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FULLY AUTOMATIC MEASUREMENT OF DIGITAL ELEVATION MODELS WITH MATCH-T

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1. Introduction

The production of digital elevation models (DEM) is a classical activity field of photogrammetry. With the upcoming availability of scanners and digital cameras, as well as fast computers, in combination with digital photogrammetric workstations, some methods and systems are being developed in order to determine DEMs automatically from digital or digitized images (cf. references). The practical acceptance of these modern systems will be strongly dependent on the accuracy and the performance of the DEM capture.

This paper describes the basic concept and method, as well as some first practical results of the program package MATCH-T, which is designed for the fully automatic derivation of DEMs from digital aerial images. The principal goal of the development is the automatic production of DEMs, at least as precisely and as fast as it is usually done by an operator. Thus, the automatic DEM capture generally aims for an accuracy level of 0.1 ‰ of the flying height and a computation time for the DEM of less than two hours, for the time being.

Conventional non-triangular DEM interpolation procedures are characterized by the fact that in a stereo-model up to some few thousand points (e.g. 1 000 - 5 000) are usually measured. From those points a more dense regular DEM grid, which may contain perhaps 10 000 - 20 000 grid points, is derived by suitable interpolation methods. Hence the interpolated DEM is certainly less accurate than the measured points. Nevertheless, it has to be emphasized that the human operator can place the points intelligently. In this way the measured points carry implicitly information about the surrounding local terrain and represent it adequately. 3D disturbances like trees, houses and bushes can be avoided, and breaklines are introduced if they are considered necessary for the modelling of the terrain surface.

Automatic procedures operating on digital images and applying image matching techniques like feature-based matching or image correlation provide little information per single point, but they permit fast and dense point measurements. Thus, large numbers of points can compensate the lack of special point information and render possible the computation of high-quality DEMs (Hahn, 1989). As far as the program package MATCH-T is concerned, automatic measurements of about 500 000 - 800 000, or even more 3D points per model are envisaged, which may result in regular DEM grids with 50 000 - 80 000 grid points, implying up to about 10 points per DEM mesh. This indicates clearly, that the method is expected to be considerably more accurate than conventionally determined DEMs. Furthermore, due to the very dense surface representation, the detection and elimination of 3D disturbances is possible, as well as the automatic detection of breaklines. The robustness of the method with respect to such terrain features is a decisive and distinctive feature compared to the well-known systems based on electronic image correlation, which have failed so far to cope with 3D disturbances.

Hereafter the development of the program package MATCH-T for the automatic DEM derivation from digitized images will be discussed and some experimental results will be presented. The system is based on previous research work by W. Förstner, M. Hahn and E. Gülch (cf. references) at the Institute of Photogrammetry of Stuttgart University. The actual program development took place at INPHO GmbH.

2. Methodical and technical concepts of MATCH-T

As already pointed out there are some general requirements for an automatic DEM procedure. They can be summarized in the following specifications, according to which a DEM should be:

(1.1) accurate (about 0.1 ‰ of the flying height)
(1.2) fast (less than 2 hours per model)
(1.3) dense
(1.4) robust (detection and elimination of 3D disturbances like single trees, houses etc.)
(1.5) autonomous (no necessity of an initial DEM, except a very crude one)
(1.6) capable of breakline detection and of
(1.7) internal and external quality control.

A characteristic feature of the method used in MATCH-T for the achievement of these items is the use of epipolar geometry within normalized images and a hierarchical image data structure including image pyramids and feature pyramids. This basic image data structure renders possible a fast and autonomous determination of the DEM without any pre-knowledge about the DEM. Presuming reasonably good texture in the images an interest operator will provide a large number of points. After feature-based matching and 3D intersection an arbitrary dense representation of the terrain surface is derived. Thus, the method will guarantee both accuracy and robustness, is capable of automatic breakline detection and will provide internal quality checks.

Apart from these methodical concepts there are some technical aspects concerning the efficient system realization on a computer. They are interdependent to some extent. The present MATCH-T program package has been conceived with regard to the following items:

(2.1) batch programs
(2.2) efficient and fast data file structure
(2.3) parallelization and vectorization
(2.4) introduction of control parameters
(2.5) editing and visualisation functions
(2.6) user interface
(2.7) plausibility checks
(2.8) status monitoring
(2.9) common operating system, programming language and system software

The main system should preferably consist of several batch programs which allow an almost autonomous determination of the DEM without external interference. Control parameters are to be introduced from a central control parameter data file before the programs are started.

The enormous requirements with respect to speed (item 1.2) demand the introduction of a data file structure which makes possible the efficient and fast management of the large amounts of data. Several image data formats should be included, as well as the management of all sub-images within one compact data file.

Parallelisation and vectorisation are most convenient in order to minimize the computation time of time-consuming procedures like resampling and linear image filtering. In fact, the development of MATCH-T started on a PC carrying out the time consuming procedures on a vector processor very efficiently (Hahn et al., 1991). Despite the significant acceleration by parallel processing it has to be taken into account that powerful workstations with high computation performance (e.g. 20 MFLOPS and more) become available. Thus, one has to balance between a special, very efficient (maybe hardware-related) solution, and a more common but slower solution, which can compensate the lack of speed by using more powerful common workstations.

Editing and visualisation functions, as well as a user interface, should put the user into a position to interact with the system before, during and after the DEM process. At the beginning there is certainly often a need to define excluded areas or breaklines by polygons. Furthermore, control parameters must be defined, preferably by a comfortable user interface, in order to avoid troublesome command file editing. Before starting the whole automatic DEM procedure principal plausibility checks are to be performed concerning the logical and geometric consistency of the input data.

During the DEM computation process full or temporary graphic monitoring of interim results and of program status should be possible. At the end, when the DEM product is established, it is necessary to evaluate statistical parameters and to indicate possible problem areas. In addition, it must be possible to apply an external quality check, in case necessary, either by using internal information of the DEM, or by using an additional display and operator measurements on a digital stereo workstation. At this point it should be emphasized that the new generation of digital photogrammetric workstations, which are designed to replace analytical plotters (Kaiser, 1991; Lammerts, 1991), are specially suited for such editing and visualisation tasks. The three-dimensional checking and re-measuring of DEM problem areas by an operator could be done interactively, resulting in a thorough check of the digitally derived DEM.

As far as the operating system is concerned, it is evident that the operating system UNIX becomes more and more common. Most of the powerful workstations are running under UNIX and have the programming language "C" as a standard. It seems also that the X-Window system and OSF/Motif will be standards for some years, too.

For the time being some restrictions were imposed on the actual program development. In the first phase of the development the system has been limited to aerial images with known exterior orientation. Also, the automatic breakline detection has been postponed. Hence, only pre-measured breaklines can be considered at present. As far as the image data structure is concerned, only single image data files are introduced, which can be tiled in suitable patches. Parallelisation or vectorisation of time-consuming processes have also not been worked out on the present workstation version.

In the following the major items of the MATCH-T system will be discussed in more detail.

3. Description of the MATCH-T modules

The sequence of operations can be subdivided into four characteristic steps (see fig. 2). After an initial preparation of the project (step 1), the scanned digital images are rectified and resampled to normalized images. Hereafter, an image pyramid is built up for each normalized image and a symbolic description of the pyramid images is derived by an interest operator. This is called the pre-processing step (step 2). Afterwards, this hierarchical image data structure is used for the subsequent DEM generation phase (step 3), which is followed at the end by post-processing editing, quality control and output (step 4).

3.1 Preparation

In this first step the digitized image pair, of which the elements of interior and exterior orientation are assumed to be known, is corrected for distortion, refraction, earth curvature and radiometry, unless the corrections have been applied in advance, either by the scanning device or by other preparatory operations.

If necessary, excluded areas and breaklines have to be introduced. They can be defined either in the image as 2D polygons, or in object space as 2D or 3D polygons.

Furthermore, some control parameters have to be defined for the following batch processes, describing for instance the location of the DEM in object space and the chosen grid width. These parameters can be introduced interactively with the help of the user interface.

3.2 Pre-processing

The main aim of the pre-processing phase is to produce the basic hierarchical image data structure for the subsequent DEM generation process. In order to minimize the amount of data stored on the disc, the image pair should be scanned within the area of interest only. Thus, as far as a single photogrammetric model is concerned, a stereo overlap of about 15x23 cm^2 is the maximum case. Assuming 15 μm pixel size, the amount of data is approximately in the order of 300 Mbyte (=3 x 10^8 pixels).

Normalization:

The pre-processing procedure starts with the transformation of the digital image pair to normalized images. The generally tilted images are projected onto a theroretical plane which is parallel to the model base (Kreiling, 1978). The orientation of the plane is chosen in such a way that the projection distortion of the original images is minimized and of the same size for both images.

The application of epipolar geometry is a well-known technique, facilitating considerably the extraction of operator-specific image information, the matching of features, and the computation of DEM mass points by 3D intersections. Of course, this transformation involves a resampling process which is time-consuming. In principle, known radiometric and geometric corrections could also be applied at this stage.

The normalized images are characterized by the fact that the rows of the digital images are the epipolar lines.

Image Pyramid:

The hierarchical structure of MATCH-T is clearly reflected in the concept of the image pyramid. The digital normalized images computed in the previous step form the basis of two image pyramids of decreasing resolution levels. For the computation of a certain pyramid level the previous lower image pyramid level is smoothed with an appropriate Gauss filter approximated by a binomial filter of the order 5 or 7. Then, every second pixel of the filtered image is picked out to constitute the new pyramid level. Such an image pyramid can be interpreted as a multi-level low pass filter, in which aliasing-effects (Moiré effects) are minimized (Schmidt, 1981). The pyramidal image structure reduces step by step the image information to leave only the most significant structures and features at the upper levels. Thus, all image structures - even the large ones - fall within the range of local operators (Jähne, 1989). The image pyramid approach gets over the problem of pre-knowledge of the DEM. The DEM approximation is carried through the levels of the pyramid, beginning initially with a very rough approximate DEM, like a horizontal plane (Ackermann, Hahn, 1991).

As the pixel number is quartered per pyramid level, the data content of the total image pyramid is one third larger than the original normalized image pair. Thus, referring to the above example, the total image data increase from 300 Mbyte to only about 400 Mbyte.

Feature pyramid:

The image pyramid also serves for the extraction of image features. The associated feature pyramid is expedient in order to match homologous features on each level from which the 3D points of the terrain surface are derived. In the present approach the features are image points and are derived by the Förstner interest operator, applied independently for each level in each image pyramid. The characteristics of the applied Förstner operator - modified with respect to epipolar geometry - are a 5x3 pixel window, in which the interest value is computed by the weighted square sum of the gradient values, and a non-maxima supression, by which only significant local maxima are selected. For the subsequent matching process the sign of the gradient and the interest value are assigned to the extracted interest points as attributes. The accuracy of the interest points is approximately one third of a pixel, because no sub-pixel estimation is applied.

The image pyramid and feature pyramids represent the basic data set for the subsequent matching and DEM generation process. The total feature pyramid also comprises one third of the data more than the bottom feature level. Returning to our example, and taking into account that a feature level contains approximately 60 - 80 % of the data volume of the corresponding image level, the total amount of data of both types of pyramids to be stored on disc reaches about 700 Mbyte.

If desired, interest points located in excluded areas which are defined in the image could be eliminated from the feature pyramid. However, this reduction of the feature pyramid is not easily reversible, if the original feature pyramid was not preserved.

3.3 DEM-generation

The DEM-generation of the MATCH-T system is sub-divided into the matching process and the robust DEM modelling with finite elements. The DEM approximation is done stepwise by going through the pyramidal image data structure.

The starting point on every pyramid level is an approximate DEM, which is taken from the previous level. At the beginning a horizontal plane is introduced as initial DEM approximation. The grid width of the DEM to be determined is twice as fine as the one of the approximate DEM.

The principal aim of the matching process is the identification and location of homologous image points in certain image windows, which are defined by a reprojection of the meshes of the approximate DEM into the image. These windows do restrict the matching process to local parts both in the image and the object space, and they contain interest points stored in the related feature pyramid level. For the matching the sign of the gradients, the interest value and the correlation coefficient in a defined window are used as similarity measures. In addition, the matching is geometrically restricted to the epipolar lines and by a parallax bound between matching candidates. No special efforts are made, as suggested by Förstner (1986), to avoid mismatches completely. Hence, the list of homologous candidates is not unique. Possible matching errors are accepted as they can be identified and eliminated in the subsequent robust DEM modelling. Figure 1 shows the principal strategy of the hierarchical DEM generation.

By a 3D intersection of the homologous image points the respective object points are calculated which represent the terrain surface quite densely, still including, however, erroneous data. They may result from matching errors or from 3D disturbances like houses, trees, bushes, cars etc., which do not belong to the terrain surface. In order to obtain a reliable modelling of the terrain surface a robust finite element fitting is applied, which is designed to eliminate outliers deviating from the terrain surface.

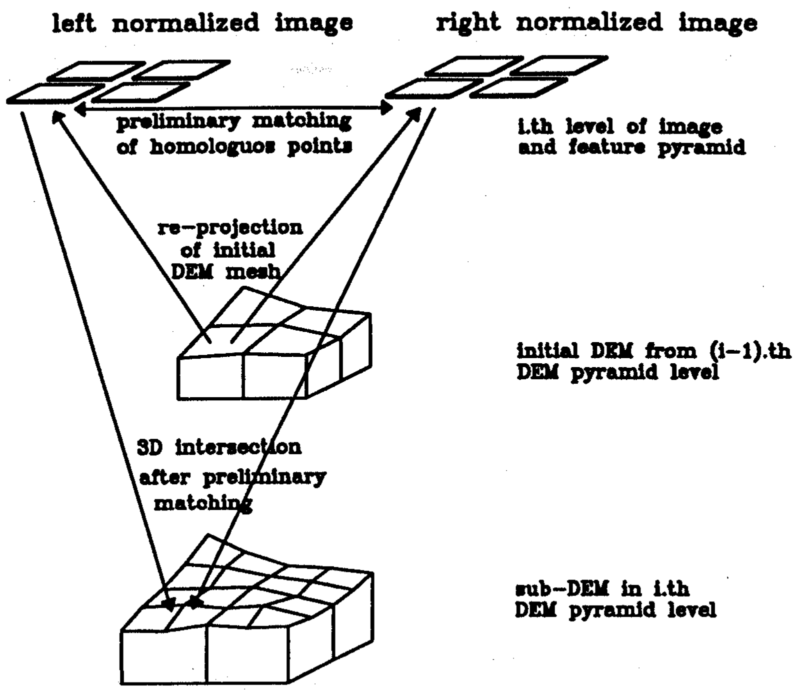

Figure 1: Strategy within the DEM-generation process

It is supposed, however, that those outliers are siginificant from a statistical point of view and can be modelled by suitable distribution functions. Therefore, the majority of the measured points will, at this time, have to refer to the actual terrain surface.

Depending on the available computer system, only limited patches of the terrain surface can be treated by the finite element model. Thus, the DEM for either pyramid level is a patch-work of several sub-DEMs, which are arranged in an appropriate overlap. The refinement of the grid width by the factor 2 leads to a successively more precise modelling of the terrain surface. Additional weighted curvature constraints in the finite element model render possible the handling of areas with an insufficient number of measured points, as well as the filtering of the measured points.

Excluded areas and pre-measured breaklines are considered throughout the whole image pyramid. Interest points lying in excluded image areas are not included in the matching process. Excluded areas which are defined as 2D polygons in object space are considered after the 3D intersection of matched homologous points.

The final product of the DEM generation is a DEM pyramid representing the terrain surface in several grid widths as a whole, even in areas which are to be excluded. Every DEM level is accompanied by an extensive set of statistical data including parameters for the subsequent internal quality check. The storage requirements for the DEM grid points and the statistical parameters amount to only 3 or 4 Mbyte, altogether, which is negligible if compared to the actual amount of data of the image and the feature pyramids.

According to the previous investigations by Hahn et al. (1988) and the actual recent experience with the MATCH-T system, the mentioned grid points result from a highly redundant filtering process. Depending on the texture of the images the matching and intersection processes provide about 500 000 up to 800 000 or more measured terrain points. Thus, an average of 10 points per raster grid is possible. Actually, this fact plays the key role for the high accuracy of the automatically captured DEM.

Figure 2 gives a graphical overview for the modules of MATCH-T and the related sets of data.

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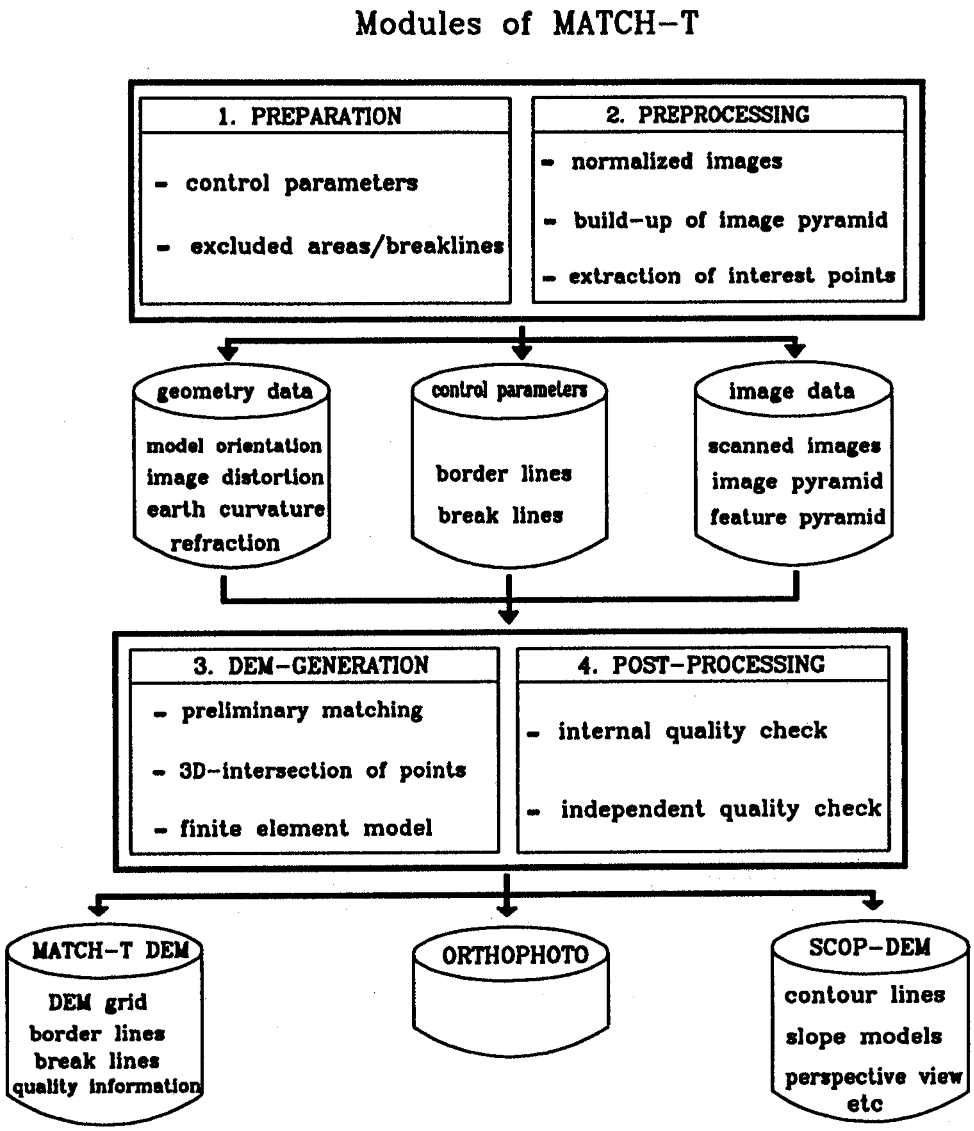

Figure 2: Modules of MATCH-T

3.4 Post-processing

Post-processing including internal and possibly external quality checks is an absolute necessity in the whole procedure of deriving a high quality DEM product.

Internal quality checks are based on the evaluation of a large set of statistical parameters stored during the DEM-generation. For that purpose, some weighted criteria are summed up for each patch in the DEM level. This leads to a quality matrix, which can be put graphically as a layer to any image in the image pyramid and which indicates areas of good and poor quality. This step serves as a first quality assessment and should guide the system user to subsequent local DEM assessments or improvements either within the system or by an additional system, preferably a digital workstation.

Besides the recommended possibility of using a stereo-workstation as a subsidiary tool, the external quality check can also be done with the help of information which is derived within the results and data of the system. As already pointed out by Hahn et al. (1991), the use of stereo orthophotos, which are derived from the DEM to be checked, might lead to an independent assessment of the DEM quality. That possibiltiy is presently under investigation.

3.5 Derived products and tools

A DEM is a product in its own value. It is a data base for the subsequent derivation of additional products such as contour lines, slope models, perspective views and orthophotos. Since the prime task of the system should be the derivation of the DEM, no efforts are made, at present, to realize such by-products within the MATCH-system, except for the digital orthophoto as it is already conceptionally included in the system-inherent quality check. However, the DEM data can be transformed to any other program systems producing the derived products.

As far as the product line of INPHO is concerned, the MATCH-T DEM with its own data structure is interfaced with the SCOP DEM package (Kraus et al., 1982; Köstli et al., 1986). Thus, all the mentioned follow-up programs can be applied for the production of contour lines, slope maps, perspective views etc. on common graphical devices.

Furthermore, some graphical tools have been developed for the visualisation of the image and feature data as well as of the raster of the DEM. Added up with the vector data of the excluded areas and breaklines, any combination with a certain image level can be produced for the inspection of the used and derived data.

4. Data structures

The prime task of the data structure in MATCH-T is the fast and efficient data access during the DEM process within the pyramidal structure. Each level of the pyramid is defined by two image data files, two feature data files and one DEM file. Those central data files constitute the main data volume on the disc. They are accompanied by other pyramid level data files which contain information about the exterior orientation and the transformation between the pixel coordinate system of the digital image and the image coordinate system as well as statistical parameters acquired during the DEM generation process.

Concerning the main data files a fast data access is obtained by using a binary format and a geometrical subdivision of both the image and the DEM. Thus, the tiles in the image-related data files are sub-images which sizes are defined by a certain block of rows and columns. The basic partitions of the binary DEM raster files are definitely the patches, which are the finite element units for the representation of sub-DEMs during the DEM process. They are defined by the grid width related to the pyramid level and a number of grid lines. Thus, taken as a whole, the disc access for the image data and DEM data during the DEM computation is minimized by the access to the tiled files.

As far as the image data are concerned, only black and white images can be processed. Nevertheless, also colour images can be handled, if transformed to black and white images.

The vector-related data in MATCH-T concerning excluded areas and breaklines are treated as closed or open 2D polygons or as 3D polygons. They are stored in ASCII-format, because the access time during the DEM process is not critical. Both, excluded areas and breaklines, are not strictly connected with the DEM, which is in fact a regular grid with constant grid width. After the DEM process two-dimensional excluded areas in the image or the object space can be projected into the DEM for correct intersection with the model surface.

5. Present state of development

On the basis of the described conceptual design of MATCH-T, as described in the previous chapters, the present state of the program development can be summarized as follows:

The batch version of MATCH-T including the main parts "pre-processing" and "DEM-generation" has been completed. "Internal quality check" has also been developed producing a quality matrix, which is visualised as a layer for each level of the digital image pyramid. Furthermore, some visualisation tools for the common graphical presentation of the pyramid data sets have just become operational. Thus, the user can, for instance, combine image data, feature data and vector data (like excluded areas and breaklines) to common visualisation for plausibility checks.

As far as the hardware is concerned, the MATCH-T system has been ported to an Intergraph Interpro 6040 and to Silicon Graphics 4D25 and 4D35 units, which represent typical and powerful UNIX workstations. Furthermore, the system runs also on a PC-UNIX system serving as a subsidiary development environment. The main part of the

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software is written in the programming language "C". For graphic tools X-Window and OSF/Motif is used. Thus, the present MATCH-T version is highly portable to any other UNIX workstation.

We have started to work out some pilot projects, testing system performance and accuracy. It is also intended to complete the user interface under OSF/Motif and to add graphical output during run time. Results and system performance will be presented during the Photogrammetric Week 1991.

6. Preliminary empirical investigations with MATCH-T

The present software version of MATCH-T has been tested in a first project which covers about one large scale photogrammetric model. The first goal of the investigation was to evaluate the accuracy and the time performance of the actual system with respect to the general requirements which were set up in chapter 2. The test was carried out on two Silicon Graphics UNIX workstations with 1.6 MFLOPS (4D25) and 6.0 MFLOPS (4D35), respectively.

The colour image pair of photo scale 1:7000 was digitized with 15 µm pixel size by the Zeiss/Intergraph PS1 PhotoScan scanner (Faust, 1990). The total volume of digitized image data amounted to roughly 230 Mbyte. The digital images were related to the fiducial marks, and thus related to the image coordinate system as defined by the camera calibration. The distortion was found to be negligible and no corrections were applied.

The relative and absolute orientation of the image pair was determined by a stereo model orientation on an analytical plotter. In addition, the control points in the images were measured digitally by an appropriate ellipse operator in order to check the digital images with respect to scale and location within the image coordinate system. Local affine transformation between digital and analog measurements of control points indicated r.m.s. discrepancies of about 4 µm which were considered acceptable for the subsequent DEM determination.

In Figure 3 an overview is given of the model, which can be largely characterized as generally plain, agriculturally cultivated, and containing some single houses. A little residential area was excluded from the DEM by a 2D polygon defined in the object space. Table 1 summarizes some relevant data of the project, as well as some statistical parameters captured during the DEM determination with MATCH-T.

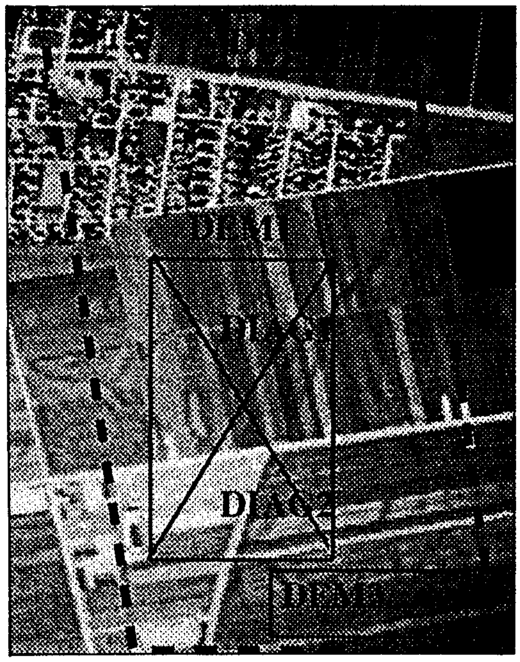
For this digitized pair of photographs the DEM was computed covering about 85 % of the net stereo overlap. Referring to table 1 the ratio between matched points and grid points indicates an average density of about 6 to 7 points per grid mesh. If the number of matched points (cf. Table 1) is compared with the number of pixels in the DEM-related image parts, a density of about 1 point per 120 pixels can be determined. Those factors deviate from the ones stated by Hahn (1989) and can be explained by the lack of significant texture in some parts of the DEM area. In some of such problem parts a number of interest points with poor significance were excluded from the DEM processing by thresholding. However, the average number of 6 mass points per grid mesh still indicate a well determined DEM.

Three parts of the area were selected for accuracy checks. They are indicated in Figure 3 as DEM1, DEM2 and DEM3. In the three parts the automatically derived DEM was checked by manual measurement of the original photographs on an analytical plotter. The check measurements were made directly on the grid points, as determined in the MATCH-T DEM. This assured a strict assessment of the DEM heights without any interpolation. In view of the small mesh size of the DEM the grid points represent directly arbitrary surface points. In addition, two profiles DIAG1 and DIAG2 were measured in the area DEM1 in order to assess the quality of the MATCH-T DEM in arbitrary terrain points. The MATCH-T DEM heights along the profiles were interpolated bilinearly within the DEM meshes.

For the indicated areas an external estimate for the accuracy (column 3) of the MATCH-T DEM was derived by computing r.m.s. values for the height differences and dividing them by $\sqrt{2}$ under the assumption that both the manual and the automatic measurements have approximately the same accuracy. For comparison the theoretical internal accuracy was determined as a mean value over all relevant patches by using the Q_{xx} - matrices of the DEM-patches and the σ_0 after the finite element adjustment (column 5). Furthermore, the reliability was evaluated by counting all height differences which were larger than three times the r.m.s. values (=outliers). All values of the individual data sets were summed up quadratically in order to indicate accuracy estimates for the total DEM. The grid width of the manually captured DEM heights was 12 m, the planimetric point distance in the profiles was approximately 10 m. Tables 2.1 and 2.2 summarize the achieved empirical results for two DEM pyramid levels, referring to a grid width of 3 m and 6 m, respectively. These grid widths correspond directly to the 15 µm and 30 µm pixel size in the images.

photo scale:	1:7000
flying height:	1000 m
pixel size:	15 µm
size of left image: (original)	9344 x 14080 pixels (= 14 x 21 cm^2)
size of right image: (original)	7680 x 13440 pixels (= 11.5 x 20 cm^2)
pyramid levels:	9
size of DEM:	543 x 1247 m^2 (7.8 x 17.8 cm^2 in image)
grid width:	3m (bottom level) (= 0.4 mm in image)
interest points (left):	2.9 10^6 points
interest points (right):	2.9 10^6 points
matched points:	499 005 points
grid points:	182 x 416 = 75712 points

Table 1: Some statistical parameters of the project



— — — - edge of total MATCH-T DEM

Figure 3: Normalized left image[1] of the investigated area

data set (1)	# check points (2)	external accuracy [m] (3)	external accuracy [‰] h (4)	internal accuracy [m] (5)	internal accuracy [‰]h (6)	outliers [%] (7)
DEM1	1428	0.07	0.07	0.05	0.05	0.7
DEM2	198	0.09	0.09	0.06	0.06	1.0
DEM3	253	0.16	0.16	0.07	0.07	0.9
DIAG1	122	0.07	0.07	0.05	0.05	0.0
DIAG2	122	0.08	0.08	0.05	0.05	0.9
total	2123	0.08	0.08	0.05	0.05	-

Table 2.1 Empirical accurary and reliability of MATCH-T DEM in bottom level of the DEM pyramid (grid width 3 m / pixel size 15 µm)

data set (1)	# check points (2)	external accuracy [m] (3)	external accuracy [‰] h (4)	internal accuracy [m] (5)	internal accuracy [‰]h (6)	outliers [%] (7)
DEM1	1428	0.09	0.08	0.06	0.06	0.4
DEM2	198	0.10	0.10	0.09	0.09	0.2
DEM3	253	0.17	0.17	0.11	0.11	0.5
DIAG1	122	0.07	0.07	0.06	0.06	0.0
DIAG2	122	0.09	0.09	0.06	0.06	0.8
total	2123	0.10	0.09	0.07	0.07	-

Table 2.2: Empirical accuracy and reliability of MATCH-T DEM in 2nd level of the DEM pyramid (grid width 6 m / pixel size 30 µm)

[1] aerial photograph taken from Bayerisches Landesvermessungsamt (Freigabenummer: 90/1008)

The results, shown in tables 2.1 and 2.2, of the empirical checks represent differences between the manual check measurements and the automatically derived DEM grid points. The r.m.s. differences divided by $\sqrt{2}$ (column 3) give separately the accuracy estimation of either method and indicate that the height accuracy of the automatically derived DEM is in the order of 8 cm or 0.08 ‰ h (15 µm pixel size) and 10 cm or 0.1 ‰ h (30 µm pixel size), respectively. Without stretching the figures too much the test has clearly shown that the height accuracy of the automatically derived DEM is particularly good, with a standard deviation better than 0.1 ‰ h.

It is only the area DEM3 where the height accuracy of 17 cm (column 3) is somewhat poorer than the average result. That particular area has rather poor image texture, which effects the quality of both the manual and the automatic measurement. In fact, in that area the number of mismatches was considerably higher and the average number of points per grid mesh was poor. It can be assumed, however, that the manual measurements have been also affected by the poor image texture, because the grid points, used for the comparison, are not suited for the direct manual measurement, in this case.

For the same reason it is likely that the majority of the outliers (column 7) may be attributed to the manual measurements, although certainly a more thorough analysis of the outliers will have to be made.

As far as the theoretical internal accuracy (column 5) is concerned, it corresponds roughly with the estimated absolute accuracy of the DEM. However the loss of accuracy in DEM3 is not indicated in the same magnitude. Thus, for the detection of such problem areas more sophisticated indicators should be provided. For instance, if the average number of matched points per grid mesh and the convergence characteristic of the finite element model is considered, a better indicator can be derived.

Summarizing, it can be stated, that this empirical accuracy test has clearly shown that the previously established accuracy expectations have been fully confirmed for open areas. It is particular remarkable, that the coarse pixel resolution of 30 µm gave almost the same height accuracy of the DEM as the high resolution.

The test was computed on the Silicon Graphics 4D25 and 4D35 units. Table 3 shows the actual computation times, on both Silicon Graphics machines, for the complete procedure of producing the DEM. The values given for the 30 µm pixel resolution refer to the second lowest pyramid level.

machine type	resolution: 15 µm grid width: 3m	resolution: 30 µm grid width: 6m
Silicon Graphics 4D35 33 MIPS 6 MFLOPS	5.3^h	1.4^h (estimated)
Silicon Graphics 4D25 20 MIPS 1.6 MFLOPS	11.2^h	2.8^h (estimated)

Table 3: Computation time for the test model on two Silicon Graphics machines

The computation times for the 15µm resolution level were actually determined on both machines, whereas the computation times for the 30 µm resolution level were estimated by quartering the computation time for the 15 µm resolution level. Altogether, the figures indicate that for both machines the automatic DEM generation meets the operational specifications, as set at the beginning, for the 30 µm resolution level. The empirical investigations have shown that the achievable accuracy on this level is quite sufficient, in particular for orthophoto production. With the Silicon Graphics 4D35, which represents a modern powerful workstation, the whole automatic DEM process using 15 µm pixel size takes not much longer than the conventional manual DEM measurement and attains a height accuracy of at least 0.1 ‰ of the flying height.

As far as the production of digital orthophotos is concerned the MATCH-T program package will be used within the Zeiss Oberkochen PHIPS product line which is designed for photogrammetric image processing (Mayr, 1991).

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Abstract:

This paper describes a program package which is designed for the fully automatic mesurement of digital elevation models from digitized aerial photographs. The large degree of automation is achieved by two factors. Firstly, homologous points in the digital images are identified by the application of an interest operator and of image matching techniques. Secondly, the problem of initial values for the unknown DEM is solved by the introduction of an image pyramid. Thus, starting in a coarse image description with low resolution and reduced image information, image matching techniques can be successfully applied and lead to a hierarchical DEM structure.

The program package MATCH-T is described and empirical investigations are presented which refer to the automatic derivation of a high resolution DEM from a large scale photogrammetric model. The results prove that the method attains in open areas an accuracy of at least 0.1 ‰ of the flying height. The computation time for the automatically derived DEM becomes also operational and lies, with a Silicon Graphics 4D35, within the range of about 1.4^h and 5.3^h in dependence of the resolution level which is used.

Zusammenfassung:

Ein Programmsystem für die vollautomatische Bestimmung von digitalen Geländemodellen (DGM) aus digitalisierten Luftbildern wird vorgestellt. Der hohe Automatisierungsgrad wird durch zwei Faktoren erreicht. Zum einen werden homologe Punkte in den digitalen Bildern durch die Anwendung eines Interest-Operators und von Bildzuordnungstechniken identifiziert. Zum anderen wird das Problem der Näherungswerte für das zunächst unbekannte DGM durch die Einführung einer Bildpyramide gelöst. Beginnend in einer groben Auflösungstufe mit geringerer Pixelgröße und reduziertem Bildinhalt können Bildzuordnungstechniken erfolgreich angewendet werden und führen auf einen hierarchischen DHM-Aufbau.

Der Beschreibung des Programmsystems MATCH-T folgt eine empirische Untersuchung über die automatische Ableitung eines hochaufgelösten DGM's aus einem großmaßstäblichen Bildpaar. Die Ergebnisse zeigen, daß eine Genauigkeit von mindestens 0.1‰ der Flughöhe im offenen Gelände erreicht wird. Die Berechnungsdauer beträgt in Abhängigkeit von der Pixelgröße, die im letzten Berechnungsschritt verwendet wird, für eine Silicon Graphics 4D35 Arbeitsstation zwischen 1.5^h und 5.3^h.

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