GENERALIZING RELIEF REPRESENTATION USING DIGITIZED CONTOURS

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ABSTRACT

This paper introduces an approach for the generalization of terrain relief represented by a digital terrain model (DTM). It also presents an automatic vector approach to improve TIN DTMs obtained from digitized contours. Important terrain skeleton information in the form of point data is extracted automatically to solve the problem of flat triangles. These points can also be used to further extract and form the skeleton lines which can be used as constraints in a generalization process. Methods to determine the planimetry and elevation of the "skeleton" points are investigated. The algorithm is tested using ISNAP, a Windows based software package developed by the authors using the C++ programming language. Examples are also given to demonstrate the potential of the proposed algorithm. Finally this paper gives an outlook for further development.

1. INTRODUCTION

Terrain relief information plays a very important role in many GIS applications. Due to the limitations of available tools, this three-dimensional information traditionally is mainly represented as contour lines in a two-dimensional space such as map sheet. As a result, relief generalization is normally (implicitly) conducted via the generalization of contour lines which is initiated by the need of map scale reductions. As a contour line is not a real terrain feature, but an (isolated) imaginary line connecting terrain points of same elevation, contour maps do not provide immediate images of relief characteristics for the readers. Generalizing contour lines therefore requires some kind of "imagination" that "captures" the relief characteristics of terrain surfaces from a set of contour lines that are naturally interrelated in a certain way through the nature of terrain relief and constraints of man-made features.

Relief generalization became an apparent subject after digital terrain models (DTM) were introduced to represent terrain relief since late 1950s. As much of the earth's surface has been mapped as contour maps, contour to DTM conversion has been a common approach to obtain a DTM.

A TIN DTM obtained from digitized contours likely contains flat triangles. Flat triangles create artificial terraces thus provide incorrect information about terrain relief, which in turn, will have effects in generalization decision-making and contouring. Several approaches have been proposed to solve this problem. Manually adding terrain skeleton information (e.g. break lines, spot-height) is an example that may solve the problem. However, it requires special skill and is a laborious approach. "Triangle swapping" is another approach, which is limited to the places where the two adjacent triangles form a convex quadrangle. An efficient method is to automatically extract terrain skeleton information from the contour lines based on their shapes and patterns. Known existing approaches are based on distance transformation, which requires to operate in raster domain (Pilouk, 1992, Tang, 1992). The raster-vector conversion and vice versa are thus necessary and may require manual editing, which implies extra processing steps.

In this paper, we first introduce an approach for the generalization of terrain relief representation, based on some existing methods, then present an automatic vector approach to improve TIN DTMs obtained from digitized contours by solving the problem of flat triangles. Critical points that represent (or approximate) the skeleton locations are extracted as additional information after the first (constrained) triangulation has been completed. The process makes use of human knowledge as well as information from the original contour lines, topology, and the properties of geometric elements of the network. Methods to determine the planimetry and elevation of the "skeleton" points are investigated. The points are then added to the point set and inserted into the current model to obtain a new surface representation by local updating. These points can also be used to further extract and form the skeleton lines which can be used as constraints in a generalization process. The algorithm is tested using ISNAP. Examples are also given, which demonstrate the potential of the proposed algorithm. Our discussion will restrict on TIN DTMs. Contour lines are used as constraints in the triangulation process.

2. A CONCEPT FOR THE GENERALIZATION OF RELIEF REPRESENTATION

While contour lines are the most comprehensive form of terrain relief representation in a 2D analogue environment, the digital terrain model is the approach for representing terrain relief in a digital environment due to its advantage in computer analysis. Terrain relief generalization hence can be regarded as an issue of DTM generalization, and (conceptually) contours can be seen as one of the graphic representational forms of a DTM in a GIS context. Thus generalization of DTMs and generalization of contour lines fall within the frameworks of database generalization and view generalization respectively (Peng et al., 1996). This relationship can be further demonstrated by the fact that contour lines of any interval can (and should) be derived from a (good) DTM, and the fact that generalization of contour lines is restricted to the graphic aspect of generalization (Bos, 1984), except for the selection of contour line interval which is associated to the spatial properties of terrain surfaces, apart from other aspects such as map scale and usages.

DTM generalization aims at reducing the spatial (relief) resolution of a source DTM to arrive at a more abstracted relief model. The factors that affect the selection of a proper resolution for an application may include, for instance, the purpose, the relevance of small details, accuracy requirement, processing time, data storage space, hardware and software limits. It is important to stress that although it is true that in general a more abstracted relief model is also more smooth and less accurate, smoothing or compression operation alone does not, in general, provide good generalization result. The key aspect is that while local and irrelevant relief details disappear, the skeleton information representing the characteristics of the terrain surface should be maintained as much as necessary. From this point of view, both DTM filtering (Loon, 1978, Zoraster et al., 1984) and DTM compression (Gottschalk, 1972, Heller, 1990) are not adequate approaches. However, they can be improved by introducing skeleton information as a constraint in the generalization process.

3. AN APPROACH TO THE PROBLEM OF GENERALIZATION

Known approaches to the problem of relief generalization can be categorized into three groups, namely: (1) DTM filtering (Loon, 1978, Zoraster et al., 1984), (2) DTM compression (Gottschalk, 1972, Heller, 1990), and (3) structure or skeleton line generalization (Wu, 1981, Yoeli, 1990, Wolf, 1988, Weibel, 1989). Weibel (1992) evaluated these three types of methods and pointed out that global filtering (or DTM filtering) achieves a smoothing effect by eliminating high frequencies from the source DTM while keeping the number of points in the model unchanged. Selective filtering (or DTM compression) selects a subset of points from the source DTM to approximate the original surface with a user-specified accuracy. While both approaches are employed for minor scale reductions, DTM filtering is intended to be used in topography with smooth forms, and DTM compression is meant to be applied to terrain of any complexity. Heuristic generalization (or structure line generalization) directly generalizes the structure lines of the terrain surface through individual generalization operators (i.e., selection, simplification, combination, displacement, and emphasis), and reconstructing the target DTM through interpolation from the generalized structure. It is intended for use in rugged terrain and is the only approach that includes the fundamental transformations (i.e., combination and displacement) required to accomplish major scale reductions (Weibel, 1992).

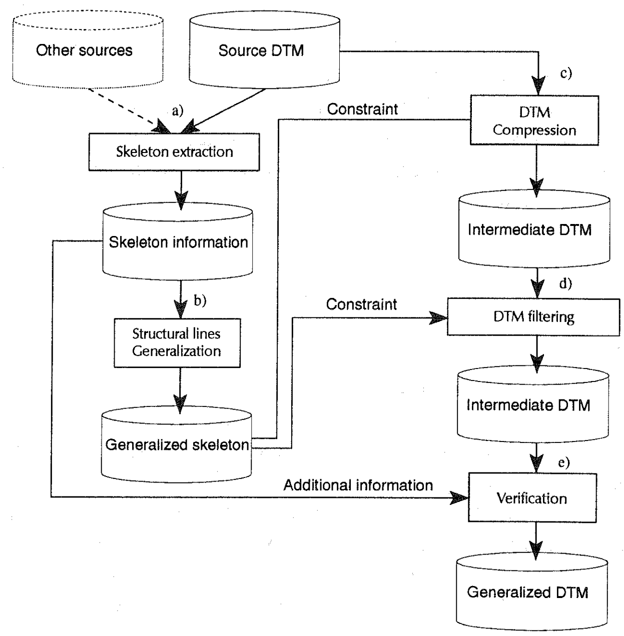


Figure 1 The proposed generalization process.

In fact, these three generalization approaches emphasize on the different aspects of generalization: DTM filtering smooths the surface but does not reduce the data volume, DTM compression reduces the data volume but does not necessarily lead to a more abstracted surface, and structure line generalization deals with skeleton transformation but ignores other properties not shown in the skeleton. Hence, an approach combining these three methods may lead to a more comprehensive solution: a) extracting the skeleton from the source DTM or from other sources; b) generalizing the skeleton through structure line generalization; c) creating the first intermediate DTM by applying DTM compression to the source DTM and using the generalized skeleton as a constraint (e.g., instead of using the non-collinear points on the convex hull and "significant extremes", the generalized skeleton can be used as the initial set of points); d) creating the second intermediate

DTM by applying DTM filtering to the first intermediate DTM and again using the generalized skeleton as a constraint; e) verifying and finally arriving at a target (generalized) DTM. Figure 1 illustrates the whole process.

4. OBTAINING A DTM FROM DIGITIZED CONTOURS

Although different methods are available for obtaining DTM data, contour maps, however, still represent a very important source of data since much of the earth's surface has been mapped in this way (Mark, 1986). Triangulating digitized contours from existing maps hence is one of the most economic ways to obtain a DTM. The Delaunay triangulation is a common approach.

Delaunay triangulation, however, implies the danger of creating flat triangles at those locations where a contour line forms a loop or sharp turns, or two adjacent contour lines have the same elevation. Flat triangles create artificial terraces that lead to a poor DTM and will cause problems in generalization decision-making and contouring.

However, these flat triangles, on the other hand, provide important information about the structural characteristics of terrain surfaces: flat triangles normally occur at morphological locations such as ridge, drainage, peak, pit and passage. In other words, flat triangles tend to be located at (or close to) skeleton locations. Our approach to improve the DTM and at the meantime solve the problem of flat triangles is based on this characteristic, thus can be refered to as a "self-diagnostic" approach. The following outline the process:

- checking flat triangles and forming flat regions (to be discussed later);
- if a flat region contains only one triangle (called "single flat triangle"), then applying "triangle swapping";
- approximating the skeleton for each flat region;
- determining the elevation for each newly introduced "skeleton" point;
- checking the elevation consistency for the whole flat region;
- inserting the new "skeleton" points and locally updating the network;
- applying "triangle swapping" for any "single flat triangle" left;
- dealing with flat edges.

1) Flat region: a *flat region* is defined as a subset of adjacent flat triangles with a) any two adjacent triangles sharing a common edge that is *not* part of any contour line, and b) only one triangle in the set can be adjacent to a triangle (of the same set) of which the three adjacent triangles are all flat triangles. Such a flat triangle is called *node-triangle*. It is an important concept in this approach as it represents a junction where several skeleton lines meet. Conditions a) and b) together ensure that each flat region corresponds to only one skeleton branch. A flat triangle with two edges being part of a contour line is called *end-triangle*, and a flat triangle with only one edge being part of a contour line is called *chain-triangle*. A flat region can be detected through a recursive process using topological relationship.
2) "Triangle swapping": for a flat region containing only one triangle T_i, in most of the cases we can find an adjacent triangle T_j, such that the common edge is not part of any contour line, and the quadrangle formed by the two adjacent triangles is a convex one. If such a T_j exists, then the flat triangle can be eliminated by simply swapping the two diagonals of the quadrangle. The new common edge of the two new triangles is likely part of a skeleton line, therefore should be marked. Exceptions normally occur along the fringe areas of a network.
3) Skeleton approximation: for each flat region, the skeleton can be determined or approximated using the component triangles of the flat region. For this purpose, first the triangles must be sorted and put in sequence. Then several methods can be used to determine the planimetry of the vertexes or "skeleton" points that make up the skeleton: a) using centroid for each node-triangle and end-triangle, and for each chain-triangle using the middle point of a line connecting the two middle points of the two edges that are not part of any contour line, b) using the centroid of each triangle and applying smoothing operation, c) using the center of the circumcircle of each triangle. The example in Figure 2 shows that while methods a) and b) provide reasonable results , the result offered by method c) largely depends on the distribution of the digitized contour points, and may violate one of the consistency rules (to be discussed later). Method a) is recommended for its simplicity.

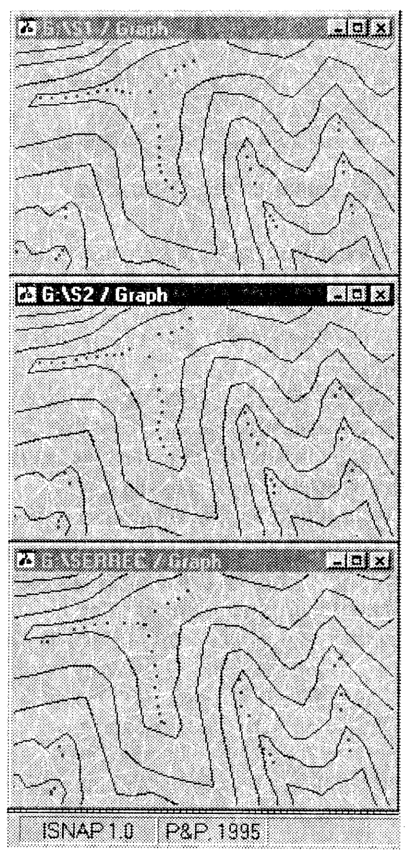
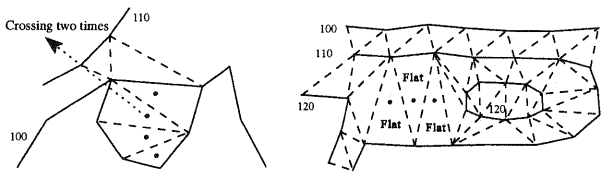


Figure 2: The planimetric locations of the "skeleton" points by the three different methods. (A) Top: Using the middle of triangle edges. (B) Middle: Using the centroid of each triangle. (C) Bottom: Using the circumcircle of each triangle.

4) Elevation interpolation: for each newly introduced "skeleton" point, the elevation is determined through linear interpolation. The basic idea is the following: first determine the triangle that encloses the "skeleton" point (the process can be significantly speeded up by the use of topological relationship); then detect the closest adjacent contour line using topological relationship and distance comparison (note that the triangle enclosing the "skeleton" point plays an important role in the process); finally draw a reference line between the "skeleton" point and the closest node on the neighbour contour line, and make sure that the line crosses the "problem" contour line (i.e., the contour line that forms (part) of the flat region). The interpolation is conducted along this line. Two aspects must be taken care of in the process: a) the number of times that the reference line crosses the "problem" contour line before reaching the adjacent contour line (see Figure 3A); b) if the reference line reaches first the adjacent contour line before crossing the "problem" contour line, then other adjacent contour lines (not the closest one) might be more suitable for the interpolation (see Figure 3B). An alternative method is to first interpolate the elevations of the first and last points of the flat region using the method described above, and then determine the elevation for each middle point through linear interpolation based on the distance and the elevations of the two "end" points. This method eliminates local irregularities and is based on an assumption that the slop between the two "end" points is constant, therefore should be used with caution.



A: The reference line crosses the contour two times B: The adjacent contour of 100 m is more suitable

Figure 3: Examples of special situation

5) Consistency checking: several rules are employed in this approach to avoid unreasonable result:

- All the "skeleton" points of a flat region must be inside the region.
- The elevations of all the "skeleton" points of a flat region must be consistent in such a way that all of them are either larger or smaller than the height of the contour line that forms (part) of the flat region.
- The absolute value of the height difference between any of the "skeleton" points of a flat region and the contour line that forms (part) of the flat region must not be larger than the original contour interval.

If any violation happens, adjustment and further checking is required.

6) Network updating: the "skeleton" points are then inserted into the original model through local updating.
7) Dealing with flat edges: if a non-flat triangle has an edge that is not part of any contour line, but with both vertexes having the same elevation, then "triangle swapping" is applied in order to avoid potential problems in contour-making. Saddle locations may be detected in this process. If two non-flat triangles share such a flat edge, and if "triangle swapping" cannot be conducted because otherwise a new flat edge will be created (i.e., the two opposite nodes of the original flat edge also have the same height), then the quadrangle formed by the two adjacent triangles represents a saddle area. In this case, a new point can be introduced into the center of the area. Its elevation can be determined by taking the average of the four vertexes of the quadrangle.

5. TESTING OF THE ALGORITHM FOR DTM IMPROVEMENT

The data source used to test the algorithm was digitized from a 1:50000 topographic map covering an area of approximately 3 km by 3 km in southern France near Bonnieux (Pilouk, 1992). The contour interval is 20 meters. The test was conducted using ISNAP, and the results are shown in Figure 4. For lack of space, only about half of the original studying area is shown in this paper. Through a visual inspection and comparison of the hillshading displays and derived contours, it is obvious that after the improvement, the terrain representation becomes more natural and the skeleton is more aapparent. The information lost in the contouring process due to the problem of flat triangles is recovered. Because of the use of topological relationship, the algorithm is fast. With a DTM containing 4400 nodes, 13178 edges, 8779 triangles, and 1154 new points, using a 486-PC (66Mz), the whole process (including network update) took about one minute to complete.

6. DISCUSSIONS AND OUTLOOK

Terrain relief generalization should rely on a (good) DTM and skeleton information must play an important role in the process. The problem of flat triangles is obvious if a DTM is to be obtained from digitized contours. It ought to be solved before a generalization process. Contours in a smaller scale map should be derived from a generalized DTM that is adapted to the new (relief) resolution requirement. Graphic or view generalization process is then directly applied to the contours in order to obtain a legibile visualization. The generalization of skeleton lines is the key aspect in the whole process, and should not be simply treated as an issue of a 2D linear network (e.g., road network) generalization. Elevation information, that represents another dimension of the spatial space, must plays a role.

The skeleton lines resulting from this method is based on the concept of medial axis, and can only be regarded as initial breaklines. Individual skeleton line branches need to be connected and their planimetric locations need to be adjusted according to the variations of the density of the contours in the neighbourhood. Figure 5 illustrates the problem and a possible solution that makes use of the topological relationship. This will be implemented and tested in the near future.

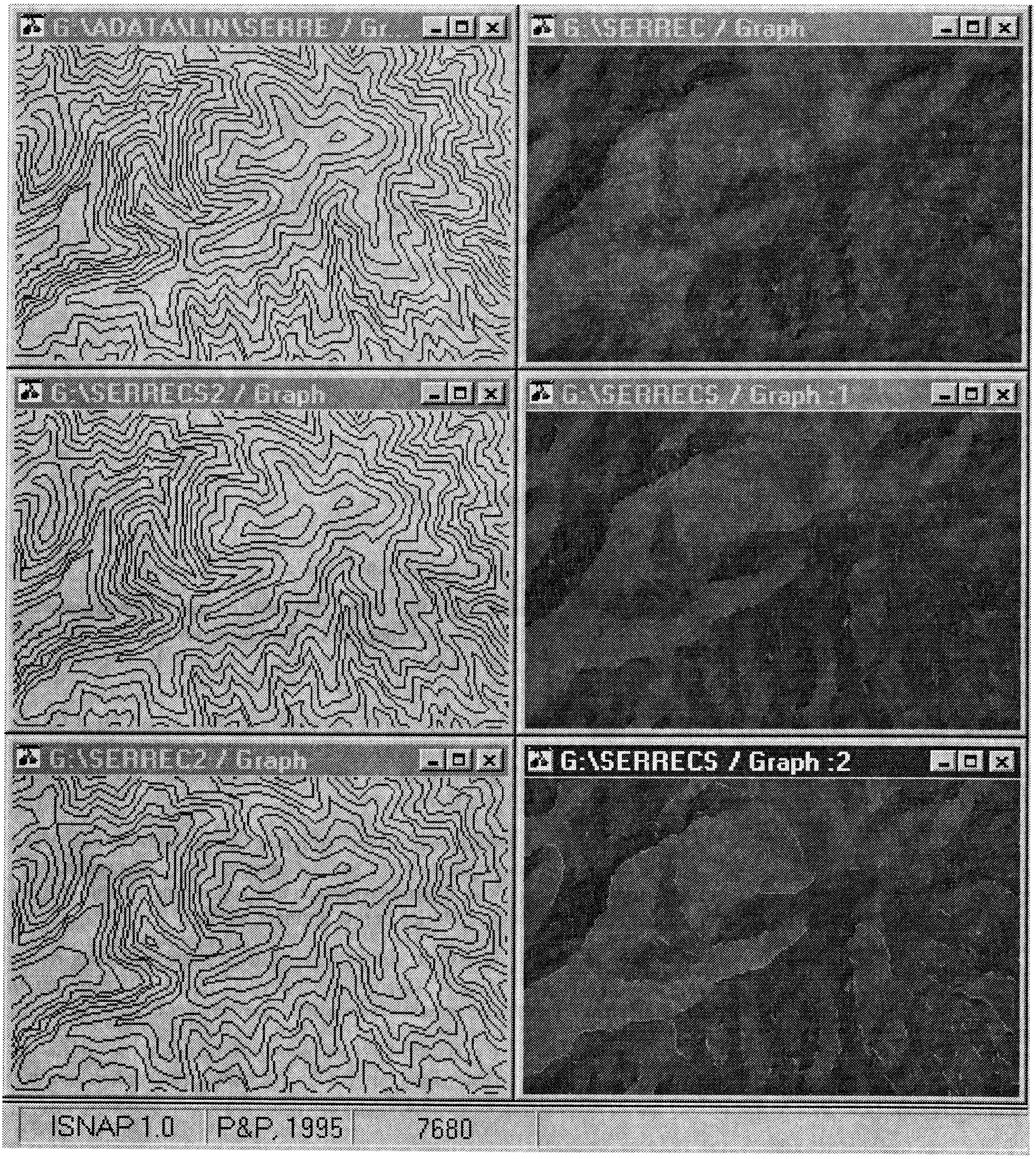


Figure 4: Testing results. (A) Top left: Original contour map. (B) Top right: Original DTM obtained from the original contour map. (C) Middle left: Contour map derived from the improved DTM. (D) Middle right: The improved DTM. (E) Bottom left: Contour map derived from the original DTM. (F) Bottom right: The improved DTM superimposed with the introduced "skeleton" Lines.

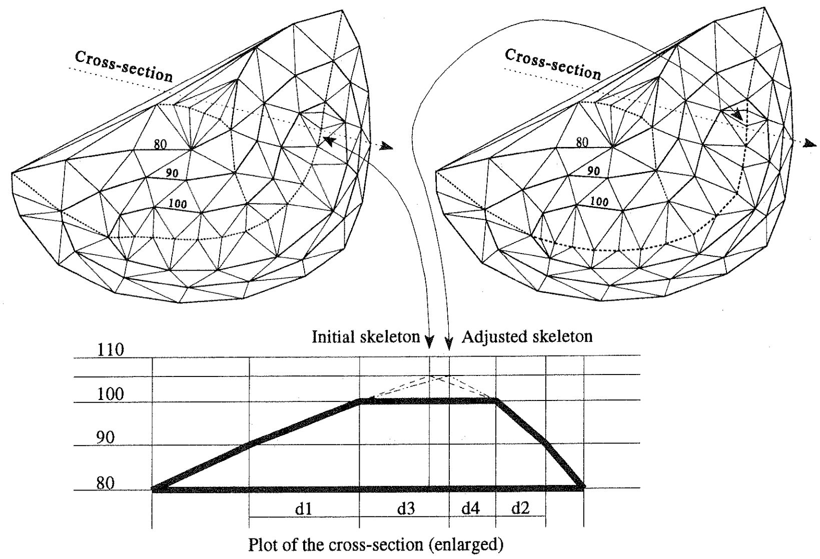


Figure 5: Adjusting initial skeleton location

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