AUTOMATIC PRODUCTION OF DTM DATA BY DIGITAL OFF-LINE TECHNIQUE

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ABSTRACT

A review is presented of the state of the art in digital off-line technique for production of DTMs. Outlined are the main process stages, their interactions, and operations involved. Data structure, strategy, algorithms, and techniques of image matching are strongly interrelated. Performance can be improved by optimising the overall process and by carrying out some pre- and post-processing operations interactively with human. Moreover, use can be made of multiple sets of image data, multi-stage strategy, external data, and of collective processing.

I. INTRODUCTION

The objective is to present an overview of the state-of-the-art and thus new developments in automation of digital terrain modelling by using off-line (or time-delayed) techniques. The intense and diversified developments make a comprehensive review in a short paper virtually impossible. Nevertheless, an attempt will be made to outline, discuss, and orderly structure the information.
Because of various restrictions, the contents are compressed and simplified. First some general issues are reviewed, concerning the automatic off-line systems. Then a description is given of the main process stages, i.e. pre-processing, image matching, and post-processing. Each of these is supplemented by a list of the corresponding development trends.

II. GENERAL

Consideration should first be given to the evolution and general trends in automation in photogrammetry, definition of the overall photogrammetric process, the main stages of automatic restitution and corresponding interactions, types of data, problems originating in input images, and properties of on-line versus off-line automatic systems.

1. Evolution

The first photogrammetric automated systems (analogue, hybrid and all-digital) were developed in the period 1958-1962. Until 1968, electronic analogue systems dominated and then emphasis was gradually shifted to hybrid systems. Since 1976, however, a transition has taken place to all-digital systems, operating both in real-time and time-delayed. The evolution has been very responsive to developments in micro-electronics and thus in computer technology.

2. Overall photogrammetric process

Definition of the overall process permits identifying the place of automatic restitution in a broader context, and its interactions with other main process stages. The overall process comprises the main (sequential) stages of planning, field preparation, air photography, aerial triangulation, automatic restitution, conditioning of outputs, and data applications.
The general objective of a system development is to maximise its effectiveness, i.e., by optimising the overall process. In this paper, however, considerations are restricted to automatic restitution for DTMs.

3. Main stages of automatic restitution

These stages, and the corresponding data flow and interactions are shown in figure 1.

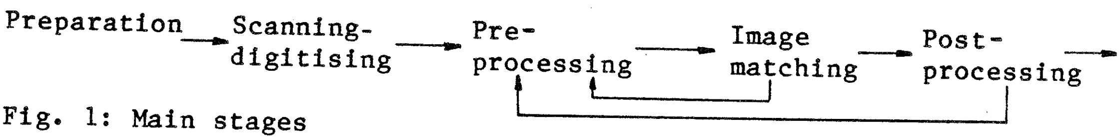

Fig. 1: Main stages

The initial stages, i.e., preparation and scanning-digitising are beyond the scope of this paper; the other three stages are discussed below. Interactions shown in figure 1 are essential for an optimal process. Optimisation concerns particularly the strategy, algorithms and techniques applied in these stages.
If distinct image features are used in combination with non-distinct regions, interactions are more involved (see figure 2).

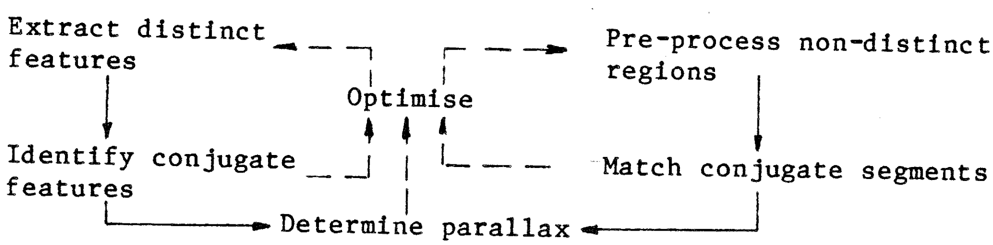

Fig. 2: Operations in two-stage matching

The feedback loops in figures 1 and 2 imply optimisation. Additional interactions are considered below.

4. Types of data

A distinction can be made between the basic and control data, and further between the semantic and metric domains. The latter can be differentiated further according to key items and corresponding attributes. Such a differentiation permits thorough analyses and effective synthesis of data structures, processing strategies, algorithms and techniques.

The basic image (pictorial) data comprise distinct features and other non-distinct (i.e., more homogeneous) regions. The former have high information content and provide a datum at image matching. They can support the neighbouring non-distinct regions (having lower information content).

5. Problems originating in images

Quality of output data depends on that of the input data and on quality of processing. Hence, input data and algorithms should be mutually balanced.
Problems originating in images are partly geometric and partly pictorial (intensity). Geometric sources of disturbances are terrain discontinuities, occlusions, roughness, ambigous levels, thin objects and periodic features.
Pictorial sources are poor image quality, different reflectance (of the same objects), and lack of signal variation.
Systems can be provided with self-adaptive capabilities to cope with some of these problems, though not with all of them.

6. On-line versus off-line systems

On-line operation is time-comstrained; hence, time delay between input and output is assumed to be insignificant. Real-time operation is a requirement for handling dynamic scenes, such as in some industrial (robots) and medical fields. Real-time systems are also applicable to mapping (and other static scenes), though real-time operation is not required.
The properties of the real-time systems include dedicated hardware, great data flow, instantenous output, limited flexibility, and relatively low storage requirement.
Off-line operation is time-relaxed, and thus suitable for static scenes. Off-line systems have the following properties: general purpose hardware can be applied, great flexibility, phased and parallel operation, but considerable storage capacity is required.
The individual main stages of the process, and for each stage the corresponding operations are discussed below in an ordred sequence.

III. PRE-PROCESSING

The aim is to condition raw image data for determining parallaxes (i.e., image disparities) and subsequent calculation of DTM data. Actual choice of the pre-processing operations should be in accordance with the strategy for the process as a whole. The list of pre-processing operations is open-ended. In the context of a specific strategy, however, a selected subset of operations is implemented.

A tentative list of operations is: merging (or linking) different data sets, excluding regions, correcting data, resampling, segmenting and structuring data, filtering and thresholding, synthesising data, image analyses, feature (or signature) extraction, integration of external (a priori) information, and predicting approximate conjugacy.

The impact of these operations on performance and reliability varies widely and it depends strongly on the overall process strategy.
The individual operations include the following.

1. Merging or linking

Two or more related data sets can be merged into a single set or they can be linked mutually. Re-scanned image data or neighbouring data (pixels or lines) can be merged, e.g., by averaging or by logical "AND" connection of the corresponding intensity values (1). Merging implies a simple form of resampling (vide III.4.).
Linking is applied to a-priori data (key- and attributes), e.g., to tie them with the image raster. This implies gridding of data (e.g., distinct lines and surfaces of morphometric and/or artificial features) into a raster. Key-features can be linked with different attributes by means of pointers or addresses. Examples are classes of regions and networks (of chains and points). Such a classification can serve for specifying the parameter values for subsequent processes. A-priori data represent an autonomous data set, and should therefore be preserved (in original form) for further uses.

2. Exclusion of regions

Anomalous and/or non-relevant regions should be excluded before further processing. Examples of anomalous regions are areas covered by clouds, water, snow or other featureless (homogeneous) areas. These can be manually delimited and excluded. Anomalous regions are inside (internal) or along boundaries (external) of the area of interest. The situation is more complicated when internal regions are nested (i.e., lakes with islands with lakes, etc.).

3. Corrections

Corrections concern both geometric and pictorial (intensity), domains. Geometric corrections can be applied for the camera (or sensor) internal geometry and its external orientation (attitude). Both can be differentiated further.
Intensity corrections concern issues such as reduction to mean level, amplitude scaling, compensation for image spread (inverse filtering), CCD sensor characteristics, etc. The choice and application of corrections requires utmost care.

4. Resampling

Correcting and resampling can be carried out separately or in combination. Resampling produces a new data set from an existing (old) one. It usually involves both geometric and intensity domains. The simplest geometric version is to form new pixels composed of 2, 4, 6.... old pixels (or of 4, 16, 36... old pixels) by averaging their intensities. Another simple version is resampling merely in the intensity domain, i.e., to produce 4 bit (i.e., 16) intensity levels from initially 8 bit (i.e. 256) levels.

The general version of resampling is mixed, however. A new image raster is created, having a different density (cell size) and orientation than the original raster. A specific case is the epipolar lay-out of pixels.
Resampling comprises two basic stages, i.e., calculation of the new pixel locations (geometric lay-out) and interpolation of the corresponding intensity levels from the neighbouring old pixels. Resampling is accompanied with some loss of pictorial data; it should therefore not be applied cyclically in an iterative process.

5. Data segmentation and structuring

Image data segmentation and their structuring are interelated, and they strongly reflect the strategy of image matching. Segmentation and structuring can refer to the spectral domains (spatial or electromagnetic), to spatial entities (i.e., lay-out of patches, segments and pixels), or to a combination of both.
Lay-out of the spatial data entities (patches, segments) can be fixed (and homogeneous) or variable, e.g. adapted during pre-processing or matching. Data entities can be arranged in a single level or in several hierarchical levels (2).
A homogeneous lay-out of data entities can be single or multiple. In the latter case segments can be shifted in x and/or y, (e.g., for half interval),changed in size (which changes overlap of segments), etc.
Further variation is attained by interchanging the roles of target and search segments (i.e., LH versus RH image). Moreover, segment size (of target) can be fixed or variable. In the latter case, it can be adapted during pre-processing or during matching.

6. Image transformations

Pictorial (intensity) transformations and matching algorithms are strongly interelated; a transformation may be regarded as an integral part of matching. Examples are Fourier, Hadamard, and exponential transforms, which can serve for image analysis and segmentation. Transformations are accompanied with some loss of image data.

7. Filtering and thresholding

Linear filters are commonly applied in order to compensate for degradation at imaging (by inverse filters) and to suppress noise (by smoothing filters). Filters and thresholds can be aplied in selective pre-processing, i.e., to enhance certain image features, for segmenting and/or compressing image data, for interpolation, etc.
Different linear filters can be merged (by convolution) into a composed filter, which increases efficiency of processing.

8. Synthesising image data

The reliability of iamge matching can be increased by creating synthetic image data from the original (or pre-processed) data. Examples are envelope data (3), compressed second difference data (2), etc.

Synthetic data can be segmented and structured as original image data. At image matching, synthetic data can be used independently, combined, or merged with the original (or pre-processed) data. They provide redundancy which can be helpful in difficult situations.

9. Image analyses

Analyses can serve for specifying (or tuning) control parameters (to be used in later stages), for establishing a powerful matching strategy, and for feature (or signature) extraction. Analyses can usually be restricted to target segments.
A differentiation should be made between methods of analysis and image properties to be analysed.
Methods can be statistical or structural. Examples of statistical methods are clustering, principal component transformation, etc. They do not imply external (a-priori) data, and have not been used in photogrammetry.
Structural (or syntactic) methods are based on the context information (in space or in time), and they can exploit external (a-priori) information. Such methods can be based on different strategies, i.e., implying sequential and/or parallel processing, and using single or multiple algorithms.
Properties to be analysed are image intensity variation, its signature, and neighbourhood. Intensity variation is decisive for the acceptance of a target segment; if not acceptable, target size should be increased or it should be bypassed.
Image signature refers to contrast, texture, directionality, etc.
Neighbourhood concerns properties such as connectivity and some other adjacency relationships.

10. Feature extraction

Feature or signature extraction implies image analysis. Techniques vary from relatively simple to complex. The simplest variant is extraction of image "primitives" (or tokens) such as edges, narrow parallel bands, corner points, crossings, etc. More involved are syntactic ("rule based") approaches, whereby primitives are assembled into 'objects'. Automatic feature classification and self-learning systems, e.g., for pattern recognition, have been favourite topics of research; nevertheless, success to date has been limited.
For a two-stage matching strategy (figure 2), however, extraction of a few primitives (e.g. edges, corner points) suffices.

11. Integration of external information

If properly selected and integrated, external (a-priori) information contributes to accuracy and reliability of matching and thus of the DTM. Such information also provides a reference for assessment of performance.
External information refers to supplementary data (e.g., mean height of trees or houses), geometric conditions, constraints and criteria, and control and check data. Geometric conditions concern lines (straight, curved, parallel), planes (horizontal, tilted), angles

(between lines or planes), etc. Constraints and criteria concern extreme values of variables and parameters, continuity of lines and/or surfaces, thresholds, etc. Control and check data comprise individual points, test fields, check profiles, etc.
External information should be adequately conditioned (i.e. structured and formatted) for use in the subsequent process stages.

12. Predicting conjugacy

For a lay-out of target segments (vide III.5), the corresponding search segments can be located approximately. A good aproximation increases reliability and efficiency of matching.
At pre-processing, prediction can be based on known terrain model geometry and/or coarse pre-measurement of the maximum parallax.
Approximate conjugacy can also be assessed during matching, i.e., from the already known neighbouring parallaxes whereby the neighbourhood can be in space (for static scenes) or in time (for dynamic scenes).
Prediction of approximate conjugacy can be regarded as part of the matching process.

Trends in pre-processing

The trends can be summarized as follows: Pre-processing and matching strategy tend to be optimised together, and external (a-priori) information is being integrated in the process. Moreover, interactive (man-machine) operation for exclusion of regions, supervision, and interference in critical situations is gaining in importance.

IV IMAGE MATCHING

By matching the conjugate data of a target segment are identified in corresponding search segment. Matching strategies and techniques can differ; table 1 indicates four basic variants.

Lay-out of segments / Algorithms	single	multiple
Single	X	X
Multiple	X	X

Table 1: Variants of matching strategies

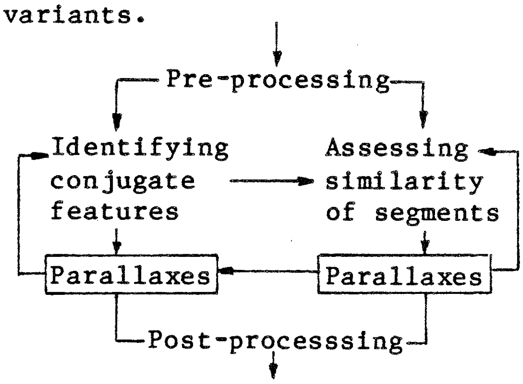

Fig. 4: Interactions at matching

Figure 4 shows a two-stage strategy of matching, including various interactions. The two stages concern distinct image features (or primitives) and non-distinct image segments. The two stages tend to reenforce each other. Parallaxes (of segments) are byproducts of matching.
Matching strategy, algorithms, techniques and corresponding hardware are strongly interrelated (figure 5).

Strategy → Algorithms → Techniques → Hardware

Fig. 5: Interrelations of components

An outline is given in the following sections of the input data, matching strategies, algorithms, techniques, hardware, and the quality indicators.

1. Input data

Matching is applied to pre-processed image data, i.e., original and/or synthesised (e.g., envelop, compressed second differences, etc.). Target segments can be laid-out in single or several patterns, which can be regular, semi-regular or irregular. Moreover, the lay-out can be in single or multiple hierarchical levels (2). A segment can contain full image data or only the compressed (relevant) data. Individual pixel intensity values can be unweighted or weighted, e.g., according to information content and/or according to pixel location in the target segment.
Another differentiation has been made between non-distinct image segments and distinct image features (primitives).

2. Matching stategy

The strategy refers to matching itself and to self-adaptive capability. Matching procedures can be single (homogeneous) or multiple. The latter can be sequential (i.e. proceeding from distinct points to edges and further to areas) or parallel (e.g., of several matching trials, several full matches or several groups of matches). Sequential and parallel calculations can be combined.
Adaptive operations use feedback or feedforeward control or a combination of both. They usually imply data resampling, which can be relative or absolute, and may or may not involve the terrain model geometry (4).

3. Matching algorithms

In accordance with the strategies, a distinction can be made between single and multiple matching algorithms. These may or may not permit inclusion of the external information (vide III.11).
The algorithms can be statistical, deterministic or mixed. The commonly used are statistical algorithms, e.g., correlation, covariance, etc. Deterministic algorithms can be applied to extracted conjugate image features (or signatures), or to calculation of specific image parameters. A mixed algorithm is, for example, an affine transformation by least squares adjustment, of a target into the corresponding conjugate segment (5).

4. Matching techniques

The techniques are governed by the strategy, algorithms, and the available hardware. Commonly applied is the similarity assessment of conjugate segments by sequential search or by image (intensity) transformation into another domain (vide chapter IV.5).

Another aproach is a geometric transformation of a target into the corresponding search segment, by using the least squares method. The last can minimise discrepancies in pixel intensities (5) or in their locations (6). Least squares method gives very accurate results, provided that the terrain is smooth, there is enough signal variation, and an approximate match has been attained. Thus, least squares method is feasible when high accuracy is required, image segments are selected carefully, and after matching by a less accurate (but more efficient) technique, e.g., by sequential search.

5. Sequential search

Searching techniques can be differentiated according to the structure of image data, sequence of matching trials, and the calculation for a single trial.
Data can be structured in single or multiple (hierarchical) levels, (vide III.5). In the latter case, search proceeds from coarse to fine image data, thus providing for great "pull-in" and reliability of matching.
For a match (single), all possible trials can be attempted (i.e., by the brute force approach) or only the promising trials. The latter implies dynamic programming with constraints.
A matching trial can be calculated fully or it can be interrupted after some initial calculation indicates a failure.

6. Hardware

In addition to a scanner-digitizer, a computer with standard peripherals is required. For interactive operation it is desirable to have a graphic CRT terminal for stereo-display. Calculations can be carried out serially by a general purpose computer; a dedicated network of processors is indispensible only for real-time operation. Storage requirements are modest because image data are segmented, and off-line operation is time-relaxed.

7. Quality control

Quality assessment is needed for acceptance at matching and for performance considerations in the subsequent stages. The criteria can be differentiated according to internal and external. Internal criteria concern the degree of similarity (i.e., maximum and "peakness" of the assessment curve), the standard error (after a least squares geometric transformation), and the neighbourhood (e.g., for gross errors). External criteria concern the parallax data in conjunction with geometric conditions and check data. The latter will be considered further in the next section.

Trends in image matching

The following trends are anticipated for off-line image matching: Improved data structures are leading to refined matching strategies and vice versa. Procedures are becoming more flexible, i.e., better adaptable to changing circumstances. External and neighbouring data are being increasingly used at matching. Quality control is gaining in importance.

V. POST-PROCESSING

Procedures used in this stage have implications in other main process stages (figure 1). Post-processing concerns the transition from segments to discrete points, editing of raw parallax data, DTM calculations, and conditioning DTM data for a master data base or for specific uses. In the following, consideration is given to these operational stages, to graphic display and to quality control.

1. Definition of conjugate points

A representative point of a (target) segment can be its midpoint, a weighted mean-point, or a distinct point, i.e., having "best image characteristics". The problem is to define the corresponding point in the conjugate segment (after matching). For plane terrain, the relation between conjugate segments is nearly linear. Thus their midpoints are conjugate (for small segments); any point-pair is related by linear (in general affine) transformation. Real terrain, however, is usually irregular and therefore cannot be accurately modelled by a regular surface (or curve). Hence, a parallax error occurs at the point transfer from one segment into its conjugate. Such errors can be minimised by using smallest possible segments (at fine matching).

2. Parallax editing

Parallax data obtained at matching are assigned to representative conjugate points (after being defined). Parallaxes of adjacent points along an epipolar line form a 'parallax profile', and several adjacent profiles a 'parallax surface'. These raw data can be edited, e.g., by using a-priori information, by analysing the raw data collectively, and/or by excluding still existing anomalous (or poor) regions.

A-priori information may contain data on anomalous regions (if not excluded at pre-processing), geometric conditions (concerning points, lines, planes, angles, etc.), morphometric data, control data, etc.

Collective analyses concern the neighbourhood, edges (i.e., boundary data of patches, models, etc., to be smoothed), and parallax signatures (e.g., for classifying terrain roughness). A-priori information can be incorporated in collective analyses.

A-posteriori exclusion of anomalous regions can be based on the estimates of matching quality in conjunction with collective analysis of the parallax data. Regions of low matching quality, i.e., with inaccurate parallax data, can be excluded (selectively) and filled-in at a later stage.

3. Calculation of DTM

A distinction can be made between the basic and supplementary calculations. The aim of basic calculation is to determine DTM points from the conjugate ("representative") image points. The collinearity algorithm is usually applied (for survey photography), which can include a correction model for deterministic errors.

Supplementary processing is needed to upgrade and/or condition raw DTM data. Common operations are interpolation, compression, resampling, aggregation and/or data segmenting. If raw data are arranged in epipolar profiles (e.g., in cylindric coordinates), they need be converted into a regular grid in a uniform terrestrial coordinate system, which implies resampling. Before being entered into a data base, the DTM data can be compressed (7).

4. Graphic display

Displays permit data verification and editing, and sometimes manual support during operation. Images, parallax data, DTM data and quality indicators can be displayed. Image display can be mono or stereo. Different techniques can be used for stereo, e.g., anaglyphic, by polarised light, and others. For visual data verification and interactive editing, parallax data can be superimposed on the corresponding image pair.
Quality indicators, such as similarity estimates, error distributions, etc., can be displayed separately, in combinations, or superimposed on corresponding images.

5. Quality control

Quality control is an essential part of the process. It requires, however, definition of suitable assessment criteria (or quality indicators) and adequate reference (or check) data. The criteria should be defined with utmost care; standard errors, error distributions (spatial and/or statistical), and corresponding thresholds are commonly used. Another important criterion is the fidelity of a surface (or profile) reconstructed from DTM data (8), and the corresponding terrain resolution (i.e., limiting spatial frequency).
Suitable references for quality assessment are geometric conditions (for geometrically regular terrain objects), check points, check profiles, a-priori known morphometric features, and some neighbourhood characteristics (e.g., local terrain roughness).

Trends in post-processing

The trends can be summarised as follows: Accuracy and reliability of DTM data increase by integrating external information and by processing the data collectively. Interactive editing by means of a graphic display terminal tends to be a requirement. Supplementary operations (for DTM) are being extended and refined, i.e, to attain higher fidelity of DTM, and quality control is being improved.

VI. CONCLUSION

Recent advances in micro-electronics have a strong impact on automation in photogrammetry. In digital off-line techniques for automatic DTM production, emphasis is being displaced from smaller towards larger photo-scales. The process stages and corresponding operations are beoming increasingly sophisticated and thus capable of handling more difficult situations than before. Effective multi-stage image matching strategies are being developed in conjunction with structuring of the image data. Use of external information, collective processing, and interactive operation tend to contribute substantially to the quality of the resulting DTM. Overall process strategy and associated quality control are important considerations.

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