GENERATION, MANAGEMENT AND UTILIZATION OF HIGH FIDELITY DIGITAL TERRAIN MODELS *)

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Abstract

The paper starts with a description of terrain data acquisition and generation of a continuous Digital Terrain Model (DTM) from these data. Then, the management of large DTMs of high fidelity and complex structure is treated. Next a review on the utilization of such DTMs is given. Vector and raster products derived from the DTM are mentioned as well as applications of DTM in digital photogrammetry. Finally it is shown how DTMs can be verified on-line using analytical plotters and optical superimposition.

1. Introduction and review

A Digital Terrain Model (DTM) is used to portray the terrain surface using digital data. Usually the heights z are represented as functions of the planimetric coordinates x and y. The history of DTM began three decades ago [Miller and Laflamme, 1958]. Today DTMs are produced for entire countries and their practical use increases continuously. In the near future the DTM will become a standard product of surveying.

The paper starts with a description of data acquisition for DTM and generation of a continuous DTM from these data. Then the management of large DTMs of high fidelity and complex structure is treated using the general DTM data base of the new program package HIFI-88 as an example. Next a review on the utilization of such DTMs is given. It includes vector and raster products derived from the DTM and the application of DTM in digital photogrammetry. Finally it is shown how DTMs can be verified on-line using analytical plotters and optical superimposition.

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2. Data acquisition for DTM

Three methods are available today for DTM data acquisition:

- manual or automatic digitization of existing contour maps,
- field surveying by tachiometry,
- photogrammetric stereo measurement.

The most commonly used method is the photogrammetric one. For the terrain description, reference points and geomorphological data are measured with adequate density, using analogue or analytical plotters. Reference points should either be acquired along contour lines or in a variable grid. The latter method, called Progressive Sampling, starts with the measurement of a basic grid. The terrain curvature is then analysed via the second height differences of adjacent grid points. If they exceed a properly chosen threshold, the basic grid is locally densified to half of the original mesh size. This procedure is repeated until the predetermined smallest grid is reached. In this way the final grid density automatically matches the shape of the terrain [Makarovic, 1973].

For a DTM of high fidelity essential geomorphological information, such as break lines, skeleton lines, and characteristic points, must be measured in addition to the reference points. Figure 1 shows the acquired data for a part of the area of the International Garden Exibition in the city of Munich. The variable grid and the break lines were measured using an analytical plotter Zeiss Planicomp and the program PROSA [Ebner and Reinhardt, 1984].

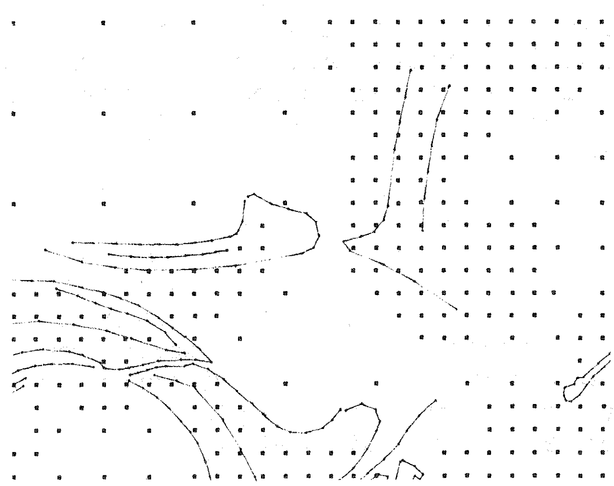

Figure 1: Measured PROSA points and breaklines

In future automatic DTM measurement by digital image matching will gain practical importance. For that the image information has to be available in digital form, i.e. in the form of density value matrices. Very high precision can be obtained by least squares matching [Ackermann, 1984]. With this method a pattern window consisting of pixels of the first image is transformed onto a larger search window consisting of pixels of the second image. The unknown geometric and radiometric parameters of this transformation are computed by a least squares adjustment, which minimizes the sum of squares of the differences between the density values of the transformed pattern window and the density values of the search window. This approach was extended by [Rosenholm, 1986] combining various pattern windows to a grid and by [Grün and Baltsavias, 1986] connecting the density values with the object coordinates and the orientation parameters of the images. Finally, the concept of digital image matching was generalized to allow for direct object surface reconstruction from the density values of the images and available control information [Helava, 1987; Wrobel, 1987; Ebner and Heipke, 1988].

3. Generation of a continuous DTM

From the acquired data a continuous DTM is generated which allows for the determination of the height z at any given position x,y. Two concepts are used in present-day practice:

- irregular DTMs, consisting of a network of plane or curved triangles; the measured points represent the nodes of this network,
- regular DTMs, built of meshes, which form a square grid in planimetry; the heights of grid points are interpolated from reference points and geomorphological data.

Grid models have the advantage of a regular structure of the data, which simplifies the use of the DTM. Several concepts are used for the interpolation of grid models. A highly efficient one is the DTM generation by the Finite Element Method. In this case an interpolation surface is defined, which is formed of local surface elements. In the simplest case separate bilinear polynomials are used for the individual grid meshes. Continuity along the borders of adjacent elements is guaranteed. The interpolation surface is determined by a minimization of the weighted sum of the squares of the discrepancies of the given reference points from the interpolation surface, and of the second differences of the heights of neighbouring grid points. At break lines the minimization of the second differences is altered in such a way that connections across the break lines are avoided. By this means an interpolation surface of minimum curvature is obtained which approximates the available reference points with optional filtering and represents the given break lines adequately.

Figure 2 shows such a grid DTM with a break line. This concept is realized in the HIFI program package [Ebner and Reiss, 1984], which is used world wide on various computers, and in the new version HIFI-88. The following chapter gives a more detailed information about this program package.

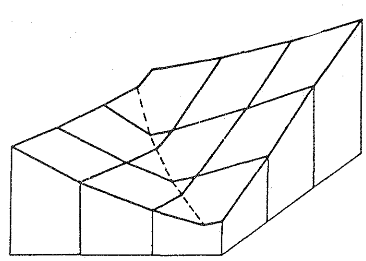

Figure 2: Grid DTM with a break line

4. Management of large and complex DTMs

The data organization and structure which is realized in the new HIFI-88 program package allows to handle country wide DTMs. Nevertheless, fast access to small sub areas of the DTM is provided. This is achieved using a DTM data base of hierarchical structure. There exist up to five levels for data handling. In the first and highest level the DTM area is subdivided into m times n equally sized square sub areas with m * n in the order of 10^3. In each sub area the information for up to 8 by 8 DTM grid meshes is stored. Consequently in the first level the data of 8m * 8n grid meshes can be managed. Usually this is not enough for handling large DTM areas. In this case all sub areas are sub-divided again into 8 * 8 = 64 smaller units. This procedure can be repeated four times. Each sub area of a lower level has only 1/64 the size of a sub area of the higher level, but each additional organization level allows to manage 64 times more DTM grid meshes. In case of m = n = 40, a 3 level organization and 20 * 20 m^2 grid meshes a 409.6 by 409.6 km^2 DTM area can be managed. Figure 3 shows the DTM access for such a three level hierarchy.

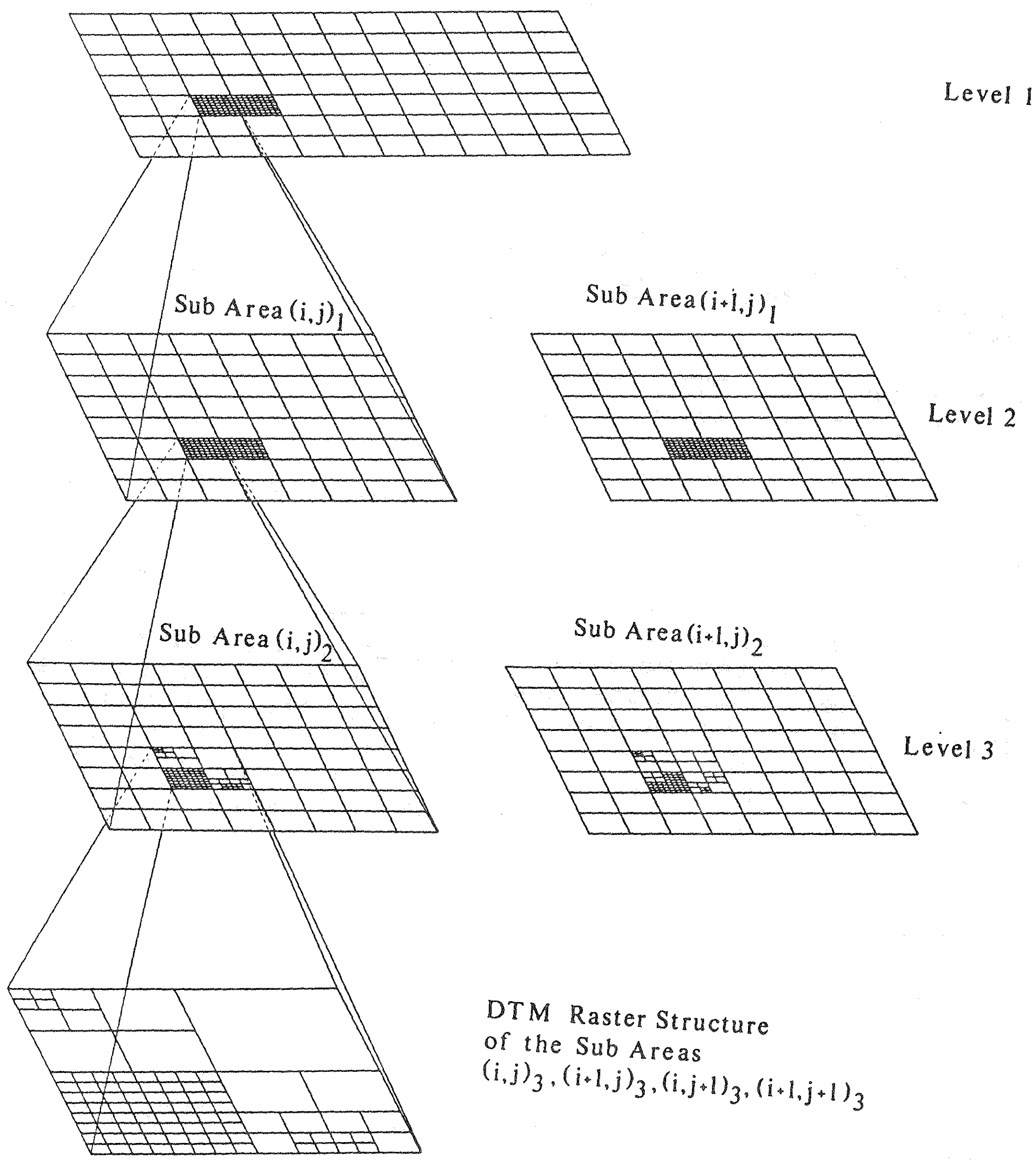

Figure 3: HIFI-88 DTM data organization

To have access to the DTM data of sub area $(i,j)_3$, first the pointer records $PR(i,j)_1$ of the first level and $PR(i,j)_2$ of the second level have to be read in order to know the path from the first to the second and from the second to the third organization level. In the first data record of sub area $(i,j)_3$ there is information about what kind of DTM data can be found and where to look for it. HIFI-88 allows to handle a rather general DTM structure in order to fulfil high quality standards for surface modelling. At the bottom of figure 3 four possible grid structures are shown. All variations from 1 up to 8 * 8 grid meshes per sub area are allowed if they result from division of bigger meshes into quarters.

This general grid structure is combined with local triangular networks within single meshes if additional non grid DTM information (e.g. break lines, hill tops or skeleton lines) is available. Figure 4 shows a sub area with grid meshes of different size, a crossing break line, and the associated local triangular networks.

To work with this DTM information, data base modules are available which allow for creating a data base, storing and extracting data and a few other options.

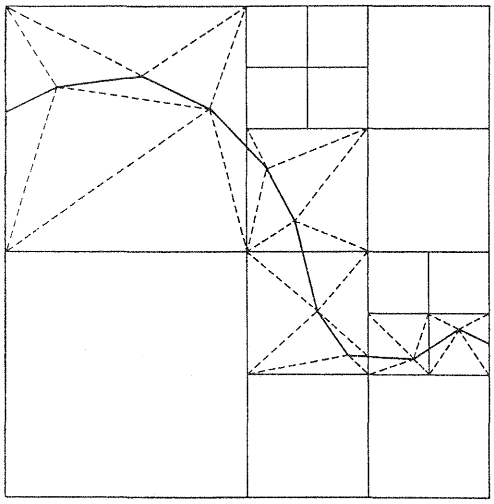

Figure 4: HIFI-88 DTM data structure

All these modules and the other programs of the package (see chapter 5) are embeded in the HIFI-88 user shell. It allows to work with the program package in a very comfortable way. There are on-line help functions available which give the user all information which is neccessary to run the programs. In addition to this on-line manuals are available. They inform the user about the details of the HIFI-88 modules directly on the screen. The communication language can be switched easily.

5. Utilization of high fidelity DTMs

From the continuous DTM generated and managed according to chapter 3 and 4, various products can be derived. Typical examples are:

- contour line maps of optional height interval
- terrain profiles, e.g for the production of orthophotos and stereo orthophotos
- perspective views in vector form and associated visibility maps
- slope and aspect information
- height difference models and volumes from two DTMs

Further products can be derived from the DTM by the use of digital raster processing:

- colour coded representations of height, slope, aspect and height difference information
- shaded relief models in orthoprojection
- perspective views of shaded relief models

HIFI-88 allows for the derivation of these products from the DTM with rigorous consideration of the general data structure described in chapter 4.

The following figures 5 to 8 show products derived from a DTM of high complexity, using this program package. The area belongs to the "Vernagtferner", a glacier located in the Ötztal Alps in Austria.

In figure 5 a contour map is represented, including the break lines which have been taken into consideration. For each contour one cubic spline is computed, approximating the DTM and guaranteeing continuity up to the second derivatives. At the break lines the splines show sharp bends.

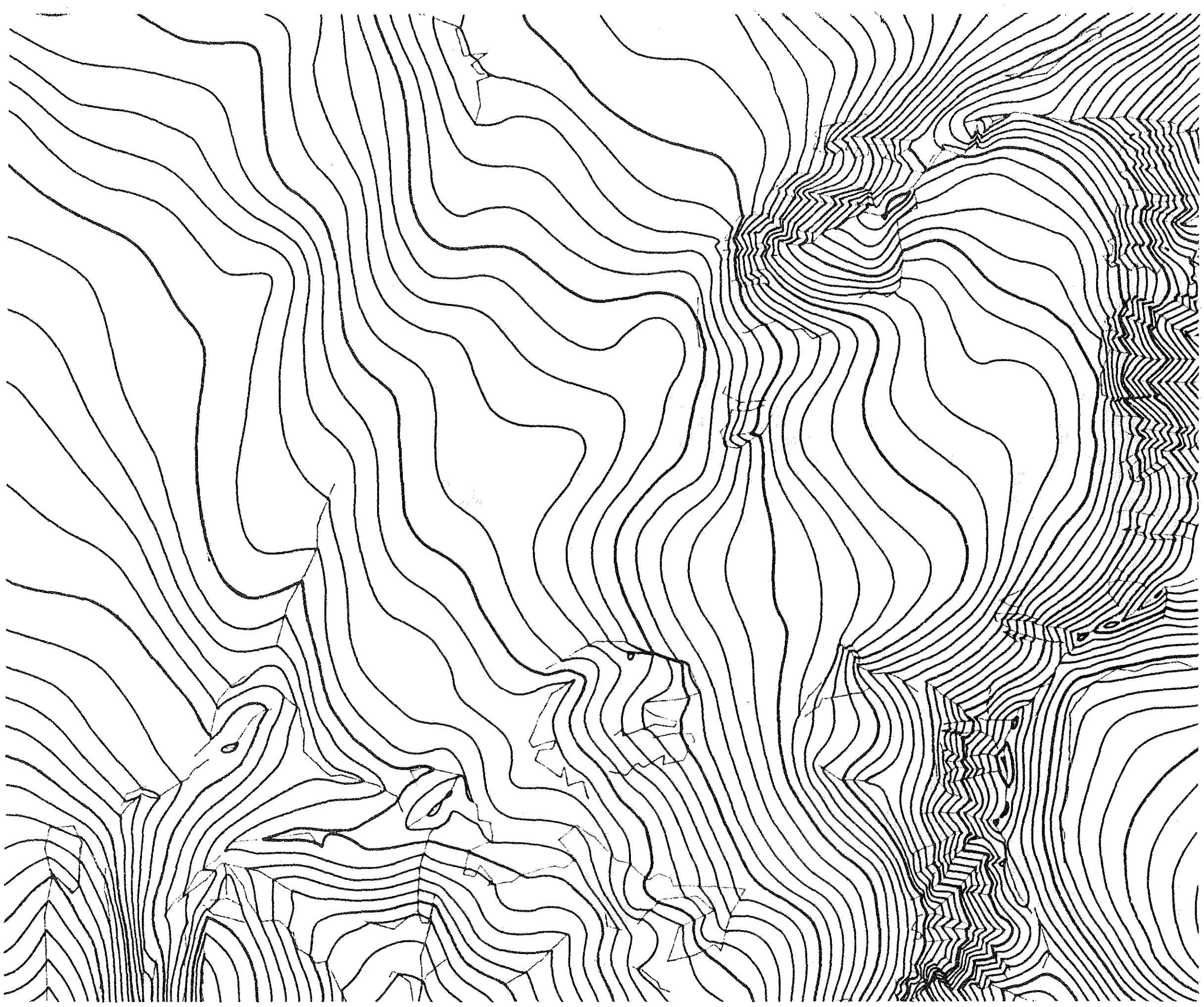

Figure 5: Contours and break lines

Figure 6 shows aspect information in form of vectors at grid points and figure 7 gives a colour coded representation of slopes.

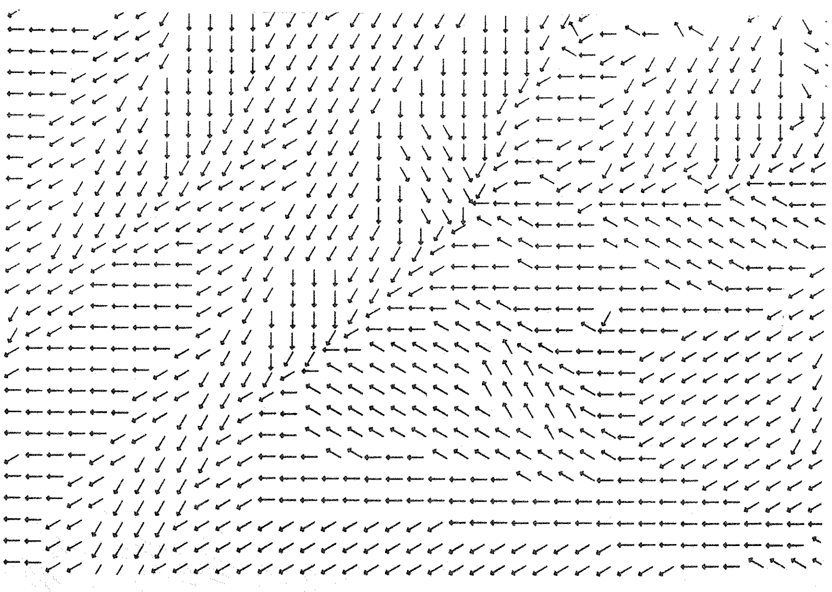

Figure 6: Aspect information in form of vectors at grid points

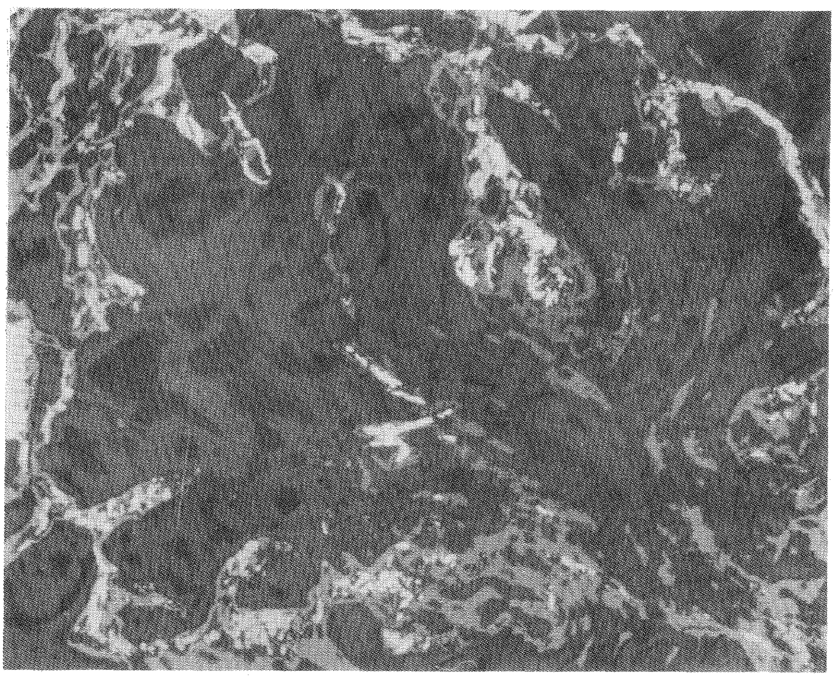

Figure 7: Colour coded representation of slopes

Finally the DTM of the Vernagtferner was combined with representative planimetry information, including the borders between different cover types, such as rock, ice, firn, and old snow. After convertion into raster form, realistic colours were assigned to the areas of the different cover types. The heights associated with the individual raster elements were interpolated from the DTM. This model of cover types and heights was illuminated artificially. From the resulting shaded relief model a perspective view was computed (figure 8).

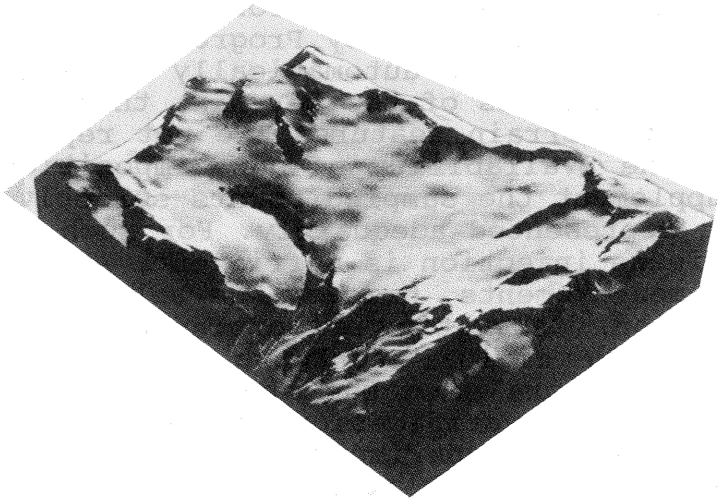

Figure 8: Perspective view of artificially illuminated model of cover types and heights

Besides these utilizations of a DTM two further possibilities shall be mentioned, which may become important in near furture. The first one is the use of a DTM as control information in aerial triangulation [Ebner and Strunz, 1988]. The second one is the production of orthophotos by digital image transformation, using scanned aerial photographs and a DTM [Mayr and Heipke, 1988].

6. On-line verification of DTM

With the growing use of DTM it has turned out that there is a need of suitable methods for DTM quality control. This means checking, whether the DTM represents the terrain within required accuracy. In practice quality control is most often done off-line by means of plotted contours, which are derived from the DTM. However, a rigorous check of these contours is only possible if they can be compared with the stereo model.

Today a comparison of DTM data and the stereo model is possible by optical superimposition. Two concepts are available. In the first case the graphical information is superimposed onto one photo of the stereo model only, and in the second case onto both photos. Practical representatives of these two concepts are the ZEISS VIDEOMAP system [Uffenkamp, 1986] and the stereo image injection of the WILD S9 system [Beerenwinkel et al, 1986].

DTM quality control by superimposition can be carried out in two successive steps. Step one is the verification of the DTM data acquisition and step two the verification of digital contours, derived from the acquired data. Step one starts with the verification of the measured break lines, skeleton lines and characteristic points. In general these geomorphological data are incomplete and incorrect to some extent, because the operator is not able to see what he has measured. The utilization of

superimposition allows for an on-line check with regard to completeness and correctness, because the measured elements are visualized directly in the stereo model. For this check only the visualization as such seems to be decisive so that mono systems are as useful as stereo systems for this purpose.
After that the mass points measured by Progressive Sampling can be checked. Although this method automatically leads to a point pattern matching the roughness of the terrain, there is still a certain risk that some terrain features are not represented in the measured data. The availability of superimposition enables the operator to supplement the sampled points selectively where the terrain is not represented adequately. For such a check of completeness mono image injection is sufficient. A check of the correctness of the measurements, however, is only possible with stereo image injection. Generating a continuous DTM from the acquired data, deriving digital contours from this DTM and superimposing these contours onto the stereo model allows for an even more comprehensive verification of the DTM [Reinhardt, 1988]. If the contours are superimposed onto one photo only, the operator is enabled to check form and density of the contours by comparing them to the local shape of the terrain. Stereo image injection makes a rigorous detection of the discrepancies between contour lines and the terrain possible. DTM verification by superimposition is realized in an on-line mode in the new version of the PROSA program. It makes use of the VIDEOMAP system as well as of the Geographical Information System PHOCUS of Zeiss [Menke, 1988].

The densification of the basic grid by Progressive Sampling and the on-line verification of the DTM is done patchwise. These patches of approximatly eyepice image size are subdivisions of the total area. Within each patch, the previously measured geomorphological data as well as the captured mass points are visualized by means of VIDEOMAP. This enables the operator to check whether the terrain is represented adequately by the acquired data. If this is not the case, Progressive Sampling can be supplemented by selectively measured single points. Within a few seconds after the completion of the data acquisition, a continuous DTM is generated for the whole patch and contours are computed and superimposed onto the stereo model. If these contours do not satisfy the requirements, additional single points can be measured and the DTM as well as the contours can be recomputed.

The DTM consists of a variable grid and triangles according to the general data structure of HIFI-88 (see chapter 4). The contours are available in polygon form, which is sufficient for the purpose of quality control.

The described procedure guarantees that the continuous DTM, finally generated from the measured data is of high reliability and fidelity.

7. Conclusion

Although Digital Terrain Modelling has reached a high standard there is a lot of research still going on. One area is automatic data acquisition by digital image matching (see chapter 2).

Another one is DTM generation from contours with utilization of the geomorphological information, implicitely contained in the contour lines [Inaba et al, 1988]. The results obtained up to now show that skeleton lines can be detected automatically. From the consideration of these data together with the contours, DTMs of excellent quality can be expected.

High fidelity and easy to use DTMs have the potential to replace the existing graphical contour maps and to describe all relevant topographical height information in digital form. They also can and will be integrated into Geographical or Land Information Systems [Ebner and Fritsch, 1986]. The final goal is to obtain fully three dimensional systems with all query possibilities.

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