THE TRIANGULATED IRREGULAR NETWORK

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Introduction

For several years, our group has developed a Digital Terrain Model based on irregularly distributed points connected into a sheet of triangular facets.

Our first motive for this research stems from problems with traditional terrain representations which were recognized as early as 1967 by Boehm. Topographic surfaces are non-stationary (Pike and Rozema, 1975), i.e., the roughness of the terrain is not periodic but changes from one landtype to another. A regular grid therefore has to be adjusted to the roughest terrain in the model and be highly redundant in smooth terrain. It is apparent that, if one is to model these non-stationary surfaces accurately and efficiently, one must use a method which adapts to this variation.
The second principal motivation came from a realization

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that the purpose of the digital terrain system is the digital representation of terrain so that "real world" problems may be approached accurately and efficiently through automated means.In response to this problem it was decided that our digital terrain system should contain those features which are the natural units of analysis for the problems to be solved. This is an important current trend in general data base construction (Mark, 1978).

These features and the boundaries between them are seen to have a higher "information content" than randomly located points on the surface. This is so both in the context of the analyses and from the standpoint of representing the surface with a minimum of storage.

Like several other researchers (Gates, 1974, Bauhuber, et.al., 1975, Gold, 1977) we realized that one simple means of meeting these specifications is to model the surface as a sheet of triangular facets. We called our implementation of this approach a Triangulated Irregular Network or TIN (Peucker, et.al., 1975).

There are two complementary approaches to the computer representation of a surface of triangular facets. One method gives primacy to the triangular facets themselves. Using that method,each triangle needs a total of six pointers to define the topology: three pointers to the nodes at its vertices (the point coordinates should be stored separately), and three pointers to the neighboring triangles. Since, by Euler's relations, there are 2N-B-2 triangular facets in a network with N nodes, B of which are on the boundary, a total of 12N-6B-12 pointers are needed.

Alternatively the nodes can be regarded as the primary entities. This is the approach that is used in the TIN data structure. The topology is captured by allowing each node to point to a list of its neighboring nodes. The neighbor list is sorted in clockwise order around the node, starting at "North" in the local Cartesian coordinate system. Applying Euler's relations, the total number of neighbor pointers will be 6N-2B-6. Thus there is about fifty percent savings in storage by representing the topology as a TIN as opposed to using its graph dual. In this implementation, the surface has been mapped onto a topological sphere by the device of adding a dummy node to represent the "outside world" or the point on the "back side" of this topological sphere.

Capturing the Phenomena: Secondary Data Structure

The TIN is conceived of as a primary data structure which contains within it a secondary data structure in which the essential phenomena and features of the terrain are represented and named as integrated, holistic objects. Different disciplines may regard different aspects of the terrain as the "essential phenomena" of the surface (Mark, 1978). We, for our own work, have adopted a set of "surface specific points and lines" to be our working, secondary, phenomenon structure. Peaks, pits and passes form the major portion of the set of surface specific points. Peaks are points that are relative maxima, i.e., higher than all surrounding neighbors. Pits, likewise, are relative minima. Passes are saddle points on the surface, relative maxima in one direction and relative minima in another.

Methods for Generating TIN's

There are two principal phases to the generation of TIN°s: the selection of the data points and their connection into triangular facets. Manual selection of the points and links which constitute the triangular network is one of the most obvious and accessible methods of creating a TIN.

Manual point selection combined with the automated triangulation is another technique which has been used. The existence of efficient programs for the triangulation of an arbitrary set of points under a variety of optimality criteria (Fowler, 1978, Gold, 1977, Shamos and Hoey, 1975) makes this approach attractive. A somewhat larger number of nodes need be recorded in order to resolve ambiguities which can be interpreted by the human operator. This is more than offset by the increased ease and speed of entry.

In light of the increasing availability of machine readable terrain data particularly in the form of very dense raster DTM's produced by automated orthophoto machines (Allan, 1978), it is becoming desirable to use automated triangulation. We have undertaken the development of a system to do this. The first requirement for such a program is that it be presented with error free input. Some automatic DTM machines produce occasional blunders or "spikes" and it is necessary that these be filtered out before the data can be presented to the TIN generation system. The first phase of generating a TIN from a very dense DTM is the extraction of the skeleton of surface specific ppoints and lines. To derive these features, we use a local geometric operator, similar to those used in picture processing, to identify possible points on ridge or channel lines (Peucker and Douglas, 1975). Subsequently, these points are linked into ridges and channels. These points are then automatically connected in a Delaunay triangulation (Fowler, 1978), then resulting model is compared with the original very dense grid, and additional support points are added at the points of worst fit until the maximum discrepancy between the TIN model and the original is within a pre-specified tolerance.

Applying the Model

Most applications of the TIN involve one or more of three basic processes:

1. Sequential element by element processes,
2. Searches - locating the closest node to a given point, or locating a point within a triangle,
3. Intersection of the terrain surface with various other surfaces by tracking their lines of intersection.

Since the nodes of a TIN refer explicitly to their neighbors, sequential element by element processes may refer to them without the penalty of having to search for them. Hill-shading and slope mapping both refer essentially only to the individual triangles on the TIN surface to obtain the location and orientation of the facets. In some cases, hill-shading will access the information about the facets which adjoin a given triangle, but this process stops at the first neighboring facet. These are the most simple methods for employing the TIN and lead to simple algorithms.

Tasks which require searching use the adjacency information in the TIN to walk through the network until a specified condition is met. The topological structure of the TIN makes this form of search quite efficient.

By a simple extension of this process, one can easily determine in which triangle within the TIN the given point lies.

The surfaces which are intersected with the terrain surface range from the relatively simple case of cutting the surface with vertical and horizontal planes to produce drop lines and contour lines up to the relatively complicated problem of intersecting the surface with the outlines of cast shadows or with a series of conic sections in order to simulate elipitical radar scans. In general, all of these surface intersection problems are handled by a tracking process. First, for each disconnected loop or segment of the intersection a starting point must be located. Once the line of intersection is located within any triangle it is a simple matter of deciding which of the three edges of the triangle the line crosses as it leaves that facet and enters the neighboring facet. Within each facet locating the line of intersection is the standard problem of solving for the root of a bivariate function. This can be done with numerical tracking procedures.

Automated hill shading

The TIN model of terrain representation lends itself to development of an automated method of hill shading. Because the TIN explicitly represents these surface lines as edges of facets, Yoeli's (1967) method and Brassels(1975) enhancements are simple to automate. Without perturbing the light source, structural edges aligned parallel to the light rays can vanish; in the TIN, the contrast across these edges can be examined directly and altered to improve the surface modelling.

Slope mapping

Graphic techniques similar to those used in hill shading are employed to produce maps of slope variation. Shading can be performed on a triangle by triangle basis, assigning each facet to the shading interval determined by its slope.

Contouring

The production of contour maps from the TIN is a simple procedure. The extraction of contour lines is equivalent to locating the lines of intersection between the terrain surface and a sequence of horizontal planes. The secondary data structure of ridges and channels is used as a guide in searching for the starting points for each contour loop. Once a starting point for a loop has been located, the tracking procedure as described above is used. The program contains provisions for darkening index contours and smoothing out sharp corners which are artifacts of the edges of triangles.

Profiles and hidden lines

A common method for construction of block diagrams extracts drop-lines or profiles from a gridded DTM along rows, columns, or diagonals of the height matrix. Proceeding from the profile closest to the observer, the method compares succesive profiles against a °horizon° profile, composed of the upper boundary of the region on the image converted by all preceding profiles. A scanner for the TIN extracts the profiles from the TIN, using the tracking process. By making use of the coherence of successive scan lines, i.e. the similarity in the edges crossed by adjacent scans, and the topological structure of the TIN, the process is very efficient (see Peucker, et.al., 1975). The advantage of using the TIN as the source of the profiles is twofold; first, the extraction of scans can be done at any angle through the region, without either an increase in computation or a loss of accuracy, and, second, the definition of features is not limited to the sampling interval of a grid.

Line of sight or radar maps

To determine the intervisibility of two points in a TIN, one can extract the profile of the surface along the path between the points, using a tracking procedure. To extend this technique, one can send rays out from a central location, at a fixed angular separation, and plot the sections of the rays that are visible from the central location.

Horizons

A horizon map depicts the boundary between the terrain and the space above. Construction of this image can be performed simply in a TIN, through direct extraction of all horizon lines. Any edge contributing to a horizon line must be both convex and must separate a visible from an invisible facet.

Integration of the DTM with Coverage Data

In many planning applications information about both the terrain surface and coverage of a cultural, political or ecological nature must be combined in the analysis. These coverage data are often represented by polygonal coverings of a region, linked by the adjacency relations of the regions.

One can refer simultaneously to a TIN model and a coverage network by using a tracking process to search along paths in both models. This allows comparisons to be made between models of the same region in a direct manner.

Summary

Our implemention of the TIN system is a research tool used to investigate the aplication of DTM°s based on triangular facets to a wide range of applications. Many tasks for which DTM's have been used are already implemented on the TIN model or can be demonstrated to be feasible. In addition, for certain demanding applications, such as intervisibility problems, the TIN has shown itself to be particularly well suited.

REFERENCES

Allam, M.M.,1978,"DTM's Application in Topographic mapping." roc. of the DTM Symposium, St. Louis, Mo, ASP, 1978, 1-15

Bauhuber, F., Erlacher, V., and Gunther, P., 1975, "A Programming System for the Manipulation of Digital Terrain Models" (in German). Organ der Deutschen Gesellschaft fur Photogrammetrie, 43:104-107.

Boehm, B.W., 1967, Tabular Representations of Multivariate Functions - with Applications to Topographic Modelling. Assoc. Comp. Machinery, 22nd Nat. Conf., Proc., 403-15.

Brassel, K.,1974,"A Model of Automatic Hill-Shading." American Cartographer, 1(1).

Fowler, R.J., 1977, DELTRI: An Efficient Program for Producing Delaunay Triangulations. Tech. Repot. 18, ONR Contract #N00014-75-C-0886, Dept. of Geogr., Simon Fraser U., Burnaby, B.C., Canada.

Gates, W.E. and Assoc., Inc., A Land Based Modelling System for Water Quality Management Studies, Report for Virginia Electric and Power, 1974.

Gold, C.M., Charters, T.D., and Ramsden, J., 1977, Automated Contour Mapping Using Triangular Element Data Structures and an Interpolant Over Each Irregular Triangular Domain. Proceedings of SIGGRAPH°77, San Jose, California, 170-175.

Mark, D.M., 1978, Concepts of "Data Structure" for Digital Terrain Models. Proc. of the DTM Symposium, St.Louis, Mo, ASP, 24-31

Peucker, T.K., Fowler, R.J., Little, J.J., and Mark, D.M., 1977, Digital Representation of Three-Dimensional Surfaces by Triangulated Irregular Networks (TIN). Tech. Rept. 10, ONR Contract #N00014-75-C-0886, Dept. of Geogr., Simon Fraser U., Burnaby, B.C., Canada.

Pike, R.J. and Rozema, W.J., 1975, Spectral Analysis of Landforms. Annals of the Association of American Geographers, V. 65, 4:499-516.

Shamos, M. and Hoey, D., Closest Point Problems, 16th Annual Symposium on Foundations of Comp. Sci., Univ. of California, Berkeley, Oct. 13-15, 1975, IEEE (1975), 151-162.

Yoeli,P.,1967,The Mechanization of Analytical Hill Shading. The Cartographic Journal, 4, 82-88.