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A HIERARCHICAL DATA STRUCTURE FOR GLOBAL GEOGRAPHIC INFORMATION SYSTEMS

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Abstract

The scheme proposed by Dutton in a series of papers (1984, 1989) provides the basis for a consistent method of representing variation over the globe using finite elements. The paper describes work at NCGIA to implement the scheme as the basis for a global GIS by developing the necessary transformations and algorithms, and by taking advantage of recent developments in 3D display hardware and software. A global GIS should allow the user to work directly with the globe, rather than through the distorting effects of 2D projections.

Introduction

Current GIS technology offers the capability of merging raster and vector data, with functions for combining data from different sources, measuring the sizes of objects, building buffers of given width, etc. (for recent surveys of GIS see Burrough 1986; Star and Estes 1990; Aronoff 1989). Data obtained from remote sensing are represented as a raster of finite rectangular elements, whereas other sources such as topographic maps provide data in vector form as strings of coordinate pairs. The ability to combine data from various sources and with various structures using GIS is seen as a major improvement in our ability to classify and interpret remotely sensed images, and as a significant extension of the usefulness of images for various types of analysis and modeling (Tomlin 1990).

Two alternative views of space are implied by the current generation of GIS. In one, space is occupied by a given number of variables, each of which has a value at every point. Each variable is visualized as a *layer* in the database, and the basic item of information is the tuple $\{x,y,z_1,z_2,...\}$. In the other, space is occupied by a collection of point, line or area objects, and is otherwise empty; the basic item of information is the tuple $\{x,y,o_1,o_2,...\}$ where o_i is a binary variable indicating the presence or absence of object i at location (x,y). In both cases (layered and object-oriented), however, the space is a plane with locations defined by Cartesian coordinates.

Geographical locations are defined by latitude and longitude pairs, (ϕ,λ). An assortment of projections of the form $(x,y)=f(\phi,\lambda)$ allow the spherical surface to be mapped to a plane, but although distortions are small for limited areas, they become unacceptable for the globe as a whole. Finite elements which are simple rectangles in the (x,y) space may be highly unequal in their actual size and shape on the sphere. Moreover the mapping of a projection must contain points or lines of discontinuity, at which the topological relationships of the sphere are lost.

For example, it is common to display global distributions using raster cells defined on a cylindrical equidistant or Plate Carrée projection, which is the mapping $x=\lambda$, $y=\phi$. The true (spherical) area of each pixel varies from 1 at the equator to zero at both poles. A square pixel on the projection is square on the globe at the equator, but shrinks to a triangular sliver at the poles. Relationships between neighbors are lost at longitude ±180, and at both poles.

The distortions of finite element representations of global data which are produced by the use of map projections have serious effects on data accuracy (resolution is not uniform despite the use of a uniform pixel size on the projection), on the ability of the user to visualize spatial distributions (a change of aspect in general requires a resampling, with consequent loss of information), and on modeling (finite element models will be distorted by the loss of topological relationships between certain neighbors). Much GCM (Global Circulation or Global Climate Model) work avoids the last point by using the spectral domain.

Based on the above arguments, four objectives seem desirable for a finite element scheme (or *tesseral* scheme, Diaz and Bell 1986) for the globe:

1. The scheme should be hierarchical, with elements at each level of spatial resolution nested within elements at all higher levels. Samet (1989a,b) has recently reviewed hierarchical schemes for the plane, and includes a brief discussion of schemes for the sphere and spheroid.

2. Elements at any level of resolution should be approximately equal in size on the globe.

3. Elements at any level of resolution should be approximately equal in shape on the globe.

4. The finite element scheme should preserve topological relationships correctly, particularly adjacencies.

Note that it will not be possible to satisfy requirements 2 and 3 simultaneously and perfectly, since a projection of a curved surface cannot be both equal area and conformal.

Requirement 1 above has several associated and desirable properties. Planar schemes for the plane, such as the quadtree, reduce all locations to a single address string, whose length determines the precision of the location. Hierarchical schemes can therefore serve as consistent methods for dealing with locational accuracy (Dutton 1989) and for avoiding the need for multiple and independent representations of objects at different levels of generalization.

We are aware of several efforts to devise tesseral schemes for the globe. Many are based on recursive subdivisions of the faces of the Platonic solids (tetrahedron, cube, octahedron, dodecahedron, icosahedron). Others are more

complex. Kimerling (personal communication) proposes projection onto a truncated icosahedron in order to provide a uniform sampling scheme for the continental US. Lukatela (1987, 1989) proposes an iteration of Voronoi polygons, which would explicitly recognize the optimization represented in conditions 2 and 3 above, but would require storage of the locations of every finite element. The scheme initially proposed by Dutton (1984), which forms the basis of this proposal, is developed from the octahedron. It has the advantage of a simple numbering scheme for finite elements, primary vertices which fall on the poles and the equator, comparatively small distortions of area and shape, and comparatively simple algorithms.

The Proposed Tesselation

In a series of papers, Dutton (1984, 1989) proposed a finite element scheme based on the Platonic octahedron, with vertices located at the poles and at longitudes of -90, 0, 90 and 180 around the equator. The surface of the earth is first projected onto the eight triangular faces, and each triangle is then recursively subdivided into four by connecting the midpoints of its edges. Elements are identified by a string consisting of a base 8 digit (level 0) followed by base 4 digits. The level 20 elements, for example, which are defined by a base 8 digit followed by 20 base 4 digits, give a spatial resolution of about 10m.

Work at the NCGIA over the past year by Goodchild, Yang, Sun and Shu has implemented this scheme by developing its geometry and numbering scheme, and many of the necessary algorithms. The basic geometry and numbering scheme are described in Goodchild and Yang (1989), and the algorithms will be described in further papers.

The transformation from (ϕ,λ) to the plane is linear; each quarter-hemisphere is mapped to an isosceles triangle using the transformation:

$$x = 2^n/\pi\,[\phi + 2\lambda(1 - 2\phi/\pi)] \qquad y = 2^n\sqrt{3}/\pi\,\phi \qquad (1)$$

where n is the level. One advantage of this transformation is that the scheme does not depend on the figure of the earth - sphere and spheroid are treated in the same way.

Each triangle is subdivided by connecting the midpoints of its sides with straight lines in the (x,y) space. On the sphere, lines of constant y will be parallels. Diagonal lines are linear equations in ϕ and λ, and are therefore straight on the cylindrical equidistant projection, but are not great circles, small circles, loxodromes or any commonly recognized lines on the sphere.

The proposed numbering scheme differs from the more elegant scheme devised by Dutton (1989) in the interests of computational simplicity, although Yang has recently developed an algorithm for converting between the two schemes. The central triangle in every recursion is numbered 0, the one vertically above (below) it is numbered 1, the one below (above) and to the left is numbered 2 and the one below (above) to the right is numbered 3. The level 0 triangles are numbered from 0 to 3 in the Northern hemisphere and 4 to 7 in the Southern, in both cases working anticlockwise as viewed from the North Pole.

The scheme provides a unique numbering for any location on the surface of the earth, to an explicit level of resolution. It can be used to locate an object of finite size by identifying the smallest triangle containing the object, or a list of such triangles. For example, the residence of Professor Waldo Tobler in Santa Barbara, CA at longitude 119° 48′ 26″ West, latitude 34° 26′ 41″ North is in tile 203023203323012211 at level 20 (resolution approximately 10m).

Vector data can be represented in the scheme using chain code. Since every triangle has three shared-edge neighbors, any linear feature can be represented as a string of base 3 digits. Let the unit of distance be one half of the length of a triangle base, and assume that the moves in the chain code occur between triangle centroids. Then the length of each move in the base 3 scheme is $2/\sqrt{3}$. A further 9 triangles are common-vertex neighbors. Of these, 6 have centroids at distance 2, and 3 at distance $4/\sqrt{3}$. Thus we can devise convenient chain codes using bases 3, 9 or 12, with 1, 2 and 3 move lengths respectively.

Algorithms

Research over the past year at the Santa Barbara site of NCGIA has developed algorithms (written in C) for the following tasks:

1. Conversion from (ϕ,λ) to finite element at a given level of resolution n.

2. The converse of (1). Both algorithms can be coded very efficiently as recursions, using binary representations of the address string.

3. Orthographic display of the triangle mesh, and vector data defined in (ϕ,λ), e.g. continental outlines from World Data Bank I.

4. Conversion of vector data to chain code, i.e. incremental moves in the triangle mesh from one finite element to another. Each triangle has three common-edge neighbors; triangles have a further 9 common-vertex neighbors except at the edges of level 0 triangles.

5. Region filling, i.e. identification of the triangles enclosed within an area defined by chain code.

6. Dilation, i.e. expansion of an area by a defined distance.

Each of these operations has its equivalent in the planar case with rectangular elements, and together they form the core of GIS functionality.

Workstations

Recent announcements in the workstation market have indicated a very rapid rate of improvement in hardware capabilities for 3D modeling. To develop a workstation environment based on the scheme outlined above requires a) a high display rate for 3D vectors, and b) solid modeling features such as the capability of rendering solids defined by polyhedral facets, z-buffering etc.

IBM's recently announced RS/6000 series of RISC workstations typifies the current hardware capabilities. The 730 model has a 3D vector display rate of over 900,000/second, which is adequate to provide real time rotation of a sphere into any aspect. Distributions over the sphere can be displayed in vector form, or in discrete element form as rendered triangles.

In the next section we outline the conceptual design of a global GIS workstation based on this type of technology. The central proposition is that recently announced 3D display capabilities will allow the development of workstation environments in which the user is able to interact directly with the globe, rather than with a 2D projection of the globe. The advantages are obvious. Change of aspect using a 2D projection and associated tesseral scheme requires both a recomputation of the projection and a tesseral resampling. For example a global dataset based on equal latitude and longitude cells is designed for display using a Plate Carrée projection in equatorial aspect. Use of standards such as C, Unix, X-Windows and PHIGS will allow easy porting of the workstation environment.

Elements of the Conceptual Design

A prototype global GIS should contain the following key features:

1. The ability to display a) vector and b) finite-element data in user-defined aspect. The user should be able to define aspect, i.e. rotate the sphere (with immediate response) using either a trackball or a pointing device. Finite-element data could be stored in a tree structure based on the triangle scheme, and displayed by rendering triangular facets. Vector data could be stored either as chain code or as strings of addresses connected by straight lines or great circles.

2. The ability to resample finite-element data from rasters based on standard projections, e.g. the cylindrical equidistant.

3. Zoom capabilities using display lists.

4. Functions for standard GIS operations, such as those implemented in simple raster GIS packages, including overlay, area measurement, and reclassification.

5. Output to a PostScript printer or plotter.

6. Housekeeping functions, including lists of available coverages, text descriptions, etc. Again the capabilities of a raster GIS could be used for

reference.

7. Use of the tesseral scheme as an index for storage of vector data, as well as a random-access tree structure for raster data. The raster structure could include the ability to store information at all levels, allowing rapid retrieval of a representation of a spatial distribution at any level of generalization.

Conclusions

In this paper we have discussed a tesseral scheme for the globe, and its implementation in current 3D display workstations. The scheme appears to have several distinct advantages over existing and conceivable alternatives.

First, as a hierarchical data structure, the approach addresses the difficulties associated with very large spatial databases in a direct way. Higher levels of the structure store spatially generalized information using short keys, while lower levels store more detailed information using longer keys. These advantages are currently available in the quadtree-based structures for the plane, but to date there has been no equivalent for global data.

Second, the scheme takes direct advantage of the features of the current generation of 3D display workstations, by representing the solid earth as a polyhedron with triangular facets. The algorithms for conversion between latitude and longitude and key are straightforward and easily implemented, and do not depend on the figure of the earth.

A global GIS which allowed the user to work directly with the globe could be of interest to a number of disciplines dealing with global data. This includes those relying on raster-based remotely sensed data as well as those dependent on vector-based data. A technology of this nature could be of substantial help to those interested in the interplay between physical and human systems on the earth's surface. The explicit treatment of spatial resolution in the hierarchical structure would allow users to merge datasets of highly variable quality without loss of important information on uncertainty. Moreover the scheme is applicable to the capture, storage and analysis of data for any solid, including significantly non-spherical planetary bodies.

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