AUTOMATIC BREAKLINE DETECTION USING AN EDGE PRESERVING FILTER

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ABSTRACT:

Breaklines are important morphological quality features of a digital elevation model (DEM). They represent areas of local maximum surface curvature and must be adequately described by the geometrical model of the DEM package in use. Most of today' s software packages for automatic DEM generation utilize breaklines which have been measured in advance by the human operator. This purely interactive process is time consuming and hence costly. In order to overcome this drawback, we propose a procedure which automatically detects breaklines during the DEM generation process. The method would reduce the interactive input of the operator to a minimum and increase the economical efficiency of automatic DEM generation.
Basically, conventional DEM filter methods are disadvantageous if they are applied to sharp height changes of the terrain. They do not take into consideration structures in the data and therefore they may also lead to a loss of information. Edge preserving filters are more flexible and largely avoid the elimination of breaklines. The advantage of the implemented method in **MATCH-T** is the detection of local surface areas of maximum curvature. In such areas the spacing of the DEM posts is automatically decreased and hence, discrepancies between the true terrain and the DEM are minimized.
The paper presents a new approach to breakline detection which is based on the principle of adaptive edge preserving filters. It outlines the procedure and its application to DEM breaklines. Practical results are presented referring to an open pit coal-mine area and an area of mountainous terrain. It is shown in particular, how breakline points and breakline directions are automatically detected in breakline areas.

1 INTRODUCTION

Digital elevation models (DEM's) are used to represent the surface in a reduced amount of data. The main information about a surface is represented in structure lines (e.g. breaklines). To minimize the model error caused by the spacing of the DEM posts and the discrepancies between the DEM and the true surface it is necessary to record the structure lines as 3D-polylines. This information is used to fit the DEM to the real terrain and to reduce the spacing of the DEM posts in the breakline areas.

A number of software packages for automatic DEM generation can handle breaklines, but all approaches have in common that the breaklines have to be measured in advance. If they have no knowledge about the morphological structure, the DEM is globally smoothed since sharp height changes of the terrain cannot be detected. In order to overcome this drawback, we present a method of DEM generation which preserves and detects breaklines using an adaptive edge preserving filter in a robust finite element adjustment.

The investigated approach uses curvatures and torsion as additional observations in the least squares adjustment. The local maximum surface curvature and the local breakline direction are derived from the residuals of that curvature and torsion observations. The terrain discontinuities are preserved by weighting the curvature and torsion observations in dependence on their residuals and considering the breakline direction during the subsequent filtering process. The weighting of the observations is based on two weighting functions and is able to eliminate gross errors in the data. Hence the influence of the gross errors is minimized.

The results of the adaptive edge preserving filter are DEM posts that lie approximately at breaklines. The accuracy of the approximation is largely dependent on the spacing of the DEM posts. The first goal of the adaptive edge preserving filter is the detection of local surface areas of maximum curvature. At such areas the spacing of the DEM posts is automatically adapted and hence, discrepancies between the true terrain and the DEM are minimized.

The next development step is to subsequently tie up the DEM posts with the maximum terrain surface curvature as 3D polylines by using the breakline direction that is also assessed by the filter. The connections of the approximate breakline points to structure lines represent the first geometrical approximation of the surface structure. Those initial breaklines derived solely in object space are verified against gray value edges in image space which are derived by applying a gradient operator to the images. The final breaklines are evaluated by fitting an object model (e.g. spline) to the breakline points corresponding to gray value edges.

The approach presented here avoids to initially start the breakline detection from image space since gray value edges does not necessarily correspond to breaklines. Instead, breaklines are analyzed in object space using an edge preserving filter method and are tracked back into the images by verifying them with gray value edges.

The paper outlines the mathematical background of the adaptive edge preserving filter for the DEM generation. The DEM and the addition breakline information are the basis in the concept of the automatic breakline detection. The practical results of the examples represent the state of development of the automatic breakline detection using an edge preserving filter method.

2 MATHEMATICAL MODEL OF DEM GENERATION

2.1 General remarks

Surface reconstruction as a part of the whole DEM generation has to cope with terrain discontinuities (e.g. breaklines, ridges, valleys) and gross errors in the data. A widely used approach for surface reconstruction is the modelling of the surface with finite elements (Ebner et al., 1984). Thereby, also curvature and torsion constraints are introduced to regularize the system in areas where surface information is missing (Krzystek, 1995). In **MATCH-T** (Ackermann , Krzystek, 1991) this basic idea was extended by introducing the principles of robust statistics (Huber, 1981, Förstner, 1989) for the elimination of single height blunders and the detection of discontinuities.

The first investigations were based on an edge preserving filter which maintains the discontinuities only if they were parallel to the object coordinate system (Wild, 1990). In order to overcome this drawback we pass over to use an adaptive edge preserving filter. Thus, we are able to adapt the filter direction according to the corresponding direction of the discontinuities. The advantage of the adaptive filtering is a better edge detection and hence a lower smoothing of discontinuities.

The knowledge about the direction of the surface structure elements leads to an advantageous side-effect. In combination with the result of the robust statistics we additionally are able to localize the surface areas of maximum curvature. To reduce the model errors we utilize these informations and adapt the spacing of the DEM posts in areas of detected discontinuities.

2.2 Model based on global edge preserving filter

For the surface reconstruction we use a bilinear finite element interpolation. To stabilize the adjustment we introduce smoothness constraints. The smoothness constraints used here are the curvatures and torsion, whose expectations are assumed to be zero.

The mathematical model for the surface reconstruction of a DEM with n*m=M grid points is represented with 4 kinds of observations and the following observation equations.

$$\begin{aligned} z_p + v_p &= a_1^T \underline{\hat{z}} \\ z_{xx}(i,j) + v_{zxx}(i,j) &= a_2^T \underline{\hat{z}} \\ z_{yy}(i,j) + v_{zyy}(i,j) &= a_3^T \underline{\hat{z}} \\ z_{xy}(i,j) + v_{zxy}(i,j) &= a_4^T \underline{\hat{z}} \end{aligned}$$

z_p = height of a masspoint P

z_{xx} , z_{yy} = curvature with $E(z_{xx})=E(z_{yy})=0$

z_{xy} = torsion with $E(z_{xy})=0$

$v_{\dots}$ = residuals of the observations

$\underline{\hat{z}}$ = (Mx1) vector of the unknown grid heights

a_1^T = vector with the coefficients of the bilinear interpolation

a_k^T = vectors of the convolution kernels (k=2,3,4)
a_2^T...: curvature in X-direction
a_3^T...: curvature in Y-direction
a_4^T...: torsion

The system is completed by the stochastic model that represent the weight matrices of the introduced observations and their a-priori standard deviations.

$$\begin{aligned} P_{z_p} &= \mathrm{Diag}\,(\sigma_0^2 D^{-1}(\sigma_{z_p}^2)) \\ P_{z_{xx}} &= \mathrm{Diag}\,(\sigma_0^2 D^{-1}(\sigma_{z_{xx}}^2)) \\ P_{z_{yy}} &= \mathrm{Diag}\,(\sigma_0^2 D^{-1}(\sigma_{z_{yy}}^2)) \\ P_{z_{xy}} &= \mathrm{Diag}\,(\sigma_0^2 D^{-1}(\sigma_{z_{xy}}^2)) \end{aligned}$$

The mathematical model is robustified by the application of weighting functions. They modify the a-priori weights of the observations with the size of their normalized residuals nv. As suggested by Förstner (1989) and Krarup et al. (1980) the weighting functions

$$w_1(nv) = \frac{1}{\sqrt{\left(1+(nv)^2\right)}} \qquad\qquad w_2(nv) = \exp^{-(nv)^2}$$

are used for the modification of the observation weights. The weight function $w_1(nv)$ is used for the elimination of the gross errors (e.g. mismatches) and the weight function $w_2(nv)$ is used for the elimination of the small errors (e.g. 3D obstacles, breaklines). The weight modification is applied in a 2-phase Gauß-Markoff process.

$$\begin{aligned} P_{z_p}^{(\nu+1)} &= P_{z_p}^{(0)} * w_i(nv_{z_p}^{(\nu)}); & P_{z_p}^{(\nu+1)} &< T & &\Rightarrow P_{z_p}^{(\nu+1)} = 0 \\ P_{z_{xx}}^{(\nu+1)} &= P_{z_{xx}}^{(0)} * w_i(nv_{z_{xx}}^{(\nu)}); & P_{z_{xx}}^{(\nu+1)} &< T & &\Rightarrow P_{z_{xx}}^{(\nu+1)} = 0 \\ P_{z_{yy}}^{(\nu+1)} &= P_{z_{yy}}^{(0)} * w_i(nv_{z_{yy}}^{(\nu)}); & P_{z_{yy}}^{(\nu+1)} &< T & &\Rightarrow P_{z_{yy}}^{(\nu+1)} = 0 \\ P_{z_{xy}}^{(\nu+1)} &= P_{z_{xy}}^{(0)} * w_i(nv_{z_{xy}}^{(\nu)}); & P_{z_{xy}}^{(\nu+1)} &< T & &\Rightarrow P_{z_{xy}}^{(\nu+1)} = 0 \end{aligned}$$

T = threshold for weights

ν = iteration steps

$P_{\dots}^{(0)}$ = original observation weight

$w_i(\dots)$ = weighting function (i=1,2)

Observations with large normalized residuals are weighted down, and are even eliminated if a given threshold T for the observation weights is reached during the iteration. The solution for the vector $\underline{\hat{z}}$ of all unknown DEM heights is found by minimizing the following function in each iteration step

$$f\,(\underline{\hat{z}}, \underline{\sigma}_{zp}, \underline{\sigma}_{zxx}, \underline{\sigma}_{zyy}, \underline{\sigma}_{zxy}) = \sum_{k=1}^{4} (\, \underline{v}_k^T \, P_k^{(\nu)} \, \underline{v}_k)$$

ν = iteration steps

k = observation type

until the estimated standard deviations of observations (a-posteriori) become constant or reach a given threshold.

A DEM generation process using an edge preserving filter without the adaptive option provides results with the expected accuracy as long as the direction of the discontinuities are about parallel to the object coordinate system. Otherwise, the surface characteristic features are not recognized in its entirety and will be smoothed. In order to overcome this drawback we pass over to use an adaptive edge preserving filter

2.3 Model based on adaptive edge preserving filter

The next step for the creation of an adaptive edge preserving filter is the consideration of a further structure information for the surface reconstruction. The system utilizes the direction of the local curvature maximum for the filtering of the DEM. For the first iteration phase of the DEM generation process the direction information is unknown and therefore introduced with the value of zero. Hence the result from the first iteration corresponds to a surface reconstruction process based on an edge preserving filter without an adaptive attribute.

The information about the surface curvature properties for the location (i,j) {i=1,n / j=1,m} is fully contained in the so called Hessian matrix (Weidner, 1994).

$$H(i,j) = \begin{bmatrix} a_2^T \hat{\underline{z}} & a_4^T \hat{\underline{z}} \\ a_4^T \hat{\underline{z}} & a_3^T \hat{\underline{z}} \end{bmatrix} = \begin{bmatrix} H_{11} & H_{12} \\ H_{21} & H_{22} \end{bmatrix} \qquad \text{and } H_{12} = H_{22}$$

For the evaluation of the structure direction for the $(\nu+1)$. iteration we have to use the curvature information in the Hessian matrix of the ν. iteration. The rotation of eigenvector of the maximum eigenvalue of the Hessian matrix represents the direction of the local curvature maximum.

$$\phi(i,j) = \frac{1}{2} \cdot \arctan\left(\frac{2\,H_{12}(i,j)}{H_{11}(i,j) - H_{22}(i,j)}\right) \qquad -\frac{\pi}{2} \leq \phi(i,j) \leq +\frac{\pi}{2}$$

$H_{\ldots}$ = Hessian-matrix elements in point (i,j)

$\phi(i,j)$ = direction of local curvature maximum

In the $(\nu+1)$. iteration the implemented algorithm utilizes the directions of the local curvature maxima for the filtering of the DEM. If we introduce the mentioned angle in the convolution kernels of the curvatures and torsion (a_2^T, a_3^T, a_4^T) we get the principal curvatures for the filter process. The maximum curvature (a_2^T), the minimum curvature (a_3^T) and the torsion (a_4^T with the expected value of about zero) do not correspond to the X- and Y-direction any more.

Using an (5*5) window for the evaluation of the direction of a local curvature maximum allows an angle determination with an accuracy of about $\pm 1^{\circ}$. The reliability of the direction determination depends on the spacing of the DEM posts and the roundness of the Hessian matrix.

The mathematical background corresponds to chapter 2.2 except for the convolution kernels of the curvatures and torsion. Thus, the detection of local curvature maxima is not depending on the rotation of the structure direction against the object coordinate system.

3 CONCEPT OF AUTOMATIC BREAKLINE DETECTION

3.1 General remarks

The scheduled concept for the automatic breakline detection is shown in figure 3.1 and represents the whole program flow of the system. All program steps will be executed during one pyramid level of the image pyramid used by **MATCH-T**. The number of pyramid levels depends on the image resolution and the image size and will be laid out automatically.

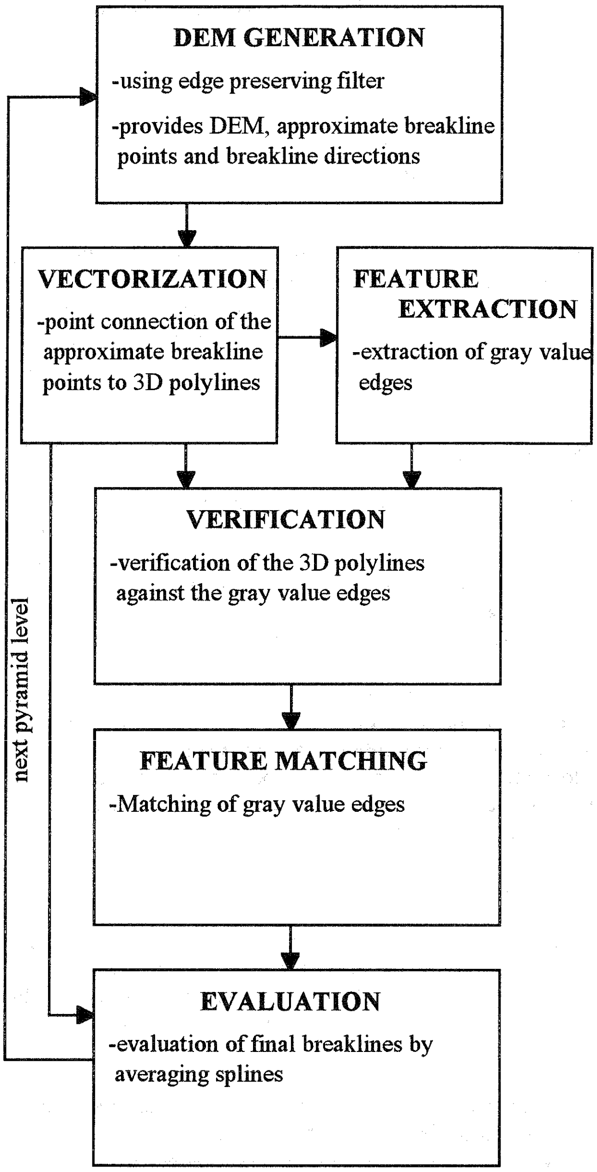

Figure 3.1: Concept for automatic breakline detection

After the DEM generation and the automatic breakline detection for pyramid level (i) have finished, the result of the system (DEM, final breaklines) will be introduced as premeasured morphological information into the next pyramid level (i+1). Once all pyramid levels have been processed by using the automatic breakline detection the system provides a DEM which consider the surface structure more precisely.

In breakline areas we are able to adapt the spacing of the DEM posts corresponding to the local surface areas of maximum curvature. The discrepancies between the DEM posts and the true terrain was minimized by using the breakline information.

3.2 DEM Generation

The use of the adaptive edge preserving filter for the DEM generation in **MATCH-T** provides the DEM and approximations for breakline points with the corresponding breakline directions. The implemented method detects local surface areas of maximum curvature and determines the direction of maximum curvature with the eigenvalue of the Hessian matrix. The result is an approximate point information of the surface structure.

3.3 Vectorization

The point information of the surface structure is not very useful for the further consideration during the surface reconstruction. Therefore it is necessary to subsequently tie up the approximate breakline points as 3D polylines by using the approximate breakline directions. The result is a rough vector representation of the surface structure. These approximate breaklines sufficiently represent the structure in object space and can be used as a preliminary description of the surface characteristic features.

3.4 Feature Extraction

The information about the gray value edges, hence the information about possible 3D structure lines, is fully contained in a gradient operator (e.g. Sobel operator). Therefore we try to merge the structure information from the object space and from the image space. To get these 2D structure lines only in the areas we are interested in, the initial breakline areas have to be transformed into the image space. The gradient operator has to be applied in the projected breakline areas and provides 2D polylines in image space, that correspond to the approximate 3D polylines in object space.

3.5 Verification

The proposed method avoids to initially start the breakline detection from image space since gray value edges do not necessarily correspond to breaklines. On the other hand if breaklines are detected in object space and are tracked back into the image space by verifying them with gray value edges, they correspond to real breaklines. Hence, we compare the transformed 3D polylines from the vectorization with the 2D polylines from the feature extraction and determine the gray value edges which correspond to real breaklines. Thus, the result is the remaining gray value edges and hence breakline features in the image space.

3.6 Feature Matching

The matching part of the automatic breakline detection contains the matching of the elements of the remaining gray value edges in the image space and the transformation in the object space.

3.7 Evaluation

The final breaklines are optionally evaluated by fitting an object model (e.g. averaging spline) to the breakline points corresponding to gray value edges.

4 PRACTICAL RESULTS

4.1 General remarks

The practical investigations refer to the already existing part of the development - DEM generation. They elucidate the differences of the mentioned filter methods (chapter 2). The results of the first geometrical approximation of the breakline areas and the corresponding breakline directions presented for an open coal-mine excavation area and a mountainous terrain are shown.

4.2 Properties of the filter methods

The differences of the global and adaptive filtering of the DEM takes the most effect for structure lines not parallel to the X- or Y-direction of the object coordinate system. Therefore we show the different effects of both filter methods for a rectangular area defined in object space which contain the mentioned structure lines (e.g. road, forest).

The following DEM's in this chapter refer to the indicated part of the mountainous data sample and correspond to the marked image section in figure 4.1.

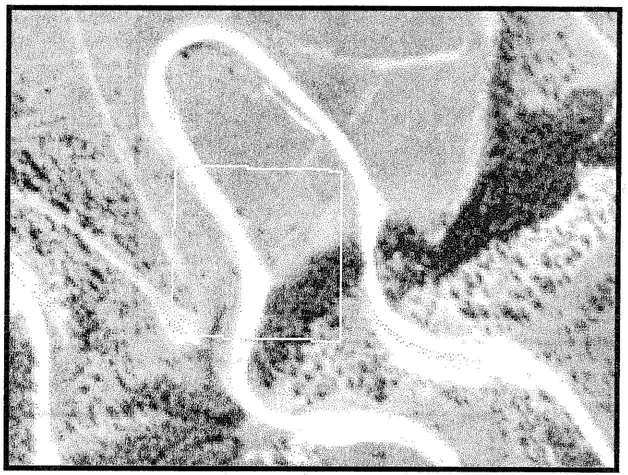

Figure 4.1: Image section corresponding to the DEM

Figure 4.2 and figure 4.3 show the DEM's of the global filtering and adaptive filtering for the surface reconstruction. Both filter methods represent an edge preserving filter but nevertheless they provide a different result. The height differences of the DEM posts are summarized in a differential DEM in figure 4.4.

$$h_{diff} = h_{global} - h_{adaptive}$$

The main differences obviously occur in areas of local curvature maximum, where the corresponding breakline direction is not parallel to the X- and Y-direction (i.g. road). That means, these breaklines are better recognized by the adaptive edge preserving filter, hence the smoothness constraints (curvatures, torsion) are more weighted down. Therefore more discontinuities in the data are maintained and the reliability for the automatic detection of the approximate breakline points and the corresponding directions are more efficient.

Model errors due to the spacing of the DEM posts, determine to a large extent the accuracy of the DEM. The adaptive filter method optimizes the detection of discontinuities, especially of breaklines rotated against the object coordinate system. This optimal detected structure information is used to adapt the grid width in the breakline areas. Thereby we are able to minimize these model errors by using the adaptive filter method.

The influence of the adaptive characteristic on the DEM is restricted to undulating terrain. In areas of local curvature maximum we have positive or negative height differences in the differential DEM. The sign of the curvature determines the sign of the height difference. Basically the global filter method smoothes structure lines during the surface reconstruction which are not fully recognized.

If the structure feature represent a valley (positive curvature), the adaptive filter method lead to a less height of the DEM posts in comparison to the global filter method. If the structure feature correspond to a ridge (negative curvature) it is vice versa.

$h_{diff} > 0$ (positive curvature)

$h_{diff} < 0$ (negative curvature)

In flat terrain the height differences between the globally filtered DEM and the adaptively filtered DEM are negligible.

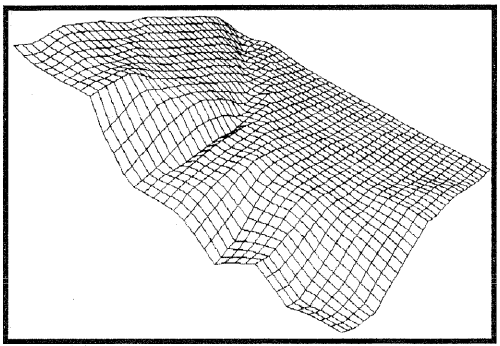

Figure 4.2: Globally filtered DEM

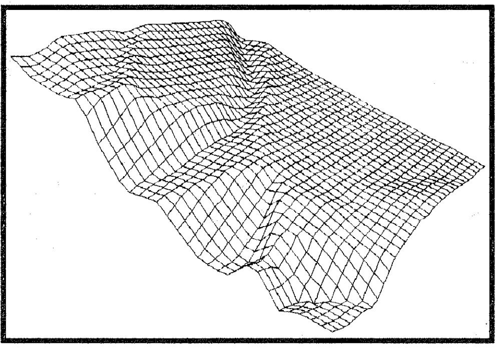

Figure 4.3: Adaptively filtered DEM

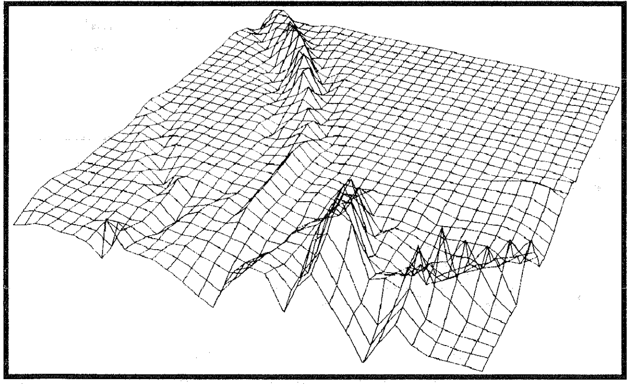

Figure 4.4: Differential DEM

The quantitative difference is expressed by the r.m.s. height difference and amounts to

$$\text{r.m.s.} = \sqrt{\frac{\sum (dd)}{n}} = 0.64 \text{ m}$$

d = height differences of the DEM posts

n = number of DEM posts

Finally we conclude that, the use of the adaptive edge preserving filter takes effect in areas of breaklines not parallel to the X- and Y-direction of the object coordinate system. Because of this the recognition of small surface undulations reacts more sensible leading to a better success rate in automatic breakline detection and grid width adaptation.

4.3 Derivation of structure information

The first step for the automatic breakline detection is the derivation of structure information (approximate breakline points and corresponding local breakline directions) in the object space during the DEM generation process. The implemented adaptive edge preserving filter provides this information. For that reason we use this surface reconstruction method to deal with the following data.

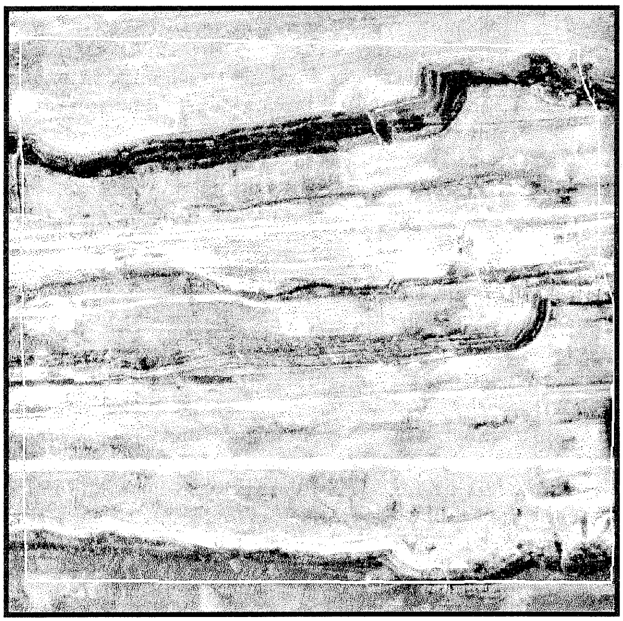

Figure 4.5: Open coal-mine excavation area

Figure 4.6: Mountainous terrain

The investigated areas for the automatic breakline detection are rectangular areas defined in the object space corresponding to the marked areas in the digital images above. The details for the used projects are summarized in the following table.

	Open coal-mine excavation	**Mountainous terrain**
image scale	1 : 8000	1 : 8400
image resolution	15 µm	30 µm
image type	black / white	black / white
DEM size (X/Y)	540m / 640m	700m / 800m
max./min. spacing	12m / 3m	16m / 4m
min. / max. height in the object space	15m / 106m	1913m / 2199m
number of automatic detected breakline points	3911	3170

Table 4.1: Details of the projects

The first practical applications refer to the current state of the development (chapter: 3.2). The following figures contain the final results of the DEM generation process using an adaptive edge preserving filter. The derived structure information is superimposed to the DEM's and symbolizes the local surface areas of maximum curvature in the object space.

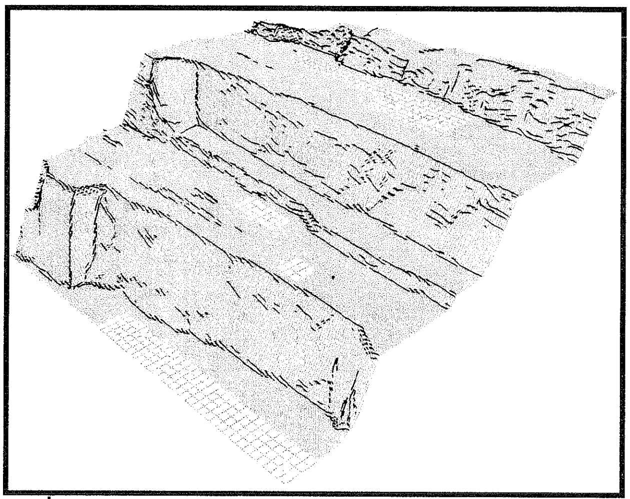

Figure 4.7: DEM of open coal-mine excavation area

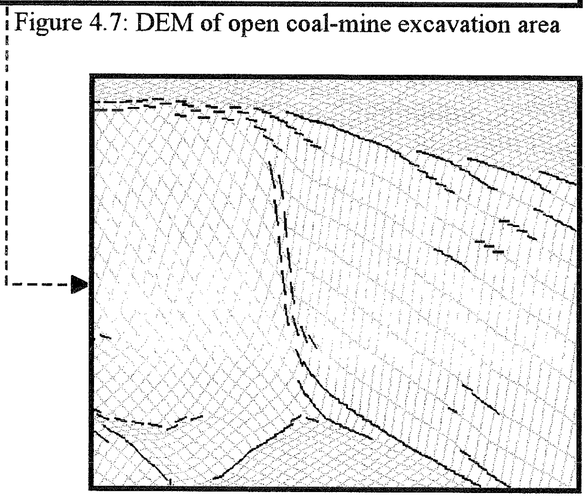

Figure 4.8: Breakline area (detail)

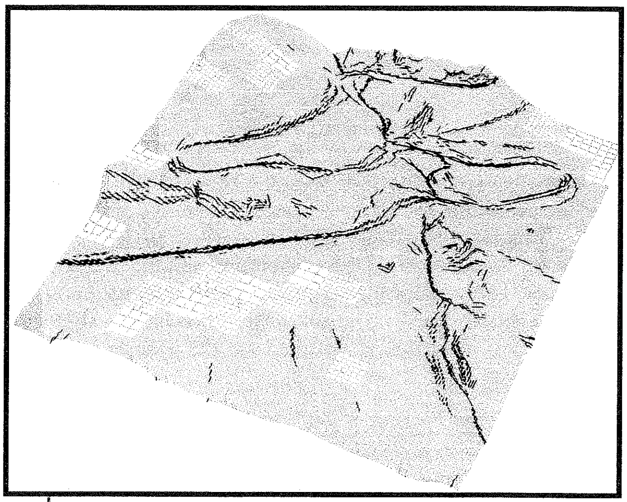

Figure 4.9: DEM of mountainous terrain

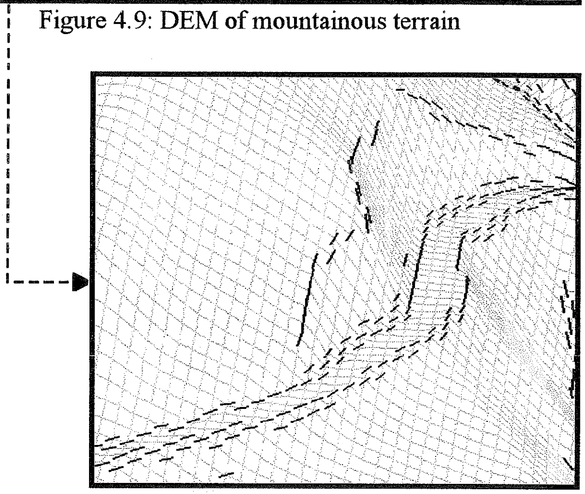

Figure 4.10: Breakline area (detail)

The representation of the breakline points and their corresponding breakline directions are realized by vectors. The vectors direct to the local minimum of curvature, hence the direction of the local maximum of curvature is perpendicular to those vectors.

The detail figures elucidate the reliability of the breakline detection. The first geometrical approximation of the breaklines depends on the spacing of the DEM posts to a high degree. An unsuitable grid width (e.g. grid width too large) can lead to difficulties due to the vectorization of the point information.

The algorithm derives a band of vectors in some breakline sections along the real breakline. Only breaklines parallel to the object coordinate system provide a clearly breakline description. During to the fact of ambiguities during the vectorization of the point information we are forced to generalize the gained result for the next steps of the breakline detection (chapter 3). But nevertheless, the band of points to the left and right of the real breakline is a sufficient representation of the breakline for the surface reconstruction.

To increase the reliability of the breakline detection and to minimize the model error caused by the quantization of the DEM we introduced the variable grid width indicated in the DEM presentations above. The automatic adaptation of the grid width is controlled using the extracted breakline information. In comparison with breakline areas it is not necessary to cover surface areas of poor undulations with the same point density.

5 CONCLUSION

The paper presents the developments of the edge preserving filter for the automatic DEM generation. The use of the adaptive information preserving filter is proved to be a suited method for the automatic DEM generation and the detection of breaklines. The concept for the processing of the results of the surface reconstruction (e.g. approximate breakline location and corresponding direction) is outlined for the automatic breakline detection.

It is a well-known fact, that linear filtering leads to a loss of information due to the global smoothing, regardless of structures in the data. Therefore we passed over to information preserving filter methods. At first we investigated a global edge preserving filter without an adaptive property. This application has the disadvantage that the filter process is not in general information preserving, because only the discontinuities in X- and Y-direction are exactly recognized.

In order to overcome this drawback, we propose to use an adaptive information preserving filter. The implemented algorithm in **MATCH-T** utilizes the local structure directions of the surface characteristic features for the optimal detection of discontinuities. The dependency of the rotation of the local curvature maximum against the object coordinate system for the edge detection is reduced to a minimum.

The adaptive surface reconstruction process provides the geometrical approximation and the corresponding local direction of the surface specific structure lines. The practical results show the efficiency of this step referring to an open coal-mine excavation area and mountainous terrain. We can see that the breaklines are represented by a band of breakline points to the left and right of the real breaklines. This fact lead to ambiguities during the attachment of the point information to the breaklines. For the surface reconstruction process it is sufficient to have this point information of the breaklines.

The optimized detection of the breakline areas allows us to minimize the model error caused by the spacing of the DEM posts. In local surface areas of maximum curvature we adapt the grid width according to the detected discontinuities.

The concept for the automatic breakline detection outlines the treatment of the point information of the breaklines. It was shown, that the introduction of breakline information from previous pyramid levels into the next leads to an improvement of the quality of the DEM.

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