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Measurement by image matching - state-of-the-art in digital photogrammetry

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ABSTRACT

Interpretation is the most important aspect of a measurement process in digital photogrammetry. In this process geometric properties, spectral properties, and semantic information of objects in the real world are derived from the captured images. If we intend to support the measurement process by various techniques of image matching we have to think about the role of interpretation within matching. For interpretation many abstraction levels exist; some of them are discussed in this paper in the context of image matching.
Another point for discussion results from the fact that today digital photogrammetry is mainly analytical photogrammetry on digital systems. In consequence at least (and to be optimistic) for the next five years we expect that the main body of image matching algorithms has to output that what photogrammetric tools like aerotriangulation algorithms are able to process further: points.
In image representation points are elements of the symbolic image description level. Unfortunately the higher accuracy is obtained by matching on the iconic image level. A way out of this discrepancy is the formulation of a new theory. We use the iconic image data and its structural low level interpretation to formulate an integrated model for image matching. Together the models for mapping from iconic to symbolic as well as the models for matching different views of the scene can be expected to be stronger than the models for matching either on the iconic or on the symbolic level individually. The integration of both cues might be a step further to approach the power of a human operator who is able to match images on both representation levels. For photogrammetric purposes we treat the integration of iconic image data in connection with distinct points.

1. INTRODUCTION

Interpretation is the most important aspect of a measurement process in digital photogrammetry and beyond that presumably in all disciplines processing images. In this process geometric properties, spectral properties, and semantic information of objects in the real world are derived from the digital images.
In order to underline this statement let us look back to analytical photogrammetry. For registration, representation, parameter estimation and evaluation, storage in files or GIS, and visualization, software tools on hardware platforms like analytical plotters exist. That all helps the operator to do his job, for example, point transfer. A first step in point transfer is the preparation, i.e., to look for the left and the right image in a strip and to look how the overlapping strips fit together. To ''look for'' means to recognize the scene globally as it is captured from different points in space by using the experience of the operator and his capabilities in image interpretation. For this recognition step the existing software tools did not help. The main step in point transfer is the search of areas in the images which are suited for point transfer, the definition of points in these regions, the identification and localization of the corresponding points in the overlapping stereo partners and the registration of its position. The measurement process of course not only consists in pressing keys on a board in order to registrate some coordinates as sometimes believed; it comprises the detection of suited regions, the localization of points, the matching to find the corresponding points in all other images and the registration of the point position in all images. Searching for suited regions usually needs a complex interpretation of the image by the operator. For example, a region is rejected because a large 3D object, e.g. a tree, prevents insight from some direction or because image structure in a region may lead to confusion. But occlusion analysis and analysis of repetitive patterns are completely different interpretation tasks. By interpreting the stereo model the operator

checks whether the corresponding image points result from one real 3D point or from a virtual one. The point location must be on a reasonable surface, e.g. not anywhere on bushes, and this surface of course should not move, etc.
This small example indicates that we have to consider a lot of different aspects of interpretation ("suited region, real 3D point, reasonable surface, do not move") in the photogrammetric measurement processes. As long as they are mastered by knowledge and experience of the operator only minor attention was drawn on interpretation. Just the opposite now is true if at least parts of the measurement process are solved by image matching. Quoting Förstner(1991): "The classical distinction between object location, reconstruction and recognition results from the simplicity of the objects dealt with or the ability to use human guide within the interpretation process. The generally high complexity of objects or even scenes in digital photogrammetry makes the distinction obsolete."
Another point for discussing image matching is the question on what is generally expected from a measurement process in digital photogrammetry. Looking to the hardware (a recent survey can be found in Heipke, 1993) it is quite clear that general computer workstations with high resolution stereo graphic equipment, 3D-mouse and standard peripherical devices are - or at least in near future will be - what is called a digital photogrammetric workstation. All components can be found on the dynamically growing market of graphic workstations. Actually there are still unsatisfactory limitations, e.g., in stereo viewing, where standard electronic modules limit the vertical to be only half of the horizontal resolution, or in data storage, where tens or hundreds of gigabyte (typically an aerial image block) up to now can not be handled reasonably.
If the software tools from analytical photogrammetric systems are transferred to digital stations the operators in principle can work again in a familiar way. Obligatory on doing the job at a graphic workstation are attractive user interfaces visualized on the graphic surface. Tasks of the photogrammetric work are activated by some keys. In consequence, all processes are hidden behind an interface, e.g. the interface "point transfer", which the operator needs to solve point transfer at the digital station. It is not necessary to emphasize, that the organization and communication between this processes is a difficult and demanding task. Up to now the total spectrum of analytical photogrammetry is not yet available on digital systems. But actually interactive measurement tasks like orientation, point transfer, mono plotting, 3D vector data acquisition, editing of DTMs, and some others can also be processed on digital systems. We do not want to underestimate the efforts of transferring the program packages into the environment of graphic workstations, but this transfer leads methodically to what could be called analytical photogrammetry on digital systems.
For the measurement process in digital photogrammetry a direct consequence of transferring existing software from analytical to digital is a condition for the measured output: *only points are really welcome*. Interior, relative and absolute orientation, as well as aerial triangulation is solved by algorithms which process points, or to be more precise, the measured coordinates of 2D and 3D points. The name point transfer indicates that the result of this measurement task are just (and only) corresponding points. Looking to the conventional generation of DTMs the common input are 3D points. Additionally breaklines are captured and they are measured as an ordered set of points. The line then results from defining (which is also a measurement aspect) the type of connection. This listing is far from being complete. Isolines in height plans are sequences of points which are interpolated mostly within the plotting step. If objects like houses are captured for representation in a map the situation is similar to that of capturing breaklines. Perhaps some expected geometrical conditions like rectangular corners and closed polygons are introduced as a part or a postprocessing step of measurement, etc. To prevent from misinterpretation: we don't argue against points. Measuring breaklines by capturing 3D points and representing them by 3D polygons are in general excellently suited for practical purposes. But in principle all processes could also benefit from other observables. Observations found by segmentation or matching are, e.g., the parameters of straight

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lines with two or four observed values in 2D or 3D, respectively, or the normal vector of a tangent plane on a certain object. Orientation procedures for example with lines are known but not very common in photogrammetry.

2. THE MEASUREMENT PROCESS

After this lengthy introduction we disuss more concisely some aspects of the measurement process in a single image and in a stereo image pair. The aim is to define expectations on matching procedures, which support or guide or replace the operator's job. Image matching is the task of finding the correspondence between a description of some images of a scene or of finding the correspondence between a description of the images and a description of the model (including projection) of the scene. For short we will speak about image-to-image and image-to-model matching. In both cases our interest is directly linked to the scene. Moreover, as we will see, knowledge about and models of at least parts of the scene are involved.
Existing matching procedures like those for surface reconstruction often try to set up one model for simultaneous estimation of all shape parameters in the overlapping area of images. For example the region size in an aerial image is about 4000 × 8000 pixels. Such a formulation is absolutely inadequate to human processing. The foveal vision field is about 2 degrees and the resolution in this field corresponds to an image resolution of about 200 × 200 pixels. Thus human processing concentrates on a small region within the field of view. Terms like eye fixation and focus of attention characterize the human processing. This and the fact, that the most successful developments in computational vision are inspired by biological vision (e.g. Marr and Hildreth, 1980) we want to keep in mind in the following discussion.
The first example addresses measurement in a single image. For recovering interior, or, which is significantly more difficult, exterior orientation the measurement process includes:

1. A model of the object, e.g., of the ground control points (gcps) for exterior orientation.
   If the gcp is a target like a small disc usually some signalization is added around the disc. But also a sketch of the location of a gcp relative to its environment (''close to a bright stone are three others, further there is a neighbouring tree, a street or crossing of streets, etc.'') might be drawn to help the operator to find the gcp later on in the image. Drawing the sketch implies the imagination on how the scene looks like from space. To make this work easier often maps or images are used.
2. Search for the object in the image needs broad knowledge.
   The model or the sketch, which could be considered to be a very useful model for the recognition step, enables the operator to identify that region in the image, in which the object is located. Prior knowledge like rough estimates of the location of the search area (e.g. upper left corner in the image) simplifies this task. In addition procedural knowledge like working from coarse structures to fine details (e.g. first look for crossroads then analyze the local area) is a very important aspect. Procedural knowledge might be implicitly represented in the sketch or explicitly formulated in terms of rules. Other cues like colour may guide or support interpretation.
3. Locate the precisely defined reference point of the gcp.
   If the model states that, e.g., the reference point is the center of a disc, then the cursor has to be located on the center of the perspective image of this disc. Alternatively to such a circular gcp texture markings like grey value corners on a flat surface are well defined targets. Also 3D corners of buildings for some tasks are sufficiently accurate (Schickler, 1992). The recognition and precise location of circular features or intensity corners in a well textured small region of the image is a relatively simple interpretation task for the operator.

Let us directly proceed with measurement in a stereo image pair. The example we choose is the common task of putting the 3D cursor on the terrain surface, and alternatively, the cursor shall be located on some distinct points of man made objects, e.g. on gables of houses. Measurement again includes:

1. A model of the object and knowledge about it. Presumably the operator has a lot of knowledge about what is topography, therefore also about knowing what is a terrain surface and what is a gable of a house.
   Modelling the topographic surface in general is extremely difficult and therefore it is realized very poor. Parts of the topography like the terrain surface is usually modelled as a smooth surface. Further some discontinuities on this surface are taken into account. All other details on the surface are considered to be terrain noise or objects. In consequence recognition of terrain areas based on this insufficient model will not work in general.
2. If we assume that the terrain height in a given region has to be measured (if the region is not given we have a search problem as in the case above, and which results in the recognition of the region) then for each measuring position the operator has to classify: is there terrain or is there anything else? It is quite obvious that this classification will be very unstable. This has to be seen on the background that the geometrical model of the terrain surface usually is a heuristic and not more.
   For measuring the height of gables such a classification procedure seems to be totally inappropriate. In order to recognize houses cues like the colour of roofs and the existence of streets may guide the process. In looking closer rough prior information about the height of the object relative to its environment and in particular shape (vertical walls, smooth roofs, straight edges) makes it possible to identify the object of being an entity of the object class ''building''.
3. For putting the cursor on a desired 3D position the operator uses both a model of the object and his capability of seeing stereo. A more or less smooth shape might be the model of the terrain surface. For the local match of image structure in the corresponding image regions edge information may be used. Surface shape and image structure together with the interpretation of the operator while viewing the context of some local points (e.g. the point is in a field, or on a road) result in a precise measurement. In the case of a house the shape model looks quite different. The roof surfaces are generally inclined planes in space and at the corner of the roof there is a vertical wall, i.e. depth discontinuity to the adjacent terrain.

The components modelling, search and localization are also considered to be the main aspects for matching procedures. Search procedures which approach the human ability on solving complex tasks are far from being developed. Relational matching with heuristic search for finding correct correspondences seems to meet most likely the expectations. Relational matching relies on a relational description with primitives like points, lines, groupings of them and their topological relations (Vosselman, 1992). The sketch describing the location of gcp's addressed above could be mapped on such a description. In connection with a focus of attention procedure (procedural knowledge) it should be possible to come to approaches which might support the operator. A main argument against such efforts from a practical point of view: the operator up to now is tremendously faster than image-to-model matching in this field. Precise localization is a considerably simpler matching task especially if targets are involved. We will discuss it in the context of other matching tasks below.
What else can we learn from these examples? Certainly we will not find a large number of applications in digital photogrammetry, which will work without support by the operator. Modelling, and this is true also in the stereo case as the seemingly simple example of putting a 3D cursor on topography shows, is usually insufficient. In consequence the second step (search,

recognition, interpretation) in practice is completely in the domain of the operators work. Image matching procedures have been successful in the third step. There also interpretation (''is the texture marking a corner?, is the surface really a plane?'') is involved, but those low-level interpretations can be treated reasonably in matching. But each kind of interpretation makes control by the operator mandatory.

3. MEASUREMENT BY IMAGE MATCHING IN PRACTICE

A common characterization of matching procedures results from the role of the operator within these procedures. In batch or automatic procedures a result is derived without direct participation of the operator. Operator assistance has to be provided in a postprocessing step in order to verify the result and furthermore often correction is necessary. In semiautomatic procedures a part of the measurement task is solved by matching. Mainly the search tasks are provided by the operator and local matching is the main issue of the automatic parts. Finally, interactive procedures are solved by the operator applying only tools of analytical photogrammetry, but without image matching capabilities.

Good chances to work without corrections by an operator has the interior orientation, because only a simple model has to be set up, prior information about the position in the image is available and the possibility to approach the location by hierarchical control exists. Very advantageous is the fact that practically no disturbing or confusing structures around the imaged fiducial marks of the camera occur. But this a very unique situation. A possible error might result from choosing the model of another camera type. Because the differences between the cameras are significant it is easy to detect this mistake automatically.

Just the opposite is true if we want to derive topographic information. The extraction of objects implies recognition and location and even in tasks with minor complexity like detection of 3D discontinuities of a surface from aerial imagery we still are at the beginning. Some promising experiments on extracting buildings have been reported e.g. by Shuffelt and McKeown(1990). Closer to practice are the developments presented by Schickler(1992). In order to determine the outer orientation of an image he uses prior knowledge about the rough position of a selected house and a specific 3D model of it, which can be considered as a ground control structure (a generalized gcp). If working in semiautomatic processes, e.g., in which the operator provides an initial position and some parameters like shape or colour, continuous control and correction by the operator is guaranteed. Road following is a classical example. With limited expectations on the quality it is possible to work more efficient with such semiautomatic procedures than to measure in a interactive mode. Nevertheless mono and stereo plotting tasks will stay for a lot of years in the domain of interactive work. Semantic modelling, i.e., matching approaches that utilize semantic structures such as roads and buildings, is a research topic in this direction.

DTM reconstruction today and probably relative orientation in near future are matching algorithms which run in a batch process. Both procedures can be formulated with a similar conceptual background. For example confer the Match-T procedure for DTM reconstruction in Ackermann and Krzystek(1991) and the approach for relative orientation in Haala, Hahn and Schmidt(1993). Presumably the main argument for the batch process in DTM reconstruction is that semiautomatic control will make the process considerably slower. Both tasks are stereo measurement processes, so according to section 2, the processes are directly or indirectly based on a model for the terrain or, more generally, on the topographic surface shape. For surface reconstruction usually a smooth surface is modelled and parameters which describe this surface are to be determined. In relative orientation the role of the projected surface model is limited to be a suitable approximation which is used to restrict and locate the search areas for all corresponding points. With a coarse-to-fine control strategy the approximate values needed for matching on each refinement level are found within the process. In the DTM case objects on the surface but also terrain structures which deviate from the smoothness assumption are filtered out. This kind of classification is of pure geometrical nature and for that reason very sensitive and unreliable. In relative orientation a geometric check whether a corresponding point pair results from one 3D point is based on the epipolar constraint which is given when the orientation parameters are recovered. Usually in addition an iconic check like correlation of the windows around matched points is applied. A final control by the operator we consider to be obligatory as outlined above.

Some aspects of point transfer we have addressed in section 1. We want to add point transfer to the list of semiautomatic processes, though Tsingas(1991) has shown experiments with a batch process. Starting from the point, that the matching results are the input for aerial triangulation algorithms, the number of matched points should be limited to a reasonable upper limit. Because a rigorous geometric control takes place within the triangulation it would be desirable to include triangulation into matching. The best control of course again is the independent evaluation of the operator. By the selection of points to be transferred the operator's knowledge is brought into the matching. He locates suited areas and prevents from matching in difficult regions, as discussed in the introduction. If the selected region is a plane, the shape model gives a strong constraint for matching. If there is further a clear defined feature in this region it could be expected that the correspondence again with a coarse-to-fine control will work quite well.

The discussion of image matching in practice was up to now a conservative survey. Moreover, important for the future will be new products and new procedural possibilities based on image matching. The first aspect leads away from the theme of this paper, e.g., in environmental monitoring, in quality assessment in industrial applications or in navigation using image sequences to name only three very different fields. Some ideas on new procedural possibilities we want to discuss at the example of point transfer. The first difference to the analytical world is the simple possibility of visualizing overview images of a block simultaneously on a screen. In principle all images are digitally available and can be accessed directly. If we assume a proper management procedure other important data like the interior orientation, the coarser levels of the multiresolution image data structure, etc., are also available. Furthermore we assume that this management procedure handles prior information like the overlap or displacement of an image with all neighbouring images. A procedure for deriving such approximate displacement vector fields is presented in Haala, Hahn and Schmidt(1993). For example, a displacement vector field with a grid spacing of 100 × 100 pixels or even larger can be appropriate for our purpose. For semiautomatic point transfer the operator then selects a suited region on the basis of all the criterion (interpretations) discussed above. The approximate displacement field can be used to directly visualize the roughly corresponding windows of all neighbouring images. For this simultaneous control a coarser image resolution will be sufficient. The selection of a point in a suited region by the operator can be evaluated by local image analysis. If texture measures of a window around the point indicate a distinct point the proposal of the operator will be supported, if not, a warning can be given. But also the inverse action is possible. Prominent points can be extracted by local analysis and the operator confirms or rejects these points. In a next step the corresponding points in all overlapping images can be found by matching. The matching procedure should use knowledge provided by the operator. If the selected point is on a plane or a smooth surface then this has to be used to constrain the geometrical mapping model within matching. The final control by the operator in the stereo mode may be organized as a cyclic control procedure over all corresponding points in all images. The control of the uniqueness of the point correspondences in the 3D space and, if necessary, corrections can be done in this final step. These more detailed considerations on procedural possibilities in a semiautomatic process indicate that working at a digital station allows considerable progress from which we expect significant increase in the efficiency.

4. A NEW THEORY

Finally we want to outline some ideas on how to formulate a new theory based on an integrated model for matching image data from iconic and symbolic image description. Standard matching formulations either are based on the intensity values directly or use primitives, i.e., results of image segmentation. Because the intensity of a single pixel is totally insufficient to find the corresponding pixels in other images intensity based matching is area based. Surface models in object space or image space give the restriction for matching the intensities in a certain area. Matching on the symbolic image level implies modelling for mapping from iconic to symbolic. Image matching based on primitives, also called feature based matching, consists of searching for the corresponding primitives in the other images.
To have the advantages of both matching schemes it seems to be promising to formulate a integrated procedure like that shown in figure 1. This approach is presented by Cochran and Medioni(1992). The results of area based and of feature based processing, in particular the determined disparities, are further used in an integrated stereo processing. This integration offers possibilities for control and correction to obtain a more accurate and reliable result. In photogrammetry it is very common to use a two step procedure. In the first step small image regions are detected which are well suited for matching. With those regions in the second step intensity based matching is executed. The reason for the two steps is to obtain best precision. The idea to work in two steps is not new. For example Moravec in 1977 has favoured this technique.

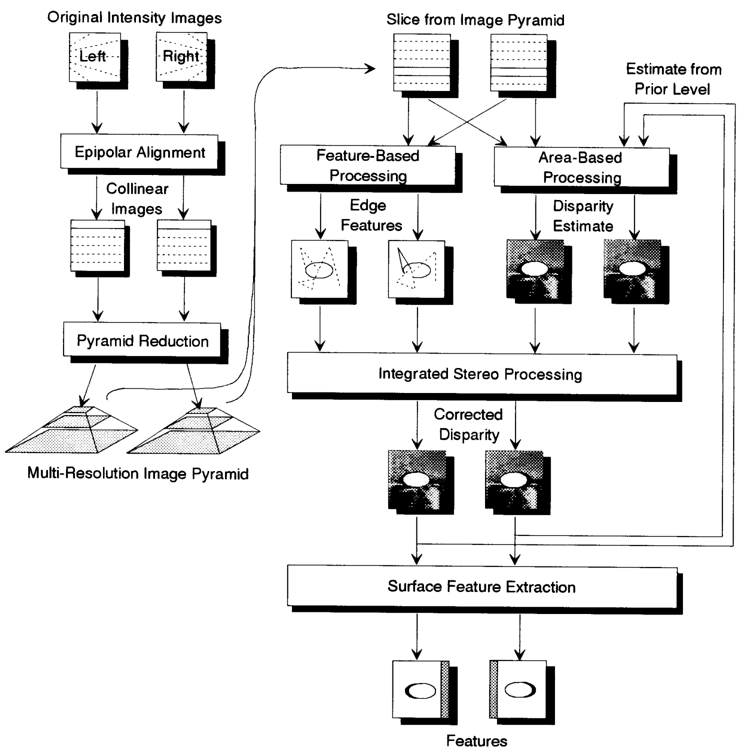

Figure 1: Integration of feature based and area based stereo processing.
(taken from Cochran and Medioni, 1992)

The kind of integration we favourize is not as in figure 1 on the output side of single matching procedures but on the input side. This means, the observations for image matching are taken from the iconic and symbolic level. To be more precise, we don't want to take the primitives after they are extracted, but we want to integrate the procedure which maps from iconic to symbolic. This implies that the formulation integrates two different kind of models. One model stands for the analysis of each image and describes the transfer from the iconic to the symbolic description level, the other model consists of constraining the geometry and radiometry as it is known from all intensity based approaches. The scheme for an integrated matching theory is sketched in figure 2. Some kind of multilevel coarse-to-fine control as indicated in figure 1 is presupposed.

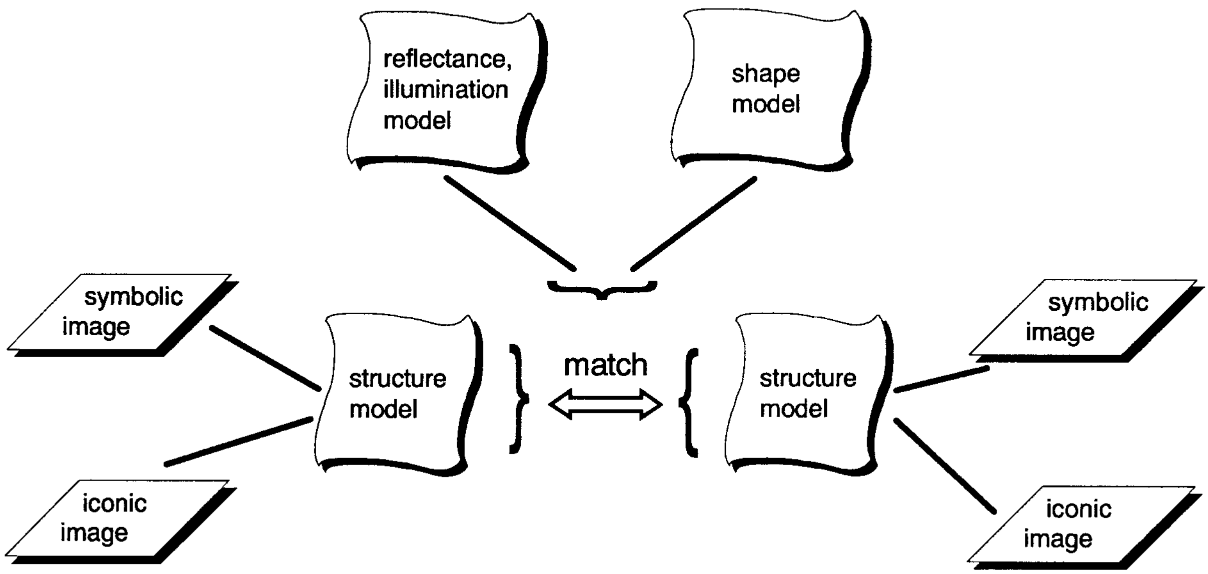

Figure 2: Integration of low level image interpretation and image matching.

In the following we want to focus on a formulation of matching in which corner extraction and location is integrated. To keep the formulations simple we use only one stereo image pair with the images I and J. The geometric model for mapping from image $I(x)$ to image $J(y)$ via the object is restricted to be a simple two dimensional shift $\boldsymbol{u} = \boldsymbol{y} - \boldsymbol{x}$. In object space this corresponds to two image planes which are parallel to the imaged object plane. Also a very simple radiometric model with an unknown offset between the intensity levels of both images is used.
It is quite clear that this simplifications are not very well suited for practical purposes, even not if matching concentrates on small regions. The real reason for choosing this model is that it is quite easy to read and that it is complete in the sense that parameters of the different types of modelling are included. Generalizations to geometric and radiometric standard formulations follow immediately.
For corner detection we use Förstner's procedure. The operator is able to detect, localize and classify points of interest (Förstner and Gülch, 1987). A first step of corner detection we consider to be a preliminary step for matching. The goal is to match not anywhere in the image but directly at grey value corners. Exact location is not necessary in this first step. The model for matching which includes the location of the corner in both images then can be formulated as follows:

1. Structural model - condition for image structure in both images

   Image I

$$\nabla I^T x + v_1 = \nabla I^T x_0$$

   Image J

$$\nabla J^T y + v_2 = \nabla J^T y_0 \tag{1}$$

2. Geometrical model - condition from surface shape mapped to image space

$$y = x + u$$
$$y_0 = x_0 + u$$

   Substitution of the shift u by the difference of explicit point locations

$$y = x + y_0 - x_0 \tag{2}$$

3. Radiometric model - condition from illumination, reflection, etc.

$$I(x) + v_4 = M(y) + r$$
$$J(x) + v_5 = M(x)$$

   Elimination of M

$$I(x) + v_3 = J(y) + r \tag{3}$$

The unknowns are the corner location in image I: x_0 and the corresponding point, i.e., the location of this corner in image J: y_0. The difference just equals the shift between the images. The radiometric parameter r is a further unknown. In consequence, for this simple case five parameters have to be estimated. Equation (1) is equivalent to the formulation of the location step for corners in Förstner, the only difference is the normalized stochastic model. Taking the residuals $v^T = (v_1^T, v_2^T, v_3^T)$ to formulate the least squares objective function $v^T v \rightarrow min$ leads to a standard adjustment formalism in which the normal equation system is build up and solved, etc. Merely linearization of the nonlinear relation for the geometric transformation in equations (2, 3) according to $J (x + u) = J (x) + \nabla J^T u$ has to taken be into account. This means that several iterations are necessary to find the solution.
For the integration of the image structure model in this formulation the geometry has a dominant role. The attribute point location is certainly the most important attribute especially for point primitives. In principle other attributes could also be involved. One of our arguments in the introduction was that for most classical photogrammetric tools points are preferred. The lack of intensity based procedures is that the area, but not a specific point in this area, is matched. If point locations (instead of some transformation parameters) are required, then they are generally introduced heuristically after matching was successful. With the integration of a structural model, specifically that for point location in both images, we found an elegant and consistent solution for this photogrammetric requirement.

With this outline of a new theory we want to finish this paper. A lot of details like classification within matching with questions like: ''becomes the preliminary interpretation 'corner' found in the preprocess stronger or weaker in the stereo formulation?'', or ''changes the interpretation to other point types?'', have to discussed further. The generalization to the models of standard matching formulations is not difficult. Our experience in extracting prominent points with interest operators is, that the selection of points is very unstable, with the consequence that for a large number of points correspondence fails. From the ''stereo location model'' we expect that this difficulties are circumvented. What might be reasonable on a first view is that the structural model and the geometric and radiometric model should integrate over the same region. But this is quite not obligatory. In practice we expect just the opposite. The window size for structure might be only 1/10 of the area used for matching. But therefore several prominent points modelled by equations (1) or similar equations individually have to be integrated. The incorporation of the detection step of the procedure has to be worked out thoroughly. All these aspects will be discussed elsewhere.

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