HYBRID DATA STRUCTURE BASED ON OCTREE AND TETRAHEDRON IN 3-D GIS

Li Qingquan   Li Deren

Wuhan Technical University of Surveying and Mapping
39 Luoyu Road , Wuhan 430070
P.R.CHINA

Commission III, Working Group III/IV

KEY WORDS: Three-dimensional, GIS, Data structure, Octree, Tetrahedron

ABSTRACT

After a review of data structures in 3-D GIS, a hybrid data structure based on Octree and Tetrahedral Network (TEN) is presented and a concept of 3-D GIS based on hybrid data structure is introduced in this paper. The problems about generation of data structure, data organization, data conversion and application are discussed.

1. INTRODUCTION

In most geoscience applications, geometric information in vertical direction is needed. It has the same significance with horizontal extent such as in air pollution monitoring. However, in conventional 2-D GIS, it is usually abstracting vertical information as an attribute such as elevation data in DTM, then spatial manipulation and analysis are carried out. If more than one observation are taken in a vertical direction such as sampling data in natural resource exploration along a vertical drilling, 2-D GIS is difficult to process. A system that has ability of full three-dimensional (3-D) manipulation and analysis is required. Also, there has requirement of 3-D GIS in oil exploration, mining, meteorology, hydrogeology, geological modeling, environmental monitoring, civil engineering, etc. Now, attention is focusing on the design and implementation of 3-D GIS, in a range of geoscientific application areas[Raper and Kelk, 1991].

Within research works of 3-D GIS, data model and data structure is one of the key problems. Before recent years, most results based on CAD models, such as Constructive Solid Geometry (CSG), Boundary Representation (BR), and made some modifications and extentions. It is obviously that CAD system cannot readily be applied to geoscience modeling. It is different from GIS in many aspects.

Despite lots of new results have been made by researchers over the world [Molenaar, 1992; Rongxing Li, 1994; Xiaoyong C.,1994a]. Due to the complexity of 3-D objects and applications, one data structure is difficult to satisfy different requirements. There have two methods for this problem. One is to develop hybrid data structure. The other is to integrate different data structures in one system. In this paper, authors present a hybrid data structure and a concept of 3-D GIS based on it.

This paper is organized as follows: 3-D data structures are reviewed in Section 2. In Section 3 after a discussion of Octree and Tetrahedral Network (TEN), a hybrid data structure based on Octree and TEN is presented. A concept of 3-D GIS based on hybrid data structure is introduced In Section 4. In Section 5 a conclusion of this paper and an application experiment are introduced.

2. 3-D DATA STRUCTURE

Data structures that can be applied in 3-D GIS are divided into two types [Rongxing Li, 1994]. One is based on surface representations, include: rectangular grids, triangulated irregular network (TIN), BR and parametric functions. The other is based on volume representations, include: 3-D array, Octree, CSG and TEN.

The former focus on the surface representations of 3-D objects such as surface of building and subsurface of geology. Representations of 3-D Objects are formed by their surface descriptions. These data structures are convenient for visualization and updating, but is difficult for many spatial analysises such as integral property calculation. Within these data structures, rectangular grids and TIN are in common used in DTM, which are familiar with us. While BR is used, a solid is defined in terms of the geometry of its bounding surfaces. Typically this is described by polygonal facets, each of which is defined by its edges, which are in turn defined by the vertices. In geoscience applications, in order to convert the observations into BR, the relationships among elements must be identified. However, objects in geoscience are usually unknown. These relationships are difficult to be determined. According to the characteristics of BR, therefore, CAD/CAM and engineering are the main application fields. Parametric polynomial functions is one of the useful method to represent free-form surface. The x,y and z Cartesian coordinates become a function of two parametries (u,v). An individual surface is described by a function **P**(u,v), where

$$\mathbf{P}(u,v)=[x(u,v),y(u,v),z(u,v)] \quad (0<u<1,0<v<1)$$

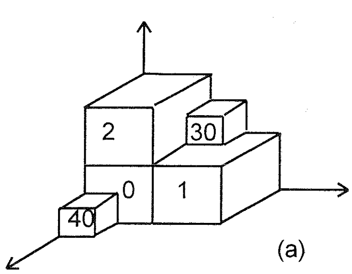
Complex surface in geoscience can be subdivided to form a contiguous set of patches, each of which is defined locally by low order, typically cubic polynomial functions. Recently, a kind of B-Spline function, Non-Uniform Rational B-Spline (NURBS), cause more attention in CAD/CAM field. Beside the advantages of B-Spline, it has no deformation after perspective and more shape control ability, which is suitable for the representation of complex surfaces in geoscience. An application has been introduced by Fisher and Wales [1992]. However, if some breaks exist in surface, NURBS is difficult to represent.

The latter focus on the volume representations of 3-D objects such as water body and geological construction. Representations of 3-D objects are erected by their volume descriptions. These data structures are suitable for spatial manipulation and analysis. But more storage space is needed. Within these data structures, 3-D array is a Voxel model which is arranged closely over 3-D space. Because of no data condensation in 3-D array, huge storage space is needed and the speed of computation is slow. Generally, 3-D array is used as a mid-representation. Octree is a data structure that has been studied and applied extensively. Octree is a compact and efficient representation, which is a hierarchical 3-D space subdivision instead of equal size and regular arranged 3-D array . CSG represents an object by a combination of predefined primitives which are regular shape volumetric instances such as cube, cylinder, etc. Relationships among these primitives include geometric transformations and Boolean operations. Because model can be established interactively by simple modeling words. CSG is one of the most used modeling technique in CAD/CAM field and often combined with BR in practice. TEN is a 3-D extension of 2-D TIN and tetrahedron is a basic primitive. Object is described by connected but not overlapped tetrahedral network. Similar to 2-D TIN, TEN has many advantages in manipulation, display and analysis. In next Section, Octree and TEN will be discussed in detail and a hybrid data structure will be introduced.

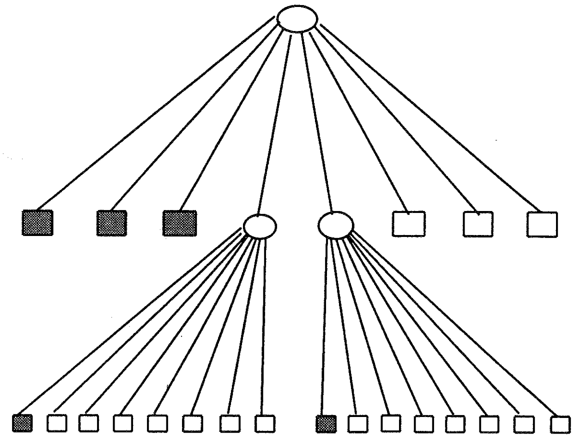
3. HYBRID DATA STRUCTURE

3.1 Octree

In tree structure of Octree, root represents a cube which includes whole object. An Octree recursively subdivides this cube into octants. Every cube would be subdivided if they were found to be non-uniform or the size of cube was larger than requirement. There have three kinds of node in Octree : black, white and grey. If n represents the depth of an Octree, it corresponds with a $2^n \times 2^n \times 2^n$ 3-D array. Figure 1 is a 2^2 simple object and its Octree representation.



(a)



(b)

Figure 1. Octree

Morton	ATT
0	1
1	1
2	1
30	1
40	1

Table 1. LQ

Morton	ATT
0	1
31	0
40	1
41	0

Table 2. 3DRE

Linear Octree (LQ) encoding is a generally used encoding method, in which only addressing code and attribute of black leaf node are stored. Morton code, which is a n digits encoding, is used as addressing code in which the location and size of leaf node are contained. Table 1 is linear Octree encoding of Figure 1.

Another efficient Octree encoding method is Three-Dimensional Run Encoding (3DRE), which can be extended from 2DRE [Jean Paul Lauzon, etal. 1985] easily. Similar to linear Octree encoding, Morton code is used as addressing code in 3DRE. According to the size, Morton codes are ordered in a set, which can be thought as a group of subsets. Every subset corresponds with a group of leaf nodes which have same attribute. In every subset, only first element is remained and others are deleted, then 3DRE of Octree is formed. Table 2 is 3DRE of Octree in Figure 1. Within 3DRE the deleted elements can be resumed by neighbor addressing codes. Compared with linear Octree encoding, 3DRE saves more storage space. It is convenient for some spatial operations such as insert and delete. However, Octree structure is not exist in 3DRE so that it only be used to describe solid object.

Because Octree is a kind of middle data structure, it cannot be generated from original observations directly. The generation of Octree is transformed from other structures such as 3-D array, BR, CSG.

3.2 Tetrahedral Network (TEN)

TEN has been concerned as a useful data structure in 3-D GIS by many researchers for a long time [Raper and Kelk, 1991]. It may be a powerful vector structure in 3-D GIS. The concept of TEN can be readily formed from 2-D TIN. Firstly, 2-D Voronoi is extended to 3-D forming 3-D Voronoi, then TEN can be derived from the 3-D Voronoi polyhedrons in the same way as deriving TIN from Voronoi polygons. TEN is shown in Figure 2 and Table 3 is a kind of data organization of TEN, in which complete 3-D spatial topological relations and attribute data are contained.

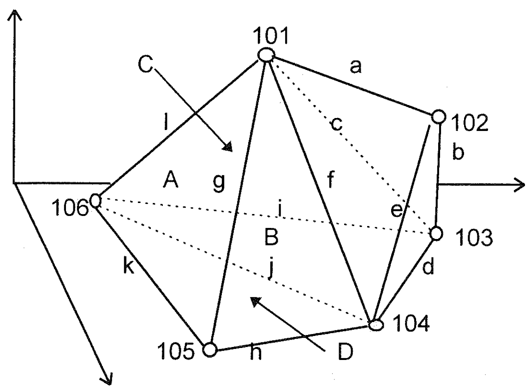


Figure 2. Tetrahedral Network (TEN)

Node

PN	X	Y	Z	ATT
101	x_{101}	y_{101}	z_{101}	
102	x_{102}	y_{102}	z_{102}	
103	x_{103}	y_{103}	z_{103}	
104	x_{104}	y_{104}	z_{104}	
...				

Line

LN	Points	ATT
a	101,102	
b	102,103	
c	101,103	
d	104,103	
...		

Triangle

TN	Segms	Tetra 1	Tetra 2	ATT
A	I, g, k	0	I	
B	g, f, h	0	I	
C	j, h, k	I	0	
D	I, f, j	I	II	
...				

Table 3. Data Organization of TEN

Comparing with other solid structure, TEN has some advantages [Xiaoyong C., 1994b] such as:

TEN is one of the simplest data structures and consists of point, line, area and volume.

TEN is a linear combination of tetrahedrons, that transformation of TEN equals to the combination of transformed tetrahedrons.

TEN not only has advantages of solid structure such as rapid geometric transformation but also has advantages of BR such as fast topological relations processing.

TEN is convenient for rapid visualization. During display tetrahedrons are arranged depending on front/back relations, then drawing from back to front.

However, TEN is not applied extensively until now because of difficulty in generation. Now two algorithms are developed. One is based on 3-D Mathematical Morphology (MM) and raster-vector hybrid processing [Xiaoyong C., 1994b]. The basic idea is that 3-D space is represented by 3-D array completely and spatial points are represented by voxels after a vector to raster conversion, then sequential dilation algorithm in MM is used to form 3-D Voronoi polyhedrons from which TEN is derived. The other is based on 3-D Distance Transformation (DT) [Morakot Pilouk, etal. 1994]. Distance Transformation that was introduced by Borgefors,G. [1984,1986] has been used in construction of 2-D TIN [Tang, L., 1992]. The difference between these two algorithms is dilation algorithm in MM or 3-D Distance Transformation used.

3.3 Hybrid Data Structure

According to the discussion in last two parts, we can find that storage space increases rapidly along with the increasement of an resolution in Octree so that the resolution cannot be in a high level. Also, Octree is an approximate representation forever. However, Octree has simple structure and convenient for spatial analysis such as integral property computation and visualization. At the same time, TEN has ability to represent object accurately and describe complicated spatial topological relations completely. Also, original obsverations are stored. But TEN is difficult to be erected and has complicated structure, and in some cases large storage space is needed.

In this paper, authors present a hybrid data structure based on Octree and TEN which is similar to hybrid data structure in DTM [Fritsch and Pfannenestein, 1992]. In which Octree and TEN are combined and advantages of each are integrated such as a more accurate representation of object by hybrid data structure without storage space increased. Hybrid data structure is shown in Figure 3. Table 4 is a kind of data organization of hybrid data structure.

Within hybrid data structure, Octree used as whole description and TEN as part description. A special attribute of Octree is used to integrate Octree and TEN together, which is "SX" in Table 4, where "S" is an identification and "X" is a pointer. If attribute of an Octree code is "SX" such as "73" in Table 4, it implies that a part TEN is connected with this Octree code and pointer can be used to find TEN data in TEN structure. On the other hand, eight vertices of the cube which is represented by the Octree code can be got easily such as (3,3,2) and (3,4,2) in Figure 4, then TEN structure in this cube is established by these vertices and feature points such as 201 and 202 in Figure 4. The realization of hybrid data structure increases the adaptability of 3-D data structure.

In many cases, it is beneficial for improving representation accuracy and reducing storage space. Also, Octree and TEN are two specialties of hybrid data structure.

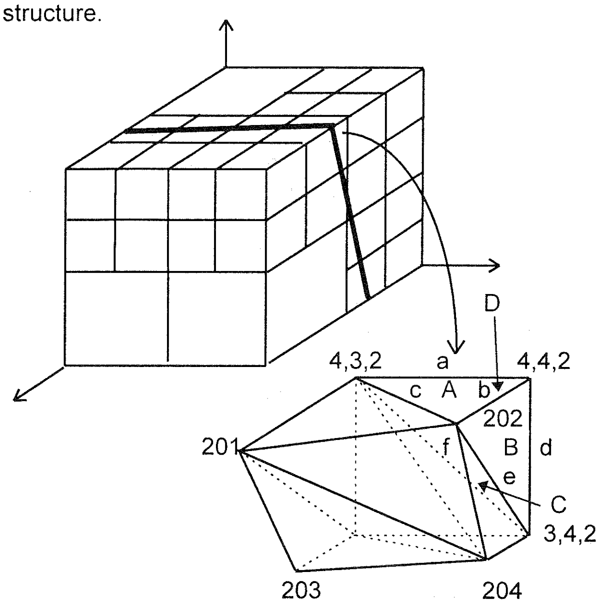


Figure 3. Hybrid Data Structure

Octree

Morton	ATT
...	
73	SX
...	

Tetrahedron

TEN	Surfs	ATT
...		
I	A, B,C,D	
...		

Triangle

TN	Segms	ATT
A	a, b, c	
B	b, d, e	
C	c, e, f	
D	a, d, f	
...		

Line

LN	Start	End	ATT
a	4,3,2	4,4,2	
b	202	4,4,2	
c	4,3,2	202	
d	4,4,2	3,4,2	
...			

Node

PN	X	Y	Z	ATT
201	x_{201}	y_{201}	z_{201}	
202	x_{202}	y_{202}	z_{202}	
203	x_{203}	y_{203}	z_{203}	
204	x_{204}	y_{204}	z_{204}	
...				

Table 4. Data Organization of Hybrid Data Structure

Although hybrid data structure has some advantages in representing geo-objects, it should be appreciated properly. For instance, in geological modeling, while geology construction is regular and complete, Octree may be a suitable data structure; while geology construction is tattered and many faults included, TEN may get a better result; while a few faults are involved in geology construction which is complete, hybrid data structure is useful. Additionally, data structure selecting also depends on some other factors such as data type, object characteristic, spatial operation and analysis, etc.

4. 3-D GIS BASED ON HYBRID DATA STRUCTURE

4.1 A Concept of 3-D GIS

A concept of 3-D GIS based on hybrid data structure is shown in Figure 4 depending on the discussion in front Sections. Five modules in this framework are User Interface, 3-D Modeling, Data Conversion, Spatial Operation and Relational Database.

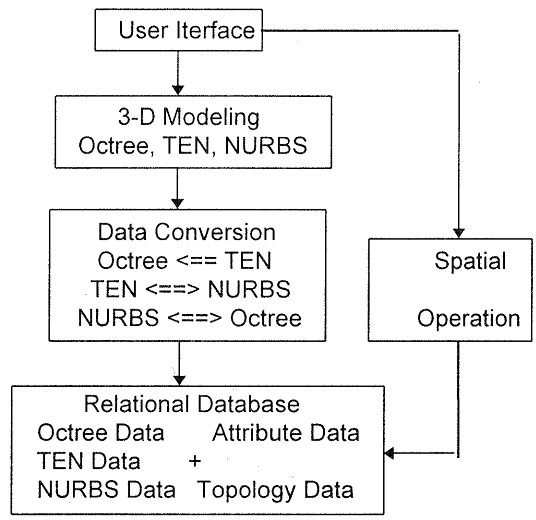


Figure 4. Framework Of 3-D GIS

Interactive user interface provides possibility of intercourse between user and system from it user can control system and get results. Three 3-D modeling methods in 3-D Modeling module are Octree, TEN and NURBS. Octree is a kind of raster structure which can be built from 3-D array that is formed by spatial interpolation of observations. TEN is vector structure which can be generated directly from dispersed observations. The combination of Octree and TEN is used to form hybrid data structure. NURBS is a parametric function also a vector structure which is erected from subsurface observations. Data conversions provide a link among different data structures and data which come from different resources can be uniformed in one structure. Also, lots spatial analysises can be carried out readily by selecting different data structures. Spatial operation provides all kinds of spatial manipulations and analysises such as 3-D visualization, geometric transformation , etc. Relational database is a useful tool in data management. After some extension spatial manipulation and query are carried out in relational database. Relational database is efficient for management of TEN data. When resolution is high, spatial index is needed for Octree data in relational database. Because parametric coordinates of NURBS are purely local and cannot serve as part of a primary spatial indexing for some spatial searches, relational database is not very suitable for NURBS data. In addition, topology data and attribute data are integrated in all kinds of data.

4.2 Data Structure Conversion

There have three kinds of data structure conversion algorithms in our 3-D GIS. One is an algorithm from TEN to Octree, which is vector to raster conversion, can be developed from the results of Tanninen and Samet [1986] and Atkinson, etal. [1985]. Another is algorithm between TEN and NURBSs which is similar to the generation of TIN from contours and contours from TIN. The third is algorithms between Octree and NURBSs. The algorithm from NURBSs to Octree can be formed from Fisher and Wales [1992]. The algorithm from Octree to NURBSs is realized firstly interpolating subsurface points from Octree, then establishing NURBSs parametric coordinates. Some algorithms of these have been realized in author's research work.

5. APPLICATION AND CONCLUSION

An application of 3-D GIS is being carried out by authors in WTUSM, CHINA. Test area is a 9 km X km coal field, in which about 100 drillings are spaced. There have three coal layers and several rock layers. Test data include sampling data of drillings, information of earth surface, location of drillings and position of faults. Research works involved establishment of 3-D model of test area by use of different data structures, 3-D visualization and some spatial analysises for different geology constructions such as coal layer and fault. A HP Workstation, Starbase graphic library and C language are used.

In 3-D GIS, objects are very complex. For example, in Mine Information System there have ore body, gallery, shaft, earth surface and building, etc. None of the structures has ability to represent all objects well. Also, each structure has it own advantages in spatial operation and analysis such as raster is convenient for Boolean operation and vector is easy for geometric transformation. Hybrid data structure may be a better means to balance different requirements. In this paper authors pay more attention in hybrid data structure and integration of data structures in 3-D GIS. A hybrid data structure based on Octree and TEN is presented and a concept of 3-D GIS is introduced, and some related issues such as data organization, formation of data structure, data conversion and application are discussed. These works are contributions to the development of 3-D GIS.

REFERENCES

Atkinson,H., I. Gargantini and M.V.S. Ramanath, 1985. Improvements to a Recent 3D-Border Algorithm. Pattern Recognition, Vol.18, Nos 3/4, pp. 215-226.

Borgefors,G., 1984. Distance Transformations in Arbitrary Dimensions. Computer, Vision, Graphics and Image Processing. Vol.27, pp. 321-345.

Borgefors,G., 1986. Distance Transformations in Digital Images. Computer, Vision, Graphics and Image Processing. Vol. 34, pp. 344-371.

Fisher, T.R., and R.Q. Wales, 1992. Three-dimensional Solid Modeling of Geo-Objects Using Non-Uniform Rational B-Splines (NURBS). In: Three-dimensional Modeling with Geoscientific Information Systems. Kluwer Academic Publishers, pp. 85-105.

Fritsch,d. and A. Pfannenestein, 1992. Integration of DTM data structures into GIS data Models. In: International Archives of Photogrammetry and Remote Sensing, Washington, USA, Vol. XXIX, Part B3, pp. 497-503.

Jean Paul Lauzon, etal. 1985. Two-Dimensional Run Encoding for Quadtree Representation. Computer, Vision, Graphics and Image Processing. Vol.30, pp.56-69.

Molenaar, M., 1992. A Topology for 3D Vector Maps, ITC Journal, 1992-1, pp.25-33.

Morakot Pilouk, etal., 1994. A Tetrahedron-Based 3D Vector Data Model for Geoinformation. In: Advanced Geographic Data Modeling, Netherlands Geodetic Commission, Publications on Geodesy, No.40, pp.129-140.

Raper,J. and B.Kelk, 1991. Three-dimensional GIS. In: Geographical Information Systems: Principles and Applications, Longman, London, Vol. 1, pp.299-317.

Rongxing Li, 1994. Data Structures and Application Issues in 3-D Geographical Information Systems. Geomatica, 48(3), pp.209-224.

Tamminen,M.and H.Samet, 1986. Efficient Octree Conversion by Connectivity Labeling. Computer Graphics, 18(3),pp.319-324.

Tang,L.,1992. Raster Algorithms for Surface Modeling. In: International Archives of Photogrammetry and Remote Sensing, Washington, USA, Vol. XXIX, Part B3,pp. 566-573.

Xiaoyong, C. and K. IKEDA. 1994a. Three-dimensional Modeling of GIS Based on Delaunay Tetrahedral Tessellations. In: International Archives of Photogrammetry and Remote Sensing, Munich, Germany, Vol. 30, Part B3/1, pp. 132-139.

Xiaoyong, C. and K. IKEDA. 1994b. Raster Algorithms for Generating Delaunay Tetrahedral Tessellations, In: International Archives of Photogrammetry and Remote Sensing, Munich, Germany, Vol. 30, Part B3/1, pp. 124-131.