

DEVELOPMENT OF A HYBRID MODEL FOR THREE-DIMENSIONAL GIS

SHI Wenzhong

KEY WORDS hybrid three dimensional model; TIN model; octree model; GIS

ABSTRACT This paper presents a hybrid model for three-dimensional Geographical Information Systems which is an integration of surface- and volume-based models. The Triangulated Irregular Network (TIN) and octree models are integrated in this hybrid model. The TIN model works as a surface-based model which mainly serves for surface presentation and visualization. On the other hand, the octree encoding supports volumetric analysis. The designed data structure brings a major advantage in the three-dimensional selective retrieval. This technique increases the efficiency of three-dimensional data operation.

1 Introduction

Three-dimensional (3-D) Geographical Information Systems (GISs) are very important for the application fields such as urban planning and management, geological subsurface modeling, mining and oil exploration. In a 3-D GIS, an object can be described in horizontal (x, y) and vertical (z) space. This spatial coordinate system allows more than one object to locate at the same horizontal location with different vertical positions. This is essential for the volume calculation, profiling, slope and aspect calculation.

Most of the existing commercial GIS are designed for two-dimensional (2-D) spatial data processing. There is a strong requirement on 3-D GIS application and research (Raper, 1989). Lack of real 3-D GIS data models and structures makes it impossible to carry out sophisticated 3-D spatial analysis. These make 3-D data modeling become of increasing interest in the GIS community. The major research issues may include: 3-D spatial data model, 3-D topological data model, 3-D database, 3-D spatial query and 3-D visualization.

This paper focuses the context of 3-D data modeling. Basically, the 3-D computational models can be classified into two major groups: surface- and volume-based representations. Surface-based geometric representations describe geometric characteristics of objects by using micro surface cells or surface primitives. The typical surface-based models include Grid Shape model, Facet model, Boundary Representation (B-rep). On the other hand, volume-based geometric representations describe the interior of objects by using solid information. The typical volume-based models may include 3-D array, Needle model, octree and Constructive Solid Geometry (CSG). Both surface- and volume-based models have their own merits and shortcomings in handling 3-D GIS data. An integration of the two models is expected to maintain the advantages of both. There are hybrid models developed in CAD/CAM mainly for handling regular objects. However, there is very little research on integration of surface- and volume-based 3-D models in the GIS community, where irregular objects are to be handled. This is thus identified as the focus of this paper.

2 Background

Many problems exist in the 3-D GIS development. Those mainly are: data volume, 3-D topolo-

SHI Wenzhong, Associate Professor, Department of Land Surveying and Geoinformatics, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong
E-mail: lswzshi@polyu.edu.hk

gy, spatial query and 3-D visualization. The development of the hybrid model is to partially resolve these problems. The idea of the integration of surface- and volume-based model solves some of the problems caused by the weakness of a single type of the models.

Computer graphics (CG), computer-aided design (CAD), and computer-aided manufacturing (CAM) were the driven forces behind the rapid development of geometric modeling schemes (Mortenson, 1985). In the GIS community, the development of 3-D models is passive and mainly dependent on what developed in CG and CAD. Current GIS builds up the relationships between the elevation attribute and other spatial and non-spatial data. With these elevation attributes and associated 2-D geometric elements, 3-D models can be displayed by CAD systems. However, differences between GIS and CAD systems, such as dimensions and characteristics of the described objects, topology and attribute data, spatial analysis make it necessary to develop specialized 3-D data structures. Thus the requirements from the GIS community can be met. 3-D GIS database design and database using relational data concepts had been done in the early 90s. However, there is still a lack of practicable scheme for developing a real 3-D GIS (Li, 1994).

In the CAD/CAM community, CSG and B-rep are the most commonly used 3-D models. A CSG consists of the Boolean combinations of the simple primitive volumes. A B-rep consists of the discrete bounding surfaces, curves and points of the solid together with the adjacency relationships between the geometric entities. The idea of combining CSG and B-rep in modeling process was started from the early 80s, while industrial people found difficulties in modeling volumetric objects bounded by free-form surfaces. This is the basis of the integration of surface- and volume-based models.

Kunii *et al.* (1995) proposed that there is often a need to derive the boundary of an object space. His paper also presented a method for automatically identifying the outermost boundaries of octree-indexed objects. It made the boundaries be derived flexibly and be converted to a variety of representa-

tions. It is now popular in the computer graphics community.

Octree model is used in the CAD/CAM community for providing a discrete approximation to an object. It is converted from the CSG model for fast displaying and generating meshes. Due to the approximate surface provided by the octree, it is seldom used in manufacturing process.

In the GIS community, the surface-based model, e.g., TIN, is commonly used for 3-D surface analysis. Point-to-point analysis, cut-and-fill analysis, calculation of slope, aspect, volume, surface area and surface length are all achieved by its modeling capabilities of a TIN. Volumetric spatial analysis has to be simplified into surface analysis. Most of the existing commercial GIS are not specifically for the geo-sciences and are mostly 2-D GIS. Peking University (1995) introduced a volumetric data modeling, Digital Volume Model (DVM) for displaying and analyzing mineral deposit.

Li (1994) carried out a research on 3-D data structure and application. In that study, two models were developed. One was a surface-based model and the other was a volume-based model. The surface-based model was mainly used for visualization and the volume-based model was used for spatial operation. Dynamic visualization, animation, and fast rendering techniques are applied to the surface-based model. Octree and CSG were used for the volumetric part of the model.

In this paper, a hybrid 3-D GIS spatial data model will be presented, which is composed of both surface- and volume-based geometric representations. The hybrid 3-D model contains rich surface information and detailed volumetric information in an effective way. The paper will first introduce the hybrid model and give two application examples of the model. An analysis to the model will be given finally.

3 The hybrid 3-D model

3.1 Model design

The hybrid 3-D model is designed as an integration of a surface-based model and a volume-based model. This idea is shown in Fig. 1. The hybrid

model thus includes the two individual 3-D models and the linkage of them.

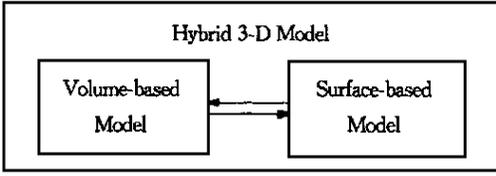


Fig. 1 The Concept of the hybrid 3-D model

In the hybrid model, the surface-based model is for performing analysis and visualization of three-dimensional surfaces, e. g., intervisibility of points and profiling. On the other hand, the volume-based model is for 3-D data operations and analysis. Each location (x, y) may have several z values expressing elevation elements such as holes, tunnels, wells or even different rock types locating in different elevations. Considering the requirements in GIS, TIN is adopted as the surface-based model. The octree is adopted as the volume-based model in this hybrid 3-D GIS model. In the following sections, the TIN and octree are introduced independently, and then the linkage of the both.

3.2 The surface-based model: TIN

A facet model approximates an object surface cell which may be of different shape. A triangle facet model has its surface cells defined as triangles of various sizes and is called a TIN. A database of a triangle facet model includes not only coordinates of vertices of all cellar triangles, but also topological relationships between triangles. In the areas where the surface varies very slowly triangles of large sizes can be used to represent the surface; while in areas with rapid surface changes finer triangles can approximate surface variations more precisely. Therefore, the storage space needed for a triangle facet model is proportional to the number of triangles used, which depends on surface characteristics and the required resolution of the resulting triangle facet model.

One of the advantages of the TIN model is the preservation of the originality of measured input data. The nodes of the triangles are original points; the triangles themselves are polygons; and the sides of the triangles are a special case of chains which are straight-line segments with the nodes being on-

ly vertices. Furthermore, because of their stable structure and simplicity for processing, triangle facet models are widely used in the generation of DTMs, visualization of 3-D object surface, shading and ray tracing.

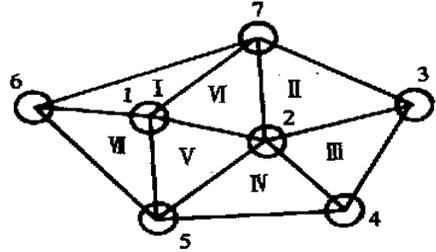


Fig. 2 An example of TIN

In the various ways of storing TIN topology, the most common one uses triangle as a basic object, with topological links to adjacent triangles and a list of nodes. In this model, each record of the triangle topology table lists the three adjacent triangles and three nodes of the triangle in the clockwise order. Spatial coordinates of each node (x, y, z) are stored in a separate record. This structure allows efficient processing where area adjacency is used. Tables 1 and 2 show an example using this model for representing the TIN in Fig. 2.

Table 1 List of node coordinates

Node	Coordinates
1	X_1, Y_1, Z_1
2	X_2, Y_2, Z_2
3	X_3, Y_3, Z_3
...	...
...	...
7	X_7, Y_7, Z_7

Table 2 List of triangle topology

Triangle	Node	Adj. Δ
I	1, 6, 7	VII O, VI
II	2, 7, 3	VI O, III
III	2, 3, 4	II, O, IV
IV	2, 4, 5	III O, V
V	5, 1, 2	VII VI, IV
VI	1, 7, 2	I, II, V
VII	6, 1, 5	I, V, O

Note: O= outside

3.3 The volume-based model: octree

The octree representation describes an object hierarchically. An original octant is defined first, as similar to a 3-D binary array, the octant is the smallest cube containing the object. At the first level this original octant is divided into eight sub-oc-

tants by halving the original octant in 3 directions. Then, each sub-octant is checked if it is occupied by the object. The sub-octants are classified into three categories: F=Full (fully occupied by the object), E=Empty (no object element exists in the sub-octant), P=Partial (partially occupied). On the other hand, these eight sub-octants correspond to eight

digits from 0 to 7, which are enable the octants to be related to a 3-D Cartesian coordinate system. P-octants will be further subdivided into eight sub-octants at the next level, which are again classified. This partition procedure continues until all sub-octants are either full(F) or empty (E). An example of linear octree is shown in Fig. 3.

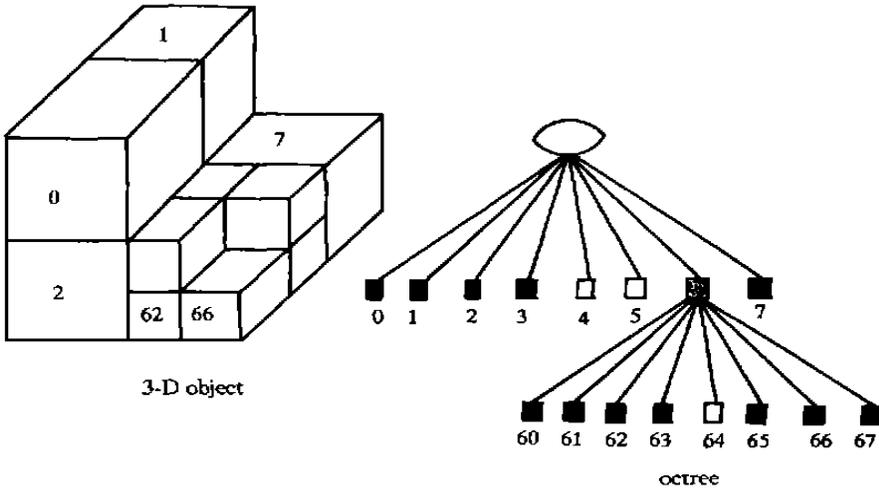


Fig. 3 Linear octree: 0, 1, 2, 3, 7, 60, 61, 62, 63, 65, 66, 67

In order to save storage space, E-octants are not registered. A linear octree data structure that lists only octree codes of F-octants is often used. Storage space requirement for a linear octree is relatively low in comparison with other volume-based representations. It increases if the required octree resolution is high. Because of its hierarchical data structure, octree representation is very efficient in spatial analysis, Boolean operations, and database management.

Octree is actually an encoding method to reduce the storage space requirements for 3-D raster data, which is an extension of a quadtree structure in three dimensions. This three-dimensional hierarchical data structure provides both advantages in data compression and efficient spatial addressing, and it is always planar-enforced.

3.4 The linkage between TIN and octree

In the hybrid model, each TIN facet is designed to contain its own octants. This is realized by setting up a linkage file of pointers. A TIN facet thus can be efficiently linked with the corresponding data octants. In the hybrid model, TIN is mainly used for visualization and finding topological relationship. Once a triangular facet (or more) is chosen,

its relevant octree data is decoded for handling spatial operations. Fig. 4 shows a triangular facet in the TIN model. Fig. 5 shows a 3-D volume data in octree model. Fig. 6 shows the above two data sets organized by the hybrid model. The TIN model works as a surface-based model covering the details of the 3-D volume data represented by the octree model.

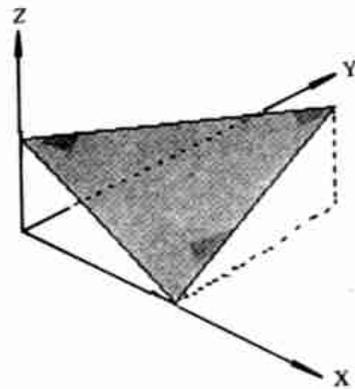


Fig. 4 A triangular facet in the TIN model

3.5 Data structure of the hybrid model

The hybrid data structure is composed of five files: ADJ Δ file, NODE file, COORD file, POINTER file and OCTREE DATA file shown in Tables

3~7. In this data model, the triangles are the basic spatial objects. Each triangle has its topological attributes which describe the nodes, the adjacent triangles and the pointers to the relevant octree elements.

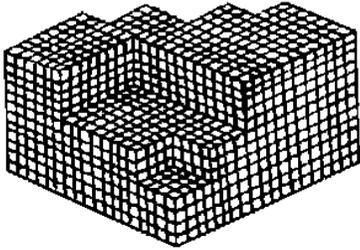


Fig. 5 A 3-D volume data in octree model

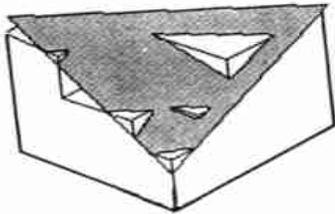


Fig. 6 Data sets in the hybrid model

TIN model works as a surface-based model covering the details of 3-D volume data represented by an octree model.

The ADJ Δ file stores the adjacency relationships of the different triangles. The NODE file indicates the three nodes which fix the limits of each triangle. The COORD file contains the x, y, z coordinates of each node. The POINTER file locates the octree data stored in the OCTREE DATA file of each triangle. The OCTREE DATA file stores the octree data which represent the volume under each triangle. Fig. 7 shows an example which is stored in the five tables by the hybrid data structure.

4 Application examples

4.1 Selective retrieve

Since in the hybrid model the triangle is the basic unit. It is therefore possible for a user to retrieve an interested area. In the developed prototype it is realized by clipping the interested area and omitting the unselected ones. As a result, only the octants within the interested area are retrieved other than all areas. Data retrieving time can be reduced if the

selected area is smaller, and the usage of storage space is more efficient. Although the data size is smaller by using octree encoding, limiting the amount of data retrieved is further helpful in reducing storage space. Therefore, retrieval time in the system is reduced. Fig. 8 illustrates an example of selective retrieve using the developed prototype based on the hybrid 3-D GIS model.

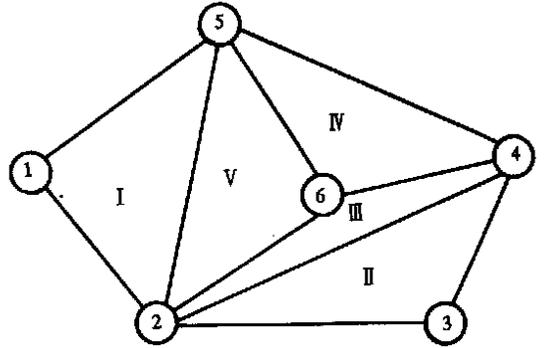


Fig. 7 A network to be modeled by the hybrid model

Table 3 List the three adjacent triangles for each triangle

ADJ Δ file	
Δ	Adj. Δ
I	0, V, 0
II	III, 0, 0
III	V, IV, II
IV	V, 0, III
V	I, IV, III

Table 4 List the three nodes which define each triangle

NODE file	
Δ	Node
I	1, 5, 2
II	2, 4, 3
III	2, 6, 4
IV	6, 5, 4
V	2, 5, 6

Table 5 List the coordinates of each node

COORD file	
Node	Coordinates
1	X_1, Y_1, Z_1
2	X_2, Y_2, Z_2
3	X_3, Y_3, Z_3
4	X_4, Y_4, Z_4
5	X_5, Y_5, Z_5
6	X_6, Y_6, Z_6

Table 6 Indicating location of octree data. The two pointers indicate the data range in the file

POINTER file		
Δ	Layer	OCTREE ptr.
I	1	160
I	2	239 371
II	1	6 178
III	1	79 103
IV	1	104 150
V	1	151 238
V	2	373 516

Table 7 Store octree data

OCTREE DATA file		
Address	Octal-key	Level
1	1	18
2	30	17
3	37	17
4	572	16
5	573	16
...

4.2 Visualization

Fig.9 illustrates an example of applying the hybrid model to visualize terrain data, geological and engineering data. The tunnel is an engineering data located under the terrain. The individual structures are geological data. Both geological and engineering

data are stored as 3-D raster layer encoded by octree. TIN model is used for storing the terrain data. Both TIN and octree data are integrated in the hybrid model. With this result, we can visualize volume (engineering and geological) data and surface (terrain) data simultaneously.

5 An analysis of the hybrid model

5.1 Merit of the hybrid model

The hybrid model is composed of both TIN and octree model. It therefore maintains the advantages of both. For instance, the model can perform ren-

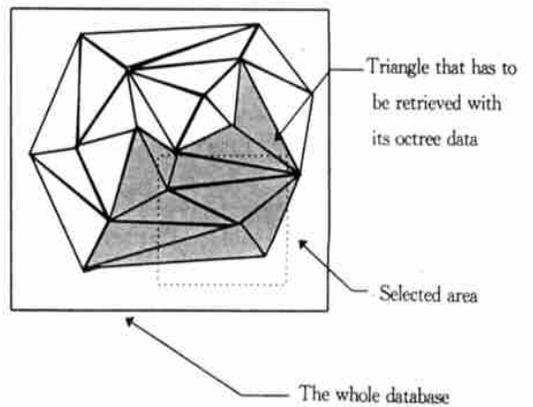


Fig. 8 An example of the selective retrieval

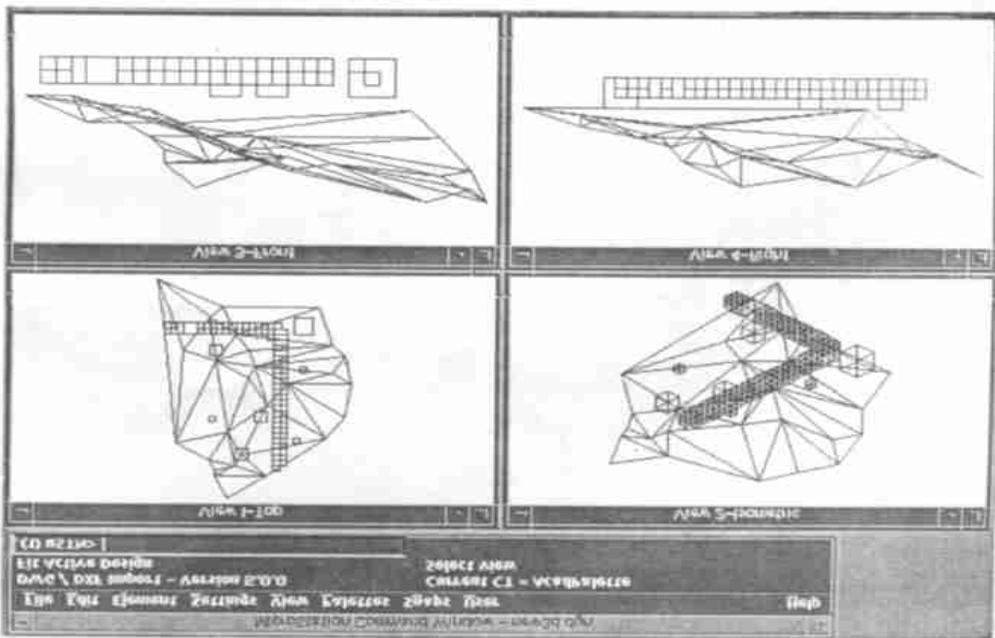


Fig. 9 Application of the hybrid model for visualizing surface data, geological and engineering data

dering techniques such as texture mapping or ray-tracing. The model takes the advantage of octree

such as efficient addressing and efficient data storage. The hybrid model is efficient in process of topological search. The hybrid model is also efficient in retrieving relevant volumetric data of a triangle in TIN. The selective retrieve is an example.

5.2 Limitation of the hybrid model

The configuration of octree data needs to be changed when that of the TIN is changed. It takes long time to encode, decode and resample octree data. Accuracy of the TIN model is greatly affected by sample point accuracy, sample point distribution, data source, and the configuration of network. Manual editing of interior data is a time consuming process.

6 Conclusions

A hybrid 3-D GIS model, which can handle surface- and volume-based data simultaneously has been developed in this study on the basis of TIN

and octree data models. The TIN model works as a surface-based model which can model the irregular terrain surface in GIS. On the other hand, the octree is adopted because of its efficiency in 3-D address retrieving storage and data compression. It shows that the model is efficient in 3-D selective retrieval and visualization when both surface- and volume-based data are used simultaneously.

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