3D GIS, where are we standing?

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1. Introduction

Since early ’90 GIS has become a sophisticated system for maintaining and analysing spatial and thematic information on spatial objects. The need for 3D information is rapidly increasing. 2D GIS analysis has shown its limitations in some situations, e.g. noise prediction models (noise spreads out in three dimensions) (Kluijver and Stoter, 2003), water flood models, air pollution models, geological models (Van Wees, 2002), real estate market (CEUS, 2003; Stoter and Ploeger, 2003). Other disciplines that have met the need for 3D geo-information are: 3D urban planning, environmental monitoring, telecommunications, public rescue operations, landscape planning.

The breakthrough of 3D GIS seems to go slow. The developments in the area of 3D GIS are pushed by a growing need for 3D information from one side and new technologies on the other side. In (Zlatanova et al., 2002) the side of new technologies were addressed by discussing the current status of 3D GIS considering developments reported by vendors and researchers. In VI Matrix (a Dutch magazine for real estate) the developments of 3D GIS in the Netherlands were described (Oosterom et al., 2002 (1); Oosterom et al., 2002 (2)). This paper continues on these discussions and gives an extended overview on the status of 3D GIS in both research and practise.

We start with a description of technology developments in 3D GIS. Then we address the main complexities of 3D GIS: organisation of 3D data, 3D object reconstruction, and visualisation and navigation in 3D environments. 3D analysing and 3D editing can be added to this list. More on 3D analysing can be found in (Zlatanova and Stoter, 2003). An example of the implementation of a specific 3D analysis, 3D buffering, is described in (De Vries, 2001). More on 3D editing can be found in (Stoter and Zlatanova, 2003). We end this paper with a discussion on where to go for a serious breakthrough of 3D GIS.

2. Technology progress

An important development is improvement of 3D data collection techniques (aerial and close range photogrammetry, airborne or ground based laser scanning, surveying and GPS). Sensors are faster and more accurate than before. Other new techniques that push 3D GIS developments are hardware developments: processors, memory and disk space devices have become more efficient in processing large data sets, especially graphics cards also used by gaming industry. Furthermore elaborated tools to display and interact with 3D data are evolving.

GIS software-tools have also made a significant movement towards 3D GIS. Zlatanova et al., 2002 present a survey on mainstream GIS software: ArcGIS (Esri, 2003), Imagine VirtualGIS (Erdas, 2003), PAMAP GIS Topographer (PCIGeomatics, 2003) and GeoMedia Terrain (Integraph, 2003). Zlatanova et al., 2002 conclude that major progress in 3D GIS has been made on improving 3D visualisation and animation. However, 3D functionality is still lacking such as generating and handling (querying) 3D geo-objects, 3D structuring, 3D manipulation and 3D analyses (3D overlay, 3D buffering, 3D shortest route). This is caused by the specific character of 3D data compared to 2D. Bottlenecks are still organization of 3D data, 3D object reconstruction, and representation and navigation through large 3D models. These three issues are addressed in sections 2.1 to 2.3.

2.1 Organisation of 3D data

3D representations

For modelling 3D objects, several 3D abstractions are possible (Mäntylä, 1988).

Constructive Solid Geometry (CSG) is an approach for modelling 3D objects by solids. Solid modelling has its origin in CAD. The basic primitives in constructive modelling are spheres, cubes, and cylinders and they are used with varying parameters. Set operations are applied to the basic primitives to construct 3D bodies, such as union, intersect and difference. The advantages of CSG that they are good in computer-aided manufacturing: a brick with a hole drilled through it is represented as “just that”. The disadvantages for real world modelling are that the objects and their relationships might become very complex.

A second type of 3D representation is the tessellation representation, e.g. voxel. A voxel is a volume element (3D "pixel"). A 3D object is represented as a 3D cubical (or spherical) array, with each element holding one (or more) data values (boolean or real). Voxels are appropriate in modelling continues phenomena such as geology, soil etc. Voxels are regular in modelling: the basic unit of the model is the same. A disadvantage of voxels is that high resolution data requires large volume of computer space. Another disadvantage is that surface is not regular by nature: it is always somehow "rough".

A third method for representing 3D data is using tetrahedrons (TEN) (Carlson, 1987; Verbree, 2003). A tetrahedron is the simplest 3D primitive (3-simplex) and consists of 4 triangles that form a closed object in 3D coordinate space. It is relatively easy to create functions that work on this primitive. The tetrahedron object is well defined, because the three points of each triangle always lie in the same plane. A disadvantage is that it could take many tetrahedra to construct one factual object.

A last method for representing 3D objects is a boundary representation. The 3D object is represented by bounding low-dimensional elements (vertex (0D), line (1D), polygon (2D), polyhedron (3D)), which are organised in various data structures. This can be either simple boundary representations such as planar faces and straight edges or complex boundary representations such as curved surfaces and edges. The main advantage of boundary representations is that it is optimal for representing real-world objects. The boundary of the objects can be obtained by measurements of properties that are visible (i.e. "boundaries"). Furthermore most of the rendering engines are based on boundary representations (i.e. triangles). Disadvantages are that boundary representations are not unique and that constraints (rules for modelling) may get very complex. For example in 3D a boundary element could be a face (topologically described), a triangle or a polygon (geometrically described), with constraints such as planarity, number of points and arcs, the order of edges and nodes, relation with neighbours etc. Constraints in 3D are even more complex: open space, neighbours, planar faces etc.

Geo-DBMS

GISs are evolving to an integrated architecture, as was first described in (Vijlbrief and Van Oosterom, 1992) in which both spatial and non-spatial data is maintained in one DBMS (Figure 1). In mainstream DBMS spatial data types have been implemented according to the OpenGIS Consortium specifications for SQL (OGC, 1999). The implementations are 2D and are based on the geometrical model defined with a boundary representation. Recently topology management has been implemented (Van Oosterom et al., 2002; Laserscan Radius, 2003; Quak et al. 2003) based on the geometrical model in Oracle Spatial 9i (Oracle, 2001). Oracle Spatial has announced topology structure support in the next version of Oracle (10i).

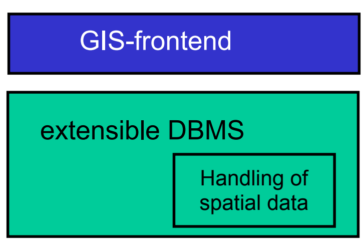

Figure 1: integrated architecture of GIS (Vijlbrief and van Oosterom, 1992).

Current DBMSs do not support 3D objects, although z-coordinates can be used to store 3D objects. The only 3D functionalities in 3D that are available in DBMS are length and perimeter of polygons and polylines in 3D (PostGIS, 2003; Mapinfo, 2002) and spatial indexing in 3D (for example 3D R-tree in Oracle Spatial). (Stoter and Zlatanova, 2003) describe how 3D objects can be organised in a DBMS within current techniques both in the geometrical model and the topological model (using boundary representation). (Arens et al. 2003) implemented a true 3D primitive (polyhedron) as an extension on the geometrical model in Oracle Spatial 9i, which included operators to validate the 3D objects and 3D operators such as distance in 3D and point-in-polyhedron. The implementation has been based on the proposal described in (Stoter and Van Oosterom, 2002).

Interesting research results have been achieved to organise 3D objects in DBMS, however DBMS vendors still have not made the step to implement 3D objects in their geometrical model. Reasons for this may be that OGC still woks on the specifications for 3D features and consensus on a 3D topological model has not been achieved yet. Another limiting factor is the relatively low, but growing market demand for 3D support in DBMS. Current trend is to develop specific ad hoc solutions for using 3D geo-information.

2.2 3D object reconstruction

3D GIS requires 3D representations of distinct objects. 3D object reconstruction is a relatively new issue in GIS, since generating 3D models (e.g. designing) used to be done with CAD software, e.g. MicroStation Geographics (Bentley, 2003). Traditionally, (2D) GIS makes use of data collection techniques such as surveying and measurements of the real world. Since a lot of 3D data is available in CAD designs, a relevant question is if CAD models can be used in 3D GIS.

The 3D models created in CAD software are mostly industrial models designed for production purposes. Geo-applications nowadays require much more advanced functionality, e.g. linking information to the real-world objects and the possibility to identify individual objects in a 3D environment. In 3D GIS, 3D geo-objects need to be available as identifiable objects.

A lot of research is conducted in the last several years toward automation of 3D object reconstruction (especially man-made objects). There are variety of approaches based on different data sources and aiming different resolution and accuracy. We consider four general approaches for constructing 3D models:

- bottom-up: using footprints (from existing 2D maps) and extrude the footprints with a given height using laserscan data, surveying, GPS or photogrammetry data. The problem with this approach is that the detail of roofs cannot be modelled. Since one value is used for every footprint, the buildings appear as blocks in the model. The approach however is very fast and sufficient for applications that do not need high accuracy (do not need roofs) and many details.
- top-down: using the roof obtained from aerial photographs, airborne laserscan data and some height information from the ground (one or more height points near the buildings, DTMs). These approaches emphasise the modelling of the roofs (Bignone et al 1996, Grün and Wang, 1998). Obviously the accuracy of the obtained 3D models are dependent on the resolution of the source data.
- detailed reconstructing of all details. The most common approach is to fit predefined shapes (building primitives) to the 3D point clouds obtained from laser scan data (Vosselman, 1999) or 3D edges extracted from aerial photographs (Lowe, 1991, Foerstner, 1994). The advantage of this approach is the full automation and the major disadvantage is that it is very time-consuming since the algorithms used are very complex.
- combination of all of them e.g. laserscan data and topographic data (Hofmann et al 2002), aerial photographs and maps (Haala, 1999, Suveg and Vosselman 2002), etc.

There is not a universal automatic 3D data collection approach. The optimal way of 3D reconstruction is often completed by manual methods or semi automatic methods. Also modelling details makes the 3D construction labour-intensively. Details should therefore be adjusted to the requirements of the application. The approach of combining all the approaches above contains some risks since many data sources are used and combined, all with different scale and qualities. Using only few data sources gives better overview and it minimises quality risks. At the moment, the manual approach is still needed to reconstruct large-scale detailed 3D models, which is a bottleneck for modelling urban areas in 3D. More research is needed to make the process of 3D construction more (semi)automatic.

2.3 3D visualisation

Specific aspects that come with visualising 3D geo-data compared to 2D geo-data are projections, readability of data (approaching realism by using stereo, shading, shadow, motion), and selecting 3D elements. Also interacting in 3D environments (exploring 3D models) asks for specific techniques. 3D models usual deal with large data sets, requiring efficient hardware and software. Different levels of detail (high detail when objects are close by and low detail when objects are further away) in a model improve efficiency of navigating through a model (Kofler, 1998, Pasman and Jansen 2002). Different representation of objects such as low-resolution graphics, meshed imposter (part of polygons visible for the user) or simple imposter (image of the current view) (Pasman et al 1999) can be stored in the DBMS or created on the fly. The main problems of storing multi representations are fitting high detailed data to data that is represented at a low level of detail and the redundant storage of representations. To make a view realistic one can further add illumination, shade, fog, textures, colour and material to the geometry.

In case of 3D GIS, several new elements need to be organised in the database compared to 2D data. Not only the spatial information and attributes of the object is needed but also characteristics such as physical properties of objects (texture, material, colour), behaviour (e.g. on-click-open) and different Levels Of Detail representations.

Virtual reality and augmented reality

Using VR (Virtual Reality)/AR (Augmented Reality) techniques improves visualizations of 3D geo-data (Verbree et al., 2000), e.g. putting textures on objects and facilitating navigating through the 3D environment (Gruber et al 1995).VR is a realistic representation of data (2D, 2.5D, and 3D), which means that details and physical properties are represented highly realistically even together with sounds and behaviours of the objects. Manipulation and interaction in the views can take place by mouse click, animations, navigation and exploration. In AR a user explores and navigates in the real world augmented by VR (computer generated data).

All kinds of devices are nowadays available to support visualisation in VR/AR environments (Zlatanova 2002), such as elaborated 3D display (Head Mounted Device, workbench, panorama, CAVE, Cockpit); wire and wireless devices for positioning (gyros, accelerators, GPS, GSM, WLAN); sensor devices to track the movements of the user (Power Glove, indoor outdoor tracking systems) and various acceleration hardware.

3D web-visualisation is also progressing. The research on spatial querying and 3D visualisation using VRML (Virtual Reality Modelling Language) and X3D (Extensible 3D) has resulted in several prototype systems (Coors and Jung, 1998; Lindebeck and Ulmer 1998; Zlatanova, 2000; de Vries and Stoter, 2003). X3D is an XML version of VRML, launched in May 2003 by the Web3D Consortium (Web3D, 2003), in order to integrate with other web technologies and tools.

3D visualisation on mobile devices

The 3D capabilities of mobile devices are largely restricted in several hardware aspects (e.g. dedicated 3D hardware chip, floating point calculations are done by the software, hardware division circuits for integer division are missing, large amounts of texture cannot be processed due to memory restriction and slow processing speed). Besides, the algorithms have to be adapted for the low-resolution screens of mobile devices and mobile-devices provide limited colour and shading options.

Despite the problems, the progress in 3D visualisation on handheld devices is striking. The researches are busy with providing mobile users with 3D navigation (Rakkolainen and Vainio, 2001). A number of companies offer already 3D rendering engines for mobile devices. Currently, games and entertainment software is mostly in focus. Examples of such companies are: Superscape-Swerve (Superscape Swerve, 2003), HI Corporation (HI Corporation, 2003), Xen Games (Xen Games, 2003) and Fathammer Inc. (Fathammer, 2003). The navigation software TomTom (TomTom, 2003) provides '3D birds eye' view of a navigated route. Most of the 3D visualisation tools/games are available simultaneously for different devices: PDA, PocketPC and mobile phones. Still, the efforts are toward developing 3D games and not for supporting 3D GIS. In some countries 3D gaming on mobile phones (e.g. Japan, using the rendering engine Mascot Software of Hi Corporation) is already a standard item ranging from car racing to fishing and taking care of personal virtual pets (Donelan, 2003). All these rendering engines use their own core libraries.

Two standards for visualisation of 3D graphics on mobile devices are already available or under development. The first one is OpenGL for Embedded Systems (OpenGL ES), based on OpenGL (the mostly adopted cross-platform graphics API) is on hand for downloading at (Khronos, 2003). The South Korea Telecom already announced (June, 2003) their choice of OpenGL ES as its standard graphics API for 3D applications. The second standardisation initiative for 3D graphics display on mobile devices is Java Specification Request 184 (JSR 184). This standard focuses on scalable, small-footprint, interactive 3D API (based on J2ME technology) and is ready and announced for public comments (Java communication Process, 2003).

3. Where to go

GIS applications, which offer true 3D functionalities other than 3D visualizations, are still rare. Also GIS and DBMS vendors are not matured towards full support for 3D. It seems the users are waiting for vendors to make a step to 3D and vendors are waiting for an extensive request for 3D information from practice. In this respect, the role of the researcher pursuing new 3D solutions is very critical.

In order to mature 3D GIS, a 3D geometrical model should be fully supported by DBMSs based on OpenGIS specifications for 3D features, which still have to be completed. The native support of a polyhedron by DBMS will have significant consequences for the 3D modelling in the coming years. However the polyhedron primitive has its limitations, since curved faces have to be approached by a set of flat faces. Implementing a 3D primitive with more complex characteristics will make it possible to model objects closer to reality. Such a primitive needs further research. Complex primitives have already been implemented in CAD, which raises questions such as whether and how to transfer the CAD implementations to GIS.

The topological equivalent of the polyhedron primitive will require more time and it will take at least 6-7 years until it will be fully supported in DBMSs. First the focus will be on the support of 'internal' topology (i.e. between the low-dimensional primitives) for efficient representation of one polyhedron. Whether 'external' topology support in 3D is needed (in which 3D space is completely subdivided into 3D objects without any overlaps or gaps) is an issue still to be researched and tested. Some support for 'external' topology will definitely be necessary. The model should support sharing nodes, faces and edges between 3D objects for maintaining integrity and consistency of the data. A solution could be embedding the objects in 3D space. The classical example of two 3D objects that touch, while the faces are not the same is still challenging. In general, when do two objects touch in 3D space: when they have a common face, or a common edge or a common point? In this respect, tetrahedrons and topological models based on tetrahedrons are much simpler and easier to maintain. In order to evolve the polyhedron model based on cylindrical and spherical patches to its topological equivalent, fundamental research issues have to be addressed.

Once 3D geometrical models and topological models are supported in geo-DBMS, a robust set of functions to convert between the geometrical model and the topological model has to be provided. Apart from the 3D models themselves, functions to validate the 3D geometrical models and to check the consistency of the 3D topological models are needed. 3D spatial functions are also part of 3D implementations. The spatial functions can be distinguished in geometrical functions (e.g. distance, volume, aggregation), topological functions (e.g. do two 3D objects touch and what is the dimensionality of the touch relationship) and editing functions.

The CAD and GIS front-ends should be able to read 3D output and write it to both the topological and the geometrical model in DBMSs. Editing of the 3D models has to be further elaborated: instead of editing only individual elements (triangles, or lines), the front-end have to be able to preserve the topology of the 3D object.

At present, 3D implementations will be focused on boundary representation. Since CSG may appear appropriate also for large-scale real-world 3D objects (threes, traffic signs, building ornaments, statues), future 3D GIS may ask for the use of CSG and maintenance of CSG primitives in DBMS. The implementation of CSG will take long, since the discussion on this has not even started yet. Merging CAD, which has implemented CSG, and GIS may support this development.

These developments at vendor's side might be still insufficient to push GIS community toward using true 3D. A very critical issue remains collecting and inserting 3D data, which is a time-consuming process at the moment. In the coming years object reconstruction most probably will remain semi-automatic. The automation of this process is an important condition for the breakthrough of true 3D GIS, as will be the reducing costs of data needed, due to multiple use of same data by many users.

Finally, where is 3D GIS? 3D GIS is mostly seen as a nice visualisation tool. However, it should not be forgotten that the real use of 2D GIS was pushed by nice presentations (maps and pictures) that GIS could provide. In many cases 2D GIS was nothing more than a map-producer only several years ago. At the moment, the status of 3D GIS is similar. In this respect, the researchers have the challenging role to mature 3D GIS. The researchers have to show both vendors and GIS users the possibilities and constraints of 3D GIS in order to obtain a serious breakthrough of 3D GIS, being more than a visualisation tool.

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