

Trends in 3D GIS Development

Siyka ZLATANOVA¹, Alias Abdul RAHMAN² and Morakot PILOUK³

¹ GIS Technology Section, Delft University of Technology, Thijssseweg 11, 2629JA, Delft, The Netherlands. s.zlatanova@citg.tudelft.nl.

² Department of Geoinformatics, Universiti Teknologi Malaysia, 81310 UTM Skudai, Johor, Malaysia. alias@fkg.utm.my.

³ Environmental System Research Institute (ESRI), 380 New York Street, Redlands, California, USA. mpilouk@esri.com

Abstract:

Currently, a variety of software is capable of handling a wide range of spatial problems, beginning with approaches for describing spatial objects to quite complex analysis and 3D visualisation. However, an increasing number of applications need more advanced tools for representing and analysing the 3D world. Among all types of systems dealing with spatial information, GIS has proven to be the most sophisticated system that operates with the largest scope of objects (spatial and semantic), relationships and provide means to analyse them. However, what is the status of 3D GIS? It is the aim of this paper to find the answer by analysing both available software and efforts of researchers. An overview of several software packages and 3D case studies performed in Oracle and Microstation is given to provide knowledge about the 3D functionality offered by commercial systems. The most significant achievements in the 3D research area concerning key issues of 3D GIS, i.e. 3D structuring and 3D topology are summarized to portray the current research status. At the end, some of the issues and problems involved in developing such a system are presented and recommendations on directions for further research are made. The scope of the paper is limited to 3D GIS systems and research in vector domain. Problems of subsurface applications are excluded as well.

1 Introduction

The need for 3D information is rapidly increasing. Currently, many human activities make steps toward the third dimension, i.e. urban planning, cadastre, environmental monitoring, telecommunications, public rescue operations, landscape planning, transportation monitoring, real-estate market, hydrographical activities, utility management, military applications. Practically, the area of interest grows significantly when 3D functionality is offered on the market. Moreover, the role of geo-information in all kinds of business processes is getting quite transparent. Terms such as “location-specific information” and “location-based services” become a part of the daily business language to denote the link between the virtual world of information (transactions, events, internet communication) and the real world of information - customers, inventory, shipping and the like. Most business transactions rely on information systems to operate successfully, as the geo-information (location-specific information) is critical for many of them (see Sonnen and Morris, 2000). Once the developments in 3D GIS provide a compatible functionality and performance, the spatial information services will evolve into the third dimension.

Traditionally, GIS system should be able to maintain information about spatial phenomena and provide means to analyse it and thus gain knowledge of the surrounding world. In general, consensus on the demanded functionality of GIS was achieved years ago. The tasks or the functions of a GIS are specified as follows (see Raper and Maguire, 1992): 1) data capture, 2) data structuring, 3) data manipulation, 4) data analysis, and 5) data presentation. Indeed, 3D GIS aims at providing the same functionality as 2D GIS. Unfortunately, such 3D systems are still not available on the market. A variety of different software (i.e. 2D GIS, DBMS and CAD) is employed to maintain the objects of interest and extract the required information. Due to the

deficiencies of all the systems to handle 3D objects, the data are often spread between several systems. For example, one system is used for data storage and another for 3D visualisation. This situation often faces inconsistency problems, which leads to extra time, efforts and money to find the appropriate solution.

This paper summarises the current status of 3D GIS development. Firstly, we concentrate on recent achievements reported by vendors. We briefly present our survey on the possibilities of some GIS's available on the market and analyse two case studies completed on commercial systems. Secondly, we review attempts by researchers toward providing an appropriate structures and operations for 3D spatial analysis and visualisation. Final discussion recommends directions and topics for further research and implementations.

2 3D GIS in the market

There are few commercial-of-the-shelf (C.O.S.T) systems that can be categorised as systems that attempt to provide a solution for 3D representation and analysis. Four systems are chosen for detailed consideration, because they constitute a large share of the GIS market and provide some 3D data processing functions. The systems are the 3D Analyst of ArcGIS (see ESRI Inc.), Imagine VirtualGIS (ERDAS Inc., <http://www.erdas.com>), GeoMedia Terrain (Intergraph Inc., <http://www.integrgraph.com>) and PAMAP GIS Topographer (PCIGEOMATICS, <http://www.pcigeomatics.com>). Parts of the following text are based on available literature and Web-based product reviews.

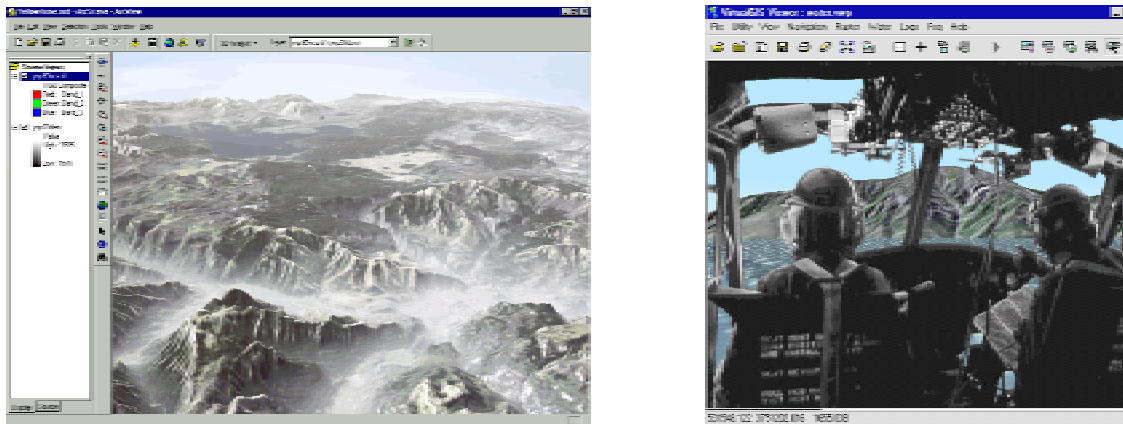


Figure 1: Commercial GIS: ArcScene, ESRI (left) and Imagine Virtual GIS, ERDAS (right)

2.1 Traditional GIS vendors

ArcGIS 3D Analyst, ESRI: The 3D Analyst (3DA) is one of the modules available in ArcGIS GIS. ArcView is designed to provide stand alone and corporate wide (using client-server network connectivity) integration of spatial data. With 3DA one can manipulate basically 2.5D data such as surface generation, volume computation, draping raster images, terrain inter-visibility from one point to another. The system works mainly with vector data. Raster files can be incorporated into 3DA, but only for improving the display of vector data. During the last three years, ESRI has further developed the 3D Analyst for the ArcGIS 8.1 environment. ArcGIS consists of the Desktop and Workstation components. The Desktop component is based on personal computer (PC) and Microsoft Windows operating system, while the Workstation component is available for both PC and UNIX platforms. ESRI also introduced a new ArcScene desktop application as part of the 3D Analyst extension to ArcGIS 8.1 (Figure 1, left). ArcScene is a stand-alone application that provides all the capabilities similar to 3DA with enhanced 3D visualization, flyby, texture mapping on building facades, 3D symbols, animation and surface analysis for both raster and vector data. Commonly used CAD data formats (e.g. DGN, DXF, DWG) can directly be read and displayed in ArcScene. ArcScene can also access and display both raster and vector data stored on the multi-user geographic database using ESRI Spatial Data Engine (SDE) or data service on the Internet in

the distributed environment using ESRI ArcIMS. Although major progress on improving 3D visualization, animation, and data access has been made, full 3D geometry for 3D representation, topological relationships and analysis remain as areas to be addressed.

Imagine VirtualGIS, ERDAS: It is worth mentioning that the Imagine system was originally developed for remote sensing and image processing tasks. The recently provided GIS module is called VirtualGIS and supplies some 3D visual analysis tools. It is a system that has an emphasis on dynamic visualisation and real-time display in the 3D display environment. Interesting 3D visualisation features of the system are: 1) the possibility to include rapidly 3D models in a selected polygon or along a line (e.g. 3D models of trees in a forest area) and 2) the *logo layer* that can accommodate a 2D image into the 3D scene and stretch it over the entire view as foreground (e.g. cockpit in a fly animation, Figure 1, right). Besides these and other extensive 3D visualizations, the system also provides fly-through capabilities. As with 3DA this system also centres on 3D visualization with true 3D GIS functions hardly available.

GeoMedia Terrain, Integraph.Inc: GeoMedia Terrain is one of the subsystems that work under the GeoMedia GIS. The system runs under the Windows operating systems. The Terrain system performs three major terrain tasks, namely, terrain analysis, terrain model generations, and fly-through. The navigation tool *ActiveFlight* provides the three most common navigation modes -- free flight, constant above ground elevation and terrain avoidance. It also offers the ability to save and restore viewpoints. In general, the GeoMedia Terrain serves as DTM module for the GeoMedia GIS without true 3D GIS capabilities.

PAMAP GIS Topographer, PCIGeomatics: It runs under Windows operating systems. PAMAP GIS is a raster and vector system considered by many (Limp, 2002) the most integrated system (i.e. points and lines are represented as vectors and areas as raster). Four main GIS modules, i.e. Mapper, Modeller, Networker and Analyser form the core system. Topographer, similarly to other terrain systems, provides terrain analysis and display system with the ability to perform a number of functions including the calculation of slope, aspect, visibility, and the generation of perspective views. As a decision-making tool, Topographer gives answers to visibility and planning issues, such as site location and viewing areas. Besides 3D terrain data, Topographer can process any 3D data, including temperature, rainfall and pollution concentrations. Again, true 3D objects cannot be handled by the system

In summary, all the systems revealed little provision of 3D GIS functionality in terms of 3D structuring, 3D manipulation and 3D analysis but most of them can efficiently handle 3D data in the 3D visualization aspect. A fully integrated 3D GIS solution has yet to be offered by general-purpose GIS vendors.

2.2 Geo-DBMS

The GIS, i.e. integration of semantic and geometric data, and spatial relationships, seems to be the most appropriate system ensuring a large scope of analysis and thus serving many applications and daily activities. Therefore, vendors dealing with either spatial or semantic information attempt to achieve the GIS functionality already for years. CAD vendors (such as Autodesk, Bentley) provide means to link 2D, 3D geometry to semantic data and organise topologically structured layers; DBMS (Oracle, Informix) introduce spatial descriptors to represent geometry data and maintain them together with the semantic data. A logical consequence of all the attempts is the agreement on the manner for representing, accessing and disseminating spatial information, i.e. the OpenGIS specifications (<http://www.opengis.org/>). This agreement makes possible efforts of vendors and researches from different fields to be united and streamed to one direction, i.e. development of a functional GIS. The result is the changed role of DBMS. This is to say, it becomes *Geo-DBMS*, an integrated “container” of semantic and geometric properties of real-world objects attempting to provide functionality to store, retrieve and analyse spatial data

Here, we will briefly present the representation of geometry in Oracle Spatial (<http://technet.oracle.com/products/spatial/content.html>). The geometric characteristics of spatial

objects are defined by the *geometric type*. Currently, the supported geometric types are 2D but 3D coordinates are accepted. The rules for objects description are very simple and intuitive. Lines and polygons are represented as an ordered set of coordinates (2D or 3D). Self-intersecting lines are allowed but self-intersecting polygons are not supported. Polygons with holes are maintained as well. Oracle is an object-relational DBMS and the geometric types are defined using exactly the object-oriented approach. They are defined in the *mdsys.sdo_geometry* object-relational model and contain information about type, dimension, coordinate system, holes of objects, and provide a list with the coordinates.

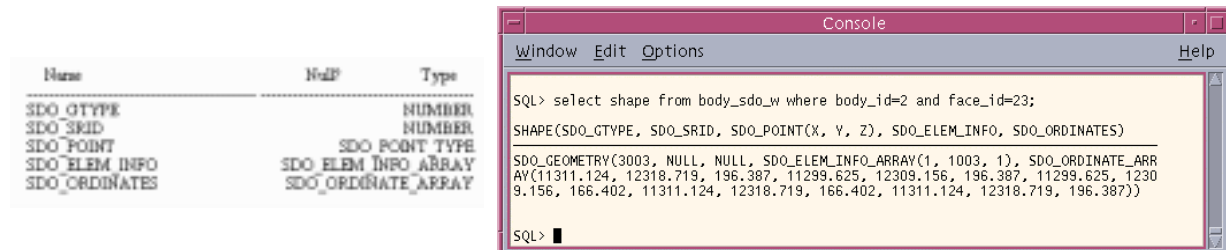


Figure 2: Oracle's *mdsys.sdo_geometry* object (left) and representation of one polygon in Oracle Spatial 8i (right)

In Oracle Spatial 9i, the *SDO_GTYPE* allows decoding of seven geometric types namely *point*, *line* or *curve*, *polygon*, *collection*, *multipoint*, *multiline* or *multicurve* and *multipolygon*. The type *collection* gives the possibility of different geometric types to be organised and considered as individual spatial objects. Figure 2 shows the representation of one 3D polygon (a face from a 3D object).

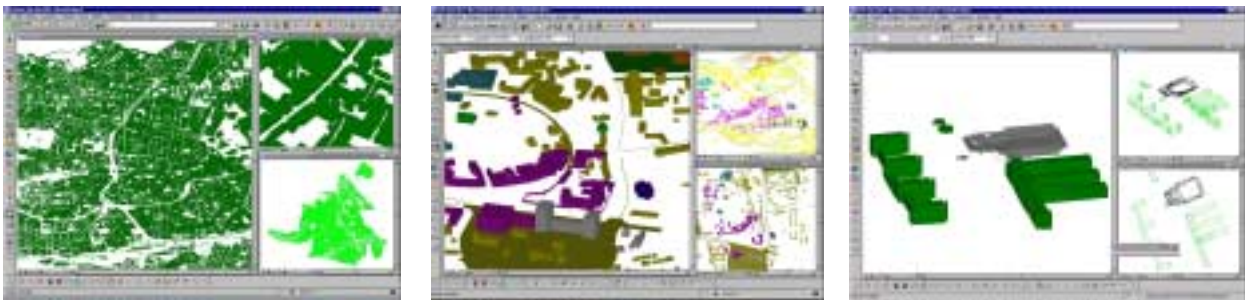


Figure 3: The data sets used in the experiments: Vienna (left), Enschede (middle) and TUDelft (right)

3 Experiments with Oracle Spatial and GeoGraphics iSpatial

Several CAD/GIS applications (MicroStation, AutoCAD, MapInfo) already embrace OpenGIS specifications. We have selected MicroStation Geographics iSpatial (<http://www2.bentley.com/products/default.cfm>) to investigate the 3D functionality offered at present. GeoGraphics iSpatial establishes a connection directly to Oracle Spatial. The spatial objects within GeoGraphics iSpatial are defined in a hierarchical structure. *Project* refers to as the root and represents the data for the entire study area. The second level is the *category*, which groups features with a similar theme (e.g. buildings, rivers). One project can have many categories but a category may belong to only one project. *Feature* is at the third level and represents one or more objects in the real world (e.g. the bank building, the school building). A feature incorporates all the attribute and geometric data available for a particular real object. A category may have many features but a feature may belong to only one category. Feature is the basic structural unit in GeoGraphics iSpatial. To be able to distinguish between different spatial objects stored in Oracle Spatial 8i, each object has to be assigned to a feature. Furthermore, edited and newly created objects cannot be posted in the database without attributing predefined features to them. Geometry of the objects is organised in one or more *spatial layers*.

To investigate the functionality of the two software products in representing, maintaining and visualising 3D spatial objects, we have completed two case studies following two different approaches. In the first case study, we have the 3D data organised in Oracle Spatial in user-defined relational tables and the task was to access, query and edit them from GeoGraphics. In the second case, the 3D data were available in a DGN file and had to be imported in Oracle Spatial.

3.1 Case Study 1: 3D data organised in user-defined relational tables

A set of 21,000 buildings from the city of Vienna is used for the test (Figure 3, left). The data were initially organised in a 3D topological model, i.e. SSM (Zlatanova, 2000), and mapped into several relational tables in Oracle. A procedure written in PL/SQL (i.e. a high-level programming language in Oracle) converted the data from the topological to the geometric model of Oracle Spatial. A similar topology-geometry procedure is described in Oosterom *et al* (2002). Currently, the 3D objects can be represented in Oracle Spatial as a set of polygons in two different ways. Table 1 shows the two possible descriptions (columns in the relational tables) with respect to the different geometries used. In the first representation, each building has unique identifier (ID), stored in the column BODY_ID (Figure 4, left). The column FACE_ID contains the unique ID of the face. The geometry of each face is organised as 3D polygon (SDO_GTYPE=3003, 3D polygons) in the column SHAPE. Apparently, several records (at least 4) represent every 3D object in the relational table. Although a bit inefficient, this structuring facilitates some types of queries (due to the stored relationships between the faces and the 3D object). For example, the query “find the neighbouring building” can be completed by comparing the IDs of the faces composing the buildings and thus avoiding the coordinate comparison.

Table 1: Descriptions of BODY_SDO table by: 3D polygons and a 3D collection.

Name	Null?	Type	Name	Null?	Type
MSLINK	NOT NULL	NUMBER(10)	MSLINK	NOT NULL	NUMBER(10)
BODY_ID		NUMBER(10)	SHAPE		MDSYS.SDO_GEOMETRY
FACE_ID		NUMBER(10)			
SHAPE		MDSYS.SDO_GEOMETRY			

In the second representation (Figure 4, right), the MSLINK column includes the ID of the building and the SHAPE column contains the 3D coordinates of all the polygons composing one building. Thus, every building is described as a collection of polygons (SDO_GTYPE=3004, 3D collection). Although the number of records is reduced (i.e. one building is represented by only one record), the redundancy of coordinates cannot be avoided. Each triple of coordinates is repeated at least three times in the list of coordinates (i.e. in SDO_ORDINATES).

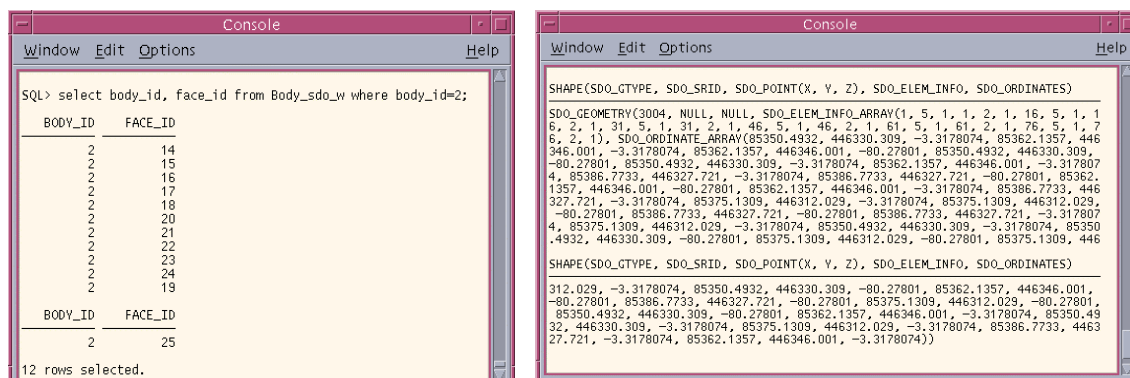


Figure 4: 3D object represented as a set of polygons (left) and as a collection (right) in Oracle Spatial

GeoGraphics iSpatial interprets these two representations differently. In the first case the building is visually one object, but it is composed of individual polygons. The entire building can be selected only by placing a “fence” around all the polygons. In the second case, the building is interpreted as a “group”, i.e. a single click of the mouse will highlight the entire building. However, in order to edit the object, the group has to be “dropped” into the constructing individual

polygons. To send the changes back to the database, regrouping of the polygons will be required. Otherwise, the object will be considered a set of several new polygons. The steps to assess and query objects are described in details in Zlatanova *et al* (2002). Basically, three major steps have to be followed:

- Establishing a reference between spatial layers (in GeoGraphics) and the relational tables (in Oracle Spatial). Since the table with the geometric types (in Oracle Spatial) already exists, it needs to be declared as a spatial layer in GeoGraphics.
- Creating semantics, i.e. features and categories
- Linking features with the spatial objects. Running an appropriate script within Oracle is one of the easiest ways to complete this operation in case of many objects.

3.2 Case Study 2: 3D data organised in DGN file

The data set for the second case study is obtained from a semi-automatic procedure for 3D reconstruction developed at ITC, Enschede, The Netherlands (Tempfli, 1998). The manual digitising of points characterising roofs of buildings in a photogrammetric stereo model (from aerial photographs) creates a “skeletal point cloud”. The 3D reconstruction then consists of automatically computing and assembling all the faces (roof faces and walls) of the building from this point cloud. The model obtained in this way contains planar closed polygons, whose normal vectors point towards the outside of the building (to ensure correct 3D visualisation). The procedure is capable of processing a number of objects (not only buildings) as the reconstruction rules for other topographic objects are in most cases simpler than those for buildings. All reconstructed objects are organised in the topological data structure 3D FDS (Molenaar, 1992). In addition, a new DGN file with the 3D reconstructed model is created. This procedure (running on *SocetSet*, Leica) was applied to reconstruct the centrum of Enschede (Figure 3, middle). Another adaptation of the same idea for *SoftPlotter* (<http://www.autometric.com/NEW/Products/Production/sp.html>) is presented in Vermeij and Zlatanova (2001), which allowed the reconstruction of several buildings in the campus area of the TUDelft. The 3D objects of these two procedures were also successfully imported in Oracle Spatial by the following steps:

- Creation of features and categories.
- Selecting the entire geometry (polygons or group of polygons) per spatial objects in GeoGraphics and attaching a feature to it.
- Posting the spatial objects to the database.

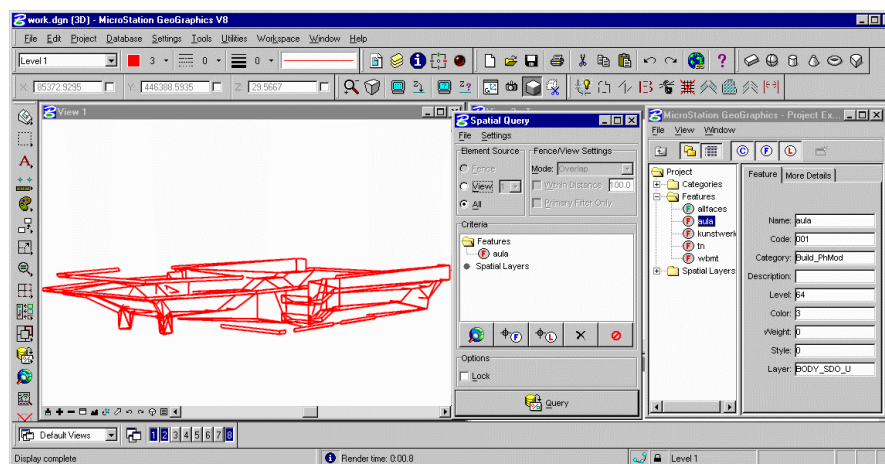


Figure 5: The Aula, TUDelft: 3D model queried in GeoGraphics

In both cases studies, after completing the representations (in GeoGraphics and Oracle) it was possible to query, visualise and edit the objects. The query can be performed with respect to the features defined in GeoGraphics. For example, a query on feature “buildings” will result in visualisation of all the buildings. If a feature (e.g. “the Aula”) is attached to only one spatial object, then only that object will be extracted from the database (Figure 5). Apparently, this is

quite convenient for editing and updating large 3D models. Rendering of thousands of polygons can be easily avoided.

3.3 Analysis of the offered 3D functionality

The case studies have clearly shown that the operations needed to access and manipulate spatial data are still not transparent, standardised and user-friendly. The user is expected to have excellent skills in both systems, i.e. understanding the conceptual representation in GeoGraphics iSpatial and being aware of the implementation in relational tables in Oracle Spatial.

Data Structuring. The concepts implemented in both systems follow closely the OpenGIS specifications, i.e. the notation of a *geographic feature*, and the way in which spatial characteristics are represented by geometric and topological primitives. Nevertheless, the implementations are still not completely application independent. The test has revealed that one significant part of the information about the geographic feature is maintained at a database level. However, the notations (table names, columns, object definitions) have very specific application-oriented (in this case MicroStation) meaning. For example, if the user decides to keep the database and change the CAD package, he/she will need to create the feature-geometry link from scratch.

As was mentioned before, despite the lack of a real 3D object, description of 3D data is possible in the geometry types of Oracle spatial. The Z value is maintained together with the X,Y values, i.e. it is not an attribute. Another positive discovery is the definition of *mdsys.sdo_geometry* object in Oracle Spatial, which allows a straight forward extension toward describing a 3D object. Stoter and Oosterom (2002) propose new values of the *mdsys.sdo_geometry* parameters object to describe 3D objects (e.g. tetrahedron, polyhedron, polyhedron with holes, etc.). The SDO_ORDINATES array is suggested to have two sections, i.e. a list of coordinates and references to the list. This approach will reduce considerably the size of the array, which is a critical consideration in maintaining 3D data.

The support of parameters to describe physical properties of 3D objects is still missing. Currently, feature description (in FEATURE and UGFEATURE tables) permits properties of lines (e.g. colour, width, gaps width, type line) to be specified, but properties of polygons are not considered. For example, the colour of a polygon (in rendering mode) is selected with respect to the colour of the line. 3D realistic visualisation is practically not possible due to lack of a mechanism to specify texture parameters per face.

Data Analysis. Real possibilities to analyse 3D data in GeoGraphics iSpatial and Oracle Spatial are still missing. Tools to perform spatial operations (2D topology or operators using the geometric model of Oracle) are provided but they operate with only X, Y coordinates. Some of the operations accept X, Y, Z values but the computations are purely 2D.

Data Manipulation and Visualisation. Apparently the greatest benefits of the DBMS-CAD integration are in the area of visualisation and data editing. It is well known and frequently commented that the amount of data to be visualised in 3D increases tremendously and requires supplementary techniques (LOD, on-fly simplification, etc.) for fast rendering. Having 3D data stored in a database, the user has the possibility to extract only a limited set of data (e.g. one neighbourhood instead of one town) and thus critically reduce the time for loading. For example, the whole Vienna data set is loaded for about 40 minutes, while one building comes up for fractions of a second. Locating, editing and examining a particular object also becomes quick, simple and convenient. Indeed, the elements that can be edited correspond to the geometry representation in Oracle Spatial. In our cases, one building is the aggregation of several faces but practically the accessible elements are “loose” polygons. The editing operations are restricted to the defined objects (in our cases polygons and their vertices). For example, a shift of one vertex will change the vertex of the selected polygon. Moreover, many of the parametric shapes (spheres, cylinders, cubes and all types of extruded shapes) provided by MicroStation cannot be posted to the database, i.e. they have to be simplified to points, lines and polygons.

4 3D GIS in the research

The research in 3D GIS is intensive and covers all aspects of acquisition, storage and analysis of real world phenomena. Among all, 3D analysis and other related issues (topological models, frameworks for representing spatial relationships, 3D visualisation) are mostly in the focus of investigations.

Topological model: The topological model is closely related to the representation of spatial relationships, which are the basis 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. Several 3D models have already been reported in the literature. Each of the models has strong and weak points for representing spatial objects.

Carlson (1987) proposed a model called the simplicial complex. The simplex is the simplest representation of a cell. 0-simplex is a point, 1-simplex is the straight line between two points, 2-simplex is the triangle composed by three 1-simplexes and 3-simplex is the tetrahedron composed by three 2-simplexes. He uses the simplexes to denote spatial objects of node, line, surface, and volume. The model can be extended to n -dimensions. Molenaar (1992) presents a 3D topological model called 3D Formal Vector Data Structure (3DFDS). The model maintains nodes, arcs, edges and faces that are used to describe four types of features named points, lines, surfaces and bodies. Compared to the simplex approach, 3DFDS has fewer restrictions on the objects, e.g. the 2-cell (face) can have arbitrary number of 1-cells. Furthermore, some spatial relationships are explicitly stored, i.e. face-body. The model belongs to the group of Boundary representations (B-reps). Cambray (1993) proposes 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. Pigot (1995) developed a 3D topological model based on 0,1,2, 3 cell, which maintains an explicit description of relationships between cells. 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 (i.e. TIN and 3D FDS), which produced a practical approach to the problem. Moreover, the author developed the Tetrahedron Network (TEN) data structure that is based on simplexes. The structure assures a strict consistency check, built on the generalised Euler's Equality. De la Losa and Cervelle (1999) and Pfund (2001) propose object-oriented models similar to Molenaar's one but they have included several more explicitly stored spatial relationships. For example, De la Losa maintains the relationship arc-faces and introduces a strict ordering of faces. Zlatanova (2000) discusses some aspects of the data structuring and 3D visualisation with respect to data query over the Web. The proposed data structure lacks the 1-cell in order to improve the performance of the system. Abdul-Rahman (2000) focuses on the object-oriented TIN (2D and 3D) based GIS. The conceptual and the logical model are developed based on Molenaar's data model.

Consensus on a single 3D topological model is not achieved. A topological model appropriate for one application can be completely inapplicable for other application. Therefore Oosterom *et al* (2002) propose maintenance of multiple topological models (in the database) as the rules and constraints of each model are explicitly represented in a metadata table. Functions have to provide consistent migration between the topological models as well as to the geometric model.

Formalism for detecting spatial relationships: OpenGIS consortium has adopted two frameworks to detect spatial relationships known as Egenhofer operators and Clementini operators based on the 9-intersection model (see Egenhofer and Herring, 1992, Clementini and Felice, 1994). Although the topology is considered the most appropriate mechanism to describe spatial relationships, the study on other mathematical frameworks continues. Billen *et al* (2002) propose another framework (i.e. the Dimensional model) for representing spatial relationships, built up in affine space and convexity properties of the constructing elements (named dimensional elements). The Dimensional model allows larger variations in the grouping of spatial relationships compared to the 9-intersection model.

Data Presentation: Advances in the area of computer graphics have made visual media a major ingredient of the current interface in the communication and interaction with computers.

Therefore, research related to the visualisation of real world 3D data is mostly “shifted” to the computer graphics society. Many viewers and browsers as stand-alone applications and plug-ins have been developed to quickly visualise and navigate through 3D models for a variety of applications. New algorithms and implementations are reported daily. The design criteria, however, are fast rendering techniques based on internal structures rather than utilisation of database representations. TerraExplorer (http://www.skylinesoft.com/corporate/corporate_home.asp), the current leader for visualising large 3D textured data from the real world and the first software with acceptable performance, also requires re-structuring of data.

3D Web applications: 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. 3D data were not even transferable over the Web until five years ago. The first attempt to disseminate and explore 3D data, i.e. VRML, appeared to be rather “heavy” for encoding real geo-data due to the lack of a successful compression concept. Despite the drawbacks, the language became a tool for research visualisation. Researchers could concentrate on data structuring and analysis and leave the rendering issues to browsers offered freely on Internet. The research on spatial query and 3D visualisation utilising VRML has resulted in a few prototype systems (Coors and Jung 1998, Lindenbeck and Ulmer 1998, Zlatanova 2000). GeoVRML (VRML extended with geo-nodes) and the new standard X3D (<http://www.web3d.org/news/x3d/>) are among promising opportunities for representing 3D data on the Web. A key goal of the X3D standard is definition of interoperable, light-weight components for 3D Web and broadcast applications beyond VRML 97.

5 Summary

In this paper we reported our observations and experience with current 3D GIS developments. The major 3D progress is observed in the area of data presentation. All traditional GIS vendors provide extended tools for 3D navigation, animation and exploration. However, many of these systems still are lacking full 3D geometry. OpenGIS specifications seem to have been adopted rapidly by DBMS, CAD, and GIS developers. In this order of thoughts, the understanding for GIS is changing. Instead of a monolith, desktop, individual system, GIS is becoming an integration of strong database management (ensuring data consistency and user control) and powerful editing and visualisation environments (inheriting advanced computer graphics achievements). At present, only the first step is made, i.e. the implementations focus mostly on the geometry. 2D topological representations and operations are intensively in the process of implementation. The third dimension with respect to topological issues is still in the hands of the researchers.

The case studies clearly showed the benefits of a standardised spatial data structuring as well as revealed the very early stage of the integration. The large number of specialised settings, the application dependent feature-geometry linkage, the limited semantic hierarchy, the spatial operators utilising only X, Y values, are some of the issues that need further improvement.

Although, there are quite a significant number of works devoted to 3D data structuring, the research is concentrated around a few basic ideas, as the level of explicitly described spatial relationships varies. Each suggested data structure exhibits efficiency and deficiency with respect to particular applications and operations to be performed. Still 3D GIS functionality needs to be addressed: 3D buffering, 3D shortest route, 3D inter-visibilitys are some of the most appealing for research. Integration of object-oriented approaches with the 3D GIS raises research topics at a database level toward standard object descriptors and operations.

3D visualisation within 3D GIS requires appropriate means to visualise 3D spatial analysis tools to effortlessly explore and navigate through large models in real time. Observations on the demand for 3D City models show user preferences for photo-true texturing. Trading photo-true texture brings up necessities to store parameters for mapping onto the geometry.

Acknowledgements

We express our sincere gratitude to Bentley Systems Europe, ITC, The Netherlands and The Graz University of Technology, Austria for their respective contribution to the case studies.

References

- Abdul-Rahman, A., 2000. The design and implementation of two and three-dimensional triangular irregular network (TIN) based GIS. *PhD thesis*, University of Glasgow, UK. 250pp.
- Billen, R., Zlatanova, S., Mathonet, P. and Boniver, F., 2002. The Dimensional model: a framework to distinguish spatial relationships. In: Richardson, D. and van Oosterom, P. (Eds.), *Advances in Spatial Data Handling*, Springer-Verlag, Berlin, pp.285-298.
- Cambray, de B., 1993. Three-dimensional (3D) modelling in a geographical database. *Proceedings of Auto Carto 11*, Bethesda, Maryland, pp.338-347.
- Carlson, E., 1987. Three-dimensional conceptual modelling of subsurface structures. *Technical Papers of ASPRS/ACSM Annual Convention*, Baltimore, Vol. 4 , pp.188-200.
- Clementini, E. and Di Felice P., 1994. A comparison of methods for representing topological relationships. *Information Sciences* (80), pp.1-34.
- Coors, V. and Jung, V., 1998. Using VRML as an Interface to the 3D Data Warehouse. *Proceedings of VRML'98*, New York, pp.121-127.
- de la Losa A. and Cervelle B., 1999. 3D topological modelling and visualisation for 3D GIS. *Computers and Graphics*, 23 (4), pp. 469-478.
- Egenhofer, M. J. and Herring, J. R., 1992. *Categorising topological relations between regions, lines and points in geographic databases*. Technical report 94-1, NCGIA, Univ. of Maine.
- ESRI, 1997. *Using ArcView 3D Analyst*. ESRI Publication, Redlands, California, USA, 118pp.
- Lindenbeck, C. and Ulmer, H., 1998. Geology meets virtual reality: VRML visualisation server applications, In: *Proceedings of WSCG'98*, 3-19 February, Plzen, Czech, Vol. III, pp. 402-408.
- Limp, W.F., 2002. GIS raster packages, *GeoEurope*, <http://www.geoplance.com/ge/2000/0600/0600rs.asp>.
- Molenaar, M., 1992. A topology for 3D Vector Maps, *ITC Journal*, 1992-1, pp.25-33.
- Oosterom, P. v, Stoter, J., Quak, W. and Zlatanova, S., 2002. The balance between geometry and topology. In: Richardson, D. and van Oosterom, P. (Eds.), *Advances in Spatial Data Handling*, Springer-Verlag, Berlin, pp.209-224.
- Pfund, M., 2001. Topologic data structure for a 3D GIS. *Proceedings of 3rd International Workshop on Dynamic and Multi-dimensional GIS (Inter. Archives for Photogrammetry and Remote Sensing*, Vol.34, Part 2W2), 23-25 May, Bangkok, Thailand, pp.233-237.
- Pigot, S., 1995. *A topological model for a 3-dimensional Spatial Information System*, PhD thesis, University of Tasmania, Australia.
- Pilouk, M., 1996. *Integrated modelling for 3D GIS*. PhD thesis, ITC, The Netherlands, 200pp.
- Raper, J. and Maguire, D. J., 1992. Design models and functionality in GIS. *Computer & Geosciences*, 18(4), pp.387-394
- Sonnen, D. and Morris, H., 2000. *Location in CRM: Linking virtual information to the real world*, IDC White Paper, 12pp., <http://www.idc.com>
- Stoter, J. and van Oosterom, P., 2002. Incorporating 3D geo-objects into a 2D geo-DBMS. *Proceedings of ASPRS/ACSM*, 19-26 April, 2002, Washington, USA, CDROM, 12pp.
- Tempfli, K., 1998. 3D topographic mapping for urban GIS. *ITC Journal*, 1998-3/4, pp. 181-190.
- Vermeij, M. and S. Zlatanova 2001. Semi-automatic 3D building reconstruction using Soft Plotter, *Proceedings of the International Symposium on "Geodetic, Photogrammetric and Satellite technologies: development and integrated applications"*, 8-9 November, Sofia, Bulgaria, pp.305-314
- Zlatanova, S., 2000. *3D GIS for urban development*. PhD thesis, ITC, The Netherlands, 222pp.
- Zlatanova, S., Rahman, A.A. and Pilouk, M., 2002. 3D GIS: current status and perspectives. *Proceedings of the Joint Conference on Geo-spatial theory, Processing and Applications*, 8-12 July, Ottawa, Canada, 6pp. CDROM