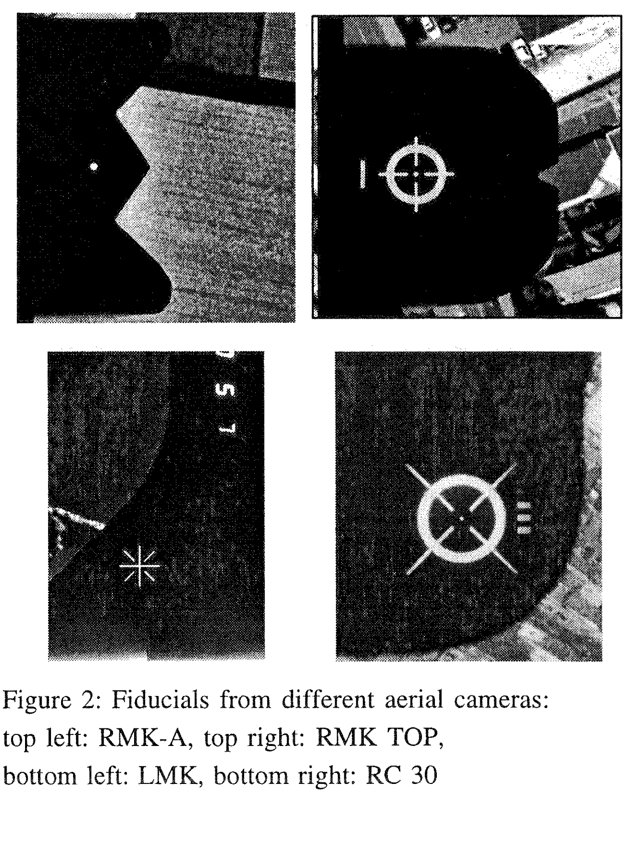

Figure 2: Fiducials from different aerial cameras:
top left: RMK-A, top right: RMK TOP,
bottom left: LMK, bottom right: RC 30

- imagery with different pixel size,
- black and white as well as colour imagery,
- positive and negative imagery,
- a varying number of fiducials,
- imagery with unknown pose.

The last point refers to the position of the film image during scanning. Assuming that the images have not been placed at an arbitrary angle on the scanner, eight different poses are possible, and the correct pose can only be found by locating an asymmetrically placed pattern such as the image number in the digital image.

The input for interior orientation comprises the digital image, the camera calibration report detailing the camera type, the image coordinates of the fiducials, the lens distortion and information about the asymmetry pattern, and the scanner report including the pixel size of the digital image. The output consists in the pixel coordinates of each fiducial, the parameters of the chosen transformation from pixel to image space, and computed accuracy figures. Since there are only a limited number of fiducials in each image, the achievable degree of redundancy is limited in interior orientation. Thus, particular care must be taken in order to recognize and eliminate blunders.

In order to solve the given task essentially a number of steps have to be carried out:

- approximate positioning of fiducials,
- subpixel positioning of fiducial centres,
- positioning of the asymmetry pattern,
- computation of transformation parameters.

In concert with the strategy considerations mentioned in chapter 2 the approximate location of the fiducials should be determined in an image with reduced resolution. In a higher pyramid level, the fiducial centre is not visible, and the whole fiducial should be used as a primitive. Due to the regular shape and size of the fiducial and its homogeneous brightness distribution, binary template matching lends itself for this task. As an alternative at this low resolution the fiducial can also be described by its outline and subsequently located by means of polygon matching.

Subpixel positioning of targets has been a research subject for a considerable length of time (see e.g. Mikhail 1984; Luhmann 1988; Trinder 1989; Tichem, Cohen 1994). Due to the small size of the fiducial centre area approaches are more appropriate than edge detection algorithms trying to identify the perimeter of the fiducial centre. Three possibilities come to mind:

- centre of gravity methods,
- least squares matching, and
- cross correlation.

Centre of gravity measures attribute a weight to each grey value and do not sufficiently use the fiducial model. Least squares matching relies on grey value gradients. However, most gradients in the vicinity of the fiducials are rather small, and thus noise effects can have a significant influence on the results. Thus, cross correlation is the best choice. Subpixel accuracy is reached by fitting a two-dimensional function to the correlation coefficients and determining the position of its maximum.

Methods for the determination of the image pose depend on the available pattern. Therefore, no general recommendations can be given here. Note, that if the imagery is scanned directly from the film role, the pose is known a priori and does not need to be determined within interior orientation.

Examples for autonomous interior orientation were published by Kersten, Häring (1995); Lue (1995); Schickler (1995b) and Strackbein, Henze (1995). Features of these algorithms are presented in table 1. At the time of writing (April 1996) no external evaluation of these methods is known to the author. This might have to do with practical problems of automatic interior orientation. When investigating real fiducials in detail one finds that surprisingly often the contrast between the image content around the fiducial and the fiducial itself is rather poor. Another major problem can occur if older cameras have been used for the acquisition of the analogue film images: the fiducial centre is not as bright as expected. In newer cameras the fiducials are often illuminated by light emitting diodes (LED). However, a problem remains for colour images: due to the spectral characteristics of a LED the fiducials are only visible in the red channel. Dust and scratches in the images around the fiducials and scanning without proper parameter settings can further decrease the quality of the fiducials in the digital image. For instance, the area to be scanned is sometimes selected too small, and thus the fiducials are only partly present in the digital image. Examples of some of these cases are depicted in figure 3.

Reference	Approximate fiducial positioning	Accurate fiducial positioning	Pose estimation	Availability	Comments
Kersten, Häring (1995)	modified Hough transform	least squares matching	manual	internal use at swissair Photo + Surveys Ltd.	different fiducials described in terms of features
Lue (1995)	grey value correlation, hierarchy	least squares matching	manual	implemented in the SoftPlotter from Vision International	different fiducials managed through fiducial database
Schickler (1995)	binary correlation, hierarchy	grey value correlation	automatic	implemented in PHODIS ST from Zeiss	different fiducials possible, automatic pos./neg. determination
Strackbein, Henze (1995)	binary image analysis, no hierarchy	fitting of parabolas to grey value function (?)	manual (?)	internal use at the LVA Nordrhein-Westfalen	for circular fiducials only

Table 1: Approaches to automatic interior orientation

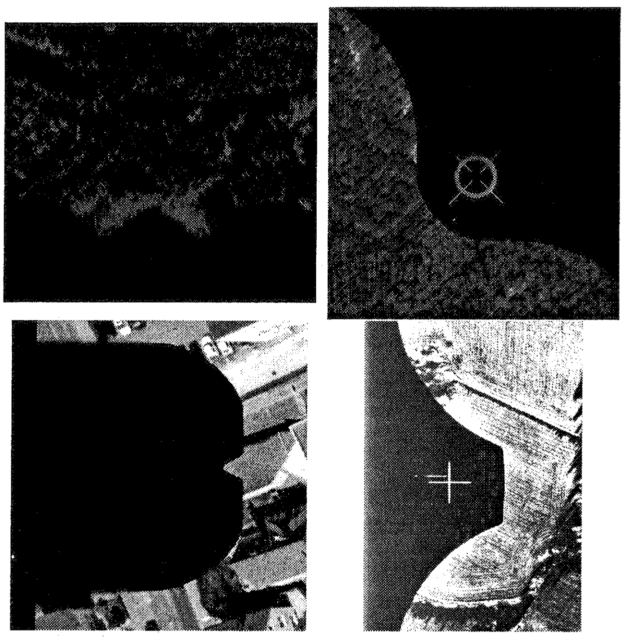

Figure 3: Examples for fiducials causing problems in the automatic interior orientation. Top left: poor contrast between fiducial and image content, top right: poor contrast between fiducial background and centre, bottom left: no fiducial in the green channel, bottom right: scratches in the vincinity of a fiducial

4 AUTOMATIC EXTERIOR ORIENTATION

The exterior orientation describes the transformation between the image and the object coordinate system. In a mapping project involving more than two images traditionally an aerial triangulation was carried out for point densification, followed by a separate exterior orientation for each model, split up into relative and absolute orientation, the latter being based on the densified points. Thus, the exterior orientation was determined twice, because (1) the results of aerial triangulation were not considered accurate enough, (2) the orientation parameters could not be used in the plotter due to missing interfaces, or (3) sometimes the bundle adjustment was carried out using smaller scale imagery than the mapping step for economical reasons.

Today, the situation has changed. The accuracy of aerial triangulation has improved, and the interface problems have been overcome. As a consequence, the exterior orientation parameters determined in the aerial triangulation are often downloaded directly for stereo plotting from single image pairs. Thus, it could be concluded that separate solutions for relative and absolute orientation are out of date, and what remains to be investigated is automatic aerial triangulation (AAT). In fact, various authors have addressed AAT, and solutions already exist (Tsingas 1992; Ackermann 1995a; Schenk 1995; see also reports on matching strategies for point transfer by Förstner 1995, on practical applications of AAT by Haumann 1995 and a discussion on commercially available systems by Kölbl 1996). However, if one looks at the different steps within aerial triangulation, the tasks of identifying conjugate features in various images, and of determining the position of control information within the images can be identified. The first task is linked to relative and the second one to absolute orientation. Thus, while AAT is the major subject in research and development in image orientation today, at a finer level the relative and the absolute orientation are still core problems which need to be solved. Obviously AAT involves other issues such as multi image matching, connecting strips with varying degree of side overlap, managing large data volumes etc. A detailed discussion of AAT can be found in Schenk (1996) and is out of the scope of this paper.

Before discussing the possibilities and limitations of automating the exterior orientation by means of indirectly determining the corresponding parameters from imagery, a few thoughts about the relevance of this task in the era of GPS and INS and sensor integration are in order. In theory, GPS and INS allow for the direct measurement of the exterior orientation parameters and thus render photogrammetric solutions for this task obsolete. The main issue is that ground control as such is not needed in the scenario of GPS/INS photogrammetry, and thus the resulting multi sensor data acquisition device becomes totally autonomous (see e.g. Ackermann 1995b for a discussion on the possibilities of autonomous multi sensor systems). The accuracy requirements for the orientation parameters of various photogrammetric applications are discussed and compared to available GPS and INS measurement accuracies e.g. by Schade (1994) and Schwarz et al. (1994). Among others Ackermann (1994), Burman, Torlegård (1994) and Hothem (1995) report on the state of the art of aerial triangulation using GPS observations for the projection centres of the camera. Without going into detail it is concluded here that while the impact of GPS and INS on photogrammetric orientation is already large and still growing, photogrammetry without ground control is not yet a reality. However, any automation in image based exterior orientation procedures has to be seen and judged in the light of the developments in the direct measurement of the exterior orientation parameters using GPS and INS.

4.1 Automatic relative orientation

The relative orientation of two overlapping images describes the relative position and attitude of two images with respect to one another. It is a 5-parameter problem. Given these 5 parameters all imaging rays of conjugate features intersect, and these intersections form the model surface. After having completed the interior orientation for both images separately, the two image coordinate systems are explicitly known. Therefore, relative orientation is a non-semantic task, and arbitrary conjugate features can be used for the computation of the orientation parameters. It must only be assured that enough features distributed across the complete model are used.

A general, autonomous module for relative orientation should be fast, accurate, robust, and reliable (see again chapter 1). Further it should not require any approximate values (in particular scale and rotation invariance should be available), and the approach should ideally work with multi temporal, multi spectral, and multi sensor imagery. The input should only consist of the images themselves and the results of interior orientation, the output are the five orientation parameters, the three-dimensional coordinates of the conjugate features, and corresponding accuracy measures.

A generic solution for autonomous relative orientation involves the following steps:

- compute image pyramids for both images separately,
- approximately determine overlap and possible rotation and scale differences between the images on the highest level,
- extract features, possibly including relations,
- match these features (and relations),
- determine coarse orientation parameters,
- proceed with extraction, matching, and parameter determination through the pyramid from coarse to fine in order to increase the accuracy of the results.

Image pyramids should be employed to take advantage of the concept of hierarchy already mentioned. Note that the repetition of feature extraction, matching, and parameter determination from one pyramid level to the next leads to a close integration of the coordinate measurement and the actual computations, two tasks which are well separated in analytical photogrammetry. In view of what was discussed about image matching in chapter 2 the mentioned steps will be described in more detail.

In order to detect overlap, rotation, and scale differences between the images matching primitives which are independent on absolute position, rotation and scale must be used. The cross correlation coefficient is known to be neither scale nor rotation invariant. Least squares matching can't be used either, because it requires accurate approximate values for the unknowns which are not available. Thus, area based matching is not an appropriate method for this task. Feature based methods can be employed to detect rotation differences between images. For example, straight lines can be detected in both images, followed by a comparison of the histograms of line direction. A detection of scale differences on the basis of the line length, however, is more problematic, because lines are often broken up into small pieces. Note that the same argument motivated the design of the line extraction algorithm by Burns et al. (1986) now widely used in computer vision and photogrammetry. Rotation invariant matching on the basis of curved lines has been carried out by Schenk et al. (1991) using the ψ-s representation of zero crossings (see also Ballard, Brown 1982 for an explanation of the ψ-s domain).

An elegant rotation and scale invariant solution which can also determine the overlap between the images is relational matching (Shapiro, Haralick 1987; Vosselman 1992). It should be noted, however, that relational matching is still a subject of intensive research, and it is difficult and time consuming to define, extract, and match structures suitable for imagery with different image content. Therefore, from a practical point of view rotation and scale differences should be eliminated or at least measured during the image acquisition phase, and image overlap should be determined prior to matching. For instance, in aerial triangulation standard overlap values are available, and rotation and scale differences usually do not exist or are at least approximately known. The same holds true for satellite imagery. Also in close range applications rotation differences around the optical axis are not common. An image scale varying within the images, however, is a common issue in close range applications, and complicates automatic relative orientation of these images considerably.

Once approximate values for overlap, rotation, and scale differences have been determined, the orientation parameters can be refined in a coarse-to-fine approach. It is argued here that feature based matching with point primitives should be used for this task, because points are geometrically more stable than lines and areas. For instance, a relative orientation based on straight lines is only possible with a minimum of three images (see e.g. Strunz 1993) and has to deal with a number of singular cases. A disadvantage of points is that they are less distinct, and usually can't be interpreted in a semantic way. However, the distinction of points can be increased by defining them as intersections between lines, and semantic interpretation of the features to be matched is not needed in relative orientation. For point extraction - to be carried out in each image separately - a number of so-called interest operators exists in the literature (e.g. Moravec 1977; Hannah 1980; Förstner 1986; Deriche, Giraudon 1993).

In the next step conjugate points are to be found. At this stage approximate orientation parameters are already known. Therefore, the collinearity equations can be used for mapping points from one image to the next, leading to the epipolar constraint (see figure 4). This geometric constraint reduces the search space from two dimensions to one, and thus increases the speed and reliability of the algorithm. Besides, a radiometric check should be incorporated. Assuming the model surface to be locally a horizontal plane, the correlation coefficient can be considered an appropriate measure, because scale and rotation difference have already been taken care of. Points are then considered to be candidates for conjugate points, if they fulfil at least approximately the epipolar constraint, and the corresponding cross correlation coefficient is above a predefined threshold. Note, however, that the epipolar constraint is valid for central perspective imagery only.

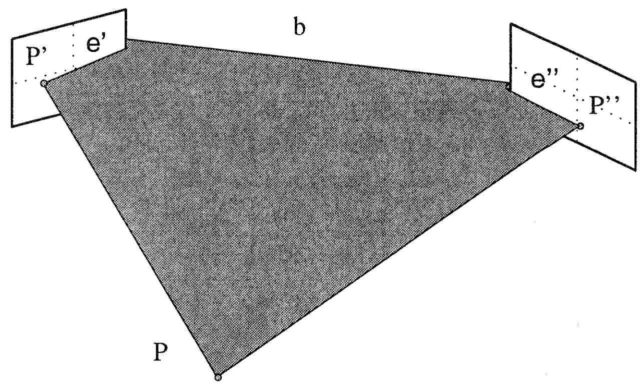

Figure 4: Illustration of the epipolar constraint: The conjugate points P' and P'' lie on the epipolar lines e' and e''. e' and e'' are the intersections of the epipolar plane and the 2 image planes. The epipolar plane is defined by the point P and the base b between the 2 projection centres.

For the actual parameter computation an iterative standard or a robust least squares bundle approach can be used. An interesting alternative is the so-called "8-point-algorithm" in which relative orientation is formulated as a linear problem of eight independent parameters. Solutions of this kind have long been known to exist (Rinner 1963; see also discussion in Brandstätter 1992). The 8-point-algorithm as it is used today was suggested by Longuet-Higgins (1981) and has since been investigated a number of times in computer vision (e.g. Tsai, Huang 1984; Huang, Faugeras 1989; Weng et al. 1989; Hartley 1995). Some applications can also be found in photogrammetry (Brandstätter 1992; Müller, Hahn 1992; Wang 1994). There are two advantages of a linear algorithm compared to a non-linear one: no initial values are needed for the unknowns in order to ensure convergence, and no computationally expensive iterations need to be performed. In this case, however, initial values are already available (as described, they are necessary for establishing the correspondence between the primitives), and the computing time for the parameter estimation is not critical as compared to that needed in the matching phase. Moreover, the 8-point-algorithm is geometrically less stable than the bundle approach, since the relative orientation only has five degrees of freedom, and thus non-linear relations exist between the 8 parameters.

After the computation of the orientation parameters and the three-dimensional coordinates of the conjugate points, remaining blunders along the epipolar line can be eliminated if assumptions about the model surface such as piecewise smoothness are appropriate. This step concludes the computations on one pyramid level.

Subsequently, the results are refined on a lower pyramid level. It is usually possible to leave out some of the levels to speed up the computations. Since the position of features in scale space is not entirely predictable (see e.g. Witkin 1983), point extraction should be carried out on each level independently. Then, matching and parameter computation are performed again, and the process is repeated until the original image resolution is reached.

Since in automatic relative orientation arbitrary conjugate features can be used, the power of redundancy can be readily exploited. Rather than a few conjugate points as in analytical photogrammetry a few hundred points are often used. Table 2 shows a typical result for the stereopair Lohja (see also figure 5). The theoretical standard deviations of the five orientation parameters are given for manual and automatic relative orientation. Although in the automatic case the standard deviation for the image coordinates is worse by a factor of 2, the orientation parameters are still more accurate by a factor of approximately 2.6 due to the high redundancy and the better point distribution. In addition the automatically generated orientation parameters are more reliable, since blunders can be easily detected due to the high redundancy. Another consequence is that singular cases of relative orientation such as the well known dangerous cylinder have no practical significance, since it is virtually impossible for all conjugate points to lie on one of these surfaces.

Imagery		black and white, scale 1:15.000, 60 % overlap	
Type of orientation		dependent	
Approach		manual (analytical plotter)	automatic (15 μm pixelsize)
Number of points		15	132
σ_0		2.0 μm	4.6 μm
Theoretical standard deviations of orientation parameters	σ_Y	0.47 m	0.18 m
	σ_Z	0.16 m	0.06 m
	σ_ϕ	11.0 mgon	4.1 mgon
	σ_ω	7.4 mgon	2.8 mgon
	σ_κ	3.0 mgon	1.0 mgon

Table 2: Comparison between the accuracy of the relative orientation parameters, example Lohja (see also figure5)

Various realisations of automatic relative orientation have been reported in the literature. The characteristics of the individual approaches are depicted in table 3. Most of them were designed to handle aerial images. Extensive tests of one algorithm (Hellwich et al. 1994; Batscheider 1996; Tang et al. 1996) have shown that autonomous relative orientation for aerial imagery is faster than and at least as accurate as manual measurements. Accuracies of approximately 0.2 and 0.4 pixels for the standard deviation of the image coordinates have been reached, and the elapsed computing time for an image pair with 15 μm pixels amounts to about 2 to 3 min on a Silicon Graphics Indy with R4400 processor (150 MHz). More than 50 different models with black and white and colour images of different content (urban, agricultural, forest, alpine environment), scale (1:3.200 up to 1:820.000) and image quality have been processed successfully. Two examples of the mentioned tests are shown in figure 5 and 6. This algorithm has been implemented in a digital photogrammetric workstation and is commercially available. User feedback in the near future will demonstrate whether or not it fulfils the requirements of practice.

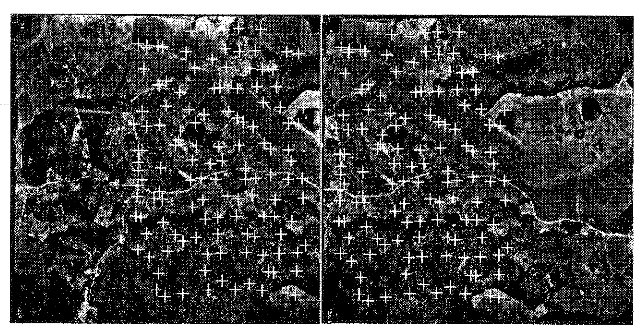

Figure 5: Conjugate points, automatic relative orientation, example Lohja

References	Matching primitives	Method for primitive extraction	Matching method	Area of application	Availability	Comments
Hannah (1989)	grey value windows around points	Hannah Operator	cross correlation (left to right and right to left)	aerial and close range imagery	inhouse development of SRI International, USA	different definition of the image and model coordinate systems
Schenk et al. (1991)	lines and points	zero crossings of LoG, Förstner operator	line matching followed by least squares matching	aerial imagery	experimental system at The Ohio State University	rotation invariant
Müller, Hahn (1992); Haala et al. (1993); Hahn, Kiefner (1994)	points	Förstner operator	feature based matching, checked by cross corrrelation	aerial imagery	experimental system at Stuttgart University	model surface as grid DTM also available
Tang, Heipke (1993; 1996)	points	Moravec operator	feature based matching, checked by cross corrrelation	aerial imagery	implemented in PHODIS ST from Zeiss	autonomous system
Deriche et al. (1994)	grey value windows around points	operator of Harris, Stephens (1988)	cross correlation (left to right and right to left)	close range imagery	experimental system at INRIA, France	no interior orientation necessary, 8-point-algorithm, Least-Median-Squares for blunder detection
Wang (1994; 1995; 1996)	relational descriptions between points, lines and areas	different image processing tools	relational matching	aerial and close range imagery	research development, Hannover University	most general of existing systems, 8-point-algorithm
Cho (1995; 1996)	relational descriptions between points and straight lines	Förstner operator, Burns-lines	relational matching	aerial imagery	research development, The Ohio State University	not rotation invariant

Table 3: Approaches for automatic relative orientation

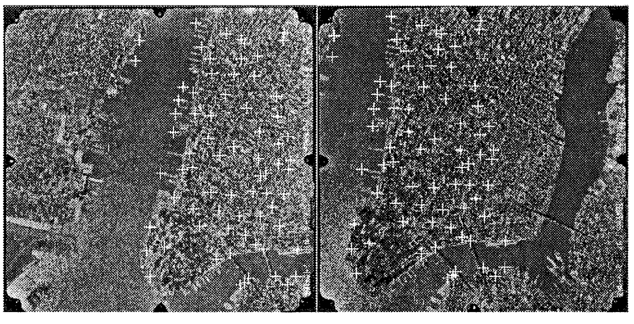

Figure 6: Conjugate points, automatic relative orientation, example Manhattan, New York City
(Images courtesy of The Ohio State University)

4.2 Automatic absolute orientation

4.2.1 How to tackle the problem

The absolute orientation relates image or model coordinates to the object space coordinate system. As in the case of interior orientation, one of the involved coordinate systems is only given implicitly. Here, it is the object coordinate system, and it is defined through control information which must be provided externally. The task at hand is thus semantic.

In analytical photogrammetry the model surface is available to the operator after relative orientation via stereo viewing. An automatic module, however, obviously does not have stereo viewing capabilities, and thus, unless the surface has been explicitly extracted, e.g. in the form of a DTM, it is not available. Therefore, automatic absolute orientation has to deal with the relationship between the image and the object coordinate system, the model system does not come into play. In case only one image is available this task amounts to matching the object space control information with features or structures extracted from the image. If two or more images are available, the extracted image features and/or structures must be matched between the images and also with the object space control information. These two steps need to be integrated into one approach in order to yield consistent results.

Traditionally signalised points were used as control information. Gülch (1994b; 1995) has tried to automate this approach, but concludes that due to radiometric variations of the signal, poor contrast between the signal and the surrounding image content, and the small signal size in pixel units, 'new concepts for ground control, adapted to image analysis' are needed. This conclusion leads to the question, which requirements control information for automatic absolute orientation has to fulfil.

In order to be reliably extractable from the imagery control information should ideally be

- geometrically well defined,
- radiometrically unique,
- visible from various directions,
- well distributed across the imagery,
- independent of image content,
- independent of image scale,
- easy to represent in two and in three dimensions,
- accessible (the object space coordinates of the control information need to be determined).

Control information which can be (and to some extend already has been) used for automatic absolute orientation includes

- image chips showing e.g. road crossings or other significant structure,
- complete orthoimages,
- point-like objects such as manhole covers,
- linear objects such as roads, rivers, and the corresponding networks,
- area-type objects such as land parcels, lakes or forests,
- three-dimensional wire frame models of objects, e.g. houses.

The topographic objects used as control information can come from a GIS or a scanned and vectorized map. In both cases it must be ensured that the data are up to date in order to separate the orientation from the revision problem. If the third dimension is not explicitly available, it must be provided in form of a DTM. In this context it should be noted that the DTM itself can also be used as control information (Ebner, Strunz 1988; Rosenholm, Torlegård 1988; Ebner, Ohlhof 1994).

As mentioned, there exists a close connection between automatic absolute orientation and the more general topic of image analysis. Automatic absolute orientation, however, is easier, because the control information is explicitly given. A generic strategy for automatic absolute orientation consists of the following steps:

- select appropriate control information,
- define the primitives to be extracted, taking into account the appearance of the control information in the images,
- design an algorithm for extraction of the primitives,
- match the primitives with the control information,
- compute the orientation parameters according to the predefined model.

Thus, the task remains very complex. It is argued here that a general solution for automatic absolute orientation will not be available in the foreseeable future. Therefore, approaches tailored to more specific applications should be investigated in which additional assumptions can be introduced:

- The image content restricts the selection of possible control information. Images of urban scenes contain many man-made objects consisting of straight lines, and thus the extraction and matching algorithms can be based on these features and relations between them, e.g. distances and angles. However, many occlusions and shadows have to be expected.
- The image scale dictates the representation and to some extend also the selection of the control information. In large scale aerial imagery point-like objects might be depicted large enough to be reliably detected. As another example, roads should be detected on the basis of edges. As the image scale decreases more generalised representations of the same control information must be used, e.g. centre lines for roads. Image scale also influences the type of transformation. For example, if satellite imagery is to be geo-referenced, a two-dimensional solution might suffice to fulfil the given accuracy requirements.
- Prior knowledge of the orientation parameters is usually available from a flight plan or direct measurements (see discussion on GPS/INS above). This information should be incorporated in any solution to automatic absolute orientation.

4.2.2 Examples for automatic absolute orientation

In this section solutions for automatic absolute orientation suggested in the literature are presented and discussed. The presentation is ordered according to the list of possible control information (see above). The intension is not to give a complete but a representative list.

Image chips were used in an early study for automatic satellite image rectification using ground control points (Malmström 1986). The chips and their object space coordinates were generated using scanned aerial photography, and were subsequently stored in a database. Area based matching was used to locate the chips in Landsat MSS imagery. To the knowledge of the author no follow up studies have been published. Possibly this is due to the sensitivity of area based matching to radiometric changes of the grey values. In multiscale, multitemporal, and multisensor matching the corresponding assumptions are easily violated.

The approach of Drewniok and Rohr (1995; 1996) was developed for urban large scale imagery. The authors use manhole covers as control points. Three-dimensional coordinates are available in a sewage cadastre. These manhole covers have a diameter of approximately 6 pixels and are assumed to exhibit a rotationally symmetric brightness pattern described by three parameters. These parameters are determined in a so-called learning phase, and the result is a template for the manhole covers. Detection of the manhole covers is then performed via least squares estimation between the templates and the image grey values. The used images show a large number of manhole covers, thus the aspect of redundancy can be exploited to advantage. In order to find the correspondence between the candidates for manhole covers in the image and the actual manhole covers in object space, a common scale factor is assumed, and a relational description based on relative distances is constructed. Subsequently, relational matching is performed, followed by a spatial resection for computing the orientation parameters. A critical point in this well designed approach is the question how well the assumed radiometric model describes the actual appearance of the manhole covers in the images.

Relational matching was also used by Vosselman, Haala (1992). Large scale colour images were registered to a scanned map. The images were pre-processed using standard image processing routines (classification followed by binarization, edge detection and line following), the maps were digitized manually. Subsequently, a relational description of the image and map content was set up. The correct match was found using tree search methods. The method was tested with roads, rivers, and land parcels and yielded promising results. The third dimension was not considered in the approach.

Dowman et al. (1995; 1996, see also Newton et al. 1994) use a similar approach. Their study on map registration of aerial and satellite imagery is based on polygons extracted from the map and the image by means of edge detection and segmentation. The matching is carried out by dynamic programming using a description of the polygons based on shape, orientation, and area. Examples are given for forest areas, and large buildings. Also this method only works in two dimensions.

Christmas et al. (1995) use probabilistic relaxation for matching road networks extracted from maps and images, respectively. Both road networks are represented as attributed relational graphs. The nodes of these graphs are line segments. Only unary and binary relations are considered. Beside other findings the authors successfully show the rotation invariance of their sophisticated approach. Again, the third dimension is not dealt with.

In an interesting approach Holm et al. (1995) use lakes and small islands for a completely autonomous orientation for satellite imagery taken over Finland. This work has its roots in a prior publication by Holm (1991). Due to the specific Finish landscape an abundance of control data is available, and the third dimension plays a marginal role only. Water bodies of the images to be orientated are mainly extracted by thresholding the histogram of the near-infrared band, and are described in terms of area, perimeter, compactness etc. After using the satellite orbit data for a coarse geo-coding feature based matching is carried out using the descriptions of the water bodies. This step is followed by a robust estimation of the parameters of a two-dimensional affine transformation. Successful tests are reported using Landsat TM, SPOT XS and NOAA AVHRR images. The system has been installed at the National Land Survey of Finland and the Environmental Data Center of Finland.

Schickler (1992; 1995a) has developed a module for absolute orientation for the production of orthophoto maps at the Landesvermessungsamt Nordrhein-Westfalen. The images are approximately of scale 1:12.000. Three-dimensional wire frame models of houses are used as control information. The work builds upon prior studies by Förstner (1988) and Sester, Förstner (1989). Assuming good approximate values for the orientation parameters (+/- 50 m for the centre of projection and +/- 1 degree for the angles) the wire frame models are projected into the image, and a search space is defined. In this area straight edges are extracted from the images. Matching between image and model edges is carried out via cluster analysis. The orientation parameters are computed in a robust least squares adjustment based directly on the matched edges. The approach has a built-in self diagnosis and was successfully tested with more than 50 images. A critical point is the availability of the control information in the form needed for the algorithm. However, with the growing popularity of city models three-dimensional wire frame models of buildings should be increasingly available in the future. Houses represented as wire frame models are also used for matching image and object descriptions by Bejanin et al. (1994). Their main emphasise, however, is on change detection, and therefore no further explanations will be given here.

In summary, automatic absolute orientation has been shown to work well in special applications. So far, only single images have been processed. In contrast to interior and relative orientation, hierarchy does not play a central role here, since the control information is in general not detectable across various image scales. Area based matching seems to suffer from the sensitivity of the grey values due to different illumination and other disturbances. Feature based and especially relational matching have a much larger potential to solve the given task. Redundancy can be exploited to some extend, if GIS objects are directly used. In this case, the rather costly signalization of specific targets becomes obsolete. It must be ensured, however, that the GIS data are up-to-date, and that their geometric accuracy is sufficient.

5 CONCLUSIONS

In this paper the state of the art of automatic image orientation in photogrammetry was presented. It was shown that interior and relative orientation can be and have been cast into autonomous modules. Relative orientation is also the core of automatic aerial triangulation. Modules for interior and relative orientation and automatic aerial triangulation are commercially available today (Braun et al. 1996; Lue 1996; Madani 1996; de Venecia et al. 1996). Most of these modules are implemented in digital photogrammetric workstations (Heipke 1995a,b; ZPF 1995). As an alternative interior orientation can also be implemented on a scanner workstation and performed immediately after scanning. Using these modules an autonomous processing chain can be set up starting from scanning the analogue photographs and leading to epipolar images which can be viewed and further processed in stereo (see also Sarjakoski 1990; Mayr, Poth 1995).

The situation is somewhat different for automatic absolute orientation. Although encouraging research results and developments towards automatic systems exist for special cases, a general solution is not feasible today. Thus, semi-automatic measurement possibilities are offered in most DPWS: the operator manually measures control information (mostly points) in one image, and matching is used to transfer this point into the other images.

Despite the substantial improvements in automatic orientation of photogrammetric imagery over the last few years presented in this paper, the future of this area is uncertain. This has to do with new sensor developments: The reestablishment of the interior orientation is not required any more as soon as digital cameras are used for image acquisition. In addition, GPS and INS make the indirect determination of the exterior orientation obsolete by providing direct measurements for the desired parameters. Due to two reasons the absolute orientation as described in this paper is expected to be the first step vanishing from the photogrammetric processing chain: (1) as mentioned the automatic extraction of control information from imagery is very difficult and automation in practice - while highly desirable - is not likely to occur in the foreseeable future, and (2) using the more mature GPS technology alone without having to rely on INS the datum of an image block, and thus the absolute orientation parameters of all images can be determined. However, the described techniques developed for automatically extracting control information from images can be transferred to GIS data extraction and database revision. Hence, new challenges remain to be tackled.

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