The 3D GIS Software Development: global efforts from researchers and vendors

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Abstract
This paper describes the 3D GIS research efforts done by the GIS research groups as well as by major GIS software vendors world wide, namely Environmental System Research Institute (ESRI) Inc., ERDAS Inc., Integraph Inc., and PCI Geomatics Inc. Research works done by the authors of this paper formed major discussion of this paper including a discussion on why the 3D GIS software is difficult to be realised. At the moment there is no real 3D GIS software available in the GIS market. Hopefully, continuos efforts by researchers in academia and commercial sectors would entailed the most sought 3D GIS software in very near future so that our understanding on real world 3D objects could be improved.

1.0 Introduction

In GIS world, most of the tasks or problems can be handled by the current GIS software. However, the demands of GIS applications need more advanced GIS software such as 3D GIS (Pilouk, 1996; Zlatanova, 2000; and Abdul-Rahman, 2000). Is 3D GIS software easily available in the market? At large, the answer is no. It is the aim of this paper to address some of the issues and problems involved in developing such system. We will describe efforts made by some vendors and some research groups in realizing the system. First, we overview the basic GIS functions which they should be available in the 3D GIS. In section 3, we discuss some of the problems related to 3D GIS, and the needs of 3D GIS. The efforts made by major vendors are discussed in section 6 while section 5 focuses on the efforts made by GIS research groups. The importance and some of the problems of 3D spatial data modelling, developing an information system based on the 3D spatial data will discussed and introduced in the later section. This paper also further discusses several types of two-dimensional (2D) GIS systems, which are related to the development of 3D GIS. Some well established systems, which are currently available in the market, are also reviewed. Since data structures, data modelling and database management are important aspects of system development, all the discussions and system overview will focus on these. A discussion on major GIS functions follows.

2.0 GIS Functions

Any GIS system should be able to provide information about geo spatial phenomena. Principally, the following tasks represent some functions of a GIS system. The tasks or the functions of a GIS (Raper and Maguire, 1992) are: (1) capture, (2) structuring, (3) manipulation, (4) analysis, and (5) presentation, and can be summarised as follows.

- *Capture* is inputting spatial data to the system. Many different techniques and devices are available for both geometric and attribute data. The devices in frequent use for collecting spatial data can be classified as manual, semiautomatic or automatic and the output either vector or raster format. Detailed discussion on data capture is not covered here.

- *Structuring* is a crucial stage in creating a spatial database using a GIS. This is because it determines the range of functions, which can be used for manipulation and analysis. Different system may have different structuring capabilities (simple or complex topology, relational or object-oriented).

  Manipulation, among important manipulation operations are generalisation and transformation. Generalisation is applied for reducing data complexity or to make the data presentation more legible. Transformation includes coordinate transformation to a specified map projection and scaling, etc.

- *Analysis,* is the core of a GIS system. It involves metric, topological and/or order operations on geometric and attribute data. Primarily, analysis in GIS concerns operations on more than one set of data, which generates new spatial information of the data. Terrain analysis (e.g. intervisibility), geometric computations (volume, area, etc), overlay, buffering, zoning, sorting are among typical analysis functions in GIS.

- *Presentation*, is a final task in GIS. That is to present all the generated information or results such as in the form of maps, graphs, tables, reports, etc.

Ideally, a 3D GIS should have the same functions as 2D GIS. However, such 3D systems are not available due to several impediments such as problem associated with spatial data structures, spatial data models, and spatial data relationships, i.e. the topology, as discussed in Pilouk(1996), Zlatanova(2000), and Abdul-Rahman(2000).

3.0 3D GIS

In this section, some problems and related issues in 3D GIS software development are reviewed and discussed. Firstly, what is 3D GIS? This type of system should be able to model, represent, manage, manipulate, analyse and support decisions based upon information associated with three-dimensional phenomena (Worboys, 1995). The definition of 3D GIS is very much the same as for 2D system. In GIS, 2D systems are common, widely used and able to handle most of the GIS tasks efficiently. The same kind of system may not be able to handle 3D data if more advanced 3D applications are demanded (Raper and Kelk, 1991; Rongxing Li, 1994) - such as representing the full length, width and nature of a borehole (some examples of 3D applications areas are listed in section 4). 3D GIS very much needs to generate information from such 3D data. Such a system is not just a simple extension by another dimension (i.e. the 3rd dimension) on to 2D GIS. To add this third dimension into existing 2D GIS needs a thorough investigation of many aspects of GIS including a different concept of modelling, representations and aspects of data structuring. Existing GIS packages are widely used and understood for handling, storing, manipulating and analysing 2D spatial data. Their capability and performance for 2D and for 2.5D data (that is also DTM) is generally accepted by the GIS community. A GIS package, which can handle and manipulate 2D data and DTM, cannot be considered as a 3D GIS system because DTM data is not real 3D spatial data. The third dimension of the DTM data only provides (often after interpolation) a surface attribute to features whose coordinates consist only of planimetric data or x, y coordinates. GIS software handling real 3D spatial data is rarely found. Although the problem has been addressed by several researchers such as Raper and Kelk (1991), Cambray (1993), Rongxing Li (1994), and Fritsch (1996), some further aspects particularly spatial data modelling using object-oriented techniques need to be investigated. Further, works of Pilouk(1996), Abdul-Rahman(2000), and Zlatanova(2000) have investigated the problems and proposed some solutions to the problems. Pilouk's and Abdul-Rahman's works were focussed on suitable data structures for the system whereas Zlatanova's work looked on the use of Web and 3D city buildings. The demand (or the need) for this kind of system is discussed in the next section.

3.1 Who needs 3D GIS

As in the popular 2D GIS for 2D spatial data, 3D GIS is for managing 3D spatial data. Raper and Kelk (1991), Rongxing Li (1994), Förstner (1995), and Bonham-Carter (1996), Pilouk(1996), Abdul-Rahman(2000) present some of the three dimensional application areas in GIS, including:

ecological studies	3D urban mapping
environmental monitoring	landscape planning
geological analysis	architecture
civil engineering	automatic vehicle navigation
mining exploration	archeology
hydrographic surveying	marine biology

The above applications may produce much more useful information if they were handled in a 3D spatial system, but it appears that 3D spatial objects on the surface and subsurface demand more complex solutions (e.g. in terms of modelling, analysis, and visualization) than the existing systems can offer.

The next section reviews the modelling and data structure research carried out in the GIS research community towards the development of 3D GIS. This will be followed by consideration of the others from major representatives of the GIS commercial sector (i.e. vendors).

4.0 Why is 3D GIS Difficult to Realise?

The difficulties in realising 3D GIS or 3D geo-spatial systems result from:

Conceptual model: although there are several data structures available for the 2.5D and 3D data, each of them has its own strong and weak points in representing spatial objects. Spatial data can be modelled in different ways. The conceptual 3D model integrates information about semantics, 3D geometry and 3D spatial relationships (3D topology). The conceptual model provides the methods for describing real-world objects and spatial relationships between them. The design of a conceptual model is a subject of intensive investigations and several 3D models have already been reported (see Brisson 1990, Molenaar 1992, Cambray 1993, Pilouk 1996, Pigot 1995, Zlatanova 2000, Abdul-Rahman 2000, Pfund 2001).

Data collection: Modelling in 3D drastically increases the cost of data acquisition, as compared with 2D. Despite the progress in automatic object detection and 3D reconstruction (see Gülch et al 1999, Lang and Forstner 1996), the manual work is still predominant. Methods for constructing the model combining data from various sources, automatic techniques for data acquisition (geometry and images for texturing), rules and algorithms for ensuring consistency of data, algorithms for the automatic building of 3D topology, etc., are the widely discussed topics in the literature.

Spatial analysis: Whilst thematic analysis and 2D spatial analysis are well studied, research on 3D spatial analysis is still at an intensive stage. Spatial relationships are the fundament of a large group of operations to be performed in GIS, e.g. inclusion, adjacency, equality, direction, intersection, connectivity, and their appropriate description and maintenance is inevitable. Similar to 2D variants, 3D GIS should be capable to perform metric (distance, length, area, volume, etc), logic (intersection, union, difference), generalisation, buffering, network (shortest way) and merging operations. Except metric operations, most of them require knowledge about spatial relationships. Formalism for detecting spatial relationships based on set topology notions has already been proposed by several authors (see Pullar and Egenhofer 1988, Egenhofer and Herring 1992, Molenaar 1998).

Visualisation, navigation and user interface: Advances in the area of computer graphics have made visual media a major ingredient of the current interface and it is likely that graphics will play a dominant role in the communication and interaction with computers in the future. 3D visualisation within 3D GIS requires a number of specific issues to be investigated, e.g. appropriate means to visualise 3D spatial analysis result, tools to effortlessly explore and navigate through large models in real time, and texture the geometry. Observations on the demand for 3D City models (see Gruber et al 1995) show user preferences for photo-true texturing, due to improved model performance in terms of detail and orientation. Trading photo-true texture raises new topics for research, i.e. collection (methods, automation), storage (original images vs. separate pieces) and mapping onto the "geometry". Specific functions of objects modelled in VR systems, and referred to as behaviours, gain an increased popularity as tools for walking through the model, exploring particular phenomena and improving the cognitive perception (see Kraak 1998, Raper et al 1998).

Internet access: Remote access to 3D spatial information is one of the newest research topics. The Web has already shown a great potential in improving accessibility to 2D spatial information (raster or vector maps) hosted in different computer systems over the Internet (e.g. http://www.visa.com, http://www.mapquest.com, http://www.mapguide.com, etc.). New Web standard (VRML, DML) have created the ability to distribute and navigate in 3D virtual worlds. The research on spatial query and 3D visualisation over the Web has resulted in a few prototype systems (see Coors et al 1998, Lindenbeck et al 1998). The design criteria, however, are visualisation- rather than spatial analysis-oriented.

Research works of Pilouk's, Zlatanova's and Abdul-Rahmans's attempt to address these major issues by investigating the possible uses of several data structures (including some 2D structures), the construction of these data structures, the utilisation of these structures in spatial modelling, the topological relationships of the 2D, 2.5D, and 3D spatial objects, the development of a database from the spatial data and the implementation of them in the form of a software which can be seen as component of 3D GIS.

5.0 Efforts by GIS Research Groups

Some recent research efforts by the GIS community have focussed on how to develop 3D systems; data structures and data models are major aspects of GIS system development. These efforts are summarised below. Much previous work done on 3D data modelling concentrated on the use of voxel data structures (Jones, 1989). This particular approach does not address spatial modelling aspects (that is also topological aspect of the data), it is only useful for the reconstruction of 3D solid objects and for some basic geometric computations. Another of the problems with this data model is that it needs very large computer space and memory.

Carlson (1987) proposed a model called the simplicial complex. He used the term 0-simplex, 1-simplex, 2-simplex, and 3-simplex to denominate spatial objects of node, line, surface, and volume. His model can be extended to *n*-dimensions.

Molenaar (1992) presented a 3D topological model called 3D Formal Vector Data Structure. The model maintains nodes, arcs, edges and faces that are used to describe four types of features named points, lines, surfaces and bodies. The model belongs to the group of Boundary representations (B-reps).

Cambray (1993) proposed CAD models for 3D objects combined with DTM as a way to create 3D GIS that is a combination of Constructive Solid Geometry (CSG) and B-rep.

Other attempts to develop 3D GIS can be found in Kraus (1995), Fritsch and Schmidt (1995), and Pilouk (1996). These attempts were based on the TIN data structure to represent 3D terrain objects but no reports exist on the any related aspects of using OO techniques for modelling and data structure.

De la Losa (1998) and Pfund (2001) proposed OO models similar to Molenaar's but have few more explicitly stored spatial relationships. For example, De la Losa maintains the relationship arc-faces as strict ordering of faces is introduced.

Spatial data modelling and structuring of 3D spatial objects in GIS has not been as successfully achieved as in CAD (Rongxing Li, 1994). Data modelling in GIS is not only concerned with the geometric and attribute aspects of the data, but also the topological relationships of the data. The topology of spatial data must be available so that the neighbouring and connectedness between objects can be determined. There are a number of mathematical possibilities for the determination of the topological description of objects. Within the TIN approach developed in this research determination of the neighbouring triangles has been developed. The information gained from the generated TIN neighbours is useful for further spatial analysis and applications. Topological relationships for linear objects as represented by TIN edges can be established. One edge is represented by a start node and an end node. From this edge topology, a chain of edges or arcs could be easily established. For TIN data, another approach is the simplicial complex developed by Carlson. A TIN's node is equivalent to 0-simplex, TIN's edge is equivalent to 1-simplex, a TIN surface (area) is equal to 2-simplex, and 3-simplex is equivalent to a 3D TIN (tetrahedron). The simplicial complex technique checks the consistency of generated TIN structures by Euler's equality formulae, see Carlson (1987) for detailed discussion.

Work by Pilouk(1996) focussed on the use of TIN data structure and relational database for 2D and 2.5D spatial data. He proposed an integrated data model for 3D GIS, which produced a practical approach to the problem. The following diagram illustrates some of the results which contributing to 3D system.

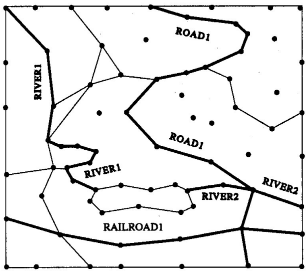

Figure 1 DTM points with line features and boundaries as constraints (after Pilouk, 1996).

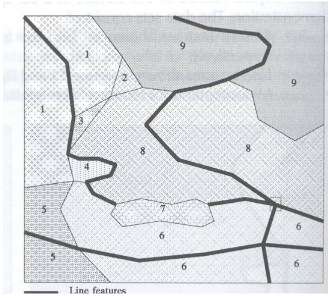

Figure 2 Overlaying of landuse and soil maps result in a multi theme map (after Pilouk, 1996).

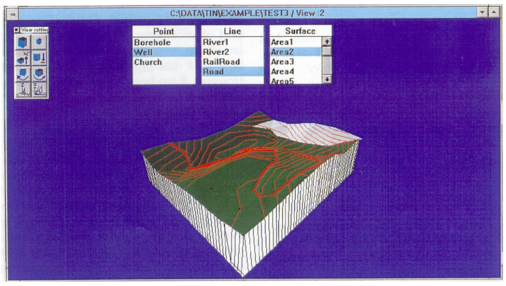

Figure 3 The result of the query from the system in perspective view (after Pilouk, 1996).

The contribution towards 3D GIS could be summarised as: the design of an integrated data model and the development of the method to construct the spatial model. The development of simplicial network data model which provides general concepts valid for spatial models ranging from 2.5D to nD. Various tests were carried out to validate the data models, and the results were very promising, see Pilouk(1996) for detailed discussions.

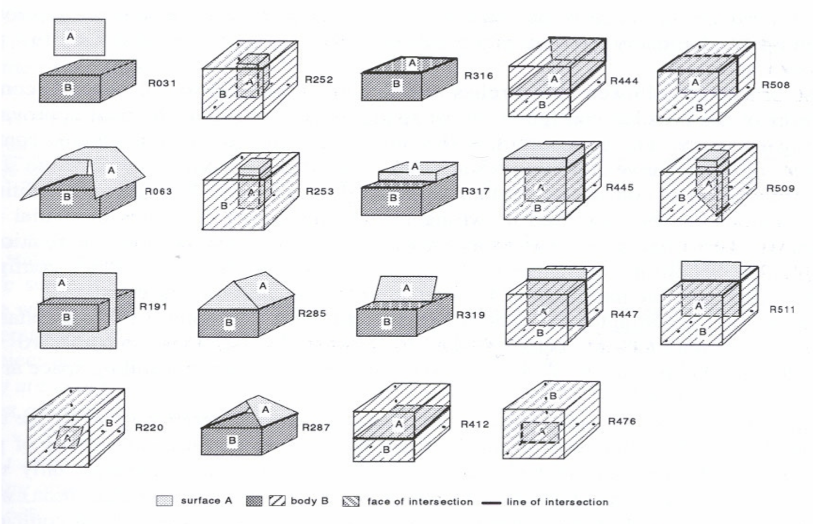

Figure 4 The body-surface 19 relations (after Zlatanova, 2000).

Zlatanova(2000) has produced quite extensive work on the subject, that is by introducing and implementing 3D spatial data models that can be used and queried over the Web. Various 3D spatial objects relationships were developed such as body and surface (with 19 relations), body and line (with 19 relations), surface and surface(38 relations). The body and surface relations illustrated in Figure 4.

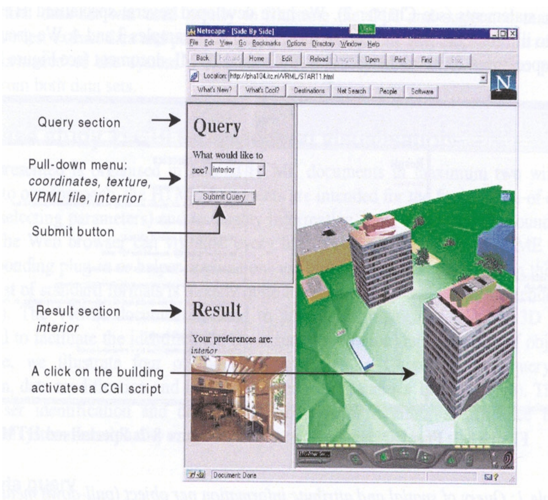

Figure 5 Query of spatial and semantic information of an object (after Zlatanova, 2000).

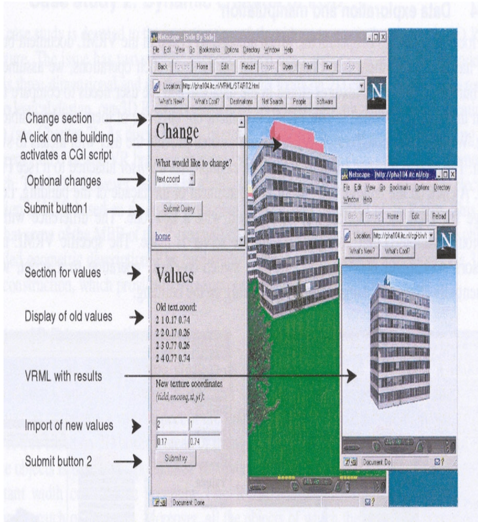

Figure 6 Editing coordinates for texture mapping of a building (after Zlatanova, 2000).

Abdul-Rahman(2000) focusses on the object-oriented TIN (2D and 3D) based GIS. The conceptual, the logical model were developed based on the Molenaar's data model and developed in object-oriented environment from scratch, that is to say from data acquisition to object-oriented database application.

Figure 7 Input from digital photogrammetry (Helava-Leica).

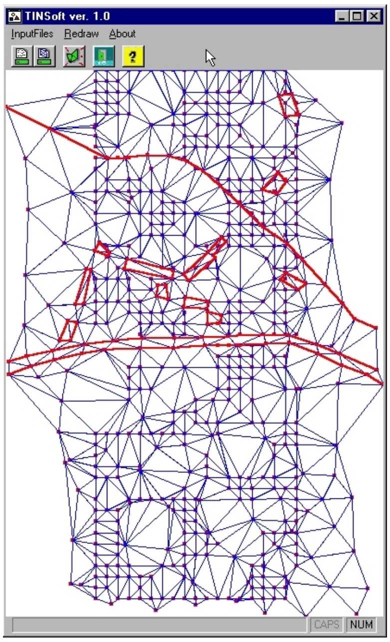

Figure 8 The generated TIN incorporated with edges as constraints.

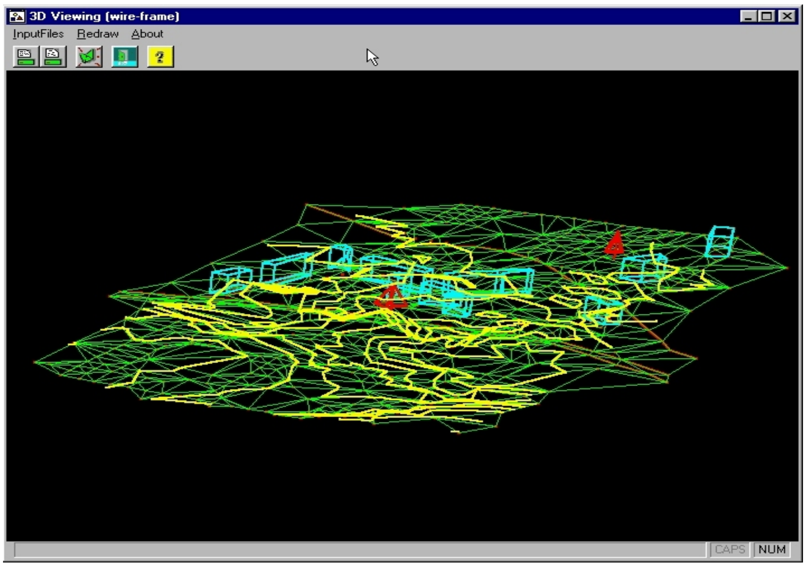

Figure 9 The generated 3D objects (buildings and trees) draped on TIN surface together with generated contours, results of the object-oriented database query (in perspective view).

His contribution towards realising 3D GIS including: defining a suitable structure for representing 2D and 3D spatial terrain and subsurface objects; designing and implementing object-oriented 2D and 3D TIN based spatial data models for the system, and validating the developed algorithms and other GIS tasks by the development of a software package in a multi document interface windows environment.

6.0 Efforts by Major GIS Vendors

There are few systems available in the market that can be categorised as a system which attempts to provide a solution for 3D representation and analysis. Four systems are chosen for detailed consideration. They were chosen because they constitute a large share of the GIS market and provide some 3D data processing functions. The systems are the 3D Analyst of ArcView (from Environmental System Research Institute or ESRI Inc.), Imagine VirtualGIS (from ERDAS Inc.), GeoMedia Terrain from Intergraph Inc. and PAMAP GIS Topographer. The following review is based on available literature and Web-based product reviews.

6.1 ArcView 3D Analyst

The 3D Analyst (3DA) is one of the modules available in ArcView GIS. In ArcView these modules are known as extensions. The system's extensions and the main GIS module, that is ArcView itself, is shown in Figure 10. ArcView is designed to provide stand alone and corporate wide (using client-server network connectivity) integration of spatial data (Maguire, 1999). The 3DA can be used to manipulate 3D data such as 3D surface generation, volume computation, draping for other raster images (such Landsat TM, SPOT, GeoSPOTV images, aerial photos or scanned maps), and other 3D surface analysis functions such as terrain intervisibility from one point to another (ESRI, 1997).

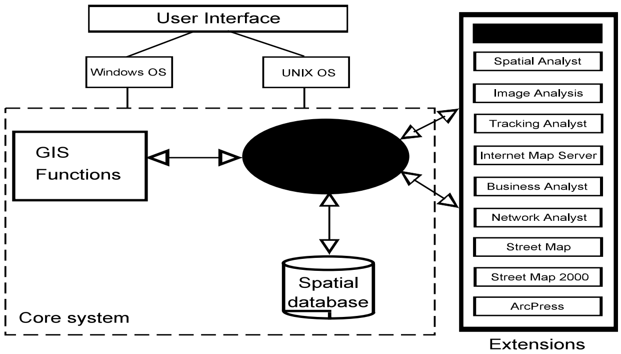

Figure 10 The 3D Analyst (shown on top of the extension's box) within ArcView system.

The system runs mainly on personal computers and accepts several operating system such Windows 95/98/2000 and Windows NT 4.0 as well as wide range of UNIX platforms (ESRI, 2000). The system works mainly with vector data. Although raster files can be incorporated into 3DA, but only for improving the display of vector data (e.g. by draping vector data with aerial photo images). (Raster files are and considerably for aspect of 2-D spatial data analysis.)

In summary 3DA can be used to manipulate 3D data especially for visualization purposes. Thus, ArcView is very much a 2D GIS system, but 3DA supplies 3D visualization and display (e.g. of data with x, y,z coordinates). 3D GIS analysis is not achieved. It is worth noting that 3DA supports the triangular irregular network (TIN) data structure.

6.2 Imagine VirtualGIS

It is worth mentioning that the Imagine system was originally developed for remote sensing and image processing tasks. Recently, the system has provided a module for GIS. The Imagine system is one of the GIS solutions developed by ERDAS Inc (ERDAS, 2000). The GIS module is called VirtualGIS. It is a module that provides a three-dimensional visual analysis tools. The system has run under various computer systems ranging from personal computers to workstations such as DEC computers, IBM personal computers, Hewlett Packard, Sun Sparc and IBM RISC machines. Currently the system works with operating systems such as Windows98/2000, Windows NT and various UNIX systems. It is a system that has an emphasis on dynamic visualisation and real-time display in the 3D display environment. Besides various and extensive 3D visualizations, the system also provides fly-through capabilities (Limp, 1999). Figure 11 shows the system overview of the VirtualGIS with its core Imagine system.

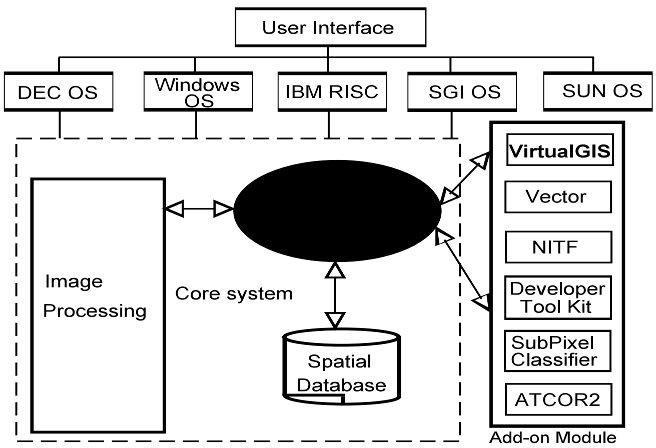

Figure 11 The VirtualGIS component (shown on top of the add-on module's box) in the Imagine system architecture.

As with 3DA this system also centres around 3D visualization with true 3D GIS functions hardly available.

6.3 GeoMedia Terrain

GeoMedia Terrain is one of the subsystems that work under the GeoMedia GIS system developed by Integraph Inc. The system runs under the Windows operating systems (including NT 4.0 system). The Terrain system performs three major terrain tasks, namely, terrain analysis, terrain model generations, and fly-through (Integraph, 2000). In general the Terrain serves as DTM module for the GeoMedia GIS as with the other systems mentioned in the previous sections where true 3D GIS capabilities are hardly offered by software vendors. Figure 12 shows the Terrain subsystem within the GeoMedia core system.

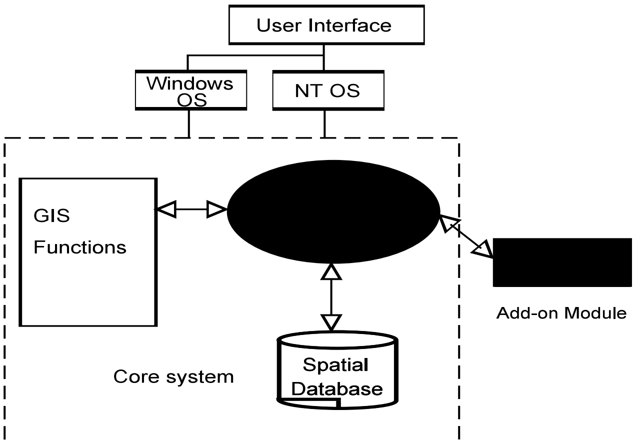

Figure 12 The Terrain component within the GeoMedia

6.4 PAMAP GIS Topographer

This GIS system is one of PCI Geomatics Inc.'s products. It runs under Windows95/98 and NT operating systems. PAMAP GIS is a raster and vector system (PCIGeomatics, 2000). Besides its 2D GIS functions, the system has a module for handling 3D data, called Topographer as in Figure 13. Four main GIS modules are offered, they are Mapper, Modeller, Networker and Analyser which form the core system. For 2D data handling, the system performs GIS tasks as in the systems mentioned earlier. For 3D data, most of the 3D functions in the Topographer work as by any DTM packages, for example terrain surface generation, terrain surfaces analysis (e.g. calculation of area, volume) and 3D visualisation (such as perspective viewing). This system also focuses on 3D display of terrain data.

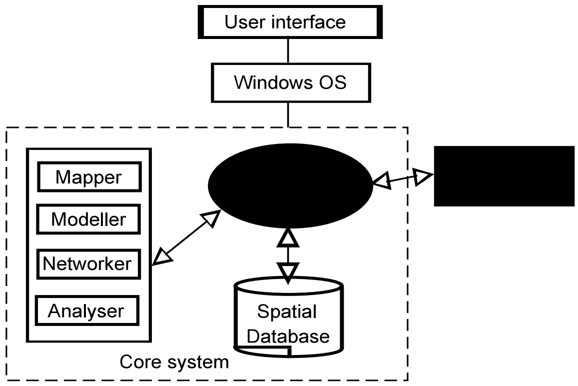

Figure 13 The Topographer within the PAMAP GIS system.

In summary, all the systems revealed little provision of 3D GIS functionality but most of them can handle 3D data efficiently in the aspect of 3D visualization. A fully integrated 3D GIS solution has yet to be offered by general purposed GIS vendor.

There are a few prototype 3D GIS systems. One of them is developed by Fraunhofer Institute (Germany). This system utilises a CAD modeller, which can generate 3D objects (such as buildings) on top of the terrain (Rimscha, 1997). Another prototype system, which was developed by an Austrian company Grintec, has tested the system within urban objects. The system, called GO-3DM also used CAD and DTM for the management of the city of Graz's 3D objects (mainly buildings) as reported by Rimscha. Despite some exciting developments in 3D visualization and the possibility of incorporating them within GIS, true 3D GIS solutions remain to be realised. This indicates that 3D GIS has far from arrived and needs further investigation.

7.0 Discussion

From the foregoing discussions the problem of spatial data structuring and spatial data modelling for real world 3D objects in analytical GIS environment remains unsolved. The only near solutions offered concentrate on the visualisation aspect as indicated in section 6. This gap of GIS functionality needs to be investigated. The effort carried out by the research groups as indicated in Section 5 focuses on the spatial data structuring and data modelling with emphasis on developing software, which will contribute towards 3D GIS in the near future.

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