DERIVATION OF A DIGITAL TERRAIN MODEL
BY DYNAMIC PROGRAMMING

O. Kölbl, I. da Silva
Swiss Federal Institute of Technology / Photogrammetry
GR - Ecublens, CH - 1015 Lausanne
Switzerland
Commission III

Abstract

The paper describes an approach to derive a digital terrain model by dynamic programming. The approach foresees two phases :

1. Height determination along profiles across the photogrammetric models

2. Filtering and smoothing of the data and derivation of the digital terrain model

The programs are developed for the environment of the Kern DSR11 analytical plotter and the Infocam information system.

1 . Introduction

The derivation of a digital terrain model with the help of aerial photographs has become routine work in photogrammetric production. However, a key-role is still assumed by the operator for this type of work. Generally, the following working phases can be distinguished when deriving a digital terrain model :

- Measuring of a regular grid
- Eventually, densification of the grid by progressive sampling
- Measurement of break lines and structure lines
- Computation of the digital terrain model
- Visual control of the computation result and, eventually, editing of the contour lines

In principle, the same working phases must be observed when a digital terrain model is derived automatically; additionally, it must be taken into account that an automatic algorithm primarily does not take into consideration whether the measurements are done effectively on the terrain surface or on obstacles like buildings or trees. It will therefore be necessary to take precautions in order to eliminate points which have not been measured on the terrain surface. In this way, there results a relative complex procedure for the automatic derivation of the digital terrain model which requires several working phases.

Currently, at the Institute of Photogrammetry, a program system is under work for the derivation of the digital terrain model which foresees the following working steps :

- Determination of a bundle of epipolar lines
- Determination of a height profile with the help of dynamic programming

- Precision height measurements in flat regions with the help of multipoint matching
- Filtering and elimination of obstacles and computation of the digital terrain model
- Visual inspection and editing of data

The program system is conceived so as to be integrated in the Kern DSR11 analytical measuring system and in this way gains profit from the particularities of a photogrammetric work station. In the following, the individual working phases are discussed in more detail and the first results of practical work are communicated.

2. The environment for the program development

As already mentioned, the program system has been conceived for the Kern DSR11 analytical stereo plotter Kern DSR11. This plotter is equipped with two digital cameras of the type Hitachi which allow to digitize the central part of the field of view and to transform the digital information for further treatment into the host computer.

The camera has a picture format of 512 x 480 pixels; the pixels projected onto the aerial photographs on the plate carrier correspond to a size of 16 x 13 microns (16 microns in X-direction). In this way, it is possible to digitize with one camera an image section of 8 x 6 mm; this section is smaller than the field of view offered to the operator in the oculars by maximum enlargement (15 x).

In order to keep the storage space requirements relatively small, it is most useful to compute image correlation section by section and to avoid the storage of more than one section. In this way the analog photographs serve as a real image storage device without requiring much space from the digital disk unit. The implementation of the correlational procedure in the analytical plotter still offers other advantages. The instrument disposes of refined basic software for orientation of the aerial photographs and also for the computation of the point coordinates from the derived parallax values. On the other hand, the instrument can easily be used for control measurements. Finally, the tracing table is currently used for graphic presentation of the profiles. Furthermore, while these facilities are of special importance for the software development, it also appears that a real production phase will profit from this environment.

3. Considerations on the measuring algorithm

A relatively high information density is necessary when obstacles covering the terrain's surface should be eliminated by automatic algorithms. Only when the measurements are dense enough is it possible to recognize steep height changes which can be due to a house or a tree. In principle, this high information density can be achieved by point measurement but also line-wise or areal measurements. For technical reasons, it appeared that a line-wise or a profile-wise procedure for elementary measurements would be the most appropriate. This consideration has been enforced by the

requirements for steering the analytical plotter. It is evident that the instrument will only work sequentially and the previous determined values will serve as approximate values for the consequent computations. In this way an algorithm has been adopted, which foresees profile measurements, thus meaning that the whole model is covered by a grid of regular lines which are currently orientated according to epipolar lines, but it is also intended in a second phase to foresee a line grid perpendicular to the epipolar lines.

Currently these profile measurements start from a well defined point given by its coordinates. Subsequently, the profile is treated piece by piece and the subdivision is given by the size of the scanning surface. The profiles result from the succession of the computation of the individual elements, each of these elements requiring a series of operations to be executed :

- Computation of the epipolar lines
- Determination of approximate height values by dynamic programming
- Precision computation of the height profiles with the help of multipoint matching

4. Determination of the epipolar lines

After orientation of a pair of photographs, the epipolar lines can be computed with the help of the orientation elements. In principle, a relative orientation would be sufficient but it is appropriate for the subsequent computation of the height values in the national system to work within a model with absolute orientation. When computing the epipolar lines, it is taken care that they pass through the central part of the camera, which also means that the floating mark of the instrument can be used as a reference for height measurements.

Of course, the relative orientation will always have a limited precision. An imprecise relative orientation but also irregular image deformations might cause considerable residual parallaxes. Consequently, it is necessary to take precautions so as to eliminate local parallaxes. The procedure of multipoint matching allows to introduce beside the X-parallaxes the Y-parallaxes as unknowns. The computed Y-parallaxes can now be used to translate the epipolar lines so that the local parallax is virtually eliminated. It is understood that this correction can only be carried out on the subsequent working surface, nevertheless such a procedure allows to reduce substantially the residual parallaxes.

A careful control of the residual parallaxes is necessary when using an algorithm which only determines the X-parallaxes. For dynamic programming, it would require a considerable amount of computation if the Y-parallax should be included. Moreover, such a procedure would reduce considerably the reliability of this search algorithm. Nevertheless a strong effect of Y-parallaxes has been observed on details with sharp borders nearly parallel to the epipolar lines. The precaution taken by computing the Y-parallaxes from multipoint matching proved very efficient.

Principally, the image correlation will be achieved with a whole bundle of epipolar lines. Currently a bundle of 25 lines is used. For the computation of the grey values of the epipolar lines, the whole image is first stored in the frame buffer. After the computation of the position of the epipolar lines, the grey values are computed by re-sampling; this re-sampling can be done optionally by nearest neighborhood interpolation by bi-linear or bi-cubic interpolation. For technical reasons, the grey values of the epipolar lines are stored in a second frame buffer. The structure of the host computer requires a strong segmentation and also a subdivision of the computation programs. Different jobs, however, cannot accede to the same files as long as these files are not definitively closed. Therefore the use of a second frame buffer proved extremely useful (cf. also [1] and [2]).

5. Dynamic programming

5.1 General principle

The dynamic programming has been developed in the United States during World War II; it was intended as a mean to determine the most economical connection between two towns for troup displacement [3]. The algorithm is essentially a search process which analyzes all possible connections between the two end points. In order to reduce the number of possible solutions, the way is subdivided in a number of intervals containing different node points. The next phase is the establishment of the cost matrix determining the cost for each possible connection of two successive nodes (cf. Fig. 1).
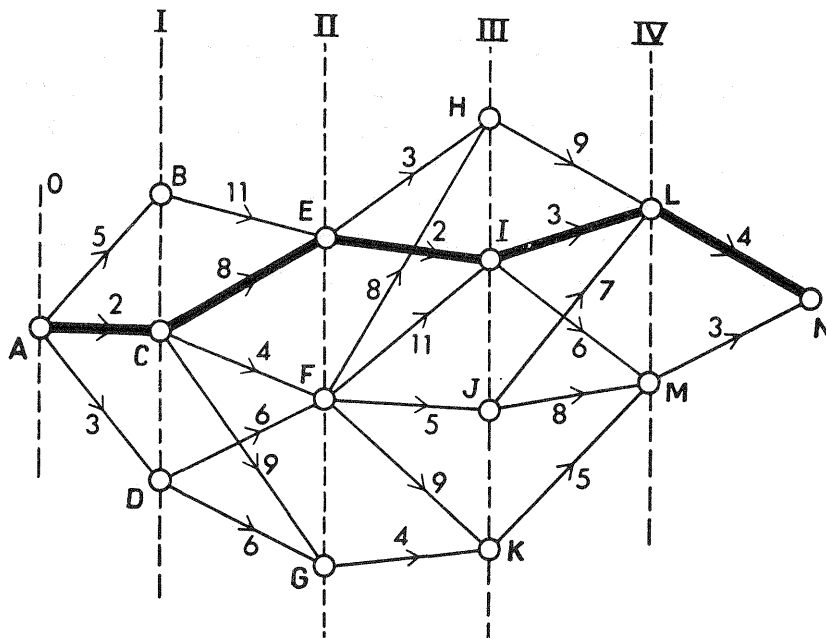

Fig. 1
Determination of the optimum path between the end points **A** and **N** by dynamic programming.

Subsequently, the algorithm computes the optimal way for each node point of an interval, taking into consideration the preceding optimal path already determined. This optimal path to the specific node point is retained and will not be changed anymore during the following computations.

The correlation between homolog images can be computed according to this principle. The costs will be determined as the differences of the grey values between the corresponding picture elements; it is understood that also other arguments than the grey values as for example the changes of the grey values and edges can be used for the cost computation.

5.2 Application of dynamic programming for height correlation

In order to explain the use of dynamic programming for image correlation, we follow the Viterbi algorithm as it was presented by Benard [2]. According to this method, we compute in the first phase the cost matrix. This cost matrix gives the discrepancies between the vector of grey values of the left (f_i) and the right image (g_i) in all combinations.

f_i :	2	2	4	6	8
g_i	cost values :	$c_{ij} =$	$\mid f_i - g_i \mid$		
2	0	0	2	4	6
4	2	2	0	2	4
6	4	4	0	2	4
8	6	6	4	2	0

Subsequently, the cumulated cost matrix is computed; this cumulated cost matrix presents the optimum path to all nodes, which means that the sum is formed between the preceding element and the element in consideration by taking care that only the smallest value will be stored. Additionally a smoothing factor is introduced in order to avoid that the optimal path ondulates too vigorously. This smoothing factor is multiplied by the number of dislocations between the optimum sum of the previous element and the considered element. This value is then added to the cumulated cost value.

$$F_{11} = C_{11} \qquad F_{12} = C_{12} \qquad F_{13} = C_{13}$$

$$F_{21} = \text{Min} \left(F_{1i} + C_{21} + \Delta F \left(1 - i \right) \right) \qquad F_{22} =$$

$$F_{31} = \text{Min} \left(F_{2i} + C_{31} + \Delta F \left(1 - i \right) \right)$$

$$\Delta F = \text{shifting factor}$$

The matrix of cumulated costs is calculated for the whole area to be treated. The minimum value of cumulated costs in the last line of the matrix is a guide-value to retrace the optimum path throughout the whole matrix.

5.3   Quality assessment of the optimum path

An important parameter for the analysis of an ordinary least square adjustment is definitely the root mean square error σ_0. A similar value can also be derived in dynamic programming. The minimum cumulated cost value which served to trace back the optimum path can be considered as an equivalent to σ_0. This value is the sum of the absolute values of the discrepancies between the two images, increased by the smoothing values. By dividing the minimum cumulated cost value by the number of lines of the matrix, a measure for the precision of the optimal path is obtained. Similarly, parallaxes of all individual pixel values as given by the optimum path can also be analyzed.

5.4   Extension of dynamic programming to a 2-dimensional surface

Up to now, the description of the dynamic programming has been limited to the comparison of two vectors, which correspond to the grey values of two epipolar lines. The extension of dynamic programming to a 2-dimensional section requires the introduction of an additional degree of freedom which allows for height variations perpendicular to the profile axes (cf. Fig. 2). This extension is possible with the introduction of a 3-dimensional cost-matrix; such a procedure demands a considerable higher computation time and more storage space. The large advantage of it is the treatment of a larger surface for image correlation, and a much better suppression of noise ensuring a more stable correlation procedure.

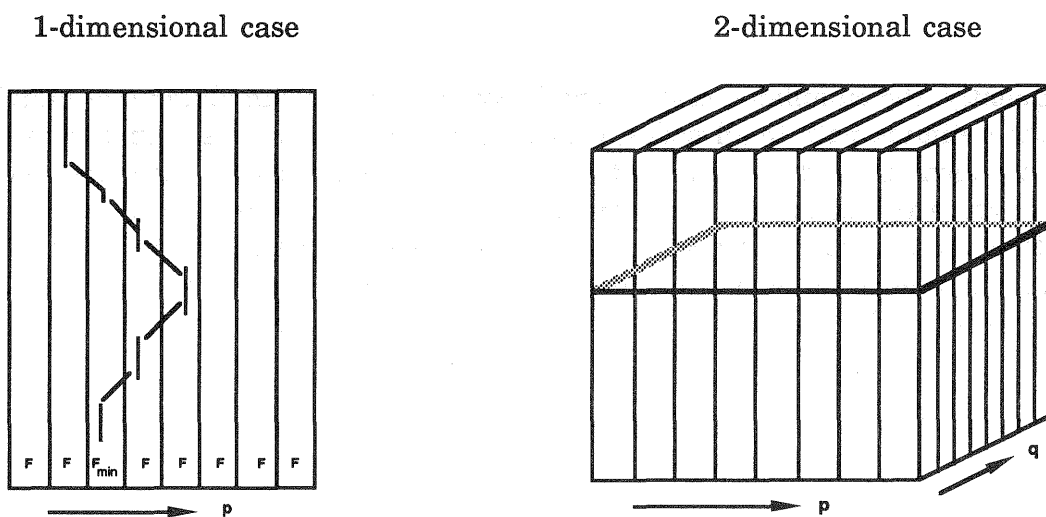1-dimensional case   2-dimensional case

Fig. 2
Structure of the cost matrix and of the matrix of cumulated costs for treatment of a single epipolar line (1-dimensional case) and a bundle of epipolar lines (2-dimensional case) with additional freedom for a cross inclination in height (q) beside height variations in profile direction (p).

6. Multipoint matching

The precision of dynamic programming is limited to the size of a pixel according to its principle. For the present work, the computation unit has been increased up to 2 and 4 pixels, mainly in order to reduce computation time. Consequently, the obtained results will be no better than approximatively 1% of the flying height. In order to increase the height precision it was necessary to incorporate an interpolation procedure.

In a first phase, the method of least square matching has been used for interpolation. However, it showed that this concept was not sufficiently flexible and subsequently the mathematical model was enlarged according to Rosenholm's proposal [5]. According to this proposal, the terrain is approximated by finite elements instead of a plain surface. In accordance with dynamic programming, the multipoint matching too was limited to a relatively narrow bundle of epipolar lines; the terrain was therefore approximated only by chain of finite elements. This precaution limited considerably the number of unknowns to be solved. Beside the X-parallaxes in the nodal points of the finite elements, two further unknowns have been introduced in order to compute a conxtant Y-parallax for the whole treated segment and in order to adapt the grey values of the two homolog images.

7. Filtering and Smoothing of the Measuring Results

The results of automatic height measurements present only partly the height of the natural terrain. As already indicated, obstacles like buildings or vegetation cover will be included in these measurements. Especially in large scale work where height precision superior to ± 3 to ± 5 m is required are these measurements not immediately acceptable. In order to eliminate these obstacles different approaches can be chosen. The most obvious way would be to recognize the houses or vegetation covers by an appropriate algorithm of pattern recognition, a rather long and tedious procedure. The efforts have therefore been concentrated on detecting apparent height irregularities and on smoothing them, and only in a second phase will elements of texture analysis be included in order to make this procedure more reliable.

For height smoothing different approaches have been analyzed. The most simple approach would be to smoothen the individual profiles. Some work has been done in this sense by using tools of artificial intelligence (cf. [6]). It showed however that the information of individual profiles does not allow to remove all ambiguities and thus would not lead to the desired reliability. It appeared consequently useful to opt for two dimensional interpolation algorithms like least square interpolation or Kriging or by finite elements. As one of the main tasks of this algorithm will be the detection of errors, it appeared appropriate to use an algorithm with a rigorous mathematical model and therefore preference was given to the finite elements.

7.1   Basic Concept of Filtering by Finite Elements

By the method of finite elements the terrain surface is covered by a succession of elementary surfaces; these surfaces are easily described by mathematical functions. When these elementary surfaces are chosen larger than the average distance between the measuring points then there will result a smoothing effect. Additionally the constraints between adjacent elements will enhance this smoothing effect. It is evident that the height determinations are the observations for which the least square solution will be adopted.

The use of finite elements for terrain approximation is a well known technique in digital terrain modelling. Most software systems use triangles as elementary surfaces; very often the tops of the triangles coincide with the measured height points. An advantage of the triangles is their flexibility

7.2   Blunder Detection

For blunder detection two different types of errors should be distinguished :

- Measuring errors due to weak correlation
- Points not measured on the ground

The correlation values resulting from dynamic programming and multipoint matching can be characterized by a number of values which give indications on the precision. These precision indicators are used to compute in a first approximation a terrain model with only highly reliable values. In the following phase, less reliable values - measured for example in a meadow with poorer contrast - are successively included.

In the second phase, obstacles hindering the terrain view are eliminated. In this phase, the usual algorithms for blunder detection can be used. In the first phase we worked with the procedure developed by Baarda; later on, a method for robust estimators was used.

7.3   Practical Results

The computation programs are still in development, nevertheless first results can be given. The input data are 6 height profiles computed by dynamic programming. The area is a zone of villas with some trees (cf. Fig. 3). The height profiles measured in a distance of 5 m follow rather consequently all obstacles. In the first iteration no special precautions are taken for filtering and the computed terrain model is about 1-2 m above the ground (cf. Fig. 4). By successive elimination of residuals designed as blunders the computed surface approaches more and more the terrain.

It is evident that a proper height presentation of the terrain cannot be done without breaklines; it is intended to also derive the breaklines from the measured profiles and including the grey values.

The derivation of a digital terrain model from the measured profiles can also be considered as a data compression procedure. Automatic height measurements produce
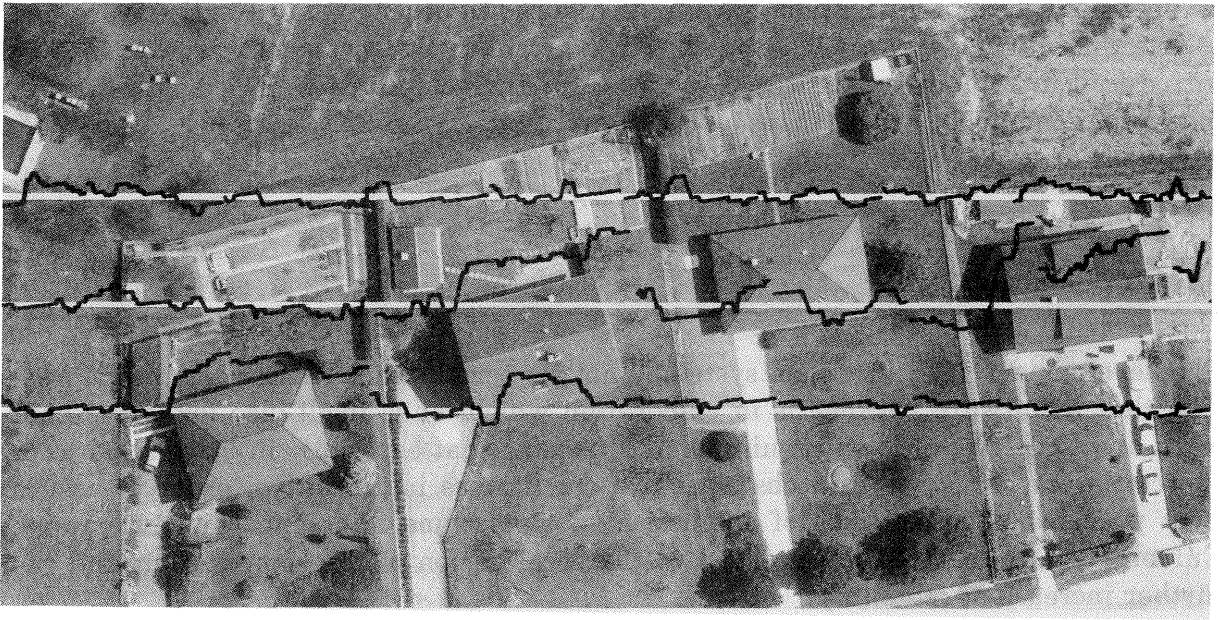
Fig.3
Overlay of a selection of the height profiles resulting from dynamic programming with a section of the aerial photograph.
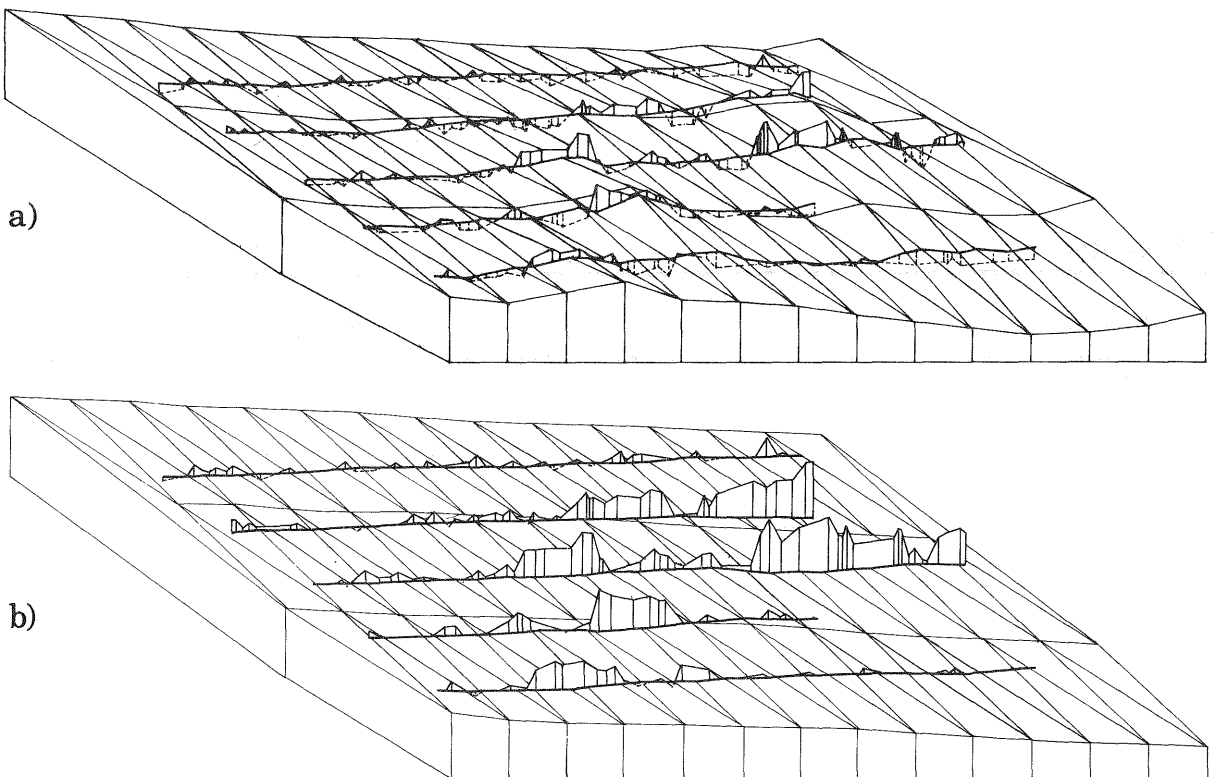

a)

b)

Fig. 4
Digital terrain model, computed by finite elements from 5 measured height profiles :
a) without precaution for elimination of obstacles
b) after filtering of terrain obstacles

an enormous bulk of data which have to be reduced in order to gain storage space and to obtain a set of data easily manipulable. The data derived from smoothing can then be introduced in a more sophisticated program for the computation of a digital terrain model for contouring, visual inspection and eventually edition.

8. Conclusions

The development of the program system is not yet terminated. There rises the impression that a software package is in elaboration which lends itself also for large scale work and for high precision requirements. It seems that especially in large scale work the considerations of terrain obstacles are much more important in order to assure high precision than the use of sophisticated algorithms for height measurements. Currently, a great attention is given to the acceleration of the computation and the further increase of reliability.

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