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Matching Strategies for Point Transfer

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ABSTRACT

The paper discusses the main aspects of automatic point transfer as basis for determining the orientation of digital imagery. Point selection, matching techniques, the role of approximate values, the object structure and the available constraints are discussed. The strategies of three approaches for point transfer in aerial triangulation are compared.

1. INTRODUCTION

Bundle triangulation has long been the heart of photogrammetric research and today is an accepted and powerful tool for indirectly determining orientation parameters and 3D-coordinates of natural or targeted points supporting a wide range of applications in mapping and in industrial mensuration.
Automation of bundle triangulation starts from the identified and measured image points and covers the full range from determining approximate values of orientation parameters and of 3D-points, blunder detection and self calibration to quality evaluation.
A completely automated and general system for bundle triangulation seems to be the prerequisite for a wide acceptance of photogrammetric mensuaration, especially in non-geodetic areas, such as architecture, machine engineering or medicine. One main obstacle for the acceptance of photogrammetric techniques in the neighbouring disciplines however is the need for manual measurements. This has two reasons: Accurate and reliable measurements require skilled operators; real time requirements make a manual observation process inacceptable.
Special solutions seem to be feasible as they can provide means for reducing the complexity of the whole process by using well established, but application dependent constraints. Due to the regularity of the imaging process and the avialable prior information aerial triangulation seems to be the first application for which a fully automated bundle triangulation can be realized. But also standardized tasks in industry allow full automation of the triangulation process.
Manual mensuration of the image points and the triangulation up to now are separate subtasks of the total process of orientation determination. The fast development of image processing tools and the availability of digital/digitized imagery requires a restructuring of this two step procedure: The access of the computer to the image content allows an interference between mensuration and orientation determination. In the classical setup, remeasuring was intentionally avoided and the number of measured points was kept as small as tolerable. Now, remeasuring is no real additional effort anymore, as the images are in direct access, and the speed of measuring allows to acquire as many points as necessary enabling to exploit the resulting redundancy for increasing accuracy and stability.
The identification of homologeous points, i. e. image points referring to the same object point in the images now becomes the critical step. Without any prior knowledge, it e. g. does not seem feasible to search for a homologeous points in all other images, which may be hundreds with each having 100s of megabytes.
In the context of aerial triangulation the identification of homologeous points is the classical point transfer, motivating the title of the paper. The mensuration of control points, which in its generality is at least as complex, is not treated in this paper. Section 2 discusses the general aspects of finding homologeous points in large sets of overlapping images, having in mind also industrial applications. The special assumptions which hold in aerial triangulation motivate strategies for point transfer, discussed in section 1, which are already documented in the literature (Tsingas 1992, Schenk 1995, Ackermann 1995) and partly implemented in working systems.

2. GENERAL ASPECTS OF AUTOMATIC POINT TRANSFER

2.1 Criteria for Point Selection

The first decision to be made is the way how to select appropriate points. There are several criteria for selecting points in images (cf. also the discussion in Schenk 1995):

1. points should lie in as many overlapping images as possible, for stability reasons,
2. points should cover the images as well as possible, again for stability reasons,
3. points should be distinct for supporting efficient matching,
4. points should possibly be suited for multi-image matching, and
5. the position of the points should be accurate enough for the final adjustment process.

Obviously the notion *"point"* needs clarification here. Points in our context refer to both, to a locatable image feature and to the geometric position of the image feature. The image feature itself may be described by the local image function (intensity, color) or its characteristic (corner, inflection point, homogeneity). This description is always used for the selection, but may also be crutial for matching.
The overlap (item 1) obviously can only be used as criterium in case approximate values (sect. 2.3) for the orientation and the object structure (cf. sect. 2.4) are available.
The coverage (item 2) of tie points depends on both, on the overlap and on the image structure, which is immediately available. This leads to a egg-and-chicken problem: One needs points in overlapping areas to determine the orientation, and one needs the orientation in order to be able to find overlapping regions.
The distinctness (item 3) of the selected points is an optional requirement, though significantly may speed up the matching (cf. sect. 2.2).
In contrast to classical matching procedures, where only two images are linked, here in general more than 2 images, regularily up to 6 images are to be connected. This requires the matching procedure to be able to handle more than 2 images (item 4), if one does not want to restrict the procedure to matching pairs of images. Therefore the point selection should reflect this, e. g. by guaranteeing visibility in many images. This may e. g. lead to the requirement points to sit on locally flat terrain.
The accuracy of the selected points (item 5) in general causes no severe problems, as simple point selectors show a precision of a pixel or less. Taking the high local redundancy into account the final result will show enough precision (cf. section 2.7).

2.2 Matching Tools

Matching is a central task in vision. In automatic point transfer we face the problem of multi-image matching as unique requirement.
Crosscorrelation obviously is not suited due to its scale and rotation sensitivity, also no technique is known how to generalize it for multi-image matching. **Least squares matching** only is suited, in case on does not has to fear occlusions and in case good approximate values may be provided, e. g. using pyramids. **Feature based matching with points** occasionaly may handle occlusions. In case the correlation coefficient of the surrounding image section is used for measuring similarity, no large rotations can be handled. Feature based matching with **edges**, though being able to handle occlusions, is sensitive to rotation errors. Matching two images with straight edges is not possible at all. Feature based matching with **blobs** or segments in general does not lead to the desired precision. **Relational matching** probably is the most powerful technique for handling the general setup, however, it is time consuming and up to now no multi-image version is known.

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The selection of the appropriate matching tool highly depends on the basic assumtions and may use the information collected in table 1.

Type	cross correlation	LSM	FB points	FB lines	FB blobs	relational matching
pull in range	**large**	*3 [pel]*	**density**	**density**	**density**	**large**
scale/rotation sensitivity	*high*	medium	medium **/low**	medium **/low**	medium **/low**	medium **/low**
accuracy [pel]	0.1	0.1	0.3-0.5	0.1-0.5	*> 1*	0.1-1
occlusion sensitivity	*high*	*high*	medium	**low**	medium	**low**
tool for image pairs	yes	yes	yes	*not possible*	yes	yes
tool for more than 2 images	*unknown*	**yes**	**yes**	**yes**	**yes**	*unknown*

Table 1: collects the properties of some of the available matching techniques,
bold = positive, italic = negative property.
LSM = least squares matching, FB = feature based,
density = average distance of features, scale/rotation sensitivity for deviations > 30 %/20E,
low = if invariant property is used.

2.3 Approximate Values

The availability of approximate values decisively influences the whole strategy. In case very good approximate values would be available any type of matching would work, on the other hand, in case no approximate values would be available, the task would not be solvable efficiently.
Approximate values are necessary for

- the orientation parameters
- the coordinates of the 3D-points and
- the fitted values of the image points, this corresponding to having solved the matching problem

In nearly all practical cases approximate values are available, even if they show a very low accuracy and reliability. Examples are navigation data, data from the mission planning, plots, index maps, standard orientations, an average height of the terrain, a CAD-model of the object, etc. If such data are not available, the need for automation may trigger the installation of a cheap gyro or a compass, or the documentation of the planned mensuration design.
Nevertheless, the design of an automated system should gradually adapt to the availability of such information, e. g. by first assuming some standard, and in case it does not succeed, then apply more expensive tools.
As a rule of thumb, least squares type techniques can be expected to converge to the correct solution, if the approximate values are better than 30 % corresponding to 20 gon in all relevant neighbouring connections, thus 100 % referring to the closest distance between points to be determined. In case of a high percentage of gross erorrs, due to false matches, least squares techniques cannot be assumed to

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succeed, requiring highly robust techniques, like the least median squares principle (cf. Rousseeuw and Leroy 1987).
The use of image pyramids is one of the remedies against poor approximate values. The classical principle, from coarse to fine, has shown to be quite powerful: The result of the matching with images of a poor resolution is used as approximation for the matching in the next finer resolution. The method is not foolproof, as errors in the higher (coarser) levels may be transferred to the lower (finer) levels, thus no correction of such errors takes place. Multi-image matching procedures (Maas 1992, Tsingas 1992), however, show high reliability.

2.4 Object Structure

The surface structure of the object direcly influences the prediction of the position of homologeous points. Flat surfaces allow interpolation of the predicted point positions. Curved, but smooth surfaces may easily lead to occlusions, in case the slope of the surface with respect to the cameras, is high. This especially hold in urban areas due to the verticallity of the walls. Breaklines prevent easy prediction and often give rise to occlusions.
A general strategy therefore needs to be independent on interpolation. On the other hand, if interpolation of predicted point positions is feasible, which implies weak knowledge about the surface structure, this should be exploited as far as possible in order to gain efficiency. Lack of knowledge on the surface structure of course only can be compensated by constraints which ar independent on the object.

2.5 Constraints

Constraints are a prerequisite for efficient matching. We want to collect some of the most important and useful constraints.

2.5.1 Geometric Constraints

Geometry provides the most powerful constraints.
For two images this results in the epipolar geometry, reducing the search from an area to a straight line (neglecting image errors at this place).
For three images the epipolar geometry only is valuable if the projection centres are not collinear. It in any case is better to use the collinearity constraint. Not only is it the most general, most simple and straight forward relation. Moreover, when analysing three images with collinear projection centres the epipolar constraint does not provide enough information, as the intersection of the three rays in 3D can only be evaluated with respect to the y-parallax.
All following constraints are in some way object dependent.

2.5.2 Intensity Constraints

Intensity constraints appear in two ways: as direct and indirect constraints between the intensity functions in the neighbourhood of the transeferred points.
Direct constraints between the intesity functions usually are realized by the cross correlation coefficient or the weighted sum of squares of the intensity differences. Requiring cross correlation to be high implicitely assumes a linear dependency between the corresponding intensity functions, a model regularily containd in least squares matching. There affine distortions, or equivalently, a sloped surfe are assumed to hold true. In both cases it is assumed that the surface around the 3D-point is planar.

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Generalization to smoothness constraints may be applied, however require large neighbourhood sizes, thus do not really relax the requirements on the surface structure.
Indirect constraints between the intensity functions refer to derived invariants. This may be the orientation or the sign of an image edge or the type of a point. Schenk (1995) uses inflection points of image lines for relative orientation, which are invariants of plane curves, thus implicitely a smooth surface is assumed around the tie points. 3D-junctions map to 2D-junctions (Förstner and Gülch 1986) and do not assume a smooth surface in their vicinity, however, need to be analysed in order to exclude T-junctions, which usually are fake points at occlusions.
Highlights of surfaces need to be taken into account in case the objects surface may cause specular reflections. As these reflections vary with viewpoint, they can be excluded by using the geometric constraints, or, in case the represent mirror images can actually be used as tie points.

2.5.3 Relations and Interpretations

Relations between object features usually are transferred to the image and only in case of occlusions neccessary are violated. Especially neighbourhood relations are useful constraints, as they are invariant with repect to a large class of distortions. However, relations between image features are error prone requiring some effort for detecting them reliably. For this reason, and because the other constraints have proven to be sufficient, at least in the case of aerial triangulation, they are not used up to now.
The same holds for interpretations, i. e. thematic attributes of image features.

2.6 Relative Orientation

In most applications, be it aerial or terrestrial triangulation, the images are taken as image sequence. As an important consequence neighbouring images are likely to overlap. This gives rise to a simple strategy for reliably determining approximate values in a local coordiante system, by sequentially performing relative orientations.
Observe, that here we refer to fully automatic relative orientation based on the digital images. For this task quite some procedures have been proposed in the literature (cf. Schenk, Lee and Toth 1992, Tang and Heipke 1993, Deriche, Zhang, Luong and Faugeras 1994, Brandtstätter 1992, Wang 1995, Hahn and Kiefner 1994).
We only want to discuss one aspect here: the necessity for direct solutions with a minimum of observations, direct means not needing approximate values. Such solutions allow to solve for the unknown parameters from a small subset of the available observations, which then can be checked by the other observations. In case this confirmation fails, a different subset can be chosen, e. g. randomly, as being proposed by Bolles and Fischler (1981) for the spatial resection. This strategy of randomly selecting and checking subsets of observations, called random consensus, is principally able to cope with nearly 50 % outliers, thus constitutes a very robust estimation procedure, especially useful for finding initial values for refined orientation determination in close range applications. An internal check on the stability (cf. Förstner 1995) of the solution is indispensable, as the mentioned direct solutions for the relative orientation require at least 8 points which need to be properly distributed in 3D in order to avoid instabilities.

2.7 Accuracy

The accuracy of the final orientation depends on the accuracy of the matched points (σ_0), then overlap of the iamges and the number of matched points. Automatic procedures can easily produce point densities which are a factor 10 or 100 higher than feasible with manual means. Therefore the automatically matched points may be less precise by a factor 3 or 10, still guaranteeing the same

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precision for the orientation prarameters. Thus the final outcome of the total procedure are highly precise and - much more important - highly reliable orientation paramters, not pass points. Therefore it does not seem meaningful to apply the matching procedure giving the highest accuracy (crosscorrelation of least squares matching), but to accept the (slightly) lower accuracy of detectable image features.
The discussion of the different aspects of point transfer will have shown the necessity to specify the preconditions of a certain application or of a class of tasks in order to decide on an efficient strategy. Aerial triangulation not only is one of the main application domains of bundle triangulation but also has reached a state which promises to be fully automated in near future.

3. POINT TRANSFER FOR AERIAL TRIANGULATION

3.1 Assumptions

Aerial triangulation refers to generally large sets of images flewn in mutually overlapping strips. The strip organization usually is planned thoroughly in order to guarantee the necessary overlap. This organization is contained in index maps, providing the least information on the orientation of the cameras. Whereas the base lines are known to at about 1 cm at image scale, possibly better with higher forward overlap, and the angles ω, φ and κ are known to some degrees, the side lap, due to difficulties in navigation may be considerably uncertain. Modern navigation aids allow to not only control the flight mission but also provide quite accurate values for all orientation parameters.
However, the main source for uncertainty results from the terrain surface. Though the average distance of the camera to the object can be kept constant quite well, the local undulations may be up to 30 % of the flying height. Taking into account the main scope of aerial triangulation, namely forming the basis for mapping, however, no prior knowledge on the terrain surface can be assumed.
A simple approximation of the geometric situation within a strip allows to determine the maximum error Δpx in the predicted x-parallax in dependency of

- the base to height ratio B/Z,
- the focal length c,
- the tolerance $\Delta\varphi$ in the two angles φ of the left and the right camera,
- the tolerance $\Delta Z/Z$ of the height Z related to Z,
- the tolerance $\Delta B/B$ of the basis related to B,

namely

$$\Delta px = 2\,c\,\{1 + 1/4\,(B/Z)^2\}\,\Delta\varphi + c\,(B/Z)\,\Delta Z/Z + c\,(B/Z)\,\Delta B/B \qquad (1)$$

assuming positive values in all cases. For $c = 0.15$ m, $\Delta\varphi = 1/20$. 3E, and $\Delta B/B = 1/10$ the maximum error Δpx in the predicted parallax is shown in Fig. 1 in dependency on the height undulations $\Delta Z/Z$ and the base to height ratio B/Z.
Observe that, due to the errors in angle and base line the minimum error already is appr. 1.5 cm, which amounts to 1000 [pel], when scanning with a pixel size of 15 µm. This even holds for very small base to height ratios. On the other hand in mountainous terrain the maximum error can reach nearly 6 cm. The figure shows clearly that increasing overlap, thus reducing B/Z, also reduces the prediction errors, favouring 80 % or even 90 % overlap within the strips for supporting automation (a situation which cannot be found in close range applications, where the first term in **(1)** normally is dominating).
Thus, any strategy needs to take into account the irregularity of the terrain quite rigorously for supporting efficient matching. This is the reason why the new approaches of point transfer contain a

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module for generating a **rough digital elevation model**. It may be coarse, but needs to be present for the whole block. Using some approximate values for the orientation parameters, the **footprint** of each image can be determined by intersecting the terrain surface with the (nominal) image prism, spanned by the projection centre and the (nominal) borders of the image, and projecting this intersection onto the **reference surface**. The footprints may then be used to automatically determine the mutual **overlap** of all images and to fix those sections in the images which are used for **tie point selection**. The foot prints are not bounded by straight lines, as usually found in index maps (cf. Fig. 2), which may be

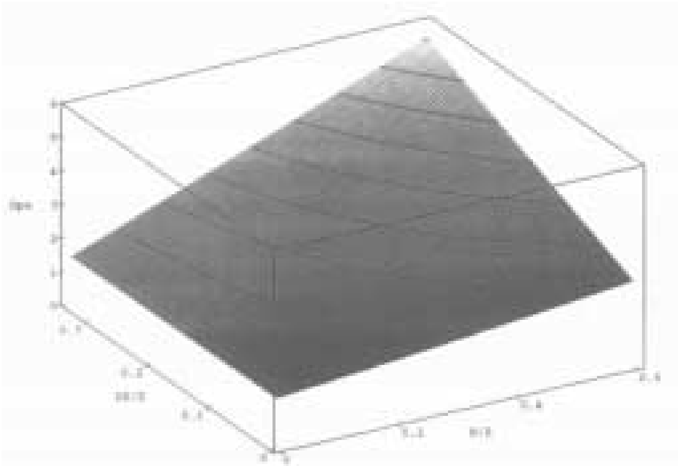

Figure 1: Maximum prediction error for the parallax in dependency on the relative height error ΔZ/Z and the base to height ratio B/Z.

irrelevant when maually analysing the overlap, but crucial in an automatic scheme.

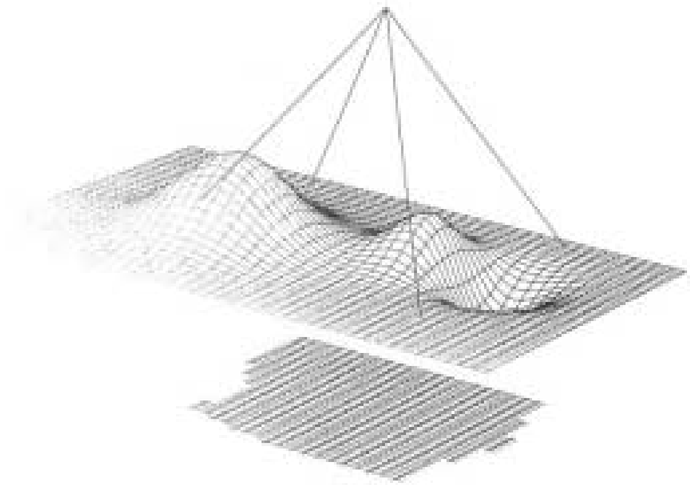

Figure 2: Footprint of an image in hilly terrain (Maple V plot).

3.2 Comparison of Three Strategies for Point Transfer

We now want to compare three strategies for point transfer available from the literature. The first one who developped a scheme for automated aerial triangulation was V. Tsingas (1991, 1992). It was motivated by the result of the thesis of Bühler and Wegmann (1987) and uses a multi-image version feature based approach as core module. Results on the OEEPE Test Forssa are reported in Fritsch, Tsingas and Schneider (1994). The development of T. Schenk and his group Schenk and Toth 1993, Schenk 1995, is based on a multi-image version of the least squares matching approach in object space, technically solved different than the approaches of Ebner, Fritsch, Gillesen and Heipke (1987) and

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Wrobel (1987), due to the necessity to handle large orientation errors. The concept of F. Ackermann (1995) aims at an operational system for automatic aerial triangulation, leading to sufficiently accurate and reliable results.
The main properties of the three approaches are collected in Table 2.

Author **Aspect**	**Tsingas (1992)**	**Schenk (1993)**	**Ackermann (1995)**
Technique			
. LSM		**X**	
. FB points	**X**		**X**
. hierarchy (levels)	**3**	**dense**	**3-4**
# Points/Image	**250-300**	**250-500**	**200-300**
Local Accuracy [pel]	**0.3-0.4**	**<0.1**	**0.3-0.4**
Local Strategy			
. sequential			
. all pairs	**X**		**X**
. simultaneous	**X**	**X**	
Local Constraints			
. collinearity		**X**	**X**
. affinity	**X**		
. smooth surface		**X**	
Local Accuracy [pel]	**0.3-0.4**	**<0.1**	**0.3-0.4**
Selection Areas	**standard positions**	**footprints**	**footprints**
GLOBAL STRATEGY			
Approximate Values			
. orientation	**index maps**	**index maps**	**GPS**
. DEM	**no**	**no**	**no**
Block Formation			
A sequential	**no**	**yes**	**no**
. relative orientation		**X**	
. scale transfer		**X**	
. link of strips		**X**	
B parallel, using constraints	**yes**	**yes**	**yes**
. local relative orientation			**X**
. local affine	**X**		
. local smooth		**X**	
Rough DEM		**X**	**X**
Exterior Orientation (Bundle)	**X**	**X**	**X**

Table 2: Comparison of three strategies for point transfer in aerial triangulation.

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Matching Techniques: Schenk uses least squares type matching for achieving highest accuracy. Tsingas and Ackermann accept the lower accuracy of the 3D-points of the feature based matching. The resulting orientation data of the block have shown to be appr. 30 % better than those achieved with highly precise manual measurement, which is caused by the high degree of averaging (cf. Fritsch, Tsingas and Schneider 1994). Of course, in case the digital elevation model is used for other purposes, e. g. for ortho photo production, as proposed by Schenk, the higher accuracy of the terrain points can be used to advantage. All authors propose to use image pyramids. The small pull in range of the least sqares matching type approach also requires to use all levels of the pyramid, whereas the larger pull in range of feature based matching allows to restrict to 3 to 4 levels of the pyramid. However, the computing times cannot be compared without going into implementation issues.

Number of Points per Image: In all cases some few hundred tie points are selected and matched. This is one order of magnitude larger than usual and compensates for the partly lower accuracy and in all cases increases reliability.

Local Strategy: Multi-image procedures require to be initiated, either to find or to preclean the preliminary correspondencies. This especially holds for all feature based matching techniques. The strategy of sequentially chaining the matches or transferring the points from one master image to all others, as done in manual mode, is not used in the automatic processes. On the contrary, all pairs are evaluated, at least in principle, in order not to introduce a bias towards a single image, and of course to avoid to define a heuristic for selecting such a master image. The multi-image technique of Schenk obviously is free of this type of local cleaning, and really working in parallel on all corresponding image patches.

Local Constraints: As discussed above, local matching requires an appropriate model. Tsingas uses the most stringent constraint. He assumes the surface to be locally planar, which holds for small patches of smooth surfaces. Schenk accepts smooth surfaces. Only Ackermann relies solely on the geometry of the bundles of rays, after having established preliminary matches between the feature points. Thus point matches are also used if they refer to corners of buildings or even to isolated points in space: no surface around the feature point is assumed to exist.

Selection Areas: Tsingas implicitely relies on good naviagation data and assumes not too hilly terrain. and assumes the areas around the standard positions to be sufficient for initiating the point selection. In view of the above discussion this solution needs reevaluation. Schenk and Ackermann determine footprints, and probably for computational reasons, restrict to linear boundaries.

The global strategy of all approaches differs to some extent, though all assume orientation data to be known and no surface model is available.

Block Formation: Only Schenk performs a sequential formation of the block, by relative orientation within the strips, scale transfer and strip transfer, using a polynomial fit. This seems to be motivated by the high requirements for accurate approximate values especially for the digital surface model. Tsingas and Ackermann only establish local matches and then immediately perfom a bundle adjustment.

Rough Digital Elevation Model: Schenk and Ackermann build up a rough digital elevation model for determining the overlap, which is updated when increasing resolution.

Final Block Adjustment: The final triangulation uses the transferred points. Tsingas and Ackermann use the selected and correctly matched feature points, therefore, the estimated σ_0 of the block adjustment gives a good indicator for the accuracy of the feature points. Schenk's tie points are artificial, in the sense that they are iteratively determined in the local multi-image matching procedure and transferred from the reference surface via the digital elevation model to the image planes. Here the estimated σ_0 of the block adjustment can be expected to be in the range comparable or superior to manual measurements.

The result of the block adjustment are orientation parameters suited for further image analysis.

4. CONCLUSIONS

The paper revealed a wide range of aspects to be discussed when automating the point transfer for a bundle triangulation. The approaches in the context of aerial triangulation have shown that in spite of the differences in detail common decisions have been made, especially the use of multi-image matching techniques. The decision which types of image points are to be used certainly needs further testing. It may very well be that in urban areas, especially when dealing with large scale imagery, problems of finding stable homologeous points and of determining overlapping areas may occur. The step to close range applications is not far, but certainly even more challenging.

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