Developing 5D spatial models for GIS

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Real-world phenomena have traditionally been modelled in a GIS in two and three dimensions. However, powerful insights can be gained by the integration of additional non-spatial dimensions, such as time and scale. While the integration of different dimensions into a higher-dimensional (hyper)cube is theoretically sound, its implementation is problematic since the data models and data structures used in the GIS world are not appropriate. This paper discusses the use of *G-maps*, one feasible data model/structure to represent 3D space+time+scale as 5D data, and proposes a specific implementation that is tailored to the needs of GIS.

1 Introduction

Spatial data modelling refers to the development of abstract mathematical representations of objects embedded in space (see Lienhardt [1991] and Burrough [1992]). Spatial models were developed largely independently in the disciplines that required them, including computer graphics, computer-aided design (CAD), geology, and geographic information systems (GIS) [Frank, 1992]. Because of their independent creation, they are a reflection of the idiosyncrasies of their domains and differ significantly in key issues (e.g. the types of geometries and singularities that are allowed, or whether they keep track of topology). One consequence of this is that in many fields support for 3D data has been long widespread and the theoretical foundations for higher dimensions are well established. In contrast, good GIS support for 3D data is a relatively recent development, while higher-dimensional GIS are in most cases a theoretical discussion, and when implemented, is usually limited to point data.

This limitation is not however due to a lack of applications in higher dimensions. While being limited to 3D space is acceptable to many users of geographic information, substantial work has been done regarding the integration of non spatial-dimensions to spatial data models, either by creating specific models for these non-spatial dimensions, or by treating them as spatial ones [Raper, 2000]. The latter approach is discussed in this article, integrating space, time [Peuquet, 2002; Worboys, 1994] and scale [van Oosterom and Meijers, 2011; Li, 1994], to form objects in 5D space (5D polytopes) [Stoter et al., 2012]. However, this approach is independent of the specific dimensions that are used.

Since there is both a need for higher-dimensional GIS, and an availability of representations developed in other fields that are able to support higher-dimensional data, there is great potential in adapting these representations to the specific needs of GIS data, and developing useful operations to manipulate these 5D objects. As a first approach, I have chosen to use a boundary representation based model, specifically *generalised maps* [Lienhardt, 1994], also known as G-maps. Other alternatives will be considered later on, such as simplicial complexes, convex polytopes, Constructive Solid Geometry (CSG) or Nef polyhedra. Boundary representation involves storing the objects as-is, and G-maps have the advantage of having been implemented in 3D (it is used in GOCAD[1] for geological modelling and in Moka[2] for geometric modelling), and of being proven to be able to represent a wide class of objects. An overview of G-maps, their properties, and an implementation apt for 5D objects is given in Section 2. Finally, I elaborate on the advantages of this approach and discuss future work in Section 3.

2 Implementing G-Maps For GIS

Generalised maps (G-maps) are an ordered topological model developed by Lienhardt [1994] based on the concept of a combinatorial map, also known as a topological map, which was described by Edmonds [1960]. They are able to represent a wide class of objects known as cellular quasi-manifolds.

Intuitively, a G-map is composed of two elements: a set of *darts*, each of which is defined by a unique combination of a specific n-cell from every dimension, and are often represented visually as half-edges or oriented edges; and *involutions* (α), bijective operators connecting darts that are related along a certain dimension. In this manner, α_0 joins vertices to form edges, α_1 connects consecutive edges within a face, α_2 connects adjacent faces within a volume, and so on.

The aforementioned elements represent the combinatorial structure of a generalised map. However, to represent the geometry of the model, an additional *embedding* structure is used. If only linear (flat) geometries are required, only the 0-dimensional point

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[1] `http://www.gocad.org/`

[2] `http://moka-modeller.sourceforge.net/`

embeddings are actually needed. These store the coordinates of each vertex.

G-maps can be considered more of a data model rather than a data structure Frank [1992], and thus there are many possible different implementations that can be made based on them. For instance, a minimal data structure that stores the combinatorial aspect of an n-G-map could involve a single type of object, a dart with $n+1$ pointers to other darts representing its involutions. However, another option could be to have a set of involutions that store the identifiers of the two darts that each of them link (e.g. in a NoSQL-style database[3]).

Nevertheless, these data structures do not support many of the characteristics of GIS data. Namely, an implementation for use in GIS requires: storing geometry at least at the vertex level, storing attributes possibly at every level (vertex, edge, face, etc.), a possibility to construct a G-map both from topological and non topological data, the ability to support geometric and topological queries, storing holes in possibly every dimension larger than zero, and keeping track of disconnected cells.

Therefore, I propose a specific model based on G-maps which is able to handle these issues. A base embedding structure is specialised with the attributes that are required for each dimension, such as point coordinates for vertices, textures for faces, or whether an object is visible or not for a solid. Additionally, links are kept between the combinatorial and geometric structures, so as to support mixed queries. Markers are kept to support concurrency and efficient access. Finally, a spatial index keeps track of non manifold configurations and disconnected objects. The result of such a model is shown in Figure 1.

3 Discussion

Using a model that integrates both spatial and non spatial dimensions by treating them as spatial ones brings several advantages, such as reducing redundancy, increasing consistency, and allowing for mixed queries along all dimensions. The generality of such a model also makes it possible to add additional application dependent dimensions, and is a strong base for future GIS. For instance, it would allow for 4D/5D topology queries, as in the example shown in Figure 2.

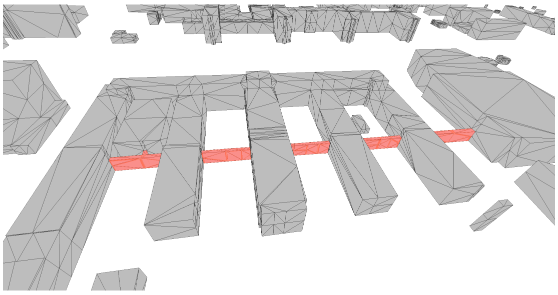

Figure 2: A new corridor linking several buildings of the TU Delft campus is built. Using 4D (3D space+time) topology, it is possible to compute the shortest path between any two points at any point in time.

In the future, I plan to work on the operations that make it possible to easily create and manipulate higher dimensional GIS objects, as well as to bring these down to 2D/3D for visualisation purposes. These two or three dimensions could be any combination of space, time and scale.

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[3] `http://www.strozzi.it/shared/nosql/`

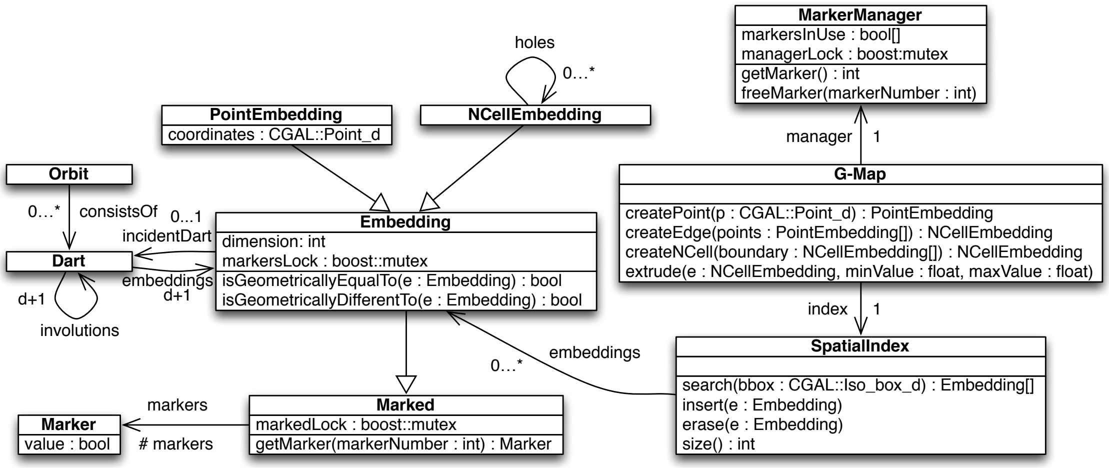

Figure 1: A prototype model of G-maps for GIS

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