MATCH-T: AUTOMATIC MENSURATION OF DIGITAL ELEVATION MODELS

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Abstract

A new digital system for the automatic generation of DEMs from digital image data is presented. The paper outlines the underlying strategic aims for a fast and economic high quality system. The software concept and the system performance is described. The programming of a batch version has just been completed.

1 Data Capture for Digital Elevation Models

1.1 The production of digital elevation models (DEM) by photogrammetric data capture has established itself very well. Measurements by a human operator, on an analytical plotter, can provide any required DEM quality, within the limitations set by photoscale and the vegetation cover of the terrain. The standard procedures are fairly economical. The data capture takes normally 4 to 8 hours (1/2 day to 1 day) of operator- and instrument-time for a pair of photographs, the actual time depending on the type of terrain and on accuracy requirements.

The accuracy and quality of a DEM is essentially determined by two aspects of the data capture which are partly interdependent: (1) The capture of morphological terrain features, in particular of breaklines, and (2) the density of the general surface points measured. It is a matter of intelligent judgement of the operator to balance between breaklines and surface points. Except for smooth terrain, to measure breaklines may take 50% or more of the total time of manual data capture.

It is the task of subsequently applied DEM interpolation programs to process the measured data into an edited DEM, whilst exploiting and preserving the inherent quality of the data. The derived DEM often consists of a regular grid, especially if large terrain areas are covered. In view of the following considerations on automation it is to be pointed out that the density of the derived DEM grid is usually about two to three times higher than that of the originally measured surface points. Therefore, the total number of interpolated raster points is about five to ten times the number of measured surface points. A pair of photographs will normally be covered by perhaps 2 000 to 5 000 surface points. Hence the derived DEM may consist of about 10 000 up to 30 000 grid points, or more. After the data capture the processing and editing of a DEM may take 1/2 man-day per pair of photographs, including up to 1/2 hour of processing time on a PC. If contour lines are to be derived and other follow-up programs applied, the time may easily be twice as long, or more. It is understood that the quoted average time requirements refer to the production of high-quality DEMs.

1.2 Measurement of a DEM is, in priciple, open to automation, on the basis of low level image processing operations, like feature-based matching or image correlation. Measuring parallaxes is an objective local operation which does not require much intelligent guidance. It is for that reason that measurement of thousands of surface points is generally considered tedious by human operators of which they would like to be relieved.

The attempts with electronic image correlation already in the 1960s have proven that automatic height measurement and automatic generation of DEMs and of contour lines is possible. They have also shown, however, that there are severe limitations. None of the known systems succeeded to get over 3D disturbances on the terrain surface, such as trees, bushes, or houses (apart from not catching the DEM below dense forest canopies which no photogrammetric approach is capable of). The automatic capture of breaklines has not been attempted as yet. However, it is certainly feasible, in principle, as breaklines represent objective features of the terrain. If, therefore, new attempts are made today to measure and generate DEMs

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[1] Presented paper to the 3rd Technical Seminar of the Sociedad Espanola de Cartografia Fotogrametria y Teledeteccion, 12 April 1991, Barcelona

automatically on the basis of digital image processing, strategies are to be pursued which would solve those problems which electronic image correlation could not.

In the following the MATCH-T system for the automatic generation of high-quality digital elevation models from aerial (or space-) photographs and its present state of development is described. The development relates to initial research at the Institute of Photogrammetry of Stuttgart University which was carried out especially by W. Förstner, E. Gülch, and M. Hahn (see [1] to [4]). The actual system and product development now takes place at INPHO GmbH, Stuttgart.

2 Strategic Aims and Concept of the MATCH-T Program

2.1 The general basis for new approaches to the automatic generation of DEMs is the upcoming availability of digital or digitized images and of fast computers, in combination with digital photogrammetric workstations. Several systems have already been developed and await testing and acceptance for practical application.

The MATCH-T system is explicitly intended to generate high-quality digital terrain models from digitized aerial photographs or from digital space imagery (like SPOT). Also the automatic generation of digital orthophotos is included. The execution is digital all the way. It is restricted, for the time being, to dealing with one pair of digital images, at a time.

The strategic aims are simple, but far-reaching. The DEM generation is to be efficient and economic by being

(1) fast (at least as fast as the conventional data capture by a human operator; eventually two hours or less per photo-pair should be reached)
(2) arbitrarily dense
(3) accurate (in the order of h/10 000, the vertical measuring accuracy of terrain points; conventional DEMs are less accurate)
In addition it should
(4) overcome 3D obstacles on the terrain surface to some extent (like trees, houses etc.)
(5) be capable of automatic capture of breaklines
(6) be capable of quality assessment of its own and of accommodating external quality control.

The key to the system is the capability of measuring a great number of points and of measuring them fast enough. The system might produce perhaps 300 000 or 400 000 terrain points from a pair of photographs. That many points will allow local analysis of 3D obstacles (item 4) and provide the basis for high-accuracy results (item 3). On that basis also the internal quality assessment (item 6) is feasible, as well as the automatic capture of breaklines (item 5), although a dense field of surface points relieves the necessity for breaklines to a great extent. At present during the first phase of development, the automatic capture of breaklines is postponed, to be treated at a later stage.

In order to be fast it is expedient to use epipolar image geometry, thus avoiding 2-dimensional matching procedures. The actual measurement of image points consists of applying an interest operator for extracting image points which serve as candidates for terrain surface points. Previous investigations [3] have shown that with feature-based matching the derived dense DEM is accurate to the order of h/10 000, thus meeting directly the specifications of item (3).

If considered necessary, however, the vertical accuracy could still be improved by applying in addition least-squares-matching which would use the previous feature points as approximate values to start from.

The system should operate as autonomously as possible. This means that the main parts of the program run as a batch program, without external interference. However, at the beginning and at the end of the batch procedure there is interaction necessary with an operator. Interactive operations would be most convenient in combination with a digital photogrammetric stereo-workstation. At the beginning it must be possible to define and provide breaklines as external or interactive input. In many cases also areas must be defined, by their border lines, which are to be excluded from the DEM, like forests, built-up areas, or water surfaces. At the end of the batch process it is necessary to supply error messages and a number of statistical parameters which allow internal quality assessment of the generated DEM. In addition, however, it is highly desirable to provide for convenient checks, thorough quality control, and possibly modification of the DEM. For that purpose various editing functions and visualisation techniques are envisaged, which would assist in the inspection and evaluation of the DEM by a human operator who might want to remeasure and modify parts of the DEM interactively.

2.2 The MATCH-T software package consists of several independent modules which are processed successively. The main partitions are (I) Input, (II) Pre-processing, (III) DEM generation, and (IV) Post-processing. Their contents are summarized in the following description.

I Input

(1) The input for the DEM processing consists of one stereo-pair of digital images, for the time being. Appropriate pixel size is in the order of 15 to 20 µm. It is assumed that the parameters of interior and of exterior orientation are known from previous operations which are not part of the DEM package. The geometric corrections for lens distortion, refraction, earth curvature, and image distortions, as well as radiometric corrections may (preferably) have been applied previously.

(2) Breaklines and/or areas to be excluded are defined by polygons, interactively or from external sources. The lines may be given as 2D polygons in image space or in object space, or as 3D polygons in object space.

II Pre-processing

The actual processing starts from the digital images, cut down to the areas of common overlap of roughly 15 cm x 23 cm extension, amounting to about 2×10^{8} pixel or about 400 Mbyte of data (order of magnitude). The orientation parameters are supposed to be given. Also, a number of process parameters are defined in advance.

(3) The first operation concerns the transformation into epipolar image geometry, by image normalisation. The image data are projected onto coincident mathematical image planes which are defined in object space. Here, at the latest, known radiometric and geometric corrections are applied. As a result the epipolar lines are parallel lines. Image normalisation always includes re-sampling.

(4) In order not to depend on any approximate pre-knowlege of the terrain the DEM is approached stepwise. For that purpose an image pyramid is formed, for either image. Upwards from the bottom layer of the pyramid (which consists of the normalized image with the originally sampled pixel size), additional layers are established, by always combining 2 x 2 pixel to form 1 pixel on the next higher level. Normally, up to 9 layers constitute the image pyramid. The upper level may contain about 1 200 to 1 300 coarse pixels, if the original pixel size was 20 µm. In that case each pixel of the top layer would have 5.120 mm pixel size and would cover 256 x 256 pixel of the bottom level. The image pyramid is completely stored which increases the total volume of image data by about 1/3.

The formation of each new image level from the previous one is not done directly, as first a smoothing Gaussfilter is applied. The filtering may not be necessary in all cases. It is, however, a safeguard measure to prevent Moirée effects to occur.

(5) After the image pyramids have been formed a large number of image points has to be identified and selected, which are potential candidates for the subsequent derivation of terrain surface points. For that purpose the Förstner interest operator is applied, specified for epipolar geometry, independently for each data set and each level of the image pyramid. A 3 x 5 pixel window is shifted along each 4th row of pixels, for instance (such parameters are kept variable in the program, of course). At each position of the window the interest value of the Förstner operator is assessed, consisting of the weighted square sum of the gradient values. Thus, for each chosen epipolar line a set of interest values is obtained, out of which all local maxima are identified and stored. They are the points of interest prepared for stereo-matching.

In addition to the interest value obtained by the interest operator also the sign of the gradient is assessed. The attributes of the points of interest are collected to form an attribute pyramid, the structure of which is equivalent to that of the image pyramid. All operations up to this point may push the volume of data into the order of 800 Mbyte.

(6) Points of interest which are located in image areas to be excluded from the DEM are dropped at this stage. If, however, the excluded areas are defined by 2D polygons in object space they can be considered only later, after the generation of a preliminary DEM on the level in question.

III DEM Generation

The image points of interest, selected in step (5) independently for all levels of the image pyramid, are candidates to form homologous pairs of points for stereo-matching and derivation of terrain surface points. The identification of homologous pairs of points takes place in combination with the successive approximations to the DEM.

(7) The preliminary matching of pairs of homologous points is done, in principle, within square-shaped areas, associated with the finite elements to be used later. For the highest level of the image pyramid the DEM is assumed to be a horizontal plane in object space, as initial approximation. The corner points of that unit area are projected into image space (via the known elements of orientation). The two related image areas (left and right image) are then rectified onto each other, maintaining, however, the epipolar geometry. Thus the homologous image areas are delineated corresponding to the DEM of that level.

Within the homologous image areas pairs of matched points are to be identified. In order to narrow down the number of combinations x-parallaxes are calculated. Points exceeding a set magnitude of parallax are excluded from further consideration. At that stage correlation coefficients for the major candidate pairs of points are calculated , in order to obtain an additional effective attribute for the identification of matching pairs of image points. With the information now available a preliminary list of matched pairs is established by taking the gradient signs, the weighted interest values and the weighted correlation coefficient into account. The result of the matching is not necessarily unique. At this stage of the process an image point may still be matched with several others, although the matching is weighted. If considered necessary, in future, the preliminary matching procedure might be expanded to additional attributes.

(8) The next step is the computation of terrain points in object space by intersection of the rays which are defined by the matched pairs of image points and the exterior orientation of the normalized image layers.

(9) The result is a cloud of terrain points. Ideally they define directly the terrain surface. However, deviations and outliers are to be expected, because of erroneous matching and of 3D obstacles on the terrain surface. As long as the majority of points refer to the actual terrain surface, it can be modelled by robust fitting of bilinear finite elements to the measured terrain points. In that process each finite element is broken down into 4 follow-up elements, and all outlying points are identified and discarded. A possible closer analysis of the residual errors for breaklines or for modelling 3D obstacles is not attempted during the first phase of the system-development.

The actual program is not handling each finite element area separately. Instead, up to 16 finite element units are treated simultaneously, leading to 64 finite elements as the next approximation to the DEM. In this way weighted curvature constraints can be considered for the terrain modelling.

(10) The DEM generation works down through all levels of the image pyramid. On each level the area unit of 16 finite elements constitutes an operational patch. The DEM is established patchwise , by breaking down the 4 x 4 grid, formed by the corner points of the previous finite elements, into an 8 x 8 grid. Thus each DEM serves as approximation for the next level. The patches are treated with some overlap, in order to ensure local continuity.

The successive DEM approximations can be stopped at any desired level. They can also be continued to any reasonably desired level of densification. The grid units on the various levels of the image pyramid are usually chosen as multiple units of the specified final DEM.

(11) Pre-determined breaklines are considered during steps (9) and (10) on the lower levels of the image pyramid. They may be given as 3D or 2D polygons in object space.

The process parameters of the system are set in such a way, at present, that perhaps 500 000 or more interest points are identified in each image, on the lowest level of the image pyramid, leading to about 300 000 to 400 000 matched pairs of image points which are processed into the same number of terrain points. They are used to ensure a good fit for the finite elements and to identify outliers. The size of the finite elements is identical with the DEM grid. It is chosen in such a way that about 30 000 to 50 000 grid points, possibly up to 80 000 points, are obtained.

At the end, the number of grid points, i.e. the density of the final DEM, may not be very much larger than that of conventional DEMs. The basic difference is, however, that the grid points of a conventional DEM are the result of interpolation between considerably less measured points. Here the finite elements which represent the final DEM are fitted, per average, to about 10 to 15 measured terrain points per element.

Consequently the accuracy of the generated DEM should be noticeably higher than in conventional DEMs. Preliminary investigations [3] have confirmed that the resulting vertical accuracy is close to h/10 000, depending on image quality and type of terrain. The same accuracy is normally not obtained for DEMs derived from operator measurements. It has also been shown that the additional application of least-squares matching, on top of the feature-based matching, will improve the vertical accuracy by < 30 %. It does not seem urgent to go for the additional accuracy improvement. At present the least-squares matching has not yet been implemented in the MATCH-T system.

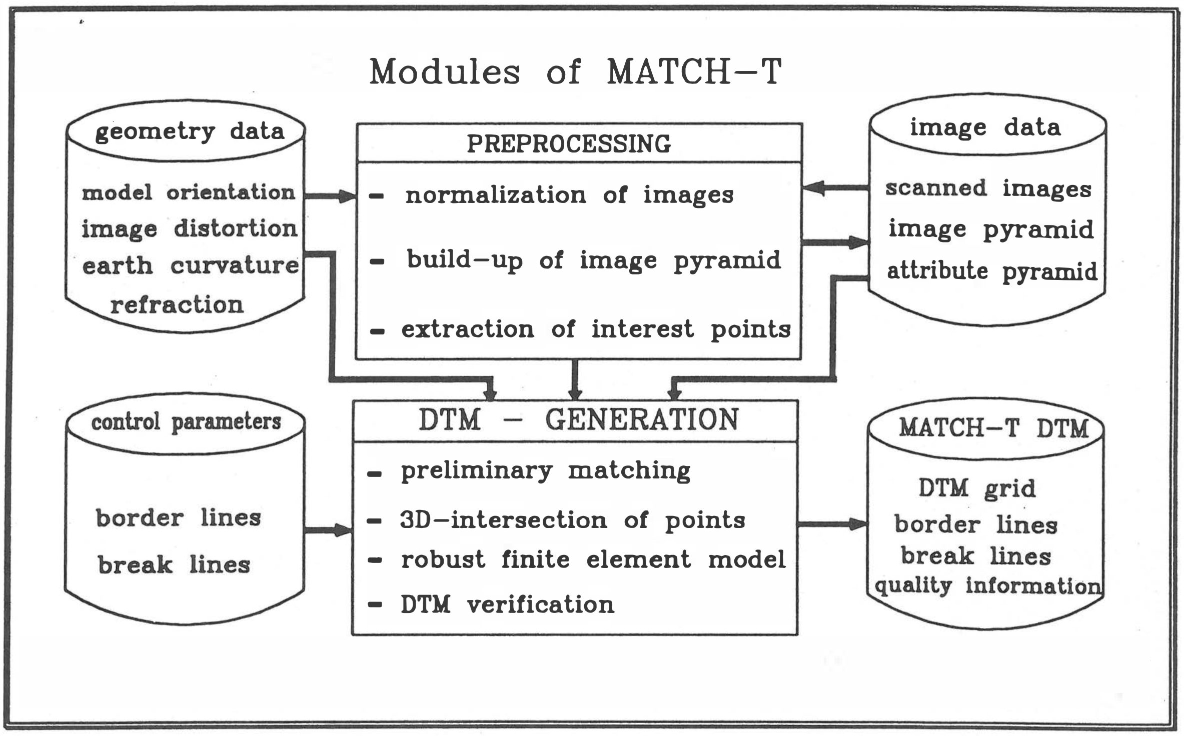

Fig. 1: Modules of the MATCH-T program package

IV Post-processing

(12) The prime task of post-processing concerns quality assessment and quality control of the generated DEM. For that purpose a number of operational system parameters and statistical parameters are supplied by the program, in addition to any error and failure messages which might point to trouble areas. Beyond that, however, it is essential to provide for the inspection, evaluation, and possibly correction of the DEM by a human operator. The possibilities to be considered depend on the available hardware. The ideal case would be an interactive digital photogrammetric workstation. With it the full range of editing functions, visualisation

functions, graphical display, and measuring functions could be utilized, covering all desirable operations in relation to controlling and updating the generated DEM.

(13) A DEM is often not a stand-alone product, but is used as a basis for a number of follow-up programs. Digital orthophotos, contour lines, slope models and perspective visualisation are common examples. It is not intended to develop such programs within the MATCH-T system, except for the digital orthophoto. Instead, interfaces are to provide access to existing programs.

Referring to the INPHO environment, the MATCH-T DEM is interfaced with the SCOP-family of DEM and derived programs. Both, the grid data of the MATCH-T DEM, and the structure data representing breaklines and excluded areas can be transformed into the SCOP data structure. Thus contour lines and perspective views of the DEM, of contours, or of other derived products can be transferred to common graphical devices.

3 Hardware Aspects and Present State of Development

3.1 About two years ago some modules of the MATCH-T concept were tentatively programmed for a PC. They served for preliminary experimentation about some performance features. In the meantime the total MATCH-T concept has been worked out and the software package designed. The programming has just been completed as far as partitions II (pre-processing) and III (DEM generation) are concerned, which cover the major parts of the system.

The MATCH-T DEM program runs under the operating system UNIX. It was ported to three different computer systems: The Compaq PC 386; the Intergraph Interpro 6040 workstation which is a 10 Mips machine with 1 Mflops; and the Silicon Graphics workstation 4D25 which has 20 Mips and 1.6 MFlops. The disc capacity required for handling one pair of photographs is in the order of 1 Gbyte. The code is mainly written in the program language C. Hence it is highly portable to any other UNIX workstation. It is intended to add graphical output during run time and a user interface featuring X-windows and OSF/ Motif. Also modules for internal and external quality checks are to be implemented soon.

3.2 At the present state of programming a batch version of the MATCH-T system has just become operational, on all three computer systems mentioned. The batch version implies that some input functions (breaklines and excluded areas) have to be handled off-line, for the time being. The same holds for the quality assessment in the post-processing module.

During the next few months the MATCH-T system will be thoroughly tested with regard to system performance and accuracy performance. It will also be applied in some pilot projects. Results are to be reported in due course.

From a first limited benchmark test with the Silicon Graphics workstation 4D25 it can be concluded (by extrapolation) that the derivation of a high-quality DEM for a complete pair of aerial photographs would take 6.5 hours, with the present batch version of the program on that workstation, and based on 20 µm pixel size. If that preliminary result will be confirmed it would mean that the system is close to an economic performance. It also means that the preliminarily set first performance target of completing a DEM for a pair of photographs in about two to four hours might be reached, if a machine with about 6 MFlops could be used, like the Silicon Graphics workstation 4D35.

References

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