DIGITAL TERRAIN MODELS:
An Overview

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Introduction

Digital Terrain Models (DTM's) are information systems that store, manipulate and display information about terrain. Their dominant component is the surface structure of terrain rather than the coverage. The latter is generally treated in Land Resource Information Systems (Dueker, 1979).

Historical Overview

Digital Terrain Models can look back on a long history of growth and diversification. In the late fifties, civil engineers started to use computers for the calculation of terrain profiles across highway trasses. Roberts and others (1962) at MIT were the first to incorporate these profiles into a system which would not only interpolate along the profiles but also between them for the computation of cut-and-fill and other data useful for civil engineers. From then on, DTM's received much attention in the research community, especially geodesy and photogrammetry, but little in the practical world, as was noticed even in the early seventies.

At the same time, however, DTM's went through a redefinition and expansion of usage. The sampling density decreased and the area covered increased - up to, in one case, more than half of the United States (Noma, 1974). The expansion of the scope and extent of DTM's has also created a multitude of different types of applications (ASP, 1978).

Structure

A typical DTM consists of one or more data bases plus procedures to input data, manipulate and display them. What holds the procedures together and allows the transfer of results from one to the other is the structure of the data base. Because of their key-role in the operation of Digital Terrain Models, data structures have been in the center of attention of many researchers.

One can distinguish between the different data structures along several lines. One relates to the regularity of the distribution of the geometric elements of the data base and distinguishes between regular and irregular structures. The second relates to the type of basic elements in the data bank and separates

1. point structures and networks
2. line structures, and
3. patch structures.

The discussion of which of the types of data structures are superior is intense and has been heated at times. It is my belief that there is no best data structure but many have advantages over their competitors if applied to certain tasks but can be quite inefficient when applied to other tasks. It is therefore quite usual to convert data from one structure into another within a DTM.

Point-structures

The most frequently used data structure is that of the regular rectangular grid. The advantage of this approach is the implicit definition of the relation between points because the point grid is viewed as a matrix in which every element can be assigned to a row and a column. This arrangement saves storage because only the z-coordinate has to be stored. The regularity of the grid also facilitates programming. The disadvantage of this structure is its inability to adapt to the changing roughness of terrain.

Irregular point structures can eliminate these particular disadvantages. By encoding only those points which are absolutely necessary for the definition of the surface, their number can be kept to a minimum. It is apparent that certain relief points and lines like peaks, passes, pits, ridges and courses are more likely to be chosen than others.

Of course, this structure needs a different way to identify the neighbors of every point. This is done by triangulation of the point set, i.e., the creation of a set of triangles which completely cover the data-area. The edges become neighborhood pointers which have to be stored together with the coordinates of the data-elements (points or triangles). This means that the storage need increases considerably, to six or more times per point depending on the particular implementation of the relationships. On the other hand, the point-ratio is 1:14 to 1:287 with respect to regular grid, depending on the type of application (Peucker, et.al., 1976).

Line-structures

Line structures are similar to point structures since lines are defined by a series of points. The difference to point structures lies in the storage organisation. Subsequent points in storage are linked by straight lines which can be interpolated in arbitrary intervals. Typical line structures are based on contours, profiles (regular) or surface-breaks (irregular) (Halmen, 1975).

Patch-structures

The approximation of surfaces by a mathematical function is a logical step for mathematicians. However, topographic terrain is too complex that any area of reasonable size could be represented by one function. One therefore has to partition the surface into patches (Jancaitis and Junkins, 1973; Jancaitis, 1975, 1977). This makes the mathematical functions more complex since smoothness along the patch boundaries has to be maintained.

Data Input

Most data for DTM's are collected for particular purposes but some general purpose data bases have been collected as well (Noma, 1974; Allam, 1978).

The automatic collection of topographic data takes place in two ways:

1. In the process of the production of ortho - photos, a very dense raster of points is collected (Allam, 1978; Jancaitis and Junkins, 1973). The number of points are usually much too dense (a 9-m mesh width is mentioned, see Allam, 1978) and often contain noise (Jancaitis and Junkins, 1973). Thus, the set is thinned or approximated by patches.

2. The second approach is the encoding of contours by scanning a contour plot (Hofmann, 1978) or applying a contour follower (Noma, 1974) and interpolating the results to a regular grid.

The manual collection proceeds either by sampling the surface at points or along lines. Points are usually collected in irregular patterns and subsequently interpolated to regular grids. One point which is often overlooked is the difference between the encoder°s unconscious attempt to digitize points along break lines and the tendency of most interpolation algorithms to smooth away any structural line.

One has therefore seen the expansion of those systems which triangulate the points, either manually (Males, 1978) or automatically (Brassel and Reif, 1979; Fowler, 1978). The resulting structure is more faithful to the original surface and allows for fast algorithms (because of the smaller number of points) but also necessitates more original programming.

An interesting approach by Makarovic (1979) tries to combine the advantages of the regular and irregular approach by starting out with a wide regular grid and then intensifying the grid (down to five and more levels) where the roughness of the terrain demands it. This represents an efficient input and storage structure - especially when supported by an interactive system - but for any application it is interpolated to a regular grid.

Photogrammeters frequently input data along lines, usually with some regularity, i.e., along contours or vertical profiles. These structures, however, are rarily maintained in their original form but interpolated to a regular grid. One system (Kraus,1973;Stanger,1973)) includes separately digitized break lines for the interpolation, thus maintaining the surface structure and some of the programming ease of the regular grid.

One interesting approach (Halmen, 1975) records the surface along breaks only. These irregular lines are of high accuracy and density (typically 140 points/hectare). The structure is maintained only for storage purposes and turned into a regular grid for any application.

Applications

The limited length of this paper forbids the attempt to give an exhaustive overview of the applications of DTM's. Instead of being very superficial, I will use the most frequent application of DTM s, contouring, to show the potential of Digital Terrain Models.

Although the number of contouring programs is legion, their diversity in structure and content is relatively small. Variations can occur in the following areas:

Geometric structure: The regular rectangular grid is by far the dominant structure. Most commercial contouring programs start out with irregular, non-connected point sets, interpolate to a regular grid and then apply a contouring algorithm. The alternative to this structure is the irregular grid which derives its structure through triangulation.

One approach (McLain,1974; Kirkpatrick, 1972) does not create the structure before contouring but does so "on the fly": A start for a contour is found along a profile. The "tangent plane" to the surface is then computed and the contour advances along a vector whose length depends on the roughness of the local terrain. At the end of the vector the surface is computed again and the exact position of the contour determined.

Memory size: The memory needed for contouring depends largely on the portion of the data set which has to be processed at a time. It is possible to process one element (Square, triangle) at a time (Gold, 1978) but in more cases the entire data set or major portions thereof are kept in memory. The difference lies largely in the approach to smoothing the contours. In the latter case, smoothing takes place "on the run", i.e. widely spaced contour points are computed and a smooth curves computed through them subsequently (Coulthardt, 1969). In the other case the surface in the area of the element and its immediate surrounding has to be smoothed.

Size of data sets: Whenever memory is too small to keep all the data, some boundary problems arise which have to be handled with additional programming efforts. These boundary problems usually relate to the smoothness of the surface and/or the contours at the"patch-boundaries". Surprisingly, these problems have been solved better and more frequently with smaller systems which process only one or few elements at a time.

Smoothing: Smoothing is extremely important for the acceptance of a contour plot, despite the fact that non-smoothed plots are more accurate than the former given the fact that only a few points on the surface are known and a linear interpolation between them is the most likely approximation.

Smoothing can be undertaken by either smoothing the surface and then contouring a very fine mesh or smoothing the contours which are constructed from a coarser mesh. The first approach is preferable from the viewpoint of the visual consistency of the surface but costs more computer time and programming efforts.

A contour program presenting topographic terrain should allow for differential smoothing. For example, at the crossing of ridges and other breaks, the contour should not be smooth. Unfortunately, only few programs (Kraus,1973; Stanger,1973) allow for this.

Annotation and other cosmetics: Labelling, differential thickness of contours, contour suppression in steep areas and other cosmetics improve the readibility of the map. Any gain in aesthetics, however, has to be weighted against considerable increases in computing time. There is a point where the manual improvement of the map can be performed less expensively. The initial simple contours are quickly produced by the computer but when the density of information increases, the computer slows down exponentially but the cartographic draftsperson excells at the same rate.

Prize: Prizes for contour programs range from a friendly word to $50,000.00 and there is little relationship between quality or versatility and prize. Those who can afford them should buy the expensive programs; they do more indeed. Those who do not have the money should not despair. There are few things that a good pen and scissor cannot do once the basic plot is produced.

Current Problems.

To conclude this very scant overview of Digital Terrain Models one should point out a few of the problems which will confront the scientific community interested in DTM's. A strong personal concern relates to the question of the resolution and the accuracy of terrain data. The present awareness of the quality of data stored and used in Geographic Information Systems is very poor. Only very few systems have any notion of the reliability and usefulness of their data (Gordon, 1979).

To take an example in the area of DTM's one can estimate the meshwidth for a regular grid given certain accuracy requirements from contour maps. Using some published accuracy standards (Gottschalk and Neubauer,1972) one can establish meshwidth for the digitization from contour maps as 4.29 times the contour interval (Mark,1978). To apply this figure to the example of the "DMA-tapes",i.e. the DTM data collected by the Army Map Service (now Defense Mapping Agency) with typical contour intervals of 200 to 500 feet in mountainous terrain the meshwidth should be more than 858 to 2150 feet. Since the data is taken from the 1:250,000 map sheets at a point density of 100 per linear inch or approximately 200 feet in the terrain, only 5.4% to .86% of the DMA data are significant, the other 95 to 99% are redundant. Or, in other words, the DMA-DTM s give a false impression of high resolution.

This example is not used to discredit the Defense Mapping Agency but to show the general neglect for the importance of the "fidelity" of data. A question has to be asked: if there is so little knowledge on data available, how often will it happen that tasks are attempted for which the available data are not sufficient? To use the "DMA-tapes" again, a test of the area around Mt. Baker, Wash., has shown that two subpeaks with heights of approximately 500 feet above the general slope were not present in the data grid and the main peak was 178 feet too low (Peucker et al, 1976). With such errors a flight-guidance system based on horizon finding techniques (Carlson, 1978) would have to fail.

In other words, data sets with high redundancies are not only wasteful with respect to storage space, but also contain the danger of being misused, usually unconsciously. We should therefore try to develop data sets which are accurate enough to satisfy the highest-resolution application. Any usage with a lower resolution can be accomodated by generalizing the data set.

Two groups of achievements seem to suggest that our discipline is moving in this direction. One is the digitization of terrain at large scales and for large areas. An example is the creation of DTM's of the Canadian North with the Gestalt Photomapper by the Canadian government (Allam, 1978), another the work on the same instrument by the USGS (White , this conference). Although not much is known about the progress of these projects, the working scales promise data sets that can be of use for most applications.

The second development is the modernization of land data systems by the North American Institute for Modernization of Land Data Systems (MOLDS). The development of these modern cadastral systems promises that over the coming decades a common base for all purposes and all scales will be provided.

One can therefore be confident that the research in DTM's will remain interesting for the coming years. The pit falls which were typical for the early stages will slowly be corrected . It seems sure that the different disciplines interested in Digital Terrain Models are moving the topic in the right direction.

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