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The Design of Environmental Geographic Information Systems [and Discussion]

M. J. Jackson, W. J. James, A. Stevens, C. W. Mitchell and D. Lane

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The design of environmental geographic information systems

By M. J. Jackson, W. J. James and A. Stevens
Laser-Scan Laboratories Ltd, Cambridge Science Park, Milton Road, Cambridge CB4 4FY, U.K.

[Pullout 1]

The development of geographic information systems (GIS) is recognized as a pre-requisite for the effective exploitation of remotely sensed data. Current commercial systems represent a solution with a strong bias from either the mapping *or* the remote-sensing market. They thus lack full cross discipline functionality and a model-oriented approach. This paper examines some of the key issues in truly integrated GIS design.

The five data types of image, object (vector), terrain, tabular and knowledge are identified along with the operations required with them within a GIS. The term 'geoschema' is introduced (analogous to schema within a database) to describe the organization of the geographical datasets. Three-dimensional data handling, the necessity of qualifying data and the user interface are given particular attention. An efficient method of implementing an integrated spatial index into the data sets is described.

1. Introduction

The development of geographic information systems (GIS) is not new; some systems such as the Canadian GIS (CGIS) (Crain & Macdonald 1984) date back over 20 years. There has, however, been a remarkable recent surge of academic, political and commercial interest (table 1). Many of these initiatives have been stimulated by remote-sensing developments. In particular the following factors are relevant:

(i) large quantities of satellite remotely sensed data are now available with good radiometric, temporal and geometric resolution; especially from the *Landsat* thematic mapper and French *SPOT* sensors;

(ii) advances in computer processing and display technology now make practical the manipulation of large quantities of geographically referenced data for commercial applications;

(iii) following the large investments in space programmes, there is growing worldwide political pressure to generate commercial returns to contribute to 'ongoing' programmes.

The development of GIS, and especially those integrating remotely sensed and other data types (so-called integrated GIS or IGIS), is now recognized as a prerequisite for the effective exploitation of remotely sensed data. However, definition of current and future user needs and the consequent software engineering issues underlying an effective design for an integrated GIS have still received only scant attention. This paper, therefore, examines some of the key issues in IGIS design, concentrating on those aspects previously given inadequate consideration.

Table 1. Some recent U.K. initiatives in GIS[1]

event	date
House of Lords enquiry into remote sensing and digitial mapping	1983–1984
Department of Trade and Industry funded study on GIS	1984–1985
Establishment of European Association of Remote Sensing Laboratories Working Group on Integrated GIS	1984
Advisory Board for Research Councils identifies spatial data handling techniques as justifying research priority	1984
Natural Environment Research Council special initiatives in GIS (includes 3 university contracts)	1984
European Space Agency sponsors study of IGIS	1985
EEC commences the CORINE GIS programme	1985
U.K. National Remote Sensing Centre GIS Group established	1985
Committee of Enquiry on geographic data handling	1985–1987
British National Space Centre awards GIS contracts	1987

[1] Also European initiatives with U.K. involvement.

1.1. *Definition of GIS and IGIS*

A brief working definition of a GIS for the purposes of this paper may be 'a computer based system for the efficient input, storage, manipulation, analysis, representation and retrieval of all forms of spatially indexed and related descriptive data'. More complete definitions may also be found (Wilkinson & Fisher 1986; Smith *et al.* 1987).

Although this definition can embrace systems incorporating multiple types and formats of data, e.g. point, line and polygon vector representations, raster data and tabular statistics, there has historically been a separation between vector, raster and non-geographical statistical systems. It has therefore been useful to introduce the IGIS acronym to explicitly refer to a GIS integrating the three data types.

1.2. *Current systems*

The simplest, and still the most common configuration for a GIS that incorporates remotely sensed and map inputs, is two discrete systems implemented either on separate or common computer systems. Data are passed between the two systems by vector–raster and raster–vector software. However, despite this software link, the systems often remain as separate cartographic GIS and image analysis systems, with only minimum integrated software development and use of the different datasets. Any operation combining raster and vector data is forced into one domain to the detriment of the other datatype. There are a number of effects: loss of attribute, topological and context information; loss of spatial resolution; introduction of data redundancy; limited interaction between the vector and image data; maintenance of both a vector and a raster database; two distinct user interfaces are maintained.

Where the two systems are on distinct hardware, there are additional disadvantages: the physical separation of the systems results in extra time needed to combine datasets; system upgrade is complicated by the parallel and often independent development of two discrete systems; the need to maintain two independent systems incurs a considerable cost penalty at time of purchase, in user training and in maintenance and support costs.

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The single workstation system represents the current commercial state of the art. All represent a solution with a strong bias from either the mapping market *or* from the remote sensing market. They thus lack full cross-discipline functionality and a model-oriented approach (as distinct from data oriented).

1.3. *Hybrid solutions*

A better solution to the GIS requirement is to provide simultaneous access to independent raster and vector datastructures and to handle the integration at a higher level. This approach is taken by Laser-Scan in its terrain validation and exploitation system (TVES) which allows the user to open and interact with separate raster and vector data files displaying registered results on a single display. The user can then manipulate map data as features (roads, rivers, woods, etc.) and terrain or images as raster data, while benefiting from an integrated view of the whole.

2. Technical requirement for future IGIS

Current IGIS design is based on *ad hoc* mechanisms of data exchange between systems or on a more integrated approach but tailored for a specific application area. In addressing the design issues for a general purpose IGIS, the following technical requirements have been identified.

2.1. *IGIS data types*

Geographic data exist in a wide variety of forms, but these may be grouped according to their *type*. Each data type may require distinct structures and methods of handling within the IGIS. The data types are: image data in raster form, for example, satellite imagery; object data in vector form, for example, digital cartographic data; terrain height data, commonly digital terrain models, contour–spot-height maps or surface models; tabular data, especially attributes, indexes, or references; rule–knowledge data, for support of decision making processes.

2.2. *IGIS operations and features*

The following list is *not* exhaustive, but includes those operations most vital to an effective IGIS.

Data input: format conversion programs, to take 'popular' digital datasets, and published interfaces, allowing users to create their own input programs; digitizing mechanisms, providing a route to input documents, and text input facilities.

Data edit: efficient, data type specific editors, for use during input and update of datasets; multidata-type editors, allowing editing in the context of several data types.

Data storage: storage of data in their 'natural' structure, avoiding data degradation; qualification of data, description of the content, characteristics and origin of any dataset; access control to datasets through ownership, and through partitioning; relation of datasets via geoschema (see §3.1).

Data access: data catalogue, which itemizes all available local and remote datasets; search and select facility, which locates datasets according to user parameters.

Data preprocessing: image processing facilities; image geolocation and classification, by reference to object and knowledge data; object geolocation and transformation, by reference to tabular or object data; object coding and definition, perhaps by reference to image data.

Data output: format conversion programs to popular datasets, and published interfaces, which allow users to generate their own output datasets; availability of qualifying data for output datasets.

Data display and plotting: display and plotting of combined data (e.g. 3D views comprising image, object and terrain data); generation of cartographic products; availability of display hardware optimized for image and object display.

Utilities: the primitive operations required by the user for extraction include: spatial association of datasets, which is based on their geoschemas and automatically applies transformations to convert between geoschemas; combination of datasets, including spatial overlay and intersection, to generate new datasets if required; search and selection of regions and objects on spatial and attribute criteria; calculations, report generation, display and plotting facilities; conversion between data types.

User interface: menu or choice driven interface, that advertises and gives access to all available facilities; data catalogue browse, which has search and select mechanism that finds relevant datasets; project definition, which specifies geoschema(s), storage partitions, procedures, etc.; geoschema definition, which specifies spatial reference system, indexes, attributes, etc.; procedure definition, which specifies sequences of primitive operations; problem definition, which generates procedures that reduce the need to understand the operation of the system.

System configuration: there are a number of desirable requirements of the IGIS design, that impinge directly on its implementation in a given processing environment: the IGIS user interface and data-handling concepts should be invariant from system to system; the IGIS software structure should be modular, allowing subsets of functionality to be implemented according to the facilities offered by the computing system; the IGIS functions themselves should have variants to take advantage of local computing facilities.

3. IGIS DATA ORGANIZATION

In meeting the technical requirements identified above, the major challenge lies in designing the structures for the data organization. These must permit the maintenance of data in its primitive input form to preserve precision and information content, while offering the user an integrated view of the whole data environment without involving data transformation or registration. In addition, the structures must provide fast and efficient spatial processing. A schematic diagram of the organization proposed is shown in figure 1. The details of this data organization are described in Jackson *et al.* (1987). The four following specific topics, however, justify comment.

3.1. *Geoschema*

This term is analogous to the use of 'schema' within a traditional database. It describes the organization of the geographical datasets. In particular it defines the spatial referencing system, indexes, classification and attribute coding schemes. The enforced presence of such information for each dataset permits the IGIS to automatically relate them by transforming, resampling or translating as required. Benefits in efficiency accrue from relieving the user of this responsibility,

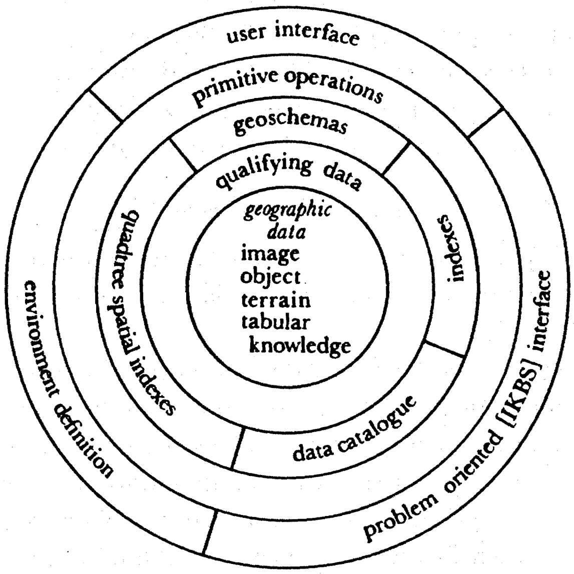

FIGURE 1. Diagram of integrated GIS.

although further gains may be made if all the data are deliberately coerced into the same geoschema. The user can concentrate more on the content of the datasets, rather than their representation.

3.2. *Data handling*

Absolute height, slope, aspect, range and terrain roughness are necessary parameters in considering many environmental issues. Examples include the distribution of selected flora and fauna, modelling snow-melt or run-off characteristics, geological interpretation and cross-country mobility studies. The surface form is also important to image classification, particularly with the greater look angles which are obtained with TM, off-nadir *SPOT* data, SAR images, airborne scanner data, etc. Until now, remote sensing and cartographic GIS systems have largely been two dimensional because of the cost and technical limitations. As a result, vector, raster and quadtree based systems have neglected the third dimension in both practical implementation and theoretical development.

The solid modelling and 3D systems used in CAD would not appear to be very applicable to 3D GIS (Besl & Jain 1985). Many of these are based on constructive solid geometry where an object is built of primitive shapes such as cones and cylinders. This is inappropriate for representing terrain. Another approach, and one favoured by military simulator systems, is the use of surface boundary representation. This is a more favourable approach for terrain and includes triangular as well as polygonal approaches.

Despite the increased complexity of 3D systems, a future trend towards representation and display of the third dimension within IGIS systems is anticipated. Data are becoming more generally available as a result of military programmes, and the increasing power of workstations now makes the computations practical. In addition, many new hardware developments for 2.5D and 3D vision are planned. These include an Alvey project (Alvey MMI137 (Muller, this symposium, p. 381)) involving the transputer (Inmos 1986) as a flexible general-purpose vision engine, and more specific graphic displays (BCS Systems 1987). Such devices offer the computational power necessary for real-time display and animation.

From a design viewpoint, an incremental development initially offering 2.5D surface representation would seem most attractive, with full 3D capabilities to follow.

3.3. *Qualifying data*

The importance of qualifying data has also been neglected in the past, particularly in image-based GIS. These data accompany any geographical dataset and may generally be divided into historical and status information.

The historical qualifying data references the data and procedures from which the dataset was created and modified. It allows the user to trace the sources of the data. Each record will specify a procedure, the data inputs, and any other data used by the procedure. For example, a classified satellite image may record creation by a segmentation process that used a specified source image, reference object, terrain height and rule data, followed by modification through a classification process that used further reference object data and a different set of rules.

The status information comprises data in addition to the content of the dataset (often termed 'header data' because of their location in the file). It includes geographical coverage, description of content, scale, accuracy, currency, etc. Some of this will be required by processes that manipulate or interpret the data.

Qualifying data is essential when bringing together geographic data from different sources, or when distributing data to a wide user base that had no involvement with their generation. It will be particularly relevant as greater use is made of knowledge or GIS-assisted techniques of image classification. It should be the primary input to error-train analysis, or to expert systems 'advising' on what is appropriate when combining datasets.

3.4. *Spatial indexing*

Much of the research effort to date on integrated GIS has concentrated on low-level data structures (such as the quadtree (Samet 1984)), which can hold both vector and raster data in a uniform way. Although this use of quadtrees may be justified for certain types of operation, especially in the context of predefined projects, they do not offer a sensible general purpose solution to IGIS integration. However, they do have benefits in providing an integrated spatial index and as such play a major role in the design proposals presented in this paper.

At the highest level of area storage, the operator is aware of one common spatial index into the data. At 'lower' levels the index contains references from the structure into the particular (raster or vector) datasets. Obviously, the design and implementation of the spatial index and the underlying datastructures have a significant effect on the speed and flexibility of the IGIS system.

Although a detailed description of integrated spatial addressing schemes is beyond the scope of this paper, the approach identified may be summarized as follows.

Vector data are stored in a geometry file and spatially indexed by a PM3 quadtree (Samet *et al.* 1985). Quadtree nodes are successively subdivided until there is a single data point at each leaf. Any lines passing through the leaf's area (connecting other data points) are also recorded with the leaf data. An example of a portion of a vector map decomposed in this way is presented in figure 2. The quadtree is implemented as a pyramid and intermediate levels of

FIGURE 2. Example of PM3 decomposition of a map.

(*Facing p.* 378)

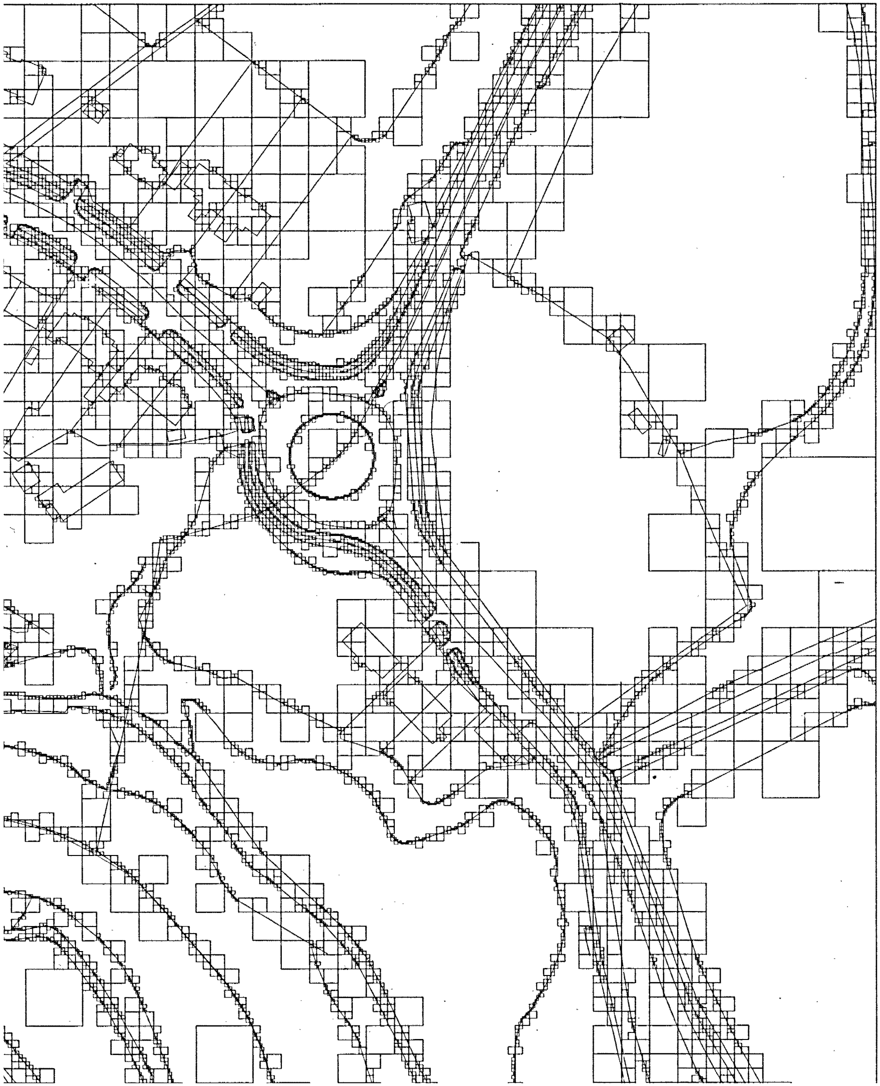

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Figure 2. Example of PM3 decompositi

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the spatial hierarchy contain summary information about features referenced by the lower levels. The quadtree is truncated at a predetermined level for storage efficiency but all the vector information is still represented at its original spatial resolution.

Raster data of low-dimensional order (such as binary data) may be stored in a region quadtree. However, most raster data, and especially those derived from remotely sensed images, are highly dimensional (e.g. several bands of 8-bit information) and cannot be efficiently held in a quadtree. For these data, a better option is a form of grid file with data stored in a regular patchwork of local raster 'tiles'. A hierarchical spatial index in the form of a quadpyramid can be superimposed on the tiled data to provide summary information at its higher levels. For pixels that have been registered to vector information, the two quadpyramids can be chosen such that the areas covered are identical and that the vector quadtree has at some level a node representing the same area as the raster pixel.

4. Conclusions

Much of the abundant literature on GIS, has concentrated either on relatively simple discrete case studies, on generalized discussion of GIS applications or on specific aspects of the low-level data structures for integration. For effective system design, the detailed structure and organization of the entire system is critical, and the whole IGIS environment must be considered, from the moment a magnetic tape is loaded onto the system, through to final plot, display or report. In particular, the use of qualifying data is important to understand the pedigree and reliability of any output, and the IGIS metadata is vital to the organization of the IGIS system.

As functional capabilities increase, making use of 3D data sets, IKBS techniques and special purpose hardware, the need for an integrated approach to GIS design will become mandatory to control the large volumes of data involved. The approach presented here is a flexible and upgradable route towards such a system.

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Discussion

C. W. MITCHELL (*Department of Geography, University of Reading, U.K.*). Geographical Information Systems manipulate overlaid data sets of a number of different themes such as topography, geology and land cover, the data being referenced by grid coordinates rather than by recognizable land features. The effect of this is that there is no clear mechanism for extrapolating thematic data between environmentally analogous, but geographically separated, areas. An established method of achieving this is to recognize analogies between the recurrent natural units of the terrain (which integrate soils, water, vegetation, etc.) on remotely sensed imagery. The ability to make and test such extrapolations is an essential part of the environmental sciences.

How is it possible for a GIS of the sort described by Dr Jackson to provide this extrapolation capability?

M. J. JACKSON. The requirement to match spatially separate areas in terms of their geographical characteristics for prediction has traditionally involved the input of a high level of interpretative skills. The IGIS by providing a computational environment whereby some of the interpretation and extrapolation may be more easily quantified should greatly assist the analysis in terms of accuracy and consistency of prediction. Geostatistical techniques based on spatial correlation, principle component and factor analysis will also be aided. Intelligent knowledge-based systems (IKBS) or expert systems technology may, in addition, allow some of the empirical processes of the analyst to be automated, though the degree of interpretative skills now used by the specialist is unlikely to be matched in the short term, especially as they are based on the poorly understood abilities of the human to generate 'like areas' out of complex spatially interacting data.

D. LANE (*Intelligent Automation Laboratory, Department of Electrical and Electronic Engineering, Heriot-Watt University, Edinburgh, U.K.*). Techniques for representing three-dimensional shape within a computer have been studied for some time by researchers in the computer graphics and computer vision communities. It has resulted in techniques using polygons, parametric surfaces, octrees, the $2\frac{1}{2}$D sketch and so on. How are researchers in the remote sensing community modelling three-dimensional terrain within Integrated Geographic Information Systems?

M. J. JACKSON. Many of the 3D shape representations such as constructive solid geometry (CSG) and octrees have been successfully used in CAD-type systems. For terrain visualization the CSG approach is not efficient because of the generally gently curving nature of the surface. Octrees, by analogy to quadtrees, could be used but are really a 3D volume rather than $2\frac{1}{2}$D surface representation. Although efficient for volumetric computations they will not be particularly good for rotation, translation and scaling.

Current terrain methods are generally based on the Delaunay triangulation. Height values are assigned to each vertex and the triangular surface facets represent the slope and aspect of the local regions.

With advances in hardware to manipulate polygonal facets rapidly in 3D, future visualization methods may explore this approach. Computing advances also open up possibilities for ray tracing and fractal generation to improve surface realism.

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FIGURE 2. Example of PM3 decomposition of a map.

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