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IMAGE CORRELATION ALGORITHMS

Abstract

A review of the concepts and techniques for image correlation in photogrammetry is presented.
The different approaches may be classified according to the type and structure of the input image data, the operations involved in the overall process and their timing, and the type and architecture of the equipment components used. These classification factors tend to determine the main characteristics of the different algorithms for image correlation.
Some potentials and shortcomings of the different techniques are listed, and an attempt has been made to assess the development trends.

I. Introduction

The aim of this paper is to review the concepts and techniques for image correlation in photogrammetry. Consideration is given to an overall view of the systems and their main ingredients. The scope is limited to applications in photogrammetry, i.e. to local image processing using relatively small samples.
Image correlation will be considered only in the context of automatic generation of x- (or epipolar) parallaxes; with minor differences, the y-parallax can be handled similarly. Also excluded are the optical coherent correlation techniques, since these have not yet reached operational maturity in photogrammetry.
The basic functions involved in- and related to image correlation are identified and their properties are reviewed. A comprehensive evaluation of their performance characteristics is, however, beyond the scope of this paper.
The meaning of the term "algorithm" is, in the context of this paper, broader than merely the description of a computational procedure. It portends to cover the underlying concepts, the overall strategy, and the computational procedures involved in automatic image matching. An algorithm reflects the properties of the input data, of the required operations, and of the equipment to be employed for processing. Hence, the number of possible algorithms is considerable, though not all are feasible for implementation.
The primary incentive in formulating an algorithm is the specifications concerning the desired information product. In automatic photogrammetry, such products may be digital terrain model (D.T.M.) data, contour charts, orthophotographs and stereomates. The corresponding operational stages can be synthesised in the reverse sequence, i.e. from the outputs towards the inputs. This may be useful particularly for the initial structuring of the overall process, of which image correlation is an essential part.
The paper contains the definition of image correlation systems, a classification of the different approaches, a brief description of the basic operations involved and their variants, identification of the problem areas, limitations, and of possible solutions, and an estimate of the development trends.

II. System definition

1. Interrelations

Photogrammetric systems with an automatic image processing capability incorporated imply suitable correlation algorithms. The algorithms tend to dominate some basic operational characteristics of the systems, like the speed, reliability, and accuracy. The algorithms, the structure of image data, the operations involved, and the corresponding equipment form together an entity. Thus, the algorithms do strongly depend on the other ingredients of the system (fig. 1). Therefore it is purposeful to classify the algorithms,

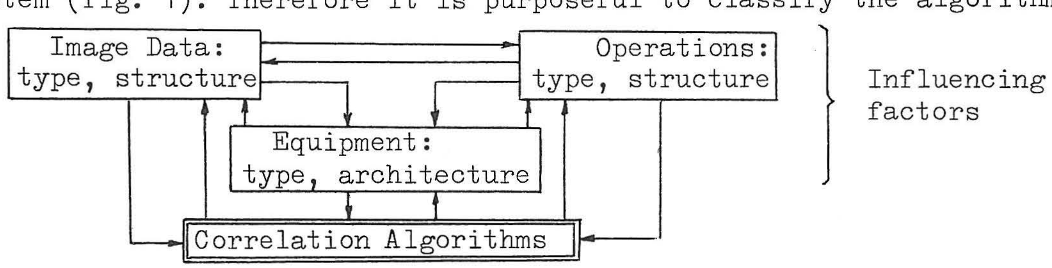

Fig. 1.: Interrelations

and thus the automatic systems, according to the three categories of influencing factors. In the following, such a classification is presented.

2. Classification

The classification is based on the three basic ingredients, i.e. the image data, the equipment, and the operations.

a. Image data

i. Data type:
- analogue:
  . signal carrier: electrical voltage, coherent light*
  . signal characteristics: direct (raw), conditioned (e.g. filtered).
- digital:
  . photometric resolution: dual level*, multiple level, edge enhanced*
  . spatial resolution for: image restoration, terrain relief (e.g. D.T.M.)
  . data characteristics: direct (raw), conditioned (e.g. filtered).
- hybrid:
  . one signal is analogue and the other digital*

ii. Data structure:
- analogue:
  . unit format: line segment, regular patch
  . spatial pattern of units: regular grid, bands, etc.
  . spectral bands (spatial): two, three or more.
- digital:
  . unit format for: scanning (A/D conversion), matching
  . spatial patterns of units: one-dimensional, two-dimensional
  . derived data: single vs. multiple level structure
  . distinct data: salient points, morphologic lines, boundaries of anomolous regions, etc.

b. Equipment for processing

i. Type of components:
- analogue:
  . digital coherent processing devices*
  . electronic sensors, processing circuits, and control elements
- digital:
  . computers, interfaces, peripheral devices
- hybrid:
  . partly analogue and partly digital components

ii. Architecture:
- on-line systems, operating in real time
- off-line systems, operating time-delayed

c. Operations

i. Real-time operations:
- scanning, sensing, A/D conversion
- preprocessing: amplitude scaling, contrast stretching, filtering, resampling, data structuring,etc.

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* These possibilities will not be considered further.

- image matching: similarity assessment, parallax determination and adaptive operations
- terrain relief definition: computation of D.T.M. data, data editing, and various conversions
- control of recording: orthophotographs, stereomates, contour charts, and other.

ii. Time-delayed operations:

- scanning, sensing, A/D conversion
- preprocessing: filtering, compressing, reformatting, resampling, structuring, etc.
- image matching: similarity assessment, parallax determination and adaptive operations
- terrain relief definition: computation of D.T.M. data, data editing and various conversions
- control of recording: orthophotographs, stereomates, contour charts, and other.

Some of the listed operations can be linked and thus carried out in real-time. The off-line operations require intermediate recording of data, their transfer and retrieval. These operations and their interrelations are defined in the two following sections.

3. Definition of on-line systems

A feasible manner of describing a system structure of a certain complexity is by means of a functional block diagram. Figure 2 represents the operations and the data flow in an on-line system. In the left half of the diagram the flow

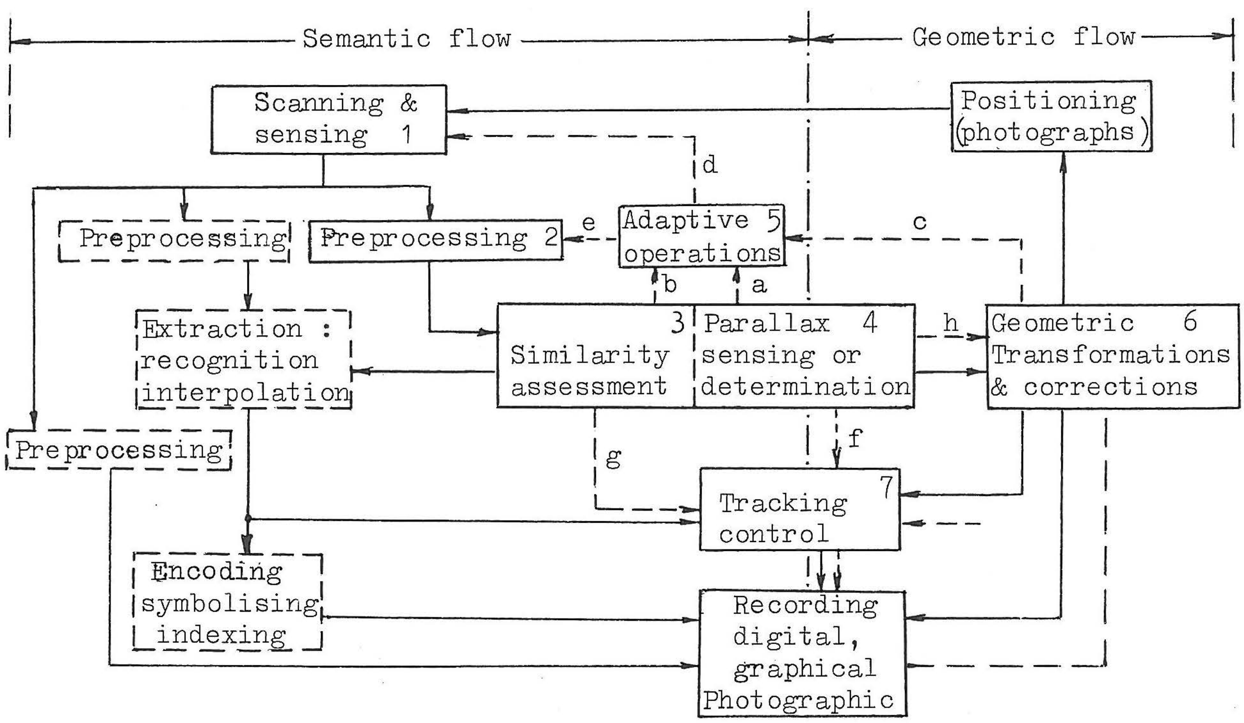


Fig. 2 : Structure of on-line systems.

of semantic (or photometric) data is shown, whereas the right half shows the flow of the corresponding geometric (or locational) data (17). These geometric data are needed for positioning (or addressing) of the elements of semantic (or photometric) information. The operations in boxes positioned across the vertical border line between the two flows involve both types of data.
The indicated flows refer to basically two different categories of information, i.e. the basic information, which is composed of the semantic and geometric

components (solid lines), and the internal control information (interrupted lines). The flows in fig. 2 represent schematically different variants of the on-line systems, though some of the equipment components (e.g. a computer) may perform more than one function or vice versa.
In image correlation, however, only the operations labelled 1 to 7 and the flows, a to h, are directly involved; they differ considerably from one variant to another. In table 1 the properties of the known on-line systems are reviewed. The meaning of the symbols is: x: presence, *: A/D conversion, o: warning signal, (x): scanning is not subjected to adaptive control.

On-line systems \ Operations flows	Operations														Control information							
	Analogue							Digital														
	1	2	3	4	5	6	7	1*	2	3	4	5	6	7	a	b	c	d	e	f	g	h
Stereomates	x	x	x	x	x	x	x								x	x	x	x		x	x	
EC-5 Planimat	x	x	x	x	x	x	x								x	x		x		x	x	
Topomat	x	x			x	x	x			x	x				x	x		x		x	o	
UNAMACE; APM	x	x	x	x	x								x	x	x	x	x	x		x		x
AS 11 B1	x	x	x	x	x								x	x	x	x	x	x		x	x	
GPM-1	x	x	x	x								x	x	x	x		x	x				x
GPM-2	x							x	x	x	x	x	x	x	x		x	x				x
AS 11 BX	(x)							x	x	x	x	x	x	x	x		x		x			x
RASTAR	(x)							x	x	x	x	x	x	x	x		x		x			x

Table 1.: Features of on-line systems.

The information of table 1 is very general as the nature of the same basic operations and of the control signals may vary widely from one system to another. Hence, the individual functional blocks and their interactions should be made transparent. Prior to this, however, the overall structure of the off-line systems should be defined.

4. Definition of off-line systems

The structure of the basic operations and the corresponding interactions can also be defined in two domains, i.e. referring to the "semantic" and the "geometric" flows. Typical for the off-line systems are the time delays between the main operational stages and intermediate recording, transfer, and retrieval. This provides great freedom in timing operations and locating parts of the system, and thus it leads to a great diversity of possible solutions. The different system structures can, however, be schematically represented by a unique functional block diagram (fig. 3.). For image correlation only, stages I and II are relevant; therefore the subsequent operational stages will be disregarded here.
The operations labelled 1 to 5 and the control signals a to d have a direct impact on image matching. For the different image matching algorithms, the nature of these operations and of the corresponding control information differs substantially. Table 2 reviews only the flow of the control information for some known off-line systems.
All operations, except scanning and sensing, are digital. They are realised by a computer and its interface, the computer being either a general purpose one or a dedicated distributed network of processors.

Off line systems	a	b	c	d
AMC-IBM: Sharp	x	x		
UNB: Masry	x	x		
UCL: Dowman	x	x		
TUK: Kreiling	x	x		
TUD: Göpfert	?	?		x
ITC: Makarovič			x	x

Table 2: Control information in off-line systems

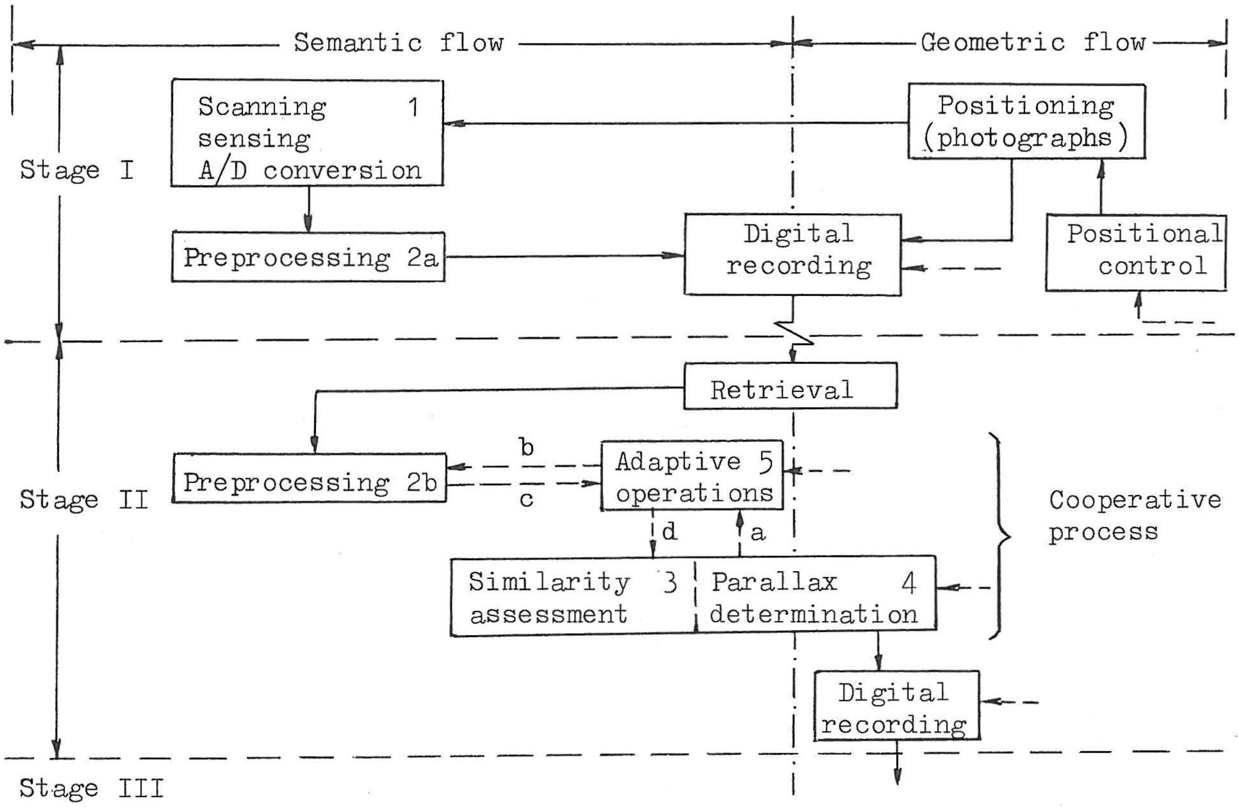


Fig. 3 : Structure of off-line systems.

5. On-line versus off-line systems

The definition of the two system types allows a global mutual comparison even before making the basic operations transparent. The main properties of the on-line and off-line systems are listed in table 3. This information is very fundamental for the choice or modelling of the algorithm for image matching.
By summarising, the on-line systems use complex equipment, which can be internally optimised as a whole, and can therefore be very time-efficient. An important feature is the possibility of the operator's intervention during operation. However, such systems are relatively inflexible and less versatile than the alternative.
Off-line systems have, on the contrary, emphasis on the different strategies and associated mathematical models, and may therefore be highly flexible and versatile. Optimisation can be applied, both to the system as a whole and to the individual operational stages. The latter may even be carried out in different locations.

The reviewed general features of the image correlation systems tend to establish a framework for the more specific algorithms of the individual functional blocks, represented in figures 2 and 3. These blocks will be illuminated in the following chapter.

On-line systems	Off-line systems
- Time constrained operation - with real time outputs (final) - Complex dedicated equipment - Great data throughput - Limited versatility (i.e. diversity of inputs and outputs) - Limited flexibility (strategies, mathematical models) - Operator support in failure states	- Time delayed operation with intermediate recording/retrieval of large data sets - Minimum of dedicated equipment - Phased but parallel operations; throughput depending on the equipment - Great versatility (type and structure of inputs and outputs) - Great flexibility (strategies, mathematical models)

Table 3

III. Basic operations

The operations involved in image sampling, preparation and matching concern local image data. These local operations should be well regulated, i.e. forming together a cooperative process. The individual operations are scanning and sensing - with or without A/D conversion, preprocessing, similarity assessment, parallax sensing or determination, and adaptive operations. Tracking control and geometric transformations are involved indirectly and will therefore be considered only marginally. This also holds, to a lesser extent, for scanning and sensing.
In the following sections, the basic operations will be outlined.

1. Scanning and sensing

The characteristics of the raw image data depend on the properties of the scanner and sensor, on the sampling parameters, and the associated properties of the A/D conversion. C.R.T. flying spot scanners have most commonly been utilised for scanning, but tend increasingly to be replaced now by laser beam scanners, solid-state scanners, image dissector tubes, and others.
The choice does not depend merely on their physical performance characteristics, but also on the strategy for the subsequent processing of the data, in particular on the algorithms for the adaptive operations. Adaptive control may or may not involve a physical rescanning of conjugated images (see III.4).
In order to increase efficiency and reliability of image matching, it is purposeful to scan images along conjugated epipolar lines (6) (21). If images need not be restored from the scanned data, the sampling parameters (i.e. spot size, step size, line spacing, etc.) can be defined such as to meet the specified accuracy of the D.T.M. data to be monitored (19). As the specifications for sampling may change from one application to another, the corresponding sampling parameters should either be tunable or the already sampled (high resolution) raw data should be resampled accordingly by (14). For each case a suitable sampling or resampling algorithm has to be formulated. The algorithm should reflect, both the overall strategy of processing and the physical characteristics of the image sampling mechanism.

2. Preprocessing

In essence, preprocessing is a part of the adaptive mechanism, which tends to provide for optimal matching. Preprocessing embraces many operations, varying widely in the different systems. Their primary function is to condition the image data for optimal operation.

The preprocessing operations can be classified (see chapter II) into the analogue and digital, and the locational (metric) and photometric (semantic) ones. Examples of typical photometric operations are: amplitude scaling, data filtering, compression, and various data analyses. Typical locational operations are: coordinate windowing, shifting, rotating, partitioning, aggregation, etc. Some operations are also mixed, i.e. comprising both components, such as: data resampling, identification of distinct (or salient) points and morphologic lines, etc.
In preprocessing most of the operations are linked serially between scanning and sensing at one end and similarity assessment at the other. They are very seldom included in the feedback loops with the scanners and sensors (25).
Amongst the various operations, data filtering and structuring are of central importance. Filtering tends to inhibit disturbances and to enhance the pertinent image data. The choice of effective filters is therefore essential (3) (9). Filtering may be combined with data compression and their structuring. Data can be structured into several spectral bands (spatial) (1), (5) (12), epipolar lines or segments thereof (23) (25), submatrices in one or more hierarchial levels (18), etc. The data structure may dominate the reliability, accuracy and time-efficiency of the entire matching process. Hence, the structuring of image data should be considered in the context of the overall process.
The preprocessed image data form the input for the assessment of the image similarity.

3. Similarity and parallax

The nucleus of the automatic operation represents the similarity assessment of a pair of image segments in conjunction with the sensing or determination of the corresponding parallax (i.e. image disparity). The degree of similarity serves as a measure of conjugacy of the two image segments under consideration. By shifting virtually one segment across the other, the degree of similarity changes gradually, with a maximum in the position where both segments are in exact coincidence (i.e. best match). The corresponding shift (i.e. disparity) represents the change in parallax.
The procedure for the assessment of similarity comprises two stages (fig. 4).

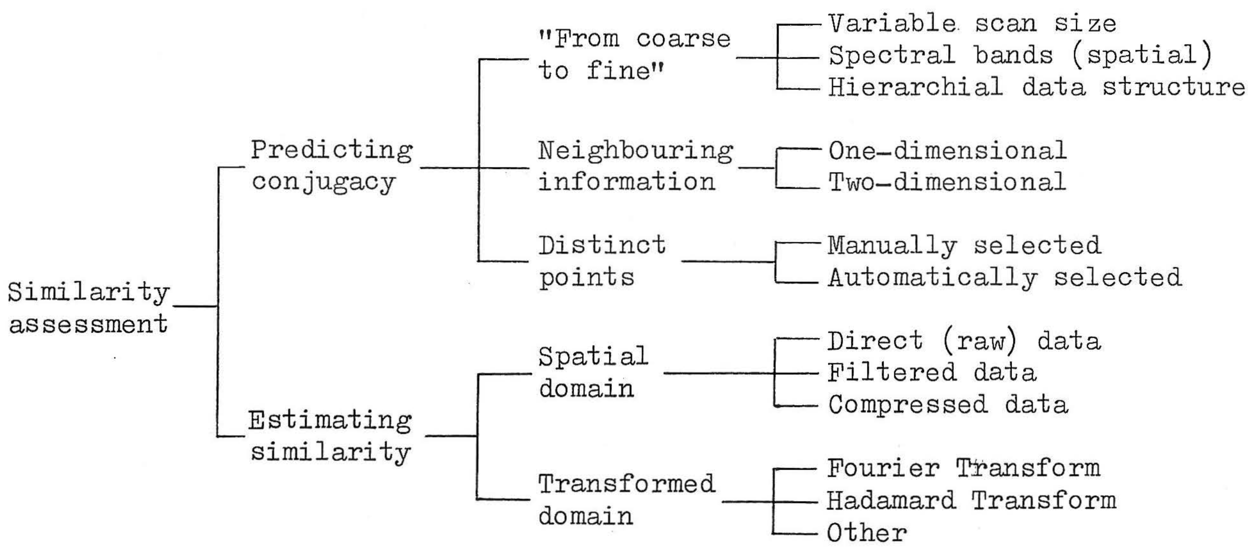


Fig. 4.: Stages and variants of similarity assessment.

- Prediction of the approximate conjugacy, which increases the reliability and time efficiency

- Quantitative estimation of the similarity, which permits accurate matching and adaptive controls.

The two stages can either be sequential or linked in a feedback loop.
Some of the approaches for prediction of the approximate conjugacy listed in fig. 4, can be applied in combination. In table 4 the different variants of prediction are reviewed for the known systems.

	Prediction variant / System	Variable scan size	Spectral bands	Hierarchial structure	One-dimens. (Neighbouring information)	Two-dimens. (Neighbouring information)	Manually (Selected distinct points)	Automatically (Selected distinct points)
on-line systems	Stereomats	x	x					
	EC-5 Planimat	x	x					
	Topomat		x					
	UNAMACE, APM		x	x				
	AS 11 B1	x	x					
	GPM-1		x			x		
	GPM-2		x			x		
	AS 11 BX				x			
	RASTAR		x	x		x		
off-line systems	AMC-IBM: Sharp			x		x		x
	UNB: Masry				x		x	
	UCL: Dowman				x		x	
	TUK: Kreiling				x			
	USAETL: Gambino					x		
	CDC: Panton					x		
	TUD: Göpfert			x		x	x	x
	UW: Keating				x	(x)		
	ITC: Makarovič			x				

Table 4: Variants of predicting conjugacy

<u>Image similarity</u> can be estimated statistically, i.e. by means of a suitable estimation algorithm (4) (9). The estimation can either be in the spatial domain or in a transformed* domain. The algorithm should be adapted to the preprocessing of the data, in particular to the data structure (18).
For further considerations it is useful to differentiate between the analogue and the digital approaches. Hybrid approaches are in principle possible, but appear to be less favourable than the digital ones, and will therefore not be considered further.
The two main operations, i.e. similarity assessment and parallax sensing or determination, will now be treated in greater detail.

* This possibility will not be further considered.

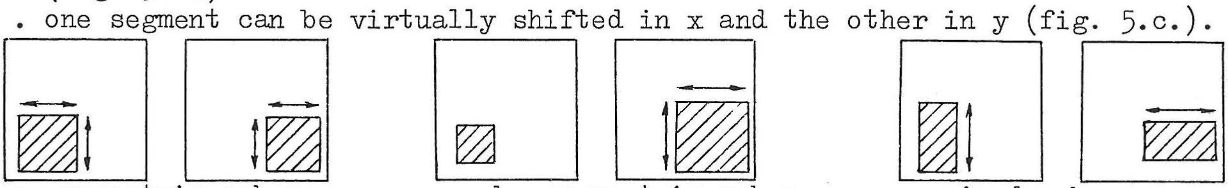
a. Similarity

i. Analogue approaches

The algorithm of the analogue correlators is continuous cross-correlation. Such correlators are built of dedicated electronic circuits, which perform multiplication of the two (preprocessed) video signals instantenously and integrate the output over a short period of time. For a successful start or restart of operation it is necessary to provide for a sufficient "pull-in range". This is attained by starting with coarse data of relatively large image segments and proceeding towards increasingly fine granulated data of smaller image segments. Such a process implies the principle "from coarse to fine" applied to the prediction of conjugacy.
The existing analogue correlators use two-dimensional image data, which is not necessarily a requirement. The generated cross-correlation signal is used to control several adaptive operations (see section III.4), to activate different displays (e.g. warning, correlation level, etc.) for interactive operation, and/or to trigger automatic search when correlation fails.

ii. Digital approaches

In digital approaches the most commonly applied algorithm is the normalised cross-correlation coefficient, though other, simpler and thus more time-efficient algorithms are also feasible (3) (4) (7) (18). The reliability and accuracy of correlation depend primarily on the quality and structure of the image data.
In digital correlation different schemes of the conjugated image segments can be used. When searching for maximum correlation
. both image segments can be virually shifted in x and y (fig. 5.a.)
. one segment serves as the "target" and the other as the "search" area (fig. 5.b.)
. one segment can be virtually shifted in x and the other in y (fig. 5.c.).



a. symmetric scheme   b. asymmetric scheme   c. mixed scheme

Fig. 5.: Image matching schemes.

The dimension of the "search" segment in the search direction is, obviously, larger than the corresponding dimension of the "target" segment. The difference should not be less than the maximum parallax expected.
Image segments can be linear or areal, i.e. represented by a single row or by a matrix of image elements (i.e. pixels). After sorting out the data of a conjugated pair of segments the similarity is estimated for the different virtual locations of one segment with respect to its conjugate. The virtual location can be changed either along a programmed path - such as to cover all the possible locations, or by applying the principle of "hill climbing". In the latter case the location is changed along the path of maximum increase in similarity, and the process is terminated after passing the maximum estimate.
The virtual location of the best match is defined by the correlation maximum. The accurate maximum may be determined by fitting a second degree parabola to the discrete values of the successive cross-correlation coefficients (16).

One of the most crucial problems concerning digital correlation is the heavy computational load. There have been two approaches to handle it.

- To implement dedicated hardware, such as a distributed network of processors (9) (15) (22)
- To reduce the load by devising the system rationally.

In figure 6 the different factors affecting the computational load are classified. A drastic reduction can be achieved by removing the redundant data, by minimising the number of matching trials, and by a predictive selection of the potentially pertinent D.T.M. points during image matching (20).

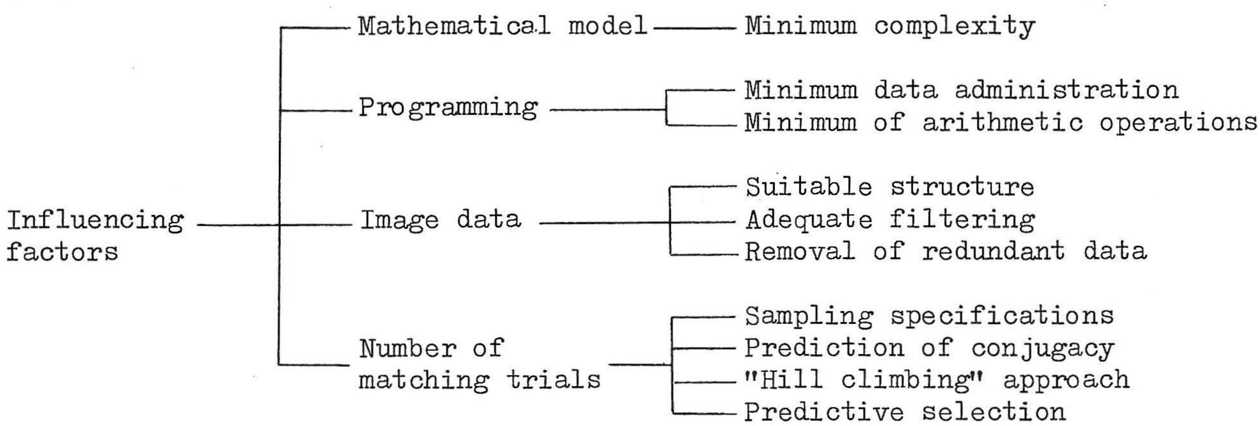


Fig. 6.: Factors affecting computational load.

Two further important problems concern the reliability and accuracy of the correlation. The corresponding influencing factors are summarised in the following lists:

Reliability:

- Quality of image data
- Data structure
- Prediction of conjugacy
- Mathematical model(s)
- Image dissimilarity
- Adaptive operations
- Search routines

Accuracy:

- Quality of image data (high frequency band)
- Data specifications (sampling)
- Mathematical model(s)
- Image dissimilarity
- Adaptive operations

As several factors occur in both lists, the reliability and accuracy are, obviously, interdependent.

b. Parallax

Sensing or determination of a parallax is closely related with the similarity estimation. With some restraints the maximum similarity determines the best match of a conjugated pair of image segments. If these segments are small enough, the match can be assigned to their midpoints. A parallax difference (i.e. disparity) is defined by the relative (virtual) shift of one segment with respect to its conjugate from the initial position to that of the best match.
In further considerations, a distinction will be made between analogue and digital approaches.

i. Analogue approaches

These approaches utilise electronic analogue circuits to generate an electrical voltage signal, which is proportional to the required parallax correction. The circuits represent double correlators, built-up of delay units, multipliers, integrators, adders, and differencing units (9) (10) (19) (20). As the circuits are band-limited, two or more sets of double correlators are used in order to cope with the entire bandwidth of the video signals. The band which provides the maximum correlation output is automatically selected. In some of the systems the parallax signal represents the current parallax vector, and has to be resolved into the x- and y-components. For this purpose the signal is instantaneously multiplied with the current speed component in x- or y, of the scanning spot. The data on speed is available from the scan generator (fig. 7). Before the resolved current parallax (correction) signal is further used, it is averaged over the time period of a full scan. The average value is representative of the midpoint of the scanned image area.

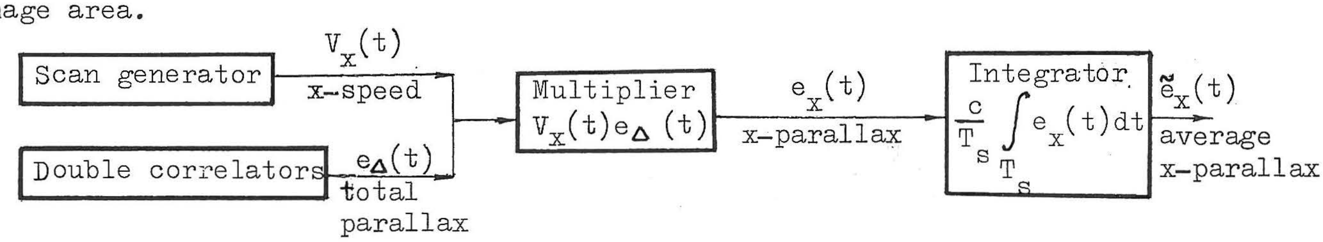


Fig. 7.: Parallax resolving and averaging.

ii. Digital approaches

In digital approaches the parallax is a byproduct of image matching, obtained by summing up all the successive (virtual) shifts of one image segment with respect to its conjugate, between the initial position and that of the best match. The parallaxes of the adjacent segments can be treated either individually one by one, or collectively. In the latter case the segments are arranged in larger entities (e.g. matrices or composed of rows of segments) which are then processed as a unit. For fine matching, however, the segments can be considered individually (11) (18).
The neighbouring image segments usually overlap. As a consequence, the corresponding parallaxes are algebraically correlated, the correlation being stronger when the overlaps are greater. This causes smoothing of the parallaxes and subsequently of the D.T.M. data.
The reliability and accuracy of parallax determination are governed by the degree of the assessed similarity for the conjugated image segments. By incorporating effective adaptive operations, the degree of similarity and thus the reliability and accuracy can be substantially increased.

4. Adaptive operations

Adaptive operations are inevitable for a satisfactory system performance. There has been a considerable variety of the adaptive operations implemented, as shown in the classification scheme (fig. 8).
The further consideration will be restricted to the most pertinent adaptive operations only, i.e. those indicated by the boxes in figure 8.
The basic need for implementation of adaptive operations emerges from the dissimilarity of the conjugated images. These are caused partly by the geometric (perspective) distortions and partly in the photometric differences for the same terrain scenery. The geometric distortions have their origin in the changing imaging geometry and in the effect of terrain relief, whereas the photometric differences originate in the varying light reflectance (or radiance), times of exposure, and spectral properties of the sensors (i.e. film and filter).

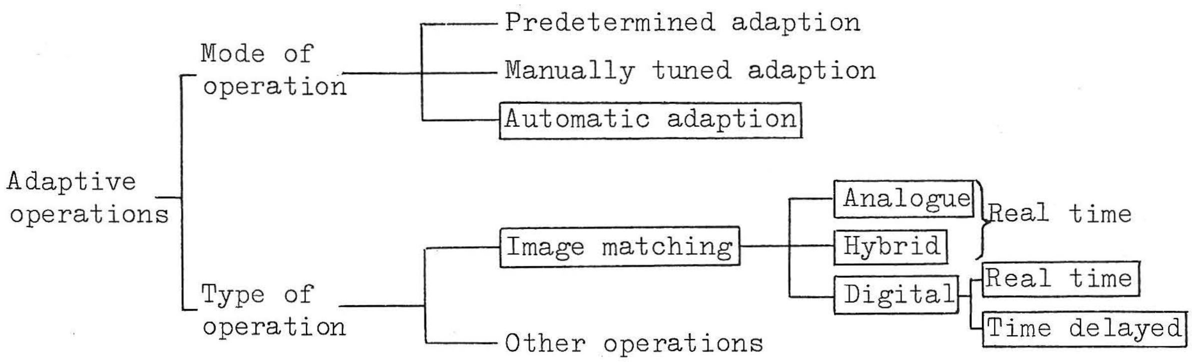


Fig. 8.: Classification of adaptive operations.

The adaptive operations have been restricted mainly to the geometric corrections, since a satisfactory compensation of the photometric differences is beyond the present state of the art.
The imaging geometry can be well controlled, and thus the application of the corresponding corrections is relatively easy. The corrections for distortions caused by terrain relief, which is not known apriory, are more involved. Hence, the adaptive operation is usually iterative, generating alternatively the local parallaxes and correcting for the corresponding image distortions.
This iterative correction is embedded in the process of parallax generation, which proceeds graudally from "coarse to fine".
For further considerations it is purposeful to differntiate between the analogue, hybrid and the digital approaches.

i. Analogue approaches

In analogue systems adaptive controls are applied to the scan size and shape Some other controls (e.g. of tracking speed) influence image matching only indirectly, and will not be considered further.
The control mechanism for the scan size is simple and straightforward. The size is inversely proportional to the instantaneous level of cross-correlation (fig.9). Thus in the case of low similarity the scans should expand and vice versa.

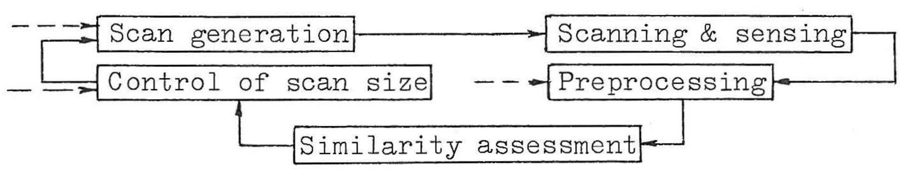


Fig. 10.: Feedback control of scan size.

The size may change continuously or stepwise. Sometimes double or triple electronic gates are used (8) (24). A large gate may serve for the cross-correlation and the y-parallax, and a small gate for the x-parallax.
The control mechanisms for scan shaping are considerably more involved due to the differing geometric distortions of the conjugated image segments. The task of the adaptive control is to accurately match the two scans with the conjugated image segments. To this end several methods have been applied. According to table 5 they can be classified into the absolute and relative and further into those making use of the "model geometry" and those not using it.
The absolute method uses an ortho-correct scan as the datum. The two image scans are shaped by using the perspective (or other) relations between the segment ΔS in terrain model and the corresponding images $\Delta x'$ and $\Delta x''$ (fig.10).

Geometry / Methods	Model geometry	
	used	not used
Absolute	Stereomats AS 11 B1	-
Relative	UNAMACE APM	EC-5 Planimat Topomat

Table 5: Approaches to scan shaping and the corresponding systems.

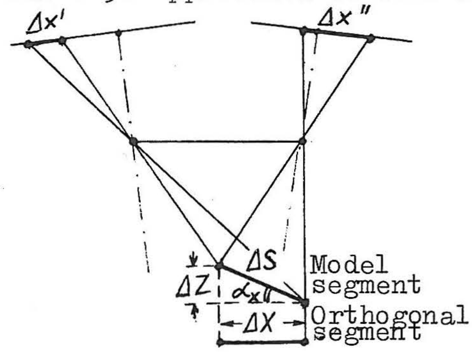


Fig. 10.: Model geometry

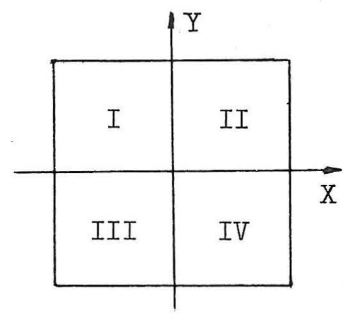


Fig. 11.: Quadrants of scan

Usually a first order approximation is applied which requires knowledge about the segment slope and its location in the model. Thus:

$$\Delta x = \frac{\partial Fx}{\partial X} \Delta X + \frac{\partial Fx}{\partial Y} \Delta Y + \frac{\partial Fx}{\partial Z} \quad (\Delta X \tan \alpha_x + \Delta Y \tan \alpha_y)$$

$$\Delta y = \frac{\partial Fy}{\partial X} \Delta X + \frac{\partial Fy}{\partial Y} \Delta Y + \frac{\partial Fy}{\partial Z} \quad (\Delta X \tan \alpha_x + \Delta Y \tan \alpha_y)$$

Fx and Fy represent the equations (usually collinearity) which relate the model space with the corresponding image plane. The differential coefficients of such linearised equations are generated in rea-time, by analogue or digital means, as a byproduct of the geometric transformation (see fig. 2, box 6). The terrain slope components α_x and α_y can be estimated by different techniques. Most commonly the scan is subdivided into four quadrants (fig. 11), and for each of them the x-parallax is separately determined. The slope components are proportional to the parallax differences in the x- and y-direction, i.e.

$$\alpha_x \sim (\Delta p_{xII} + \Delta p_{xIV}) - (\Delta p_{xI} + \Delta p_{xIII})$$

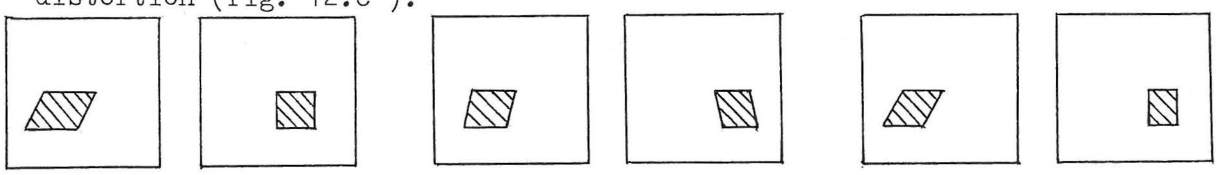
$$\alpha_y \sim (\Delta p_{xI} + \Delta p_{xIII}) - (\Delta p_{xIII} + \Delta p_{xIV})$$

In the absolute method, the sequence of computation is from the orthogonal projection (input: ΔX) to the model (ΔS) and further to the two images (output: $\Delta x'$ and $\Delta x''$). This method is feasible when orthophotographs and stereomates are printed in real-time by electronic means.

The relative methods may or may not use the model geometry. When the geometry is involved, the method is very similar to the absolute one. The only difference concerns the model segment ΔS which is derived from one of the image segments (e.g. $\Delta x''$), and is used for the determination of the conjugated image segment ($\Delta x'$). Thus ΔX in the orthogonal projection is bypassed.

The sequence of computation is from one image (e.g. input: $\Delta x''$) to the model (ΔS) and further to the other image (e.g. output: $\Delta x'$). The scan shape of the reference image (e.g. RH) can therefore remain unchanged, and it serves as

the "target", whereas the scan of the conjugated image has to be shaped accordingly (fig. 12.a.).
Most commonly, however, the relative methods do not exploit the model geometry; instead the instantanous x-parallax is analysed. For a mutual (i.e. relative) adjustment of the two scans there are three different approaches:
- One scan functions as target and the other is shaped accordingly (fig.12.a)
- Both scans are shaped, e.g. each for a half - but in the opposite sense (fig. 12.b)
- Each scan is partly shaped, such as to compensate for different types of distortion (fig. 12.c).



a. One scan is fully adaptable, another is fixed. b. Both scans are fully adaptable. c. Each scan is partly adaptable

Fig. 12.: Relative (mutual) scan shaping.

In the mixed schemes (figs. 12.b. and c.) the maximum shaping is smaller than otherwise.
The relative distortions are estimated from the parallax analysis, and are approximated by first- (or second) degree polynomials. The corresponding coefficients are generated instantaneously by means of dedicated electronic circuits (5).

ii. Hybrid approaches

In hybrid approaches some of the operations are analogue and others digital (24). The digital operations may merely replace some of the analogue counterparts, such as parallax analysis and control of scan shaping (24). However, digital techniques also permit implementation of entirely new concepts, such as the "gestalt memory" and the associated "matrix transformation" in the Gestalt Photo Mapper GPM-1 (11). This system operates patchwise and stationary, and uses the absolute method of scan shaping. Thus the patches form a regular grid pattern in the orthogonal projection. A patch is formed of a matrix of small image segments for which the x-parallaxes are generated by an analogue correlator. These are A/D converted and used for the transformation of the segments in the orthogonal projection to the two image planes. The corresponding positional data are D/A converted and used for the control of the scan generators. The corresponding displacements of the segments in the image planes represent the required corrections for the image distortions. The process of parallax generation and scan shaping is iterative, as it proceeds "from coarse to fine".

iii. Digital approaches

In digital image matching the adaptive operations concern the sample size and the resampling of image data. Resampling can either be realised by physical rescanning or by purely digial means.
The different digital approaches are classified in figure 13. However, not all of them are technically feasible.
As most of the issues listed in figure 13 have alreay been discussed in section III.3, further consideration will be limited to the "mode of control", "type of adaptation", and "data resampling".

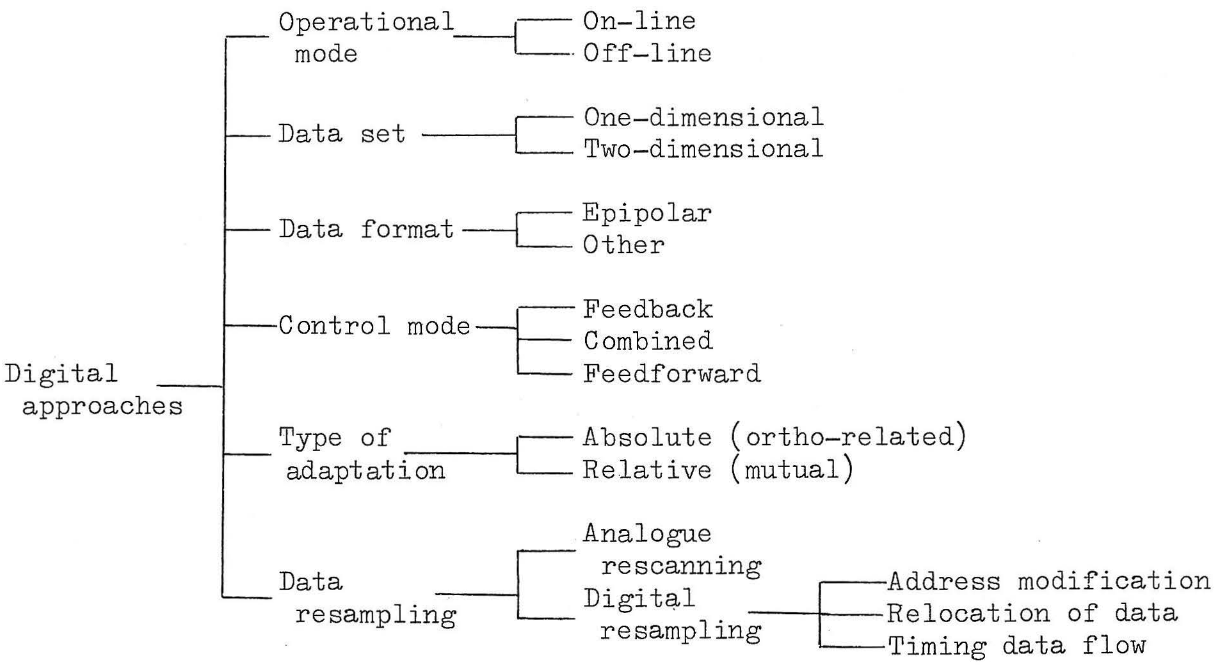


Fig. 13.: Classification of digital approaches.

System \ Properties	On-line	Off-line	One-dimen.	Two-dimen.	Epip. geom.	Other geom.	Feedback	Combined	Feedforward	Absolute	Relative	Rescanning	Resampling
GPM-2	x			x		x	x			x		x	
AS-11 BX	x		x		x		x			x			x
RASTAR	x		x		x		x	x		x			x
AMC-IBM: Sharp		x		x		x			x	?			x
UNB: Masry		x	x		x		x				x		x
UCL: Dowman		x	x		x		x				x		x
TUK: Kreiling		x	x		x		x				x		x
USAETL: Gambino		x		x		x			?		?		?
CDC: Panton		x		x	x				?		?		?
TUD: Göpfert		x		x		x			x		x		x
UW: Keating		x		x	x						?		x
ITC: Makarovič		x	x		x				x		x		x

Table 6: Features of the digital systems.

The main features of the known systems are reviewed in table 6.
From this table it is apparent that feedback control is most commonly applied, i.e. with resampling in a closed loop (fig. 14). Such a feedback control is applicable to both on-line and off-line systems.
Feedforward control is feasible for the off-line systems where processing is applied sequentially to the hierarchially structured image data (20). After matching in a certain level is completed, the obtained parallaxes can be used to resample the data in the next lower level (fig. 15).

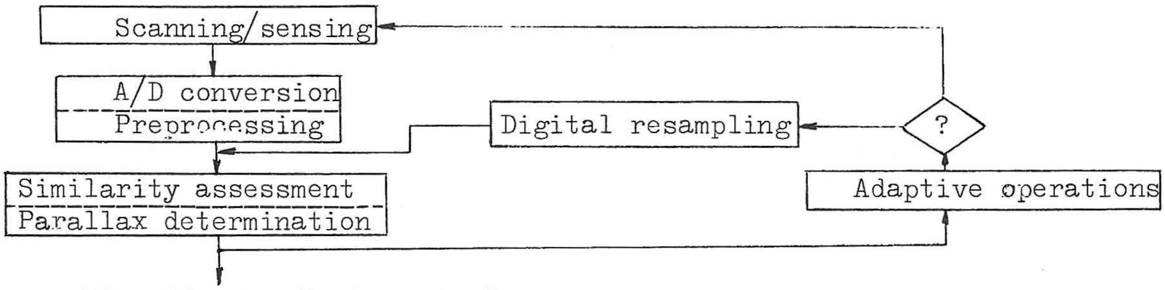


Fig. 14.: Feedback control.

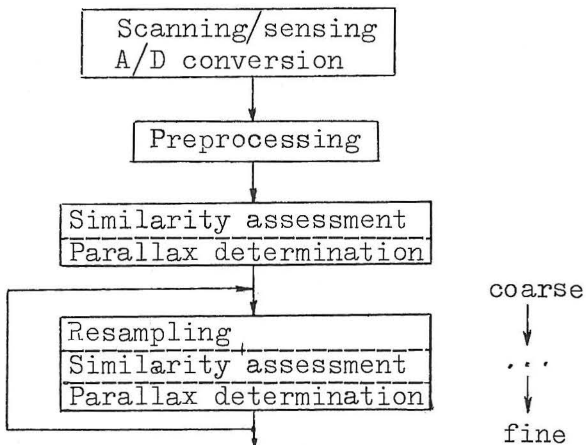


Fig. 15.: Feedforward control.

Feedback and feedforward controls can also be applied in combination. For instance the size and arrangement of the image segments and of the pixels within a segment can be varied during the process in a fixed preprogrammed manner, whereas feedback control involves merely the resampling of image data. The consideration made about the methods of scan shaping in analogue approaches can also be transferred to the digital approaches. The absolute method is required when orthophotographs and stereomates are printed on-line using electronic means, and/or a regular D.T.M. grid is generated collectively for larger units (2) (12).
In digital systems using feedback control (fig. 14) data resampling is either by physical rescanning or pure digital. As the first alternative has already been discussed under the analogue and hybrid approaches, our further considerations will be restricted to purely digital resampling.
According to the classification in figure 13 digital image data can be resampled by one of the following techniques:

. by changing the data storage addresses (7)
. by relocating the data in the storage (this is inefficient)
. by timing the data flows in the real-time process (12).

On-line systems use special hardware for this purpose.
The input information for resampling is the "absolute" or "relative" distortions, derived from the model geometry and/or the x-parallaxes. The simplest version of resampling is merely scaling of the image segments, i.e. a contraction or expansion (3) (16) (21). A row of pixels, representing an epipolar line segment, is expanded or contracted by generating a bigger or a smaller number of pixels from the original one. Such resampled data are entered in the next matching iteration.
In the time domain a contraction or expansion corresponds to a higher or lower speed of the data flow. The required effect of local contraction or expansion is attained (12) by regulating the two speeds of flow of the conjugated data sets.

Since timing of the data flows is very flexible, one may handle effectively even very unfavourable situations, such as abrupt changes in terrain surface.
Similar flexibility is also attained in the off-line systems by resampling in the spatial domain.

5. Quality indicators

The adapative operations discussed can be supplemented by monitoring the various quality indicators, both for the input images as well as for the correlation. Typical indicators pertaining to images are the local amplitude variance and the power spectrum, and those pertaining to correlation are the correlation level, the correlation peak, the maximum slope of correlation function, the percentage of failed matches, etc.
The quality information can be used differently, e.g. for specifying and presetting certain input parameters (pixel size, step size, image segment, etc.), and for tuning of some parameters during real-time operation (gains, steps, speed, etc.).
Quality indicators can also be used for triggering the automatic search routines, for automatic control of the tracking speed, and for activation of the warning signals, asking for the operator's intervention.
Some of the quality indicators may also be used to weight the output data for further application-oriented processing (22). Quality should be indicated troughout all phases of the process, to provide for optimal interactive operation.

IV. Problem areas and possible solutions

The major problem areas have already been identified in the context of the adaptive operations. The most crucial source of difficulties is dissimilar conjugated images, in particular the photometric differences. The possibilities for reduction of the effect of these differences are very limited. The disturbing effect of the dissimilarity, both the geometric and photometric, is especially pronounced for large scale images. Discontinuities in the terrain, such as buildings, trees, etc., cause hidden areas and shadows in addition to great geometric distortions. The missing terrain data on images cannot be supplemented by the adaptive operations.
When images recorded by sensors of different spectral characteristics are used, they contain somewhat different information. Matching of such mixed image parts may therefore be inaccurate - even if certain quality criteria are met.
Recently, attempts have been made to improve the adaptive capability in image matching by more sophisticated preprocessing of the data, inclusive of the feature extraction techniques. However, it is questionable whether the eventual gain in performance justifies the corresponding increase in the amount and complexity of processing.
The above considerations indicate that the most crucial problem is the reliability of image matching. The reliability can be effectively improved by optimising the input data and the process as a whole, rather than to restrict optimisation to the adaptive operations only. Hence, the following factors should be involved:
- Profound planning of the survey mission (inclusive the sensor and other photometric characteristics)
- Intelligent preprocessing of image data (inclusive structuring, isolating anomalous regions, and adding supplementary data)
- Collective processing of image segments (permitting use of small segments and thus a fine adaptation to terrain geometry)
- Effective algorithm strategy, in particular for adaptive operations (i.e.

feedback, feedforeward control, search routines, etc.)
- Optimal interactive operation (by display of: conjugated images, quality indicators, warning signals, and by providing manual support in real-time).

Another major problem area concerns the computational load involved in digital image matching. As this has already been discussed in section II.3., it will not be further considered here.

V. Conclusion

The development related to image correlation in photogrammetry has been fragmentary, and is characterised by increasing complexity and diversity of the methods and means. Hence, there is a need for an orderly approach to the problem area as a whole.
The recent development trend has been from analogue to digital techniques, and in the latter case the epipolar geometry has gained in importance. The use of epipolar geometry is effective in image matching, though it may cause some distortions in orthophotographs if produced on-line.
When developing a new automatic system with the image matching capability incorporated, it should be optimised as a whole, inclusive the input data. A fundamental, but often insufficiently considered principle is to balance the complexity and sophistication of the algorithms against the quality of the input data.
In general, the performance and reliability of image matching can be improved by specifying rationally the input- and the process parameters, by intelligent conditioning of the image data - inclusive their structuring, by implementing an effective matching strategy, and by a well devised interactive man-machine operation.

References

1. Bertram, S. "The Universal Automatic Map Compilation Equipment" Phot. Eng. Vol. 31, No. 2, March 1965.

2. Crawley, B.G. "Gestalt contours", The Canad. Surveyor, Vol. 28, No. 3, September 1974.

3. Dowman, I.J., Haggag, A. "Digital image correlation along epipolar lines", I.S.P. Com. II. Symposium, Paris, 1978.

4. Gambino, L.A., Crombie, M.A. "Digital mapping and associate digital image processing", A.S.P./A.C.S.M. Convention, St. Luis, March 1974.

5. Hardy, J.M. at all "An electronic correlator for the Planimat", I.S.P. Congress, Com. II., Lausanne, 1968.

6. Helava, U.V., Chapelle, W.E. "Epipolar scan correlation", Bendix Techn. Journal, Spring 1972.

7. Helava, U.V. at all "Digital processing and analysis of image data", Bendix Techn. Journal, Spring 1972.

8. Chapelle, W.E. at all "Automation in photogrammetric ompilation", Bendix Techn. Journal, Summer 1968.

9. Helava, U.V. "Digital correlation in photogrammetric instruments", I.S.P. Congress, Com. II. Helsinki, 1976.

10. Hobrough, G.L. "Automation in photogrammetric instruments", Phot. Eng. Vol. 31, No. 4, July 1965.

11. Hobrough, G.L., Hobrough, T.B. "Image correlation speed limits", I.S.P. Com. II. Symposium, Munich, 1970.

12. Hobrough, G.L. "Digital on-line correlation", B.u.L., No. 3, 1978.

13. Johnson, E.C., Di Pentima, A. "Image correlation system for analytical stereoplotters", I.S.P. Congress, Com. II, Lisbon, 1964.

14. Keating, T.J. at all "An improved method of digital correlation", Phot. Eng. Vol. XLI, No. 8, 1975.

15. Konecny, G. at all "Digitale Prozessoren für Entzerrung und Bildkorrelation", B.u.L., No. 3, 1978.

16. Kreiling, W. "Automatische Auswertung von Stereobildern durch digitale Korrelation", I.S.P. Congress, Commission III, Helsinki, 1976.

17. Makarovič, B. "Fundamental considerations on automation in stereorestitution, I.S.P. Com. II Symposium, Bad Godesberg, 1966.

18. idem "Digital image registration by means of compressed data" A.S.P./A.C.S.M. Fall Technical Meeting, Little Rock, October 1977.

19. Makarovič, B., Tempfli, K. "Digitising images for automatic processing in photogrammetry, ITC Journal, No. 1, 1979.

20. Makarovič, B. "Automatic off-line generation of digital terrain models" in preparation for I.S.P. Congress, Com. II. Hamburg 1980.

21. Masry, S.E. "The Analytical Plotter as stereo-microdensitometer", I.S.P. Congress, Commission II, Ottawa, 1972.

22. Panton, D.J. "A flexible approach to digital stereo mapping", Phot. Eng., Vol. 44, No. 12, December 1978.

23. Scarano, F.A., Brun, G.A. "A digital elevation collection system", Phot. Eng., Vol. 42, No. 4, April 1976.

24. Szangolies, K., Kunze, W. "TOPOMAT - a new all-automatic photogrammetric restitution system", Jena Review, No. 2, 1977.

25. Wrobel, B. "Geometrische Aspekte der Korrelationssteuerung", T.U.H. Symposium on: Digital components in photogrammetry, Hannover, 1978.