THE TIN DEMYSTIFIED

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ABSTRACT The Triangulated Irregular Network (TIN), used for surface generation and representation, has received much attention since its inception by Thomas Poiker [formerly Peucker] in the mid-1970s. Many articles have been written about the advantages of TIN-generated surfaces and the promotion of new TIN-generation algorithms. Most of the available literature only touches on specific applications or techniques. Thus, no current review article is available. This article clarifies many of the ambiguities surrounding the TIN structure and offers new insights into future TIN applications.

INTRODUCTION

The focus of this paper is to review the history, development directions and applications of the TIN (Triangulated Irregular Network) data structure. Given the influx of TIN articles appearing in professional journals, it appears that a descriptive and clarifying paper is needed. This review paper will provide insight into the historical development of the TIN structure and describe the variety of implementation algorithms available, enabling the researcher to obtain a clearer understanding of the TIN structure and its uses.

However, it is important first to establish a definition of the TIN structure. Poiker (1979a) defines the TIN as an irregular point structure capable of containing the minimal amount of data that can define a surface. The neighbors of every point are found by a triangulation of the point set, thus covering the data area with triangles. With this definition in mind, a description of this paper's structure will follow.

Divided into four parts, this review first focuses on the historical development of the TIN structure. From inception to algorithmic refinement, this section examines the people involved and uncovers many of the earlier geographic "standards." The second section describes the various algorithms available for TIN construction, and will be of most interest to those searching for the algorithm which will facilitate the optimal representative data structure for their needs. The third section discusses the uses and analysis of TIN structured data. Advantages and disadvantages between the grid and TIN structure are highlighted. Finally, the fourth section provides some insight on future TIN-based research and improved methods for point selection and structure generation. First, however, it is important to obtain a clear picture of how the TIN structure developed.

HISTORY OF THE TIN

To understand the development pattern of the TIN structure, it is essential to have an idea of the research trends prevalent in the 1970s. Large amounts of theoretical and applications-based research was taking place at the Harvard Laboratory for Computer Graphics and Spatial Analysis. Major ongoing research projects were prevalent focusing on many different areas of spatial data analysis. The first mention of the TIN structure that is common today was, perhaps "Cartographic Data Structures" Poiker and Chrisman (1975) which discusses research dealing with the GEOGRAF data structure used for encoding planar data and the Geographic Data Structure (GDS) for encoding three-dimensional surfaces. At that time, Poiker was developing a geographic information system for three-dimensional surfaces. Searching for smaller and more compact ways to encode geographic information for computer use, Poicker and Chrisman began looking at improved encoding methods for the representation of high-content map information. The data structure that Poiker was developing at the time for the GDS system was based on irregularly distributed points, which were assumed to be sample points without sampling errors from a single-valued surface. From this initial idea two unique ways to build the structure became evident. In Poiker and Chrisman (1975) and even later in Poiker (1979b) the following core representations were described:

> Neighborhood relationships are created triangulating the data set and storing for every point the labels of all points which are linked with the first point by the edge of a triangle.
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> Selected points of the surfaces which lie along lines of "high cartographic information" and defining them as nodes, which represent peaks, passes, and pits.

A year later, Poiker along with Fowler, Little, and Mark (1976), working under a research grant from the Office of Naval Research, published the first work that solidified the TIN structure as a representational form for three dimensional surfaces. The initial work carried out by Poiker et al.(1976) at Simon Fraser University in British Columbia, Canada, has provided the foundation for other works published by the same principal investigator as well as Gold (1977), McCullagh and Ross (1980), Poiker (1985), McKenna (1987), and Chen (1987 1988 1989).[1] It is evident from this list of contributors, and others who are unpublished, that interest in the TIN still has much momentum. Over the years, many of these authors have been experimenting with modified and improved algorithms for TIN construction, as we will see in the next section.

TIN CONSTRUCTION

McKenna (1987) compares TIN construction to a problem of "connect the dots." For the human mind, with an eye for topographic surfaces, this "connect the dots" process may not be very difficult once some ground rules are set. First, the best triangulation of the points is the one that most closely represents the surface. Second, obtaining this "best" triangulation is done by connecting the irregularly spaced data points to form the best possible equilateral triangles. Next, a two-part examination of these methods will follow. First, each of the TIN construction methods will be examined from a non-computer programming perspective. Finally, programming data structures and algorithms will be

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[1] It should be noted that the number or sources used in this paper was rather small. Presently many more triangulation related articles have been found and are included in "TIN: A Working Bibliography", a Hunter College Department of Geology and Geography publication.

presented describing each of the TIN construction methods.[2]

These above ground rules form the basis for the two major TIN construction methods that exist today. These two techniques can be described as the *refinement method* and the *initial optimization method*. The *refinement method*, on the first pass, generates a triangulation of all points based solely on the criteria of fast processing time. In the second pass, the triangulation is massaged or molded until all triangles become as equilateral as possible. Gold (1977) made use of this method for automatically generating contours through an irregular network. The *initial optimization method* seeks to generate the optimal triangulation with a single pass of the data. The majority of research performed using the *initial optimization method* is evident in the publications of McLain (1976), Brassel and Rief (1979), and McCullagh and Ross (1980).

The *initial optimization method*, described above, uses the Delaunay Triangulation method. Other triangulation methods exist, such as Thiessen polygons: however, the Delaunay method has been shown to provide the optimal triangulation characteristics McKenna, 1987; McCullagh and Ross, 1980; and Gold 1979. In addition to the above TIN construction methods various new techniques have be proposed. One such method described by McKenna (1987) is called the Inward Spiral Method. It begins the triangulation process from the borders of the data region. The Inward Spiral method uses the McLain triangulation algorithm and is described as producing the optimal triangulation on a single pass.

The previous method descriptions may persuade the reader to believe that there are no problems associated with TIN construction. This is not true. Various problems exist which, sometimes are undocumented or overlooked. One major problem which is sometimes quickly covered is data collection. Poiker (1979b), Gold (1979) and McKenna (1987) all describe methods of data collection. In the definition of the TIN structure, irregularly spaced point observations form a major part. The TIN structure gains its flexibility by not requiring point observations in the form of a grid. Thus, the selection of high information content points is desirable. These data points can be selected by the user or automatically. Chen and Guevara (1987) describe a method for the automatic selection of very important points, VIP, from a digital elevation model (DEM) by using image processing techniques.

From a human standpoint TIN construction may seem very easy, but from a programming standpoint many ambiguities become visible. Since the very beginning of TIN research, certain drawbacks associated with this structure have been acknowledged. Poiker (1979a) notes that storage needs increase dramatically depending on the amount of topology saved in the structure.

Described below are three computer data structures associated with TIN construction. The placement of these structures here constitutes only a description of each method and does not claim to make refinements on any of the data structures presented. The first data structure has the triangles as the primary entities. Each triangle is an element in the data structure, and each is defined by a software pointer its own vertices. Pointers also exist from the current triangle to all adjacent triangles. This is the **Triangles Data Structure** and is used in the works of McLain (1976), Gold (1977), and McCullagh and Ross (1980).

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[2] Here, too, the algorithms mentioned provide only moderate assistance with programming a TIN data structure. More highly technical and descriptive articles can be found in "TIN: A Working Bibliography."

The next data structure treats the vertices of the triangles as the primary entities. Here, the network is defined by an array of vertex pointers pointing to a list of vertices connected to the current vertex by triangle edges. This vertex list can be sorted in clockwise or counterclockwise order around the center vertex, starting at "north" as defined in the current coordinate system. This, the **Connected Points** data structure requires half of the storage needed for the **Triangles Data Structure** and was first created by Poiker and Chrisman for use in the GDS and later work (1975, 1976).

The final data structure covered here is associated with McKenna's **Inward Spiral Method** (1987). McKenna points out, along with others, that each of the previous data structures has advantages and limitations and that each is suitable for different applications. The triangle list allows for speed efficient display functions such as surface shading, hidden surface removal, or the creation of surface texture, whereas, the connected points list allows for data point insertion and deletion, volumetric calculations and contouring. With these limitations in mind McKenna (1987) created the Inward Spiral data structure. Even though McKenna's structure combines excellent building blocks from the first two data structures, his structure contains redundant information which can consume processing time and disk space, McKenna, 1987.

The previous brief descriptions of computer algorithms for TIN construction represent the whole of such works. Technical descriptions provided by McKenna (1987), Gold (1977), McCullagh and Ross (1980), Poiker et al. (1976), and others do not adequately discuss computer algorithms and/or mention any sources that do. A gap like this seems to question the accuracy of such algorithms and whether or not any proposed algorithms will work correctly. Also in question are the statements of those manufacturers claiming to be using the TIN. What kind of comparisons, if any, have been made between their generated surfaces and those of Poiker et al. (1976)? These questions are gaps in the current literature regarding computerized TIN generation and construction. Aside from such gaps, the benefits and applications of using the TIN are numerous and wide ranging. The next section will discuss the major applications and tell how the TIN performs better than the grid structure.

APPLICATIONS AND BENEFITS OF THE TIN

The applications and benefits of the TIN data structure are diverse and far-reaching. Poiker (1979b) describes the following as major applications that are easier to perform using the TIN structure. They are hill shading, slope mapping, contouring, profile generation, hidden line removal, intervisibility, and horizon generation. Poiker states that the topological structure of the TIN makes certain complex procedures very easy and describes how the TIN structure is more flexible than the rectangular grid. To gain a better understanding with these applications, a brief description of each is given.

Poiker (1979b), McCullagh and Ross (1980), Gold (1977), and others have done extensive work on the generation of contours using the TIN as the underlying foundation. Poiker (1979b) states, "the extraction of contour lines is equivalent to location the lines of intersection between the terrain surface and a sequence of horizontal planes." Gold (1977) uses a best-fit plane to generate contours successively for each triangle. McCullagh and Ross propose a modified Delaunay triangulation method to create an optimal surface suitable for automatic contouring and hill shading. Although each of the above mentioned articles describes new and easier contour generation methods, only Gold (1977) actually shows a contour map produced by the author's new method.

Poiker states that a TIN model of terrain representation "lends" itself to development of an automated method of hill shading. The hill shading methods of Yoeli and Brassel can be easily automated, since the data structure of the TIN contains all necessary information for such calculations. Poiker (1979b) also states, "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 can also be performed on each triangle by "triangle basis," assigning each facet to the shading interval determined by the respective slope. McKenna (1987) also provides a description of surface shading for use with the Inward Spiral technique. However, the resulting diagrams of shaded surfaces are not realistic.

For creating profiles and the removal of hidden lines, Poiker (1979b) describes how a scanner works on the TIN to extract the profiles using a tracking process. The topological structure of the TIN allows for the extraction of scans at any angle through the region without an increase in computation or a loss of accuracy. In addition, the definition of features is not limited to the sampling interval of a grid. This description is not extremely clear, and in all the literature surveyed for this review, no diagrams or more descriptive algorithms were found.

Probably one of the biggest problems in terrain analysis is that of intervisibility. To determine whether or not position A can be seen from or can see position B is of major importance to the military. Poiker (1979b) describes how to extract the profile of the surface along the path between the points, using a tracking procedure. An extension of this technique uses angular rays showing the sections of the rays that are visible from the initial location. Much so-called "black" or classified literature probably exists along with detailed algorithms and programs, but the amount of "white" or non-classified literature which provides detailed algorithms is limited.

Finally, the plotting of a horizon is the last of the applications that Poiker (1979b) describes. Here, once again, the horizon is constructed by extraction of all horizon lines. All edges that make up the horizon must be both convex and must separate a visible facet from an invisible one. It is with these applications in mind that we will turn our examination to the future of TIN research.

THE FUTURE OF TIN RESEARCH

The main purpose of this review paper was to examine the various articles related to TIN data structures, their implementations and applications. The body of literature representing the TIN in all aspects is not incomprehensible, but quite manageable and studying it has provided many new insights into the present position of TIN research. In 1979, Gold speculated on the direction that TIN research was headed and pointed out areas where more research was needed. He hoped that future research would lead to the use of the TIN structure in relational cartographic data bases. As we look at the present condition of TIN development, we may find things very different. Today, many companies claim to have software that generates a TIN or uses a TIN for the creation of contours. Examining the literature, one sees that no specific guidelines or criteria have been established that may provide the means for comparison of surfaces generated by the TIN versus those done by conventional rectangular griding. Are these claims of TIN generation accurate for all areas selected, or are there certain conditions of terrain that may influence the performance of the TIN generation? Also not present in the literature are any truly computer programming related, algorithmic descriptions of TIN generation, triangulation or any specific automated related problems. With this is mind, we can begin to question the computer programs in use today that "generate" TINs and seek to understand better their inner structure and capabilities. Poiker, the main developer of the TIN, has provided many application ideas, but finding fully detailed algorithms, let alone working "shareware" code may be impossible.

The future of TIN development and perhaps even TIN acceptance may be judged by the articles and evaluations presented in literature. Future technical literature, I believe, should possess more algorithmic descriptions, allowing researchers to duplicate, use and improve on algorithms or processes previously defined. This type of verification process would allow greater advancements in the technical disciplines of geography, enabling present problems to be solved and new problems to be discovered.

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