ADAPTIVE INTERPOLATION OF DIGITAL TERRAIN MODELS

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Abstract

Most approaches to compute digital terrain models from contour lines attempt to reflect the diversity of terrain structures. Many of these approaches display accuracy weaknesses and produce artefacts in the terrain model. The presented paper tries to identify situations within contour data where interpolation is difficult, and to develop methods to create more accurate results by using information implicitly contained by the contours (e.g. break lines, trajectories). The first approach is to extract this information and to include it in the interpolation process explicitly. This information is particularly useful when for instance a TIN structure has to be adjusted according to geomorphologic constraints. The second approach simultaneously estimates gradients (at the contours), intermediate contours, and trajectories until the changes between two consecutive iteration steps lie within predefined limits. This process spreads a fine net of trajectories and intermediate contours which allow a simple and precise interpolation. Finally a system is outlined that spans the entire interpolation process including the possibility to measure the reliability of the interpolation for every point.

1. Introduction

Contour lines are a frequently used source for the construction of gridded DTMs. They originate from maps that are mostly derived from photogrammetric methods. Contour data are either manually digitised or automatically captured with a scanner.

The difficulty of modelling grids from contour lines lies in the uneven distribution of the terrain information. The information is limited to the contour lines. Terrain information is only represented for selected altitudes – *namely those for which altitude contours exist.*

Most existing interpolation methods that construct a terrain model from contour lines work with a mathematical approach that is applied to more or less local surface elements. An example is the bivariate-quintic interpolator that defines local surface patches over triangles [1]. These approaches are based on the assumption that the terrain surface can be satisfyingly approximated through small areas by mathematical functions. The validity of this assumption depends on the local configuration of the terrain surface. In many cases parts of the terrain given by contour lines have to be judged as massively under-defined. This matters when changes in height, slope and aspect occur within small areas. Purely mathematical solutions in such cases produce results of only very limited use. It would be preferable that terrain information as unevenly distributed as contour lines is supplemented by additional data. This data can either be included during the collection of the primary contour data, or added later if they originate from other sources. This additional effort is usually avoided, and the interpolation has to be done with raw contour data only.

However, contour data contain implicit information well suited to support the interpolation task. This information consists of trajectories, slope and aspect values between contours, and so-called structure lines. If extracted before the modelling of the terrain this information can be explicitly included in the interpolation step to produce better results.

2. Extraction of Structure Lines from Contour Data

2.1. Methods hitherto

Many authors describe methods for the extraction of structure lines (mainly drains and ridges). Some approaches use the construction of medial axes to approximate the path of ridges and drains [2]. These methods do not consider the characteristics of the surrounding area (e.g. steepness) over more than one contour. Thus land forms are not modelled according to their geomorphologic evolution (e.g., the asymmetric path of a river in a curved valley). Another approach tries to follow the structure lines by mutually evaluating slope and aspect of a starting point and advancing in this direction by one straight step of a pre-defined length until a neighbouring contour is hit [3]. This method finds a good approximation of the curved nature of structure lines in many cases but is highly dependent on the size and scale of the geomorphologic forms or the representing contours, respectively, caused by the use of a fixed and therefore not adaptive step size.

Finsterwalder deals with visual and manual reconstructions and defines the connection of two points on different contours by determining the maximum distance [4]. Mark tries to identify drain points on contours by applying knowledge about the geomorphologic factors forming the appearance of watercourses in arid regions [5]. He also connects points on different contours with the help of a distance criterion.

2.2. A geomorphologically sound approach for the extraction of structure lines

Here the reconstruction of structure lines is not the extraction of terrain features per se but to provide geomorphologically sound data to support the interpolation. Therefore, I outline the meaning of 'structure lines' by 'break lines characterising the terrain'. An application for which structure lines are particularly useful is the adjustment of a TIN structure according to geomorphologic constraints represented by structure lines and the contours themselves, bringing the triangle facets closer to the true surface [6]. The term 'structure line' does not only include drains and ridges but also significant break lines, and therefore represents any significant terrain discontinuity.

The method for structure line delineation from contour data presented in this paper is based on the approaches of Finsterwalder and Mark [4, 5]. They postulate that drainage lines and ridges are outstanding by two characteristics: First, they intersect contours at points of maximum curvature, and second, these points can be connected by an appropriate distance criterion.

To determine structure line points on contours, for each point the angle between the coincident contour line segments is compared to the angles of both the preceding and the following points on the contour. If the angle is a local minimum then the point is marked as a structure line point. Points of structure lines can either represent a concave or a convex land form, respectively, depending on which side of the contour line points upwards and which downwards.

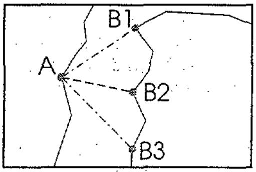

Fig. 1: Point B2 is connected with point A because of the smallest distance.

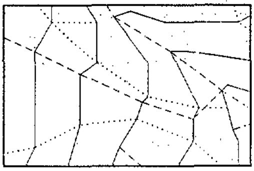

Fig. 2: Solid lines: contours; dashed lines: drains; dotted lines: ridges.

The connection of marked structure line points between the contours follows a distance criterion. Given a selected point, the distance to the connected point on a neighbouring contour has to be minimal (fig. 1). For drain points, the next lower contour and for ridge points, the next higher contour is searched (fig. 2).

Results can be improved significantly by extending the distance criterion. This extension tries to include the fact that structure lines not only connect points of minimum distance, but also of aspects (directions of steepest descent) that are as close in value as possible. For this angle criterion, aspect is defined by the bisector of the angle between the coincident contour segments. The two criteria – distance and aspect – are weighted with two coefficients and added afterwards.

The two criteria can also be used for the elimination of intersections between drainage and ridge segments. All structure line segments are first searched for intersections. Detected segments are then compared to each other with the values of the two criteria; the segment with the lower values remains in its position, the other has to be changed. In many situations, no corresponding points can be found on neighbouring contours. In these cases the search for connecting contour-specific points can be extended to include points without maximum curvature. This makes sense if, for instance, one contour line does not exhibit the properties of the neighbouring contours immediately below and above.

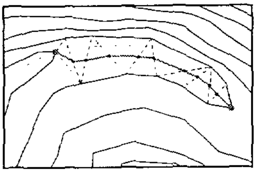

Fig. 3: Asymmetric path of the drain caused by the different slopes of the valley sides.

Problems occur if the terrain is described by contour lines as presented in fig. 3: Two corresponding points which define structure line points cannot directly be connected without intersecting contour segments. Because of this fact we call these two points 'blind' structure line points. Although this problem is crucial because it occurs in situations where the interpolation is particularly difficult, there is no comprehensive solution yet. The identification of such problem areas can be done by analysing the Delaunay triangulation of the contour points. The triangulation of this point configuration results in triangles which have their vertices on the same contour. The problem of resolving the connection of 'blind' structure line points can be approached first by detecting areas consisting of such horizontal triangles, and then to construct the topological connection by calculating the medial axes. However, to achieve better results, the paths of the structure lines would have to be constructed taking into account the steepness of the terrain represented by the configuration of the surrounding contour lines (fig. 3).

3. *Interpolation with an Iterative Method using Trajectories*

3.1. Motivation

Including the semantics of structure lines into the interpolation of terrain surfaces leads to better results than using 'raw' contour data. However, the presented methods for structure line detection rather follows a geometrical approach and only uses geomorphologic knowledge to a small degree. Interpolation can be further supported and enhanced if additional geomorphologic facts can be extracted in advance and then incorporated.

A new approach tries to achieve this goal by involving a second source of implicit information – namely trajectories – into the interpolation process. (Here we use trajectories as paths of deepest descent which implies that the intersection angles between trajectories and contour segments are perpendicular.) Trajectories cannot be constructed directly from the contour lines without an appropriate gradient estimation. The gradient estimation itself is based on a proper approximation of the trajectories. This dilemma is resolved by an iterative procedure alternating between tracking trajectories and estimating intermediate contours. It spreads a fine net containing information about height, slope and aspect of the surface. The iterative construction of this net uses contour, as well as terrain-specific, methods.

3.2. *Iterative estimation of trajectories and intermediate contours*

Trajectories, similar to contour lines, can be assumed to be approximated with short straight lines. This assumption is justified because of the rule that trajectories intersect contours perpendicularly: A trajectory between two parallel contours can be assumed to be straight. Since two contours very close together are 'almost' parallel, the approximation of the trajectory in-between is a short straight line.

By estimating the gradient of a contour line, it is possible to find points on the surface that have a z-coordinate Δz lower or higher than the z-coordinate of the contour. An intermediate contour can be created by approximating specific points with the height of the intermediate contour. Gradients are estimated again for the new contour to calculate a second one. The procedure of gradient estimation and reconstructing intermediate contours is repeated until the space between the original contours is filled with intermediate contours.

Since these intermediate contours are considered to be very close to each other, the above mentioned assumption about trajectories being straight lines is satisfied. Trajectories can then be delineated from any given point by following upwards and downwards along straight line segments building the path of steepest ascent or descent. The trajectories consist of directly connected points on the intermediate contour lines and can be considered as three-dimensional terrain profiles. Using an appropriate profile-specific interpolation method, a new estimation of the gradients for all points of the trajectories can be performed. This in turn allows an improved reconstruction of the intermediate contours. With the new set of contours, and the application of the profile-specific interpolator, the gradient estimation is improved again. This iterative process is repeated until the improvement of the gradient is lower than a specific tolerance.

However, for the estimation of the first gradients, trajectories cannot be utilised since there are no intermediate contours available at that time. To calculate a first estimate, the points representing the contour lines are triangulated by incorporating the structure lines extracted as described above. Gradients can then be estimated by using a bivariate-quintic polynomial for the surface approximation of a triangle.

The profile-specific interpolation is the crucial part of the iterative method. It approximates the trajectory with a curve. It should also allow for the inclusion of hydrological constraints: Trajectories must always 'flow down', and they might be horizontal in some places. Overhangs and changes in the sign of the first derivative are not allowed. Minimal curvature is a further goal when interpolating the profile of the trajectory. To ensure the continuity of the surface it has to be considered that all trajectories have to be somehow optimal in profile as well as in the projection on the x-/y-plane.

The result of the iterative procedure is a dense net of intermediate contours and trajectories. The interpolation of DTM points is then performed using a simple interpolation scheme on the net, such as a linear interpolation, for instance.

The usage of implicit information like trajectories for interpolating terrain from contour lines overcomes a weakness which is typical for many other approaches: It avoids the interpolation of a surface built of locally and mathematically defined patches. Instead it propagates the information initially limited to the contours iteratively over the surface. The thereby obtained dense net insures the surface to be defined by more than one neighbouring contour and therefore allows the geomorphologically correct reproduction of land forms. The choice of an adequate profile-specific interpolation method for the trajectories inherently includes hydrological constraints.

4. Conclusion

Adequate quality of a digital terrain model is not only given by good averaged accuracy, but also is reflected in how well local characteristics of terrain are represented, and how consistent the entire model is. The objective of the presented methods is to incorporate these criteria for quality with particular respect to structural features. Some of these structural elements can be defined as boundaries dividing specific regions into sub-patches of similar properties. Study of the influence of structural elements on surface modelling leads directly to refined and adaptive procedures for DTM-generation. Besides considering local characteristics of the terrain, such procedures should on the one hand allow incremental inclusion of additional data (surface-specific points, or data without any altitude specification, e.g. orthophotos), and on the other hand allow users to be interactively involved in controlling the modelling process.

Thus, the final objective of this project is the subsequent development of an interactive system that enables an iterative, stepwise generation of terrain surfaces. The tedious part of the interpolation task should be independently performed by the system, which should recognise and indicate problematic regions in order to request additional information from the user. It is therefore the aim to provide a palette of automated interpolation procedures supporting the modelling process that is driven by decisive user interactions until the result corresponds to the user's requirements.

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