Part III
Position papers

Chapter 23
Working Group I – Requirements and Applications – Position Paper: **Requirements for 3D in Geographic Information Systems Applications**

Andrew U. Frank

Geoinformation systems (GIS) contain information about objects in geographic space; the focus on geographic space [1] determines the scale of spatial objects and processes of interest at a spatial resolution of approximatively 0.1 m to 40.000 km and to changes occurring once a minute to once a million years. Geographic information is a diverse field which includes many special applications, each of which has special requirements, with special kinds of geometry and particular geometric operations.

The wide variety of requirements of individual geo-applications motivates my first (not new) requirement [2]:

Requirement 1: Construct a fully general 3D (volume) geometry management system based on a clean mathematical foundation (e.g., algebraic topology [3], specifically cw complexes).

Any 3D geometry must be represented with no special cases excluded. Many current packages are optimized for one application (e.g., 3D city models) and restrict the geometry; for example, only volumes with horizontal or vertical boundaries may be accepted. Specialized geometry software, optimized for particular applications, creates difficulties later when data from multiple applications must be integrated to construct a comprehensive view. Restrictions to particular geometries must be possible and the formulation of the corresponding consistency constraints simple (e.g., partitions of 2D, graphs in 3D, 2D surfaces embedded in 3D).

The wide range of spatial objects in a GIS is conceptually structured by level of detail; anybody can experience how one can zoom in on the world untill one sees only one's own front yard (e.g., in Google Earth)! We often conceive this as a hierarchy; however it is better to use a (mathematical)

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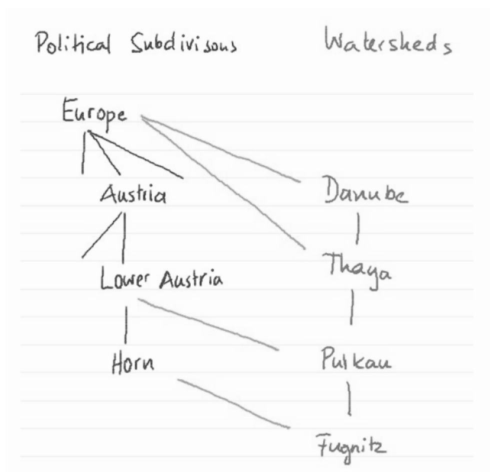
lattice structure [4, 5]. Political subdivisions are typically hierarchies (continent - country - province - county - town), as are watersheds (for example, the watershed of the Fugnitz is part of the watershed of the Pulkau, which flows into the Thaya, which goes to the Danube); if political subdivisions and watersheds are combined, the watershed of the Fugnitz is in the county of Horn, but the watershed of the Pulkau covers parts of several counties and is contained in the province of Lower Austria, whereas the watersheds of the Thaya and the Danube overlap several countries. Hence, a combined representation of the 'part-of' relation of the hierarchical structures of political and watershed subdivisions requires a lattice structure to handle the partial overlaps.



Requirement 2: Support for level of detail: a full or partial containment relation between geometric objects must be maintainable. Applications should be able to view and manage one or a few levels of detail without considration of other levels. Consistency constraints that connect between the levels are important.

GIS Applications show an approximated current state of what exists. The trend is toward including the temporal aspect and focusing on processes that occur in time and change the world[6, 7]. Processes, not states, are the focus of geography as a science [8, 9, 10]! This requires, first, that updates do not overwrite past states, but that time series of previous states are maintained. Tools to visualize and exploit such timeseries statistically and with data mining operations are needed. This requires, second, separately representable processes and the simulation of future states. Management of time series must be completed with representations of processes that can be calibrated with time series of observed past states and used to simulate future states, e.g., to predict unusual events in order to avoid them, preventing catastrophic results.

Requirement 3: Extend the fully general 3D geometry management with level of details to deal with time and processes[11]. The conceptualization of time should be very general and include continuous and discontinuous changes; it must support a lattice of partial containment relations and different temporal granularities.

These three seemingly simple requirements are, judging from past experiences, very difficult to fulfill. I therefore list here points on which I am willing to compromise:

- It is not required for the designed structures to be efficient or highly efficient (first, computer speed increases steadily; second, optimization of a working solution is often automatable).
- The representation does not need be compact, given the low prices of storage media; however, I fear that high redundancy introduces inconsistencies and increases program complexity [12].

I expect some of the current application areas to extend to 3D+T but also new applications enabled by support for 3D or time. The following examples can be used as tests for proposed approaches to see if these approaches are general enough to support all of them:

- Geology: models of the processes of deposit, folding, and erosion[13];
- Traffic management: cars moving along a street graph. Note the frequency of cars entering and leaving street segments and compare with the frequency of changes in the street graph [14]!
- Cadastral systems [15, 16]: Current systems manage a partition of 2D space that is changing in time. Requirements for 3D are emerging, and it is probably a 3D (volume) topology [17, 18];
- Flood protection: a system is needed to model water flow over a 2D surface embedded in 3D; note that water flow disappears from the surface and reappears somewhere else;
- Organization of pictures taken with a digital camera equipped with GPS having references to location in space and time;
- City planning: Visualize how the city grew and changed in the past and simulate the future;
- Disaster mitigation: models to predict the extension of a substance (e.g., oil or a hazardous gas) over a surface or in a volume under the influence of external forces (gravity, wind, water, flow).

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Chapter 24
Working Group II – Acquisition – Position Paper:
Data collection and 3D reconstruction

Sisi Zlatanova

3D Geographical Information Systems need 3D representations of objects and, hence, 3D data acquisition and reconstructions methods. Developments in these two areas, however, are not compatible. While numerous operational sensors for 3D data acquisition are readily available on the market (optical, laser scanning, radar, thermal, acoustic, etc.), 3D reconstruction software offers predominantly manual and semi-automatic tools (e.g. Cyclone, Leica Photogrammetry Suite, PhotoModeler or Sketch-up). The ultimate 3D reconstruction algorithm is still a challenge and a subject of intensive research. Many 3D reconstruction approaches have been investigated, and they can be classified into two large groups, optical image-based and point cloud-based, with respect to the sensor used, which can be mount on different platforms.

Optical Image-based sensors produce sets of single or multiple images, which combined appropriately, can be used to create 3D polyhedronal models. This approach can deliver accurate, detailed, realistic 3D models, but many components of the process remain manual or semi-manual. It is a technique which has been well-studied and documented (see Manuals of Photogrammetry, 2004; Henricsson and Baltsavias, 1997; Tao and Hu, 2001).

Active scanning techniques, such as laser and acoustic methods, have been an enormous success in recent years because they can produce very dense and accurate 3D point clouds. Applications that need terrain or seabed surfaces regularly make use of the 2.5D grids obtained from airborne or acoustic points clouds. The integration of direct geo-referencing (using GPS and inertial systems) into laser scanning technologies has given a further boost to 3D modelling. Although extraction of height (depth) information is largely automated, complete 3D object reconstruction and textures (for visualisation) are often weak, and the amount of data to be processed is huge (Maas and Vosselman, 1999; Wang and Schenk 2000; Rottensteiner et al 2005).

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Hybrid approaches overcome the disadvantages mentioned above by using combinations of optical images, point cloud data and other data sources (e.g. existing maps or GIS/CAD databases) (Tao, 2006). The combination of images, laser scanning point clouds and existing GIS maps is considered to be the most successful approach to automatically create low resolution, photo-textured models. There are various promising studies and publications focused on hybrid methods (Schwalbe et al, 2005; Pu and Vosselman, 2006) and even on operational solutions (see van Essen, 2007). These approaches are generally more flexible, robust and successful but require additional data sources, which may influence the quality of the model.

In summary, 3D data acquisition has become ubiquitous, fast and relatively cheap over the last decade. However, the automation of 3D reconstruction remains a big challenge. There are various approaches for 3D reconstruction from a diverse array of data sources, and each of them has some limitations in producing fully automated detailed models. However, as the cost of sensors, platforms and processing hardware decreases, simultaneous and integrated 3D data collection using multiple sensing technologies should allow for more effective and efficient 3D object reconstruction.

Designing integrated sensor platforms, processing and integrating sensors measurements and developing algorithms for 3D reconstruction are among the topics which should be addressed in the near future. Besides these, I expect several more general issues to emerge:

1. Levels of Detail (LoD). Presently, a 3D reconstruction algorithm is often created for a given application (e.g. cadastre, navigation, visualisation, analysis, etc.), responding to specific requirements for detail and realism. Indeed, 3D reconstruction is closely related to the application that uses the model, but such a chaotic creation of 3D models may become a major bottleneck for mainstream use of 3D data in the very near future. Early attempts to specify LoD are already being done by the CityGML team, but this work must be further tested and refined (Döllner et al, 2006).
2. Standard outputs. Formalising and standardizing the outputs of the reconstruction processes with respect to formal models and schemas as defined by OGC is becoming increasingly important. Currently, most of the algorithms for 3D reconstruction result in proprietary formats and models, both with specific feature definitions, which frequently disturb import/export and often lead to loss of data (e.g. geometry detail or texture).
3. Integrated 3D data acquisition and 3D modelling, including subsurface objects such as geologic bodies, seabed, utilities and underground construction. Traditionally, the objects of interest for modelling in GIS have been visible, natural and man-made, usually above the ground. As the convergence of applications increases, various domains (e.g. civil engineering, emergency response, urban planning, cadastre, etc.) will look towards integrated 3D models. With advances in underground detection

technologies (e.g. sonic/acoustic, ground penetration radar), already developed algorithms can be re-applied to obtain models of underground objects.

4. Change detection. Detection of changes is going to play a crucial role in the maintenance and update of 3D models. Assuming that automated 3D acquisition mechanisms will be available, the initial high costs of acquiring multiple data sources can be balanced and justified. Changes can then be detected against existing data from previous periods or initial design models (e.g. CAD). In both cases, robust and efficient 3D computational geometry algorithms must be studied.
5. Monitoring dynamic processes. The focus of 3D reconstruction is still on static objects. Although most sensors produce 3D data, hardly any dynamic 3D reconstruction is presently being done. Most dynamic software relies on geovisualisation tools (e.g. flood monitoring; Jern, 2005) for analysis and decision making.

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Chapter 25
Working Group III – Modelling – Position Paper:
Modelling 3D Geo-Information

Christopher Gold

3D geo-information can be thought of in several ways. At the simplest level it involves a 2D data structure with elevation attributes, as with remote sensing data such as LIDAR. The resulting structure forms a simple 2-manifold. At a slightly more advanced level we may recognise that the earth may not always be modelled by a planar graph, but requires bridges and tunnels. This 2-manifold of higher genus may still use the same data structure (e.g. a triangulation) but certain assumptions (e.g. a Delaunay triangulation) no longer hold. Finally, we may wish to model true volumes, in which case a triangulation might be replaced by a tetrahedralisation.

Each of these structures may be thought of as a graph - a set of nodes with connecting (topological) edges or links. Most workers in computational geometry, for example, would think in this way. However, because of the usual very large volume of geo-information the emphasis here has often been on (relational) data bases and their associated modelling techniques. More work is clearly needed on the integration of these two approaches. The discussion here uses the graph approach.

An example of a potential major application area is disaster management. This has become particularly relevant in the last few years, and the GIS response to this is very recent, as the 3D structures are not in place in commercial products. Latuada's (1998) paper on 3D structures for GIS and for architecture, engineering and construction (AEC) provides a solid summary of available structures and their different requirements. Briefly, there are surface or volumetric models and he suggests methods for combining 2D triangulations and 3D tetrahedralizations. Lee's (2001) PhD thesis correctly distinguished between the geometric and the (dual) topological structures necessary for building evacuation planning, but did not produce a unified

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data structure. Meijers *et al.* (2005), Slingsby (2006) and Pu and Zlatanova (2005) discussed the structuring of the navigation graph (using the skeleton or dual of the geometric graph) and the classification of the building 'polygons' (temporary walls, doors etc.)

While this research is very new, a few things emerge. Firstly, both primal and dual graphs are required. Secondly these graphs need to be modifiable in real-time (and in a synchronized fashion) to take account of changing scenarios. This implies a joint data structure (not a hybrid) where the two are fully combined. Thirdly, the structure should not be restricted to buildings (which have relatively well-ordered floors) but should apply to overpasses, tunnels and other awkward objects. The same model would apply to queries about fire propagation and flammability, air duct locations and air flow, utility pipes and cables, flooding and other related issues, where data is available. The model would also apply to other 3D applications such as geology, since the algebraic system expresses all adjacency relationships for complex 3D objects. While it is always technically possible to calculate a dual from its primal graph, it must be emphasized that this is often not ideal. Coordinates and other attributes may be lost, and the navigation in the one space will be easy, while in the dual it will become complex. The integration of the primal and the dual within the one data structure simplifies the number of element types necessary, permits the development of an appropriate 'edge algebra' (as is the case of the Quad-Edge in 2D - see Guibas and Stolfi, 1985) allows verifiable navigation, and assignment of appropriate attributes. (For example, the question: 'How do I get from this room to the next?' directly becomes: 'Give me the properties of the dual of this relationship - of the intervening wall or door.')

GIS is the integrating discipline/system for geo-spatial data from many sources for many applications. It is the natural context for various types of disaster management, route diversion, and flood simulation problems. It is basically a 2D system. Traditionally static, it may permit route modelling, and often include terrain models (TINs). It is a natural 'hub' for the import of various geographically-distributed data types - roads, polygon data, property boundaries, rivers etc. A major emphasis is on querying the attribute and geographic information.

While a good foundation, it does not include proper 3D structures - only 2D terrain models with associated elevations. Full 3D structures are needed for bridges, tunnels, building interiors etc. (N.B. recent work on extending TINs - the Polyhedral Earth (Tse and Gold, 2004) - has allowed bridges and tunnels, but only to give an exterior surface representation - not building interiors. This has been extended in Gold *et al.* 2006.) Thus in the long run, in an operational setting, 3D structures would need to be integrated within a commercial GIS. Zlatanova and Prosperi (2006) discuss the ongoing convergence between GIS and AEC, including the need for topological structures, as do Zlatanova *et al.* (2004)

The core requirement for volumetric models is the development and implementation of an appropriate 3D data structure so that the application may be run in the GIS context. The objective, as given above, is to have a real-time modifiable 3D data structure that integrates the primal and dual graphs, along with their attributes. This should be mathematically verifiable (an algebra) and implementable.

We may classify 3D data models into: Constructive Solid Geometry (CSG); boundary-representations (b-rep); regular decomposition; irregular decomposition; and non-manifold structures (Ledoux and Gold, 2006). Of these, b-reps and irregular decomposition models are the most relevant. B-reps model the boundaries of individual 2-manifolds (surfaces) as connected triangles, rectangles etc. but do not model the interiors. Well known b-rep data structures are the half-edge (Mantyla, 1988); the DCEL (Muller and Preparata, 1978); the winged-edge (Baumgart, 1975) and the quad-edge (Guibas and Stolfi, 1985). The quad-edge is distinctive in that it directly models both the primal and the dual graph on the 2-manifold, and may be expressed as an algebra. (It is often used to model Voronoi and Delaunay cells in the plane.) Irregular decomposition models (e.g. for constructing 3D Delaunay tetrahedralizations) may be constructed with the half-face data structure (Lopes and Tavarez, 1997); G-Maps (Lienhardt, 1994) and the facet-edge data structure (Dobkin and Laszlo, 1989). Half-edges and G-maps do not directly reference the dual structure (a property we need), and the full facet-edge structure appears never to have been implemented. Ledoux and Gold (2006) have proposed the Augmented Quad Edge (AQE) as a navigational structure, but construction operators are not yet fully defined.

These are all graph storage structures from Computational Geometry. Within the GIS community most emphasis has been put on identifying feature elements and specifying their storage in a database. The actual topological connectivity would usually be established after their retrieval into memory (Zlatanova *et al.*, 2004). A possible approach to direct storage of graph structures is suggested in (Gold and Angel, 2006), where they use a form of Voronoi hierarchy to store edge structures in 2D, with the proposed extension to 3D.

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Chapter 26
Working Group IV – Analysis – Position Paper: Spatial Data Analysis in 3D GIS

Jiyeong Lee

One of major challenging tasks of 3D GIS is to support spatial analysis among different types of real 3D objects. The analysis functions in 3D require more complex algorithms than 2D functions, and have a considerable influence on the computational complexity. In order to maintain a good performance, not only are the algorithms implemented efficiently, but also the 3D spatial objects are represented by a suitable 3D data model. However, it is a difficult task to select an appropriate data structure designed for the characteristics of the applications, for example, objects of interest, resolution, required spatial analysis, etc. (Zlatanova *et al.* 2004). A model designed for 3D spatial analysis may not exhibit good performance on 3D visualization and navigation. In other words, different data models might be suitable for the execution of specific tasks but not others. In order to maximize efficiency and effectiveness in the provision of operations, Oosterom *et al.* (2002) proposed multiple topological models maintained in one database by describing the objects, rules and constraints of each model in a metadata table. Metric and position operations such as area or volume computations are realised on the geometric model, while spatial relationship operations such as 'meet' and 'overlap' are performed on the topological model. However, it is necessary to find out whether the developed 3D data models are designed for 3D spatial analysis.

3D Grid-based data models are used to support 3D volume computations for the applications of environmental models, such as 3D slope stability analysis and landslide hazard assessment. A shortest path algorithm is also implemented for an un-indexed three-dimensional voxel space using a cumulative distance cost approach. This approach produces a set of voxels, such that each voxel contains an attribute about the cost of traveling to that voxel from a specified start point, if there is uniform friction of movement throughout the representation. The three-dimensional shortest path algorithm moves

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through the 'cost volume' along the steepest cost slope from target to origin using a 3 by 3 by 3 search kernel (Raper 2000). 3D topographic models combining 2.5D terrain models with 3D visualization systems are used for modeling noise (Stoter, *et al.* 2007) and odour contours, visibility analysis, line-of-sight analysis, and right-of-sunlight analysis in order to maintain a sustainable urban environment. The 3D city models in lower level-of-detail largely treat geographic features such as buildings as indivisible entities without internal partitions or subunits. Although the 3D topographic models have been developed and implemented for geo-science analyses and 3D visualization systems, they have some limitations with implementing 3D spatial analyses based on 3D topological relationships including adjacency, connectivity and containment.

The outputs of 3D topological analyses are in three forms: only retrieval of data for 3D visualization, the analytical querying of data once it has been structured in topological format, and the performances of spatial operations such as 3D route calculations, 3D proximity, etc. These topological analyses are relevant in applications where 3D models are extensively used such as earth sciences, geology, archaeology, chemistry, biology, medical sciences, cadastral and urban modeling, computer aided design and gaming.

In the applications, the analytical queries requiring identification of the topological relationships of adjacency and containment answer questions such as 'which regions are cut by a particular fault?', 'which Cambrian unconformities intersect Permian lime-stones?', which 3D buildings are in this 2D county boundary?', 'how many holes, or tunnels does the object have?', 'I am planning to build a tunnel of diameter X - what rock will the tunnel boring machine need to cut through?' and 'which 3D buildings will widening this road impact?' (Ellul and Kaklay 2006). In indoor location-based services to acquire indoor location information and to locate the position information into the 3D digital space using a map matching, the 3D topological queries are implemented to retrieve the context of a user's location to offer appropriate services.

The 3D spatial analysis based on 3D connectivity relationships among spatial entities within the urban modelling arena is performed to support emergency response systems. The applications require a network model through three-dimensional models of buildings for rapid determination of emergency exit paths. The network models present the topological relationships among 3D objects by drawing a dual graph interpreting the 'meet' relation between 3D and 3D objects. Such a structure might be quite powerful for calculations and visualization of 3D routing analysis and 3D topological queries (Lee, 2007). The 3D graph models are used for implementing 3D buffer operations in order to identify what is near features or within a given distance (Lee and Zlatanova, forthcoming). The 3D network models are used to define the network-based neighborhoods for 3D topological analyses in indoor space for analyzing human behaviors, such as an evaluation of neighborhood pedestrian accessibility.

Although many geospatial scientists have been interested in researching and implementing 3D spatial analysis in 3D GIS, a large amount of issues are still remained as challenging tasks in 3D geo-information analysis:

- Analytical 3D visualization to present knowledge on 3D geographic data;
- Analytical queries by identifying the topological relationships (adjacency, connectivity and containment) among combinations of 0, 1, 2, and 3D objects and between complex objects;
- Topological analytical functions including overlay and intersection analyses between two 3D, 2D, 1D and 0D combinations;
- 3D navigations through 3D indoor environments to support emergency response operations and urban modeling;
- 3D buffering and selections based on topological relationships among combinations of 0, 1, 2, and 3D objects and between complex objects.

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Chapter 27
Working Group V – Visualization – Position Paper:
3D Geo-Visualization

Marc van Kreveld

Due to new data collection techniques, more data storage and more computing power, we can make and visualize 3D models of the world. However, the quality and interaction capabilities of these reconstructions are limited. It may be only a matter of time until high-quality visualizations with walk-through and other interactive possibilities are developed. Some of the applications that can benefit from 3D geo-visualization include city architecture, landscape planning, soil analysis, geology, groundwater analysis, and meteorology.

3D visualization can be used for schematic representation of a geographic region in the style of a traditional map, but with an added 3rd dimension of space, for example, a topographic map draped over a digital elevation model. To get a visually pleasing 3D topographic visualization, 3D map objects are needed, such as 3D symbols and 3D labels.

Above-the-ground 3D data can be obtained by laser altimetry. Below-the-ground 3D data is obtained using bore holes and by several other techniques. Sometimes, data is sparse and errors may exist. For the advancement of 3D visualization, we must consider:

- how to visualize the original data,
- possible reconstructions into 3D models, and
- the uncertainty in these models.

A related question is how best to visualize data so that obvious errors can be detected and removed.

Other questions of interest to future research in 3D geo-visualization are the following:

- What is the role for animation and geo-exploration in 3D geo-visualization?

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- What 3D visualizations are effective for various purposes, like geographical 3D data analysis, and illustrative summaries of 3D geographic data?
- How should we visualize patterns that are found by spatial data mining in 3D geo data sets?
- What computation is needed for 3D visualization, and how can we do it efficiently?
- Can ideas from the graph drawing research community be used in 3D geo-visualization?
- Can ideas from the visualization research community be used in 3D geovisualization?
- How exactly should 3D dynamic/temporal visualization be done(processes, developments,...)?
- What is the best approach to the handling multiple levels of detail (e.g. smooth transition between levels)?
- Is the application of schematic abstract 3D representations possible (in a way similar to the 2D maps)? Note that this is quite different from a visualization that maximizes the realistic impression.
- How should 3D thematic maps be created (e.g. air quality, salinity of ocean, etc.)?

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