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TOWARDS THREE-DIMENSIONAL DATA STRUCTURES IN GEOGRAPHIC INFORMATION SYSTEMS

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ABSTRACT

Data modelling and database design, respectively, in geographic information systems (GIS) is dependend on the underlying structures of the data. While in the past main research was concentrated on an efficient link between the in general two-dimensional data and its corresponding attributes, the integration of terrain data demands for fully 3D-data structures.
The paper starts with models used in computer graphics describing 3D-data. It turns out that regular 3D-decompositions are not well suited for GIS-data. In terms of a two-dimensional topology the non regular geometric data of the terrain surface can efficiently be described by means of boundary descriptions. These boundary descriptions fit very well into object oriented management techniques, in which a thematic model has a higher priority than the geometric model consisting of coordinates and topology. Regarding the density of terrain data with respect to the density of situation data a separated data management comes out.

INTRODUCTION

The integration of digital terrain models (DTM) into geographic information systems (GIS) has already been proposed by B. Makarovic (1977); it was also subject in detailed investigations given by R. Adler (1978). During the seventies some work dealt already with databases for DTM (A.A. Noma, 1974, J.R. Jancaitis, 1976, A.A. Elassal, 1978, A.A. Noma/N. Spencer, 1978), but there was a lack on knowledge on the underlying structures for GIS. Within the latter ones investigations were directed at this time on digital management of cartographic data in general. Very soon it came out that GIS must be seen interdisciplinary and that most of the GIS-problems may be solved by 2.5D-structures which lead to attribute handling of terrain data.
In the meantime data structures for GIS are more transparent (C.J. Date, 1986, P.A. Burrough, 1986, M. Molenaar, 1989, D. Fritsch, 1989a). This led also to fundamental investigations and realizations on the integration of height into GIS (F. Steidler et al., 1986, D. Fritsch, 1989b, H. Ebner et al., 1990) in which DTM's are not only constituents of GIS-databases but contribute to a broadening of the GIS applications considerably (P. Riegger, 1989).

GEOMETRIC MODELLING

Geometric modelling is a substantial part of computer graphics (A. Meier, 1986). When looking at the concepts describing 3D-models one can differentiate between

- primitive instancing (PI), that means the object is represented by a fixed number of parameters (for instance a cube can be described by its edge length a)
- spatial occupancy enumeration (SOE) in which the object is given by spatial cells of fixed size. SOE is mostly used in computer tomography.

- cell decomposition (CD) represents objects of arbitrary dimension to be composed of simple spatial elements. In the contrary to SOE the space is not divided into uniform spatial cells but CD allows cells of different shape and size. (For instance, a house may be composed of a solid cube and a solid tetrahedron).
- boundary representation (BR) in which a 3D-object can be described by its boundary elements (for instance, by surfaces (blocks), edges (lines) and nodes (points). This leads to a two-dimensional topologic representation of three-dimensional surfaces being the most important phenomenon of BR.
- constructive solid geometry (CSG) uses standardized primitives for geometric modelling. Because of its primitives the graphic representation of 3D-objects costs computing time, moreover, 2D-surfaces are difficult to integrate.

At a first view some methods of geometric modelling can be used to develop three-dimensional data structures for GIS-data. But if one has in mind a total topologic decomposition which is two-dimensional and also fits into GIS data structures currently in use the boundary representation method (BRM) is the favorite one. But BRM's can also be supplemented by other methods to consider anthropogenious objects leading to a combination of solid state and boundary geometry.

BOUNDARY REPRESENTATION OF SPATIAL DATA

Within boundary representations there exist two models describing the spatial data set

- the edge model in which the object is given by the connection of nodes n. Here the edges e are functionally to describe by e=e(n). For instance, a triangulation of terrain data may be described by an edge model.
- the block model which consists of constrained surfaces and approximating surfaces, respectively. While constrained surfaces are explicitely given by the connection of nodes (e.g. parcels) the latter ones must be determined using reference points, edges, tangent vectors or curvatures. The functional description of the blocks b can be given by b=b(e,n). A grid model describing terrain data is nothing else than a block model.

In Fig. 1 the boundary representation of a contigous object in R^3-space can be seen. The object consists of a regular grid with four quadrants. Its two-dimensional topology uses the nodes, edges and blocks for a total description in terms of a combined model (e.g. edge model <u>and</u> block model). The metric information e.g. the coordinates x,y,z is <u>arranged</u> at the lowest level of the BR.
The two-dimensional topology (interior geometry of the object) can be proven on consistency at least by the set of Euler, which is necessary and sufficient (D. Fritsch, 1989a).

<u>Theorem 1</u>: For every contigous map with n nodes. e edges and b blocks it holds

$$\boxed{C = n - e + b = 2} \qquad (1)$$

a) object   b) topologic decomposition

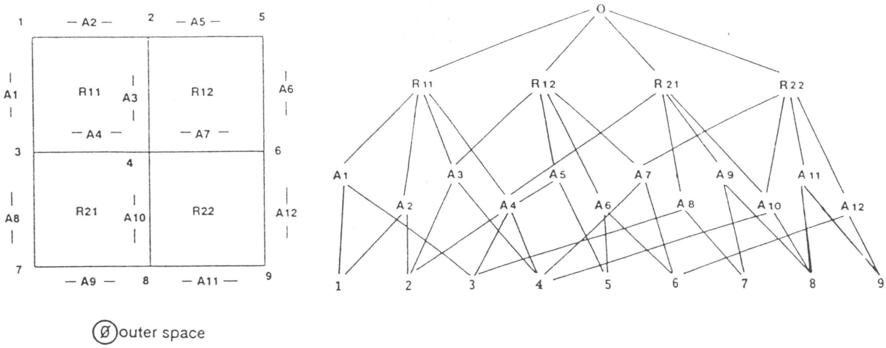


Fig. 1: Boundary representation of a simple object

C is called the characteristic of the map or of spatial objects; it must always have included the outer space Ø.
For the example above the Euler proof leads to

$$9 - 12 + 5 = 2 \qquad (2)$$

OBJECT ORIENTED MODELLING

The boundary representation is not sufficient in describing spatial data within a GIS. There is a need for more complex object descriptions in the sense that a simple object can be embedded in a more complex object and the more complex object is part of a most complex object and so on. This has led to the definition of hyper objects or super objects to be managed by thematic or feature based models (N. Bartelme, 1989). In order to set up feature based models different strategies can be found in GIS-practice. There are two main philosophies

- object oriented management (OOM)
- object oriented programming (OOP)

The object oriented management is simple in realization and has meanwhile become a standard in GIS. It extends the BRM in the sense that a further hierarchy is set up consisting of complex objects (complex features), object classes (feature classes), objects (features) and object items (feature items). This hierarchy is superimposed with the BRM, which means the thematic model is at the top, the topologic model in the middle and the coordinates are at the bottom (see Fig. 2).
The current trend in OOP combines relational databases with object oriented treatment. The main objective here is to extend the productivity of software by means of further modularizations (J.R. Herring, 1987, H.J. Schek, 1988, L. Rowe, 1990). It can be expected that common programming languages, for in-

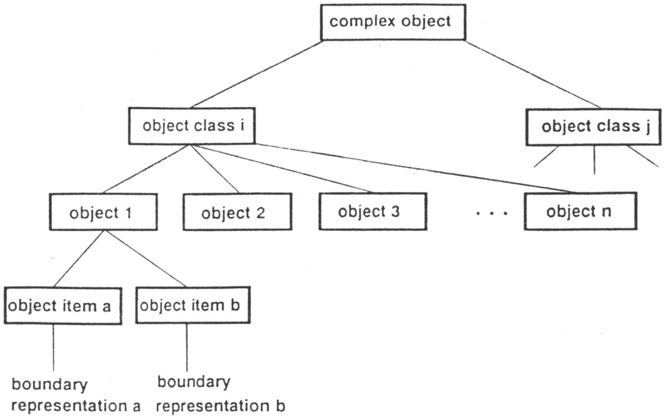


Fig. 2: Object oriented management

stance C, Pascal, Lisp, more and more integrate object oriented elements in future. By the way the OOP-languages C++ and Common Lisp started already its establishment. In Fig. 3 the OOP-procedure for a simple 3D-object (a cube) can be found.

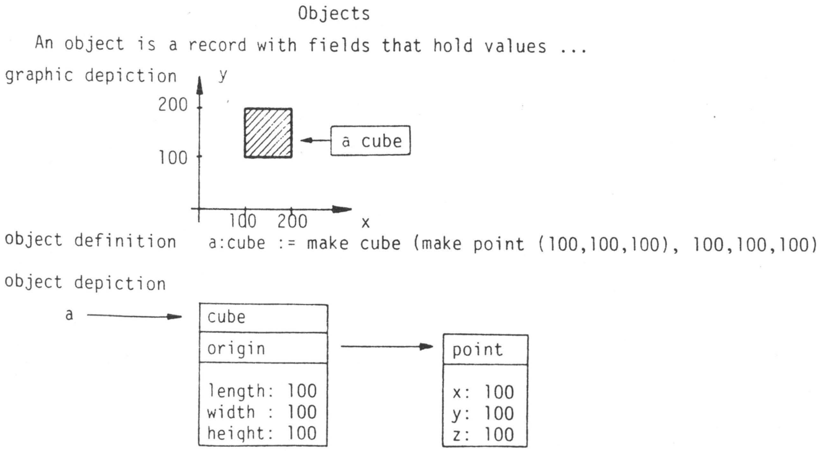


Fig. 3: Object oriented programming techniques for a cube

Object oriented programming techniques date back to the sixties when abstract data types (ADT) have been introduced. Within ADT single operations and data representations are in one module together, so that data access is possible via that module only. Within OOP the structure of a program consists of ADT instead of procedures. Therefore most efficient data structures can be expected to generate the applications more easily.

THREE-DIMENSIONAL DATA STRUCTURES

The total integration of a DTM into a GIS demands for a total unification of the underlying data sets as well as the methods being applied. Two main procedures can be used which may also be combind with each other

- three-dimensional coordinates for all geographic elements
- digital terrain models as constituents of a geographic database

While the first approach is costly in terms of storage elements - the situation elements have to be supplemented by means of additional height elements, for instance roof ridges, dominant wings of a building etc. - the latter one is easier in concept and realization. Furthermore, situation data are dense only in densely populated regions, however, in agricultural areas as well as poor populated regions dead areas must be overcomed. Therefore the integration of a DTM into a GIS is also more pragmatic from this point of view.
The following constraints have to be considered: On the one hand data storage should be non redundant leading to a data set of minimum size and, on the other hand, the response time of the system should be reasonable. In order to develop three-dimensional data structures terrain information must be connected with situation information (see Fig. 4)

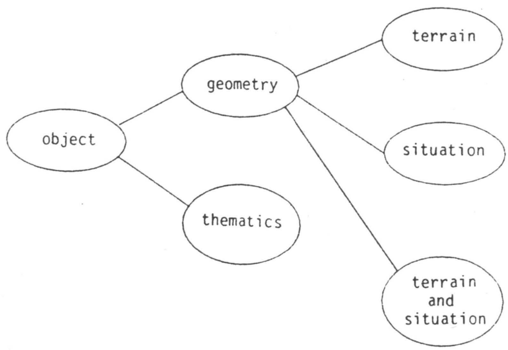


Fig. 4: Object definition

This connection is a necessity - it is demonstrated by the following three examples

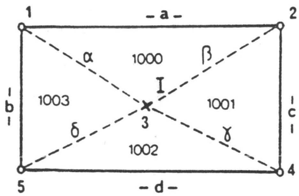
- an edge in terrain might be the boundary of a street
- a ' dead area ' of a DTM might be composed of the shore line of a lake

° the x,y-geometry of a building must be ' dead aread ' of a DTM

For that reason the geometric elements must contain further thematic (semantic) identifiers to allow for separated questions in terms of situation and terrain (D. Fritsch, 1989b). For instance, a reference point of a DTM can further be

(i) a situation node
(ii) a special height node
(iii) a non usable point.

The same subdivision is possible for edges and blocks.
In order to show up a totally three-dimensional data structure a simple spatial object consisting of a parcel with a corresponding triangulation for terrain data is given in Fig. 5.



I parcel no. I

1002 triangle no. 1002

Fig. 5: Three-dimensional object ' parcel '

Its data may be organized in a ring list leading to a network model or in a relational mode simple to demonstrate in the following (see Fig. 6).

node	coordinates	edges situation	edges terrain
1	x_1,y_1,z_1	a,b	a,α,b
2	x_2,y_2,z_2	a,c	a,β,c
3	x_3,y_3,z_3	- -	α,β,γ,δ
4	x_4,y_4,z_4	c,d	c,γ,d
5	x_5,y_5,z_5	b,d	b,δ,d

" 0-table "
(nodes)

edge	start node	end	block left situation	block right	block left terrain	block right
a	1	2	0	I	0	1000
b	1	5	I	0	1003	0
c	2	4	0	I	0	1001
d	4	5	0	I	0	1002
α	1	3	-	-	1000	1003
β	2	3	-	-	1001	1000
γ	3	4	-	-	1001	1002
δ	3	5	-	-	1002	1003

" 1-table "(edges)

block (situation)	block-no.(ID)	edges
1	I	a,b,c,d

" 2-table "
(situation blocks)

block (terrain)	edges
1000	a,α,β
1001	c,β,γ
1002	d,γ,δ
1004	b,α,δ

hull information nodes
1
2
4
5

" 2-table "
(terrain blocks)

object	object name
1	parcel I

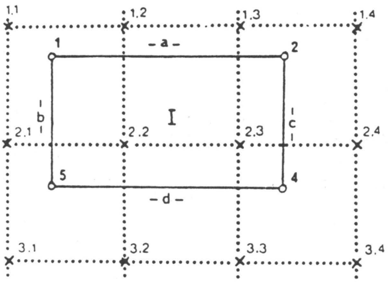
" object table "

block	size	owner
I	350 m^2	Hans Mueller, xCity

" owner table "

Fig. 6: Three-dimensional data storage of a parcel using triangulation for terrain data

The triangulation can be derived by a constrained Delauney approach or a constrained minimum weight triangulation (D. Fritsch, 1989b). This triangulation is organized in terms of blocks and edges or in a combined mode as demonstrated by the example above.
Using a grid model for the description of terrain information data storage reduces to a minimum. In Fig. 7 the parcel I is overlayed with a uniform grid. The data storage is given by Fig. 8 when using again a relational data model.



o situation node

x terrain node

Fig. 7: Three-dimensional object ' parcel '

node	coordinates	edges
1	x_1, y_1	a,b
2	x_2, y_2	a,c
4	x_4, y_4	c,d
5	x_5, y_5	b,d

" 0-table "
(nodes)

j / i	1	2	3	4
1	z_{11}	z_{12}	z_{13}	z_{14}
2	z_{21}	z_{22}	z_{23}	z_{24}
3	z_{31}	z_{32}	z_{33}	z_{34}
4	z_{41}	z_{42}	z_{43}	z_{44}

" 0-table "
(terrain)

edge	start node	end node	block left	block right
a	1	2	0	I
b	1	5	I	0
c	2	4	0	I
d	4	5	0	I

" 1-table "
(situation)

block	block-no.	edges
1	I	a,b,c,d

" 2-table "
(situation)

- see object table and owner table of Fig. 6 -

Fig. 8: Three-dimensional data storage of parcel I using a grid model for terrain data

The terrain data for the situation nodes is not explicitely available; it must be derived by interpolation methods. However, data storage becomes to minimum. For that reason, three-dimensional database systems with integrated triangular irregular networks (TIN) can not react so fast than integrated grid models. Using the available data structures for DTM data - TIN, GRID and HYBRID (TIN within GRID) - table 1 gives some characteristics of 3D-database performance.

Table 1: Characteristics of 3D-databases

terrain model	data access	data amount	performance
GRID	very fast	less	poor
TIN	slow	large	excellent
HYBRID	fast	reasonable	excellent

SEPARATED DATA MANAGEMENT

Total 3D-descriptions demand for sufficient 3D-data for all regions of interest. While during data acquisition of situation elements, for instance, parcel nodes, building nodes etc., also height values might be captured, a separated acquisition of geomorphology is a necessity in most cases. The result is a separated boundary representation which can be merged to one complete model by means of an object oriented management. The following example will demonstrate this approach in which two contigous parcels (no.1: small, with building, no. 2: large, without building) have to be described in R^3 (see Fig. 9).

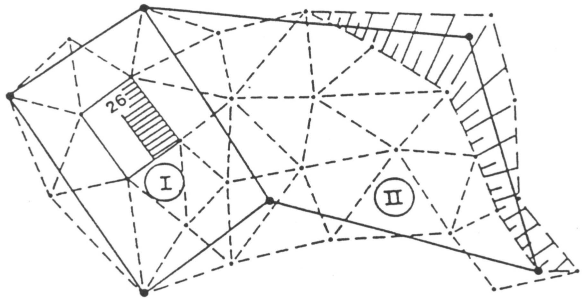


Fig. 9: 2D-geometry of a 3D-object

feature class: parcels
feature 1 : parcel 1
feature 2 : parcel 2
feature 3 : geomorphology
feature item 1a: parcel
feature item 1b: building
feature item 2a: parcel
feature item 3a: reference points with edge informations and dead areas
block model 1a : BR by means of nodes, edges, blocks and identifier 1
block model 1b : BR similar to 1a, identifier 26
block model 2a : BR similar to 1a, identifier 2
block model 3a : constrained Delauney-TIN, identifier B
attribute ID1 : owner, utilization
attribute ID 26: size x,y-geometry, floors, height of roof ridge
attribute ID2 : owner, utilization
attribute IDB : slope point, further identifiers to top slope point, to bottom slope point

The management within this scheme allows for queries of

- 3D-representation of buildings
- geomorphologic details, for instance slopes
- interpolation of points of interest

to name only few. Its consequence are two databases for geometry: one for situation data and one for terrain data. Including a third database for the non graphical data (attributes) a hybrid database have to be filled (see Fig. 10)

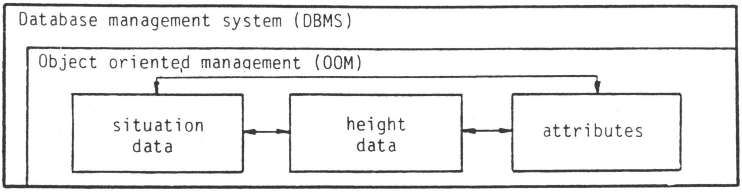


Fig. 10: Hybrid database

This approach is also the basis for the integration of efficient DTM-program packages into the GIS-environment by means of fast interfaces.

CONCLUSIONS

Three-dimensional data structures will be used more and more in GIS-applications especially in ecology and environmental research. Therefore 2.5D-solutions are no longer sufficient. The paper has shown that DTM data structures can be integrated into excisting GIS twofold: using a 3D-data model or a separated one for situation and height. Within an OOM environment hybrid data sets are merged into one database. Although geometric modelling remains a subject to be investigated furthermore some tools are available to have totally 3D-descriptions. Further developments in OOP will come to quite elegant 3D-formulizations.

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