CONSIDERATIONS ON IMAGE MATCHING - AN ENGINEERING PERSPECTIVE

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ABSTRACT:

In the domain of image matching, research and development are rapidly expanding. The first wave of development took place in the late 1950s and early '60s; it concerned both analogue and digital techniques. Most of those early developments resulted in experimental systems, not reaching operational maturity. A second development wave emerged from the recent availability of very powerful microprocessors, inexpensive mass storage devices, very fast communication means and advanced human interfaces. On the other hand, the demand for automatic image matching has increased, especially in the context of computer vision and remote sensing. Special concepts, expertise and terminology were developed in these fields. Hence, our knowledge was deepened and broadened, and at the same time some confusion was introduced in communication. This was because the background knowledge of the disciplines involved in image matching partly overlap, partly supplement and converge, and partly diverge. Thus, some time is needed to create clarity in communication and homogeneity in the common problem areas.

This paper addresses image matching from an engineering point of view. Thus a differentiation is made according to the input, techniques, and output. The input considerations are focused on the geometric constraints and conditions, and on the image entities for matching. Both items were considered already in the early '60s (Sharp et al, 1964). Recently the feasibility criteria for selection of image windows (or features) have been improved. In this paper some generalizations and potential extensions are discussed. Photogrammetric digital image matching techniques have evolved from the initial sequential and predictive approaches (Sharp et al, 1964) to increasingly profound strategies, involving image analysis, feature extraction, adaptive controls, and the least squares fit. The main topic of this paper concerns the strategies for matching and the corresponding adaptive controls. A strategy should permit flexibility in the choice of the algorithms and in their interrelationships. It should also provide adaptive capability during matching, e.g., by sequencing the process through a network of potential operations. This requires, however, isolating first the influencing factors and their qualitative states. Then the most feasible (potential) states can be selected and linked into chains, which can be serial, with feedback loops, parallel, or combinations thereof. Each chain may represent a variant of an overall matching strategy. The final choice of the strategy depends on both the prior knowledge of the specific circumstances and on the additional knowledge gained during the process. The selection rules can include the relationships between the geometric and photometric information domains.

The output considerations are differentiated according to type, degree of postprocessing, and form of representation. The common type of output is geometric information of the matched image entities and the corresponding quality estimates; these are further differentiated.

The degree of postprocessing can vary between non (raw matches) and a highly refined and conditioned DTM. The most common operations are point identification and transfer, cleaning and editing, resampling, boundary smoothing, and integration of external information. The output can be represented (in storage) by a grid or string of points, or by sets of local or global surface parameters. In both cases information can be compressed.

The quality estimates pertain to the techniques and information products; the latter are further differentiated according to the intermediate and final results. Quality assessment during matching provides control data for adaptive operations; hence, it represents an essential part of the process.

1. GEOMETRIC CONSIDERATIONS

1.1 Background

The following considerations address the geometric constraints and conditions which support image matching. The constraints reflect the imaging geometry; they can guide the search so as to attain a robust and time-efficient process, and they can provide more accurate results. Geometric constraints can support the sequential search and/or they can be incorporated in the least squares matching (LSM). In LSM the constraints improve the robustness and accuracy (Gruen, 1985).

The geometric conditions reflect the geometry of regular objects in the terrain, such as buildings, roads, canals, airports, harbours, etc., or of natural planes. They represent a part of the prior knowledge of the specific terrain. Geometric conditions imply selected descriptions of the objects, which can also support and strengthen matching.

Geometric constraints and conditions can be modelled separately or jointly; in the latter case they can be interrelated or merged. Joined models are feasible for matching close-range images of known objects, or large scale images of urban areas from the air. Thereby the sequential search and fine matching can be modelled for the specific types of objects. In the following, consideration is given to some typical geometric constraints and conditions.

1.2 Geometric constraints

Geometric constraints can guide a sequential search towards the optimum match, and/or they can be incorporated in the LSM to improve the robustness and accuracy. The control of search and the LSM are different issues, and can therefore be considered separately.

1.2.2 Sequential search

The sequence of matching trials can be predetermined by a fixed pattern or self-adaptive (e.g., by hill climbing). Geometric constraints can provide support in both cases, assuming that relative orientation has been established. The search for conjugate image points p′, p" can be confined to an arbitrary line with a point P in the virtual model space (figure 1).

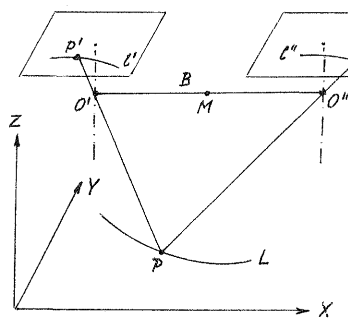

Fig. 1: Line L as constraint

By shifting the point P along L, the corresponding image points p′ and p" move along the images l′ and l" of L. The geometric relations between L and l′, l" are determined by the central perspectives (or another imaging model). Thus, the search for conjugate image points can be constrained to lines l′ and l". When the location of P on line L is approximately known, the search range along l′ and l" can be limited; the better the approximation, the smaller can be the range.

The choice of lines L should permit an easy implementation. If the constraints are independent of the object-related geometric conditions, the choice can be restricted to a few potential sets of straight lines. These can be parallel or bundled lines.

Parallel lines: The most suitable as geometric constraints are vertical lines VL (or horizontal lines HL for close-range images), near vertical lines NVL, or lines parallel to the air base B (BL; figure 1).

VL may pass through the points of a regular or irregular grid in the virtual model space (XYZ). A VL constrains the search in images to the corresponding radial lines from the nadir points (in absolutely/externally oriented images).

NVL can be used similarly, constraining the search to radial lines from their vanishing points in images (near the nadir points). In this case an approximate orientation suffices.

The NVL or VL constraint was applied in several automated stereoplotters, such as in the Stereomats of Hobrough, UNAMACE of Bunker-Ramo, and DSR-VLL of Kern.

BL, parallel to the air base, provide the epipolar constraint, which confines the search to conjugate epipolar lines. Of special interest is the case when these lines are arranged in an XY (Z constant) plane (figure 2). Such an arrangement is convenient for digitizing image pairs directly in the epipolar geometry in analytical stereoplotters.

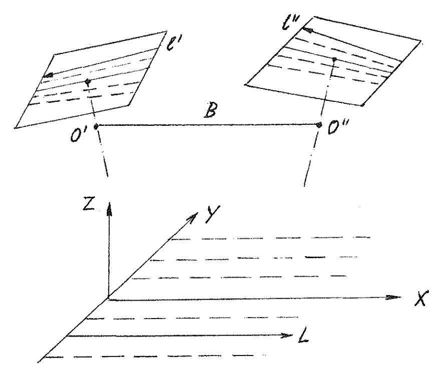

Fig. 2: BL in XY plane

Bundled lines Straight lines as constraints can be bundled in the perspective centres O′ or O", or, e.g., in the midpoint M of the air base B (figure 1). A BL determines together with B an epipolar plane. When a BL passes through O′ (or O") its image is a point in one image, and an epipolar line in the other. A bundle of BL can be arranged so as to form an arbitrary grid of selected points in a reference image. To each of these points an image entity (target window or feature) can be assigned. Then, based on prior knowledge, the approximate conjugate windows can be allocated on the other image. These search windows are laid out along the corresponding epipolar lines; their length should be extended on each side for the maximum expected search range. Thus the search can be confined to the epipolar direction and the estimated range.

If the base-midpoint M is used as the intersection point of the BL bundle, images l′ and l" are nearly symmetric. Thus the search for a window pair, assigned to a point P in the virtual model space, should proceed from a given initial state nearly symmetrically along the conjugate epipolar lines.

1.2.2 Least squares matching The robustness and accuracy of the LSM can be improved by incorporating the geometric constraints in the adjustment. When the input images are only approximately oriented, e.g., in aerial triangulation, the NVLs can be used as constraints. During iterative adjustment, NVLs gradually change to the VL constraints.

When matching is applied to large-scale images of man-made objects, the LS models can be extended with the geometric conditions of such objects. Examples are parallel, straight or curved lines, plane or curved surfaces, right angles, intersecting plane surfaces, etc. The corresponding sub-routines can be evoked by using prior knowledge and/or knowledge gained during the process.

More information about the LSM algorithms is contained in section 3.2.

1.3 Combined image tracking and search

In dynamic operation, image tracking (or roaming) is (virtually) continuous. The tracking path can be predetermined (e.g., for profiling) or it is dynamically controlled during the process (e.g., at contouring). When using digital images, "tracking" (roaming) implies a dynamic search and transfer of the potentially conjugate image windows to the working image memories. Continuous tracking is accompanied by a continuous search for the optimum match. The search is perpendicular to the instantaneous direction of tracking. Thus at profiling, tracking is in a horizontal direction (e.g., in Y) whereas the search is in vertical direction (moving VL). At contouring, the height is fixed, tracking is along the instantaneous tangent, and the search is perpendicular to it.

In stationary operation in near real-time or delayed (off-line), tracking and search can alternate. Tracking implies the transition from one window position to the next, whereas the search concerns the parallax differences (disparities) so as to attain the best match.

When terrain relief is approximately known, the tracking path can be planned so as to minimize the search. Approximate knowledge may be available prior to matching and/or during matching. Some geometric conditions of man-made objects are a priori known. Hence, the tracking patch can be located in close proximity of such object surfaces. This applies particularly to large-scale images.
The knowledge gained during matching stems either from the coarse-to-fine process and/or from the already matched neighbourhood. In the coarse-to-fine matching (e.g., progressive sampling) the relief information gained in a hierarchical level provides control for tracking in the next lower hierarchical level.

The neighbourhood information can be represented by the already matched neighbouring discrete points, profiles or contour lines. These can provide the control for tracking in the proximity of the new points or lines.

2. IMAGE ENTITY SELECTION

A basic prerequisite for reliable and accurate matching is adequate selection of the image entities (windows or features). In this context we address two important interrelated issues:
- The interrelationship between the selection criteria and the matching algorithms;
- The choice of the selection criteria.

In the following, consideration is given to these issues.

2.1 Interrelationships between criteria and algorithms

The selection criteria need to be adapted to the type of image entities and to the specific matching algorithm. Feature-based matching requires different criteria than area-based matching. The criteria should reflect the sensitivity of the algorithms to the variations in image entities, and vice versa.

When a matching strategy implies adaptive capability, some algorithms can be interchanged during the process. While 3D (relief) information is gradually gained, the selection criteria can be extended accordingly. Thus flexibility is required in both the matching algorithms and the selection criteria (figure 3).

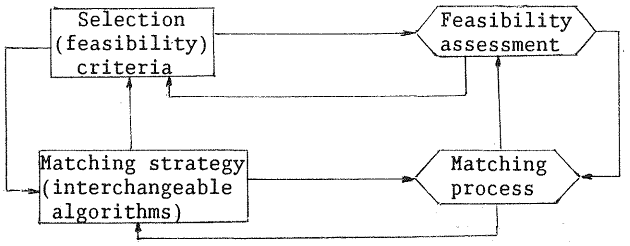

Fig. 3: Interdependent selection criteria and matching algorithms

The interdependence of the criteria and the algorithms is also inherent in the LSM, where the interest operator is extracted from the covariance matrix (Förstner, 1984). Hence, by changing the LS algorithm, the interest operator should change accordingly.

2.2 Selection criteria

For reliable and accurate matching, the photometric content of image entities is most essential; dissimilarities of the conjugate entities are of secondary importance, especially when adaptive control is applied. Thus, the feasibility assessment should be based on these factors.

The photometric content of images depends on the terrain cover and relief, atmosphere, illumination, and on the imaging and digitizing systems. Photometric dissimilarities stem from the terrain relief in conjunction with the imaging geometry and from the changing albedo (reflectance angle). Such dissimilarities impair quality of image matching.

When extracted features serve image entities, specific criteria can be set up for each feature type in the context of a given mathcing algorithm. The criteria can be, e.g., the acceptance threshold for characteristic feature descriptors and/or for combinations thereof.

When image windows serve as entities for matching, the selection is based mainly on the photometric content. Before matching, the windows can be pre-selected by means of a 2D-interest operator. During matching, relief information is gradually gained, which permits refinement of the selection by upgrading the criteria to 3D.

Simple 2D pre-selection criteria were introduced in the early 1960s, in the first automated digital photogrammetric system DAMC of IBM (Sharp et al, 1964). Further criteria were later introduced, refined and extended (Makarovic, 1977; Moravec, 1980; Däschler, 1981; Förstner, 1985). These criteria are based partly on heuristic considerations, partly on theoretical considerations, and/or partly on experimental tests. When image pairs are relatively oriented before matching, the feasibility needs to be assessed only in the direction parallel to the air base; otherwise it should be assessed in both directions (x and y).

The criteria provide one or more feasibility values for each image window, to be compared against the specified acceptance threshold(s).

A potential extension of the feasibility assessment would involve more image analysis and feature extraction in the context of the overall matching strategy.

3. IMAGE MATCHING

In the following we address some important items of image matching, in particular the overall strategy, specific approaches and algorithms, and the adaptive controls. The approaches, algorithms and adaptive controls are interrelated, and should therefore be optimized in the context of the overall strategy. Nevertheless, each of these items has its own impact on the performance and robustness of matching.

3.1 Strategies

A good strategy should provide for reliable, accurate and fast matching. It should be devised for a given setting of the input, techniques and of a specified output. Image matching involves numerous influencing factors, occurring and interacting in different combinations, and having different effects. This permits design of various strategies; the choice depends on the specific circumstances.

The influencing factors need to be identified; they can be classified according to the input, techniques (methods and means) and output (table 2). These factors can be further subdivided, and each of them can be represented by several qualitative states.

The lists of the factors and their states are open-ended, and their classification can be updated.

A matching strategy can be devised by selecting the most feasible states of the influencing factors, and by connecting them into chains. Such chains can be simple sequential, or more complex, including feedback and feedforward.
Each chain may represent a potential variant of the strategy, which can then be evaluated to isolate the best. For such an evaluation, prior knowledge alone may not suffice because a strategy depends on the suitability of the specific algorithms and of the adaptive controls, and vice versa. Hence, experimental tests are required, providing a feedback for the selection and optimization of the overall strategy.

A strategy should be flexible to allow adjustments to variations in the current states of the input and output. Flexibility is needed to cope with the changing photometric content and with the geometric and photometric dissimilarities of the conjugate images. A good strategy may include alternative sub-chains of algorithms, to be invoked by the intermediate results in the process of matching. Thus, several sub-chains can be attempted and evaluated to isolate the best.

3.2 Matching approaches

Approaches reflect the algorithms and vice-versa. They can be differentiated according to the image entities (as input) and the matching techniques; both are interdependent.

The image entities can be small image segments (linear or areal), specific image features, or combinations of these. Image entities can be arranged in a single level or hierarchically in image pyramids.

INFLUENCING FACTORS							
Input	Images	Overlap	Stereo pair	Multiple images			
Input	Images	Geometry	Intersecting bundles	Epipolar	Externally oriented bundles	Other	
Input	Images	Photometry	Raw images	Restored images	Other		
Input	Images	Entity type	Window	Feature	Window and feature		
Input	Images	Entity lay-out	Regular	Semi regular	Irregular		
Input	Ter.	Control data	Ground control	Photogrammetric (AT) control			
Input	Ter.	Prior knowledge	Relief class	Anomalous regions	Geometric conditions	Other	
Means		Hardware	Digital	Hybrid	Analogue	Open	
Means		Operation	Real-time	Near real-time	Delayed	Mixed	
Means		Performance	Low	Medium	High		
Means		Cost	Low	Medium	High		
Methods	Pre-process.	Filtering	Restoration	Enhancement	Compression	Other	
Methods	Pre-process.	Feasibility assessment	Gradient	Laplacian	Moravec	Förstner	Other
Methods	Pre-process.	Segmentation	Pixel-based	Region-based	Rule-based	Other	
Methods	Pre-process.	Structuring	One level	Hierarchical	Network	Other	
Methods	Pre-process.	Resampling	Orthogonal	Epipolar	other		
Methods	Pre-process.	Feature extraction	Edge/line	Corner point	Crossing	Other	
Methods	Matching	Space	Image	Object	Mixed		
Methods	Matching	Entity	Single point	Local array (or chain)	Global array		
Methods	Matching	Norm	Statistical	Deterministic	Mixed		
Methods	Matching	Method	Sequential search	Progressive densification	Least Squares	Mixed	
Methods	Matching	Adaptive control	None	Iteration	Relaxation	Mixed	
Methods	Matching	Interaction with pre-processing	None	Weak	Medium	Strong	
Methods	post-process	Verification	Statistical	Deterministic	Mixed		
Methods	post-process	Smoothing	Uniform	Locally adapted	Other		
Methods	post-process	Resampling	Regular grid	Proples	Contour lines	Other	
Methods	post-process	Quality assessment	Accuracy	Fidelity	Reliability		
Methods	post-process	Interaction with matching	None	Weak	Medium	Strong	
Output		Format	Point grids	Surface parameters			
Output		Type	Point location	Slope	Curvature	Local surface parameters	Global surface parameters
Output		Processing degree	Raw	Cleaned	Edited	Conditioned	
Output		Representation	Grids	Strings	Mixed		

Table 2: Influencing factors and their qualitative states

Matching techniques concern the search and fine matching; each of these can be further differentiated. Search can be carried out by iteration (feedback) or by relaxation (hierarchical feed forward). The sequence of search can be programmed, i.e., using a fixed sequence of matching trials, which can be geometrically constrained (vide section 1.2), or it can be self-adaptive (e.g., by "hill-climbing").

The robustness of search can be improved, e.g., by connecting the neighbouring image entities, after being matched individually, into strings, and then applying matching to the strings (Viterbi algorithm).

Fine matching is required to attain high accuracy. To this end the LSM is commonly applied.

Least squares matching
LSM minimizes the square differences in image intensity; it permits matching of image pairs or of multiple images (Ackermann, 1983; Förstner, 1982; Gruen, 1985; Helava, 1988a; Rosenholm, 1987). The LS algorithm should reflect the imaging process. Because this process is non linear, LSM assumes prior knowledge of the approximate values of the unknown parameters. The image entities to be matched can be arbitrary, provided that they are similar and contain enough photometric information.

Image windows can be small (centered on individual points of interest) they can be larger (covering a local array of such points) or they can represent the entire areas of the overlapping images, containing a "global" (full) array of points.

In table 3 some properties of the matching approaches are indicated.

Image entitites		Search				Fine (LSM)		
		Sequential		Coarse to fine		Single points	Local arrays	Global arrays
		Single	Strings	Iterat	relax			
Features	One level	x	x	x		x	x	x
	Hierarchy	x	x		x		x	x
Windows	One level	x	x	x		x	x	x
	Hierarchy	x	x		x		x	x
Mixed	One level	x	x	x		x	x	x
	Hierarchy	x	x		x		x	x

Table 3: LSM approaches

Image entities can be arranged directly in images (image space) or indirectly in virtual model space (object space). Matching in "**image space**" is convenient for modelling terrain relief and for automatic height control during manual tracking of selected terrain features. Both the search and fine matching can be in image space. Any geometric and photometric prior knowledge can be projected inversely to the images to support matching. Hence, resampling of the images to the "object space" is not necessary. The raw DTM output is, however, irregular. To create a common regular DTM grid, resampling is required. As DTM grids are relatively sparce, such resampling is fast, and it need not be carried out in real-time.

When matching is in "**object space**", the prior and in-process gained information of the terrain can be easily integrated. This is advantageous when determining a DTM grid directly in a common ground coordinate system, and/or when transforming input images to the orthogonal (or another, e.g., oblique) projection in real-time. To this end, however, the images have to be resampled to a common reference in object space, such as a global image raster (Helava, 1991). Such real-time resampling is computation-intensive, and it causes a loss of photometric information.

The matching algorithm should comprise three segments of the real world: the terrain region, atmospheric conditions, and the imaging system.

Each of these pertains to the geometric and photometric domains (table 4).

Domain	Real world		
	Imaging system	Atmosphere	Terrain
Geometric	Known	Partly known	Unknown or approx. known
Photometric	Known	Partly known	Marginally known

Table 4: Prior knowledge for modelling

The quality of modelling is impaired by insufficient knowledge of the atmosphere during imaging and of the terrain surface. Inaccurate models adversely affect matching. They distort the theoretical accuracy estimates, which are usually too optimistic.

The geometric part of the model requires prior knowledge of the approximate match and of the local terrain relief (or geometric dissimilarities); thus it requires pre-matching. The approximation of pre-matching should reflect the spatial frequency of the photometric content (of image entities); the higher the frequency, the more accurate should be the approximation.

Pre-matching can also provide approximation of the local terrain relief. Hence, the algorithm for geometric transformation can be adapted accordingly.

The LSM algorithms, using a fixed first-degree (affine) transformation, do not offer much flexibility. Deviations of the real terrain from the modelled surface (tilted plane), impair the quality of matching and make theoretical accuracy estimation uncertain.

The photometric part of the model should reflect the prior knowledge of the terrain cover, relief geometry, atmosphere, illumination, and of the imaging system. Because the prior knowledge is insufficient, the photometric models have to be simplified; usually a linear transformation is applied (Wrobel, 1989).
The photometric content is essential for the quality of matching; image dissimilarities, if not excessive, play a secondary role.

LSM is feasible for fine, accurate matching when the theoretical assumptions are met. It can also be applied iteratively in the coarse-to-fine search, which is computation-intensive, and thus less time- and cost-effective than other approaches.

Extensions
When using images at larger scales, matching should be linked with terrain feature (object) extraction. Interaction of the matching and extraction processes can enhance both. These can form a feedback loop and can be provided with adaptive control (Makarovic, 1984).

Another extension concerns the interaction of the image matching and the surface filling processes. These can be applied alternatively in the coarse-to-fine search and in fine matching (Rauhala, 1988; Ebner et al, 1987; Rosenholm, 1987). In the coarse-to-fine search, surface fitting can provide approximations for the next matching stage, also in regions where matching is not reliable.

3.3 Adaptive controls

Adaptive controls are necessary for adjustment of the geometric and photometric dissimilarities of conjugate images during matching. The larger the image scale, the more sophisticated adaptive controls are required.

The disturbing effects of dissimilar conjugate images can be counteracted in several ways and to various degrees. The approaches can be differentiated according to relative versus absolute, sequential versus simultaneous, and iterative versus relaxation (or fine) approaches (figure 4).

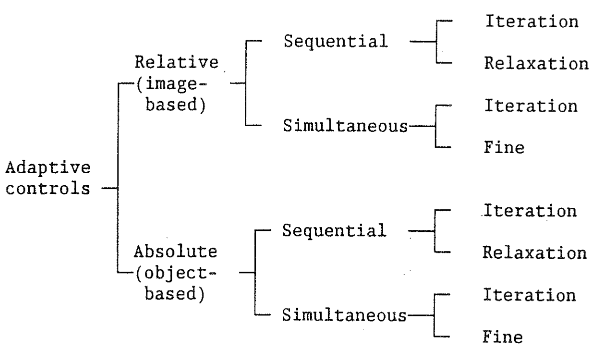

Figure 4: Classification of approaches

The geometric and photometric dissimilarities can be compensated by using prior knowledge and/or the information gained during the process. Photometric dissimilarities are also caused by changing reflection angle (albedo), which depends on the direction of illumination, local terrain slope, and the changing position of the imaging system (camera). Hence, the problem is to determine the slope values in the course-to-fine matching.

Relative approaches
The relative or image-based approaches permit a **mutual** adjustment of the conjugate image entities **without** involving terrain relief (object). Hence, photometric compensation for differential albedo cannot be applied, but the adjustment algorithm can be simple.

Sequential iteration (figure 4) represents a feedback process. In each cycle, i.e., matching trial, the values of unknown parameters and thus the compensation for dissimilarities are updated. Sequential **relaxation** represents, however, a feedforward process, from coarse to fine, down the hierarchical tree.

In each hierarchical level, the matched points can be approximated by a fitting surface, which provides approximations for matching in the next lower level. Thus, when sequencing down the hierarchical tree, the dissimilarities are being increasingly compensated (Makarovic, 1977).

Sequential relaxation and iteration can also be combined in one process. Relaxation is effective for the coarse-to-fine search, whereas iteration can improve fine matching. Some feedback can also be applied during hierarchical matching, i.e., to support the coarse-to-fine matching in difficult situations.

In the **simultaneous** (relative) approach geometric and photometric dissimilarities are adjusted simultaneously. Such approaches can be implemented iteratively or in a single step.

When LSM is applied in stationary mode (e.g., window by window), one image serves as the reference, providing the targets to which the conjugate image entities are transformed. The transformation algorithm contains geometric and photometric parameters. The relative adjustment and thus the compensations depend on the suitability of the transformation algorithm, the photometric content, and on the magnitude of the dissimilarities.

LSM can be applied iteratively, e.g., by successively blurring and shifting of image windows from coarse to fine (Hahn, 1991). The pull-in (convergency) range is limited by the maximum blur, and the computation is intensive.

Absolute approaches
The absolute or object-based approaches assume prior and/or in-process gained knowledge of terrain relief. During the coarse-to-fine matching, terrain relief is being gradually modelled. When the relief geometry is sufficiently approximated, it can be entered into the fine LSM.

The **sequential** approaches aim at gradual upgrading of the terrain relief model. In each sequential step the relief geometry (or the parallax values) can be upgraded, which in turn permits refined geometric and photometric transformations (inclusive of differential albedo) and the corresponding resampling. The resulting images provide input for the next sequential step (figure 5).

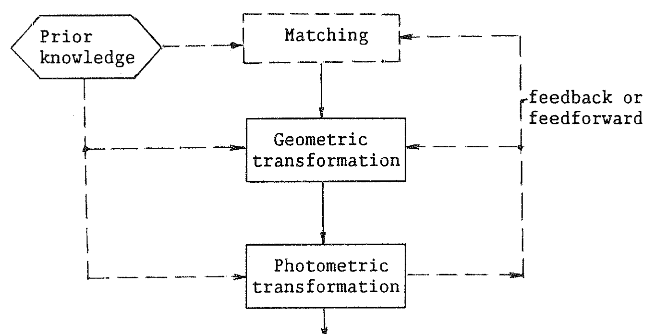

Fig. 5: Interdependent geometric-photometric adaptive controls.

Such a geometric-photometric adaptive process is essential when matching is applied to large-scale images of urban or sub-urban regions. In difficult situations, such as occlusions, the matching process can be terminated, and another potential algorithm invoked.

In **simultaneous** approaches the geometric and photometric transformations are merged. The process can iterate from coarse to fine, or it can be restricted to fine matching.

The LSM algorithm should adequately accommodate the prior and/or in-process gained knowledge about terrain. This requires flexibility of the transformation algorithms for LSM, especially for fine matching of large-scale images.

4. OUTPUT OF MATCHING

The output of matching can be processed to different degrees and can be represented in various ways. The following considerations address the output **types**, processing **degrees**, and the **forms** of representation.

4.1 Output types

The main types of output pertain to the geometry of terrain relief (object) and to the quality estimates (figure 6).

- Types
  - Geometric information
    - Basic
    - Attributes
  - Quality estimates
    - Techniques (processes)
    - Geometric information (products)

Figure 6: Classification of output types

The geometric information comprises basic items and their attributes. The **basic** information-output is parallax (disparity) values of the matched image entities or the heights. These values may refer to single points, to local arrays or strings of points (profiles, contour lines), or to global arrays of points.

Grids of points can be approximated by local (finite elements) or global surfaces. Representation of such surfaces by sets of parameter values implies compression.

The geometric **attributes** can be parameter values of the matched image entities, such as terrain slope and curvature (for each window). When relief is represented by the fitting surfaces, such attributes are implicit. Attributes can include the statistics of the parallax values (or heights), slopes, curvatures, etc.

The quality estimates concern the matching techniques (or processes) and the output products of matching. Quality of **matching** can be defined by its accuracy, reliability (of operation), and time and storage efficiency.

Quality of the **output** addresses both the basic items and their attributes. When the output is a grid of points, quality addresses the accuracy and reliability of the individual (point) matches, of matches for local (point) arrays, or of global matches. When relief is represented by fitting surfaces, quality refers to the sets of parameters and/or to error statistics (when using check points).

LSM permits theoretical estimation of the quality. Such estimates are usually too optimistic and should therefore be considered with caution. The LSM models imply simplified assumptions, which might be satisfactory for the adjustment itself, but uncertain for estimation of the matching accuracy.

Estimation of the quality of terrain relief models involves intricate problems which are not yet fully understood. This issue is, however, beyond the scope of this paper.

4.2 Degree of output processing

The raw output of matching can be postprocessed to various degrees. When matching is interacted with surface fitting in a ground coordinate system, further processing may not be necessary.

In general, however, postprocessing begins with the inspection and cleaning of the raw output of matching. Failed matches can be largely detected and removed by a collective analysis of the parallax values (or heights).

After cleaning, a transition can be made from the matched image entities to their representative points. Such points are usually the midpoints of matched image windows. After LSM some abstract points can be determined (e.g., as a weighted mean of intensity) in image targets, and then transferred to the conjugate images by a geometric transformation. The transformation coefficients can be a by-product of the LSM (Förstner, 1984). Another possibility is to discern distinct points from the matched image entities by means of a suitable interest operator. The transition from matched image entities to representative points should be included in the error analysis.

Editing implies smoothing, removal of discrepancies along boundaries between local arrays of points and/or between stereopairs, integration of information from other sources, etc. The skeleton of terrain relief, sampled selectively, can be merged with other (filling) relief information, such as point-grids, contour lines or parallel profiles. To this end, weighted resampling is most adequate. The output can be further modelled by fitting surfaces.

Postprocessing and matching can form a feedback loop, which permits optimization of both.

4.3 Output representation

The form of representation depends on the output type. The most common forms of relief representation are point-grids (regular, semi-regular, irregular), point strings (skeleton, auxiliary lines, contour lines, profiles), composites of strings and grids, and sets of parameter values of local or global fitting surfaces. The representation should conform with the standards of the corresponding GI base, or the user's specifications.

5. CONCLUSION

Engineering considerations on image matching address the overall system strategy and optimization, rather than specific algorithms. Attention is focused on the input, the matching techniques and the output. The most substantial problems concern the geometric constraints and conditions, the overall matching strategies, algorithms and the adaptive controls. These tend to provide flexibility and effectiveness.

Geometric **constraints**, emerging from the imaging system reduce the search and increase robustness and accuracy of matching. Geometric **conditions** pertain to regular objects in the terrain; they can be involved in matching of large-scale images. Constraints and conditions can be applied independently or in combination.

The **strategy** of an overall matching process can be devised when enough circumstantial knowledge is available. Such knowledge concerns the terrain region (land cover, relief, etc.), input images (geometric and photometric properties), control data, output (products) specifications, and the available means (processors, storage devices, network, etc.). The influencing factors can be classified accordingly, and differentiated further according to their qualitative states. Different strategies can be represented by chains of the potential qualitative states, which imply different matching algorithms.

Adaptive controls are required to attain flexibility during matching. During a process, geometric and photometric control data can be gained and used for tuning some parameter values of the matching algorithms, and/or to invoke exchangeable parts of algorithms (or of sub-chains).

Complexity of matching increases exponentially with the image scale. This is because of the dissimilarities of conjugate images, caused by the objects' depth. To cope with great dissimilarities, matching and object (feature) extraction should be linked in a highly adaptive way, and supported by geometric conditions.

The future development of image matching will address a flexible choice of the overall strategy, effective adaptive control mechanisms, and rational use of prior knowledge, such as geometric constraints and conditions.

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