A Unified 3D Spatial Data Model for Surface and Subsurface Spatial Objects*

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Abstract

Three Dimensional (3D) spatial modelling is an abstract representation of reality using mathematically proven relationships defined as points, lines, polygons and solids to represent man-made and natural features above, on and below the surface of the earth. 3D topology is the interrelationships existing between these objects to enable visualization, query and analysis. 3D modelling of subsurface objects and their integration with the surface and above surface objects currently lags behind despite efforts of researchers and the attempt at viewing above, surface and subsurface man-made objects for earth realism. Level of Details (LoD) for spatial objects has been extensively studied. However, these have not been extended to man-made features below the surface. LoD maps for surface and subsurface integration exist for most city centres but the 3D component is lacking and this does not enhance the Level of Realism (LoR) in most city centres. Knowledge about the surface and subsurface 3D objects for city centres, mining and 3D cadastre will create awareness among stakeholders for effective planning of a city or mine. This paper provides a discussion for 3D surface and subsurface integration. Various 3D spatial data models currently in existence for the integration of surface and subsurface models are discussed and a geometric, topological 3D object oriented model is suggested. A UML diagram for the top hierarchy class is presented and a conceptual and logical model for surface and subsurface integration is also discussed. A simulation of the above, on and below 3D spatial models for man-made constructions at different LoDs is presented. A simulation of this with regards to mining and cadastre is also presented. The model presented can be adopted in realising 3D GIS for mining and 3D cadastre can be realised in Ghana. Further work is geared towards 3D spatial analysis for such an integrated model.

1 Introduction

Spatial objects are features that can be located on the surface of the Earth by way of geographic coordinates such as latitudes, longitudes or by way of national coordinates which are in Northings (X) and Eastings (Y). These spatial representations are Two Dimensional (2D) and have been described as having unique qualities, since ideally no coordinate pair can represent two different features on the surface of the Earth. There are several limitations to Two Dimensional Geographic Information Systems (2D GIS) representations: users see feature objects (man-made or natural) in 3D, visualise the same feature objects as points, lines and polygons on maps. 2D GIS is a knowledge based tool through topology which establishes interconnectedness between the various geometric primitives such as points (or nodes or vertex), lines (arcs or segments or edges) and polygons (areas or faces) together with their semantic properties. The visualisation of feature objects in their real form is the basis of 3D GIS. With the introduction of height (Z) above sea level, features can be realized in 3D, users could also visualize 2.5D in relation to the Earth's surface, this forms the Digital Terrain Model (DTM). 3D spatial data can be in two forms, vector and raster data. 3D object primitives are expressed as node (point or vertex), line (arc, segment, or edge), face (surface or triangle) and body (volume or solid) geometries and have been assigned a zero-dimensional, one-dimensional, two-dimensional and three-dimensional respectively. An edge is a straight line comprising of two nodes, a face or surface will have 4 or more edges for a square or polygon or three edges in the case of a triangle and a solid will be bounded by faces such as six faces in the case of a cube. Edges, faces and solids may be aggregated to Curve-Geometries, Surface-Geometries and Solid-Geometries respectively (Kolbe and Groger, 2003). These primitives usually define the spatial characteristics of 3D objects. Fig. 1 shows the spatial primitives of 3D objects.

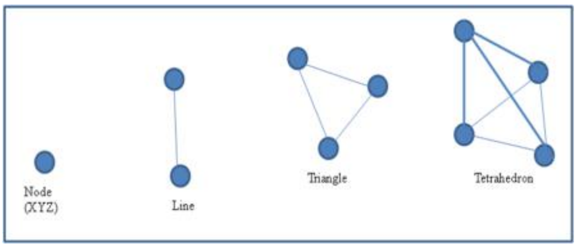

Fig. 1 Spatial Primitives of 3D Objects

The spatial primitive's node, line, triangle and solid (tetrahedron) and the aggregates must satisfy a number of integrity constraints which guarantee consis-

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tency of the model. The interiors of the primitives must be disjoint and if two primitives touch, the common boundary must be a primitive of lower dimension (Herring, 2001). Clean topology is assured when these constraints are adhered to and these ensure the condition of no redundancies. Solids are therefore disjoint and the computation of volumes of solids will not yield wrong results should solids overlap. Fig. 2 shows the formal definition of the LoDs by the Open Geospatial Consortium (OGC, 2009b).

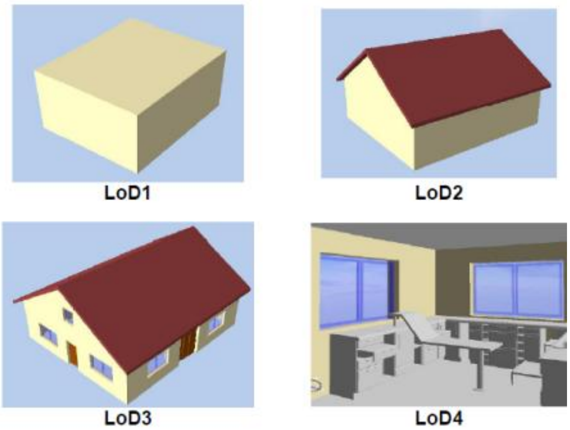

Fig. 2. LoDs as defined by OGC, 2009b.

GIS 3D models can be categorized in four ways: volume-based models, surface based models, hybrid models and vector based models. For volume-based models the smallest unit for 3D objects is the voxel, this is in the raster environment, hence a 3D object is composed of a set of voxels, examples of this include: Octree, 3D array and Construction Solid Geometry (CSG) (Samet, 1990). Surface-based models consist of a set of facets; examples of these include: boundary representation, shape and grid among others (Li, 1994). A hybrid model is the integration of volume based and surface based models, examples include: CSG and Octree (Li, 1994), TIN and Octree (Shi, 1996) and TEN and Octree (Li and Li 1996). Vector based models are based on the coordinate (XYZ) as the basic primitive in the form of a node and this has been adopted in many models for 3D GIS; examples include: Formal Data Structure (FDS) (Molenaar, 1990), Tetrahedron-based model (TEN) (Pilouk, 1996), and the Simplified Spatial Model (SSM) (Zlatanova, 2000). Fig. 3 shows some of these object representations for 3D GIS.

For the surface representations the grid is generally applied in GIS, digital terrain modeling (DTM) where height values are specified at regular intervals such as in a square, rectangular or hexagonal grid. DTM has been used to represent terrain features in various instances as reported in Petrie and Kennie (1990) for irregular data. The regular data representation was found to be not honouring some terrain

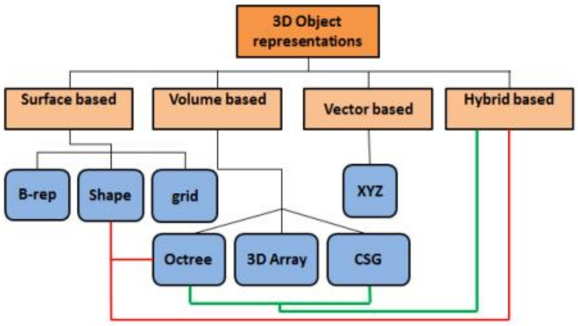

Fig. 3 Object Representations for 3D GIS

features such as embankments and overhanging walls. The shape model uses a value such as slope to replace the z value for the surface points for regular and irregular data points. Abdul Rahman and Pilouk (2008) reported this approach as having the same capability as the grid. The facet is a surface that is basically described as 2D Triangular Irregular Network (TIN) with the nodes having X, Y, Z coordinates. The Boundary representation forms objects such as edge, face and volume using the node as the geometric primitive. This research will focus on vector based data to achieve its goals: to suggest a new unified spatial data model capable of showing man-made constructions above and below the surface of the earth and to show the applicability of such a model for 3D cadastre and mining.

2 3D Cadastre and Mining

Most cadastral registration systems are parcel based systems, which are 2D, e.g. the Swedish cadastre (Ericsson, 2008), the Danish (Jorgen, 2004) cadastre and the catasto-cumini cadastre of Italy (Anon, 2005). Most of these cadastres use 2D GIS with aerial photographs and satellite imagery to build their database. Currently 2D cadastre mapping practiced in Malaysia provides vital land and property information like ownerships of the parcels. This system of cadastral information has served most of the users need for decades. However, in the very near future, 2D information may no longer be able to serve the community, especially in more complex situations such as buildings above roads in some large cities and towns such as Kuala Lumpur. One way to deal with this situation is by having a more advanced cadastral system like Multi-Purpose Cadastre (MPC). This means we need to extend the 2D cadastre system into a system that is able to deal with various aspects of cadastre such as 3D cadastre (Stoter, 2004), 3D marine cadastre, and 3D city models (Abdul Rahman *et al*, 2005). Several drawbacks from existing cadastre system such as building footprints, are hardly available within cadastre parcels, strata information is hardly linked to the stratum, real 3D buildings with proper and real textures are not available within the parcel lots and the associated database non-existent. The MPC could provide the relevant information to various agencies such as the land related and mining companies in the country. Fig. 4 shows the LA_Spatial Unit (Anon., 2009a) as proposed in the Land Administration Domain Model (LADM) which does not include spatial objects for space above and below the surface.

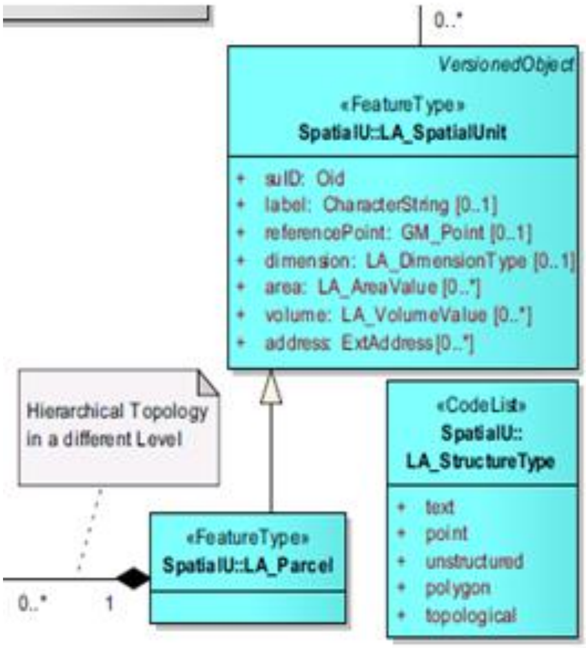

Fig. 4 LA_Spatial Unit in the LADM Model (Inan *et al*, 2010)

Abdul Rahman *et al.*, (2011), enumerated the need for MPC to embed above surface objects and underground structures. Current cadastres have employed CAD software, GIS and database in creating various systems but have not been able to sustain a fully developed system, hence user defined algorithm is required to expand the multipurpose cadastre to consider the above and below surface parcels. Mensah *et al.*, (2010) suggested a hybrid form of cadastre representation which involved using Global Positioning Systems (GPS) receivers for spatial and pictometry techniques, using a high resolution camera, for image data collection. This technique was aimed at solving problems with speculative developments which are currently prevalent in mining areas. The technique is likely to introduce problems: processing of large data, standardization and accuracy, training issues (Principles of Pictometry) and data for subsurface objects.

3 Surface and Subsurface Integration

Surface and subsurface unified models have been studied by many researchers (Abdul Rahman and Pilouk, 2008; Wang, 2006; Breunig and Zlatanova, 2006 and Zhou *et al.*, 2008). Principle in their research was enhanced forms of 3D FDS for 3D objects using 3D spatial data for both the surface and the subsurface. Molenaar (1990) proposed the 3D FDS for 2D GIS and this concept has been enhanced and made applicable by researchers for 3D GIS. This model has the point, line, surface and body as the entity object (see Fig. 5). An enhanced data model of the 3D FDS has been studied by researchers such as the 3D Triangular Irregular Network (3D TIN) by Abdul Rahman (2000), Simplified Spatial Model (SSM) by Zlatanova (2000), Object Oriented Data Model (OODM) by Koshak and Flemming (2002), Object Oriented 3D (OO3D) by Shi *et al.*, (2003), Urban Data Model (UDM) by Coors (2003) and the Object Oriented 3D Integrated Spatial Data Model (OO3D-ISDM) by Wang (2006). The current integrations for surface and subsurface involve 3D objects above or on the surface with geology at the subsurface.

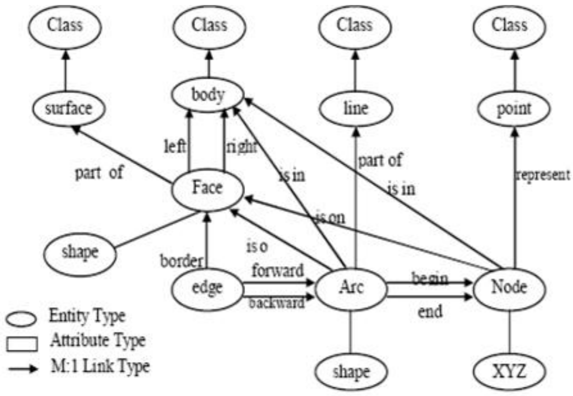

Fig. 5 The Formal Data Structure (3D FDS) (Molenaar, 1990)

Although stand–alone subsurface 3D models have been investigated and implemented (Raper, 1989; Raper and Maguire 1992; Latuada, 2006; Hack *et al.*, 2006; Apel 2006; Breunig and Zlatanova 2006; Tegtmeier and Zlatanova 2009), it is yet to be integrated with the on and above surface scenarios. Subsurface objects currently being understudied are in the areas of geology, hydrogeology, geotechnical, oceanography and geophysics. These deal with natural objects such as the spatial distribution of three-dimensional (3D) continuous geological stratigraphy, borehole information and ore modelling of a mineral underground. These feature objects are referred to as fields whilst the object view approach considers the space as being 'empty and populated with discrete entities such as buildings, roads etc (Ledoux and Gold, 2008). Most of the research carried out for subsurface 3D models have been to model the natural subsurface: Abdul Rahman (2000) used the 3D TIN for drillhole locations.This idea was extended by Wang (2006). Breunig (2001) carried out extensive research on geological bodies (GeoToolKit) using the TEN model. Tegtmeier and Zlatanova

(2009) implemented the simplex concept for subsurface geotechnical consideration. Zhou *et al*, (2008) also used the cell complex and implemented the model for geology. The OO3D-ISDM spatial data model was used for the integration of city objects and drill hole data based on the concept of 3D TIN. Wu and Shi, (2004) proposed a spatial data model based on G-GTP and E-GTP the generalized tri-prism (GTP) for geosciences applications, this model basically also uses the idea of 3D TIN to implement the models. The cell complex which is an enhanced concept from 3D TIN was applied as an integrated model in the area of city objects and geology (Pigot, 1992 and Zhou *et al*, 2008). All the models above have been used for subsurface natural feature applications. Standards such as CityGML, GeoSciML and Industry Foundation Classes (IFC) has been developed for 3D spatial artificial and natural features above and below the Earth's terrain, these features have not been integrated due to challenges in geometric, topologic and semantic heterogeneities.

4 Concepts for Integration

Various researchers have enumerated the need to integrate man-made objects for both the surface and subsurface (Emgard and Zlatanova 2008; Zhou *et al*, 2008; Ledoux and Gold, 2008; Zlatanova, 2008; Gold, 2008). Concepts from current data models (Abdul Rahman and Pilouk, 2008; Wang, 2006 and Wu and Shi, 2004) which investigated models for above, on and below surface objects basically for geology, can be extended to include man-made objects for the subsurface. Slingsby and Raper (2007), enumerated the need to link models of objects with the terrain. A hybrid of these concepts forms the basis of this research. Most 3D objects in modern cities have subsurface objects such as underground rail systems or tunnels or utility lines. Current city models are integration of above and on surface applications. Researchers have been trying to bridge the gap between 2D, 2.5D and 3D GIS for surface feature objects but this can be enhanced by looking for the 'missing link' between surface and subsurface 3D models for man-made objects and not for geosciences applications only. In an area populated with 3D objects such as a mining town with underground facilities, knowledge about underground features which includes man-made constructions and geology and its surface and above surface 3D objects, will help in locating evacuation and emergency exits should disaster occur.

An enhanced 3D TIN model is proposed for the unified model, this seeks to combine 3D TIN with the solid being formed by tetrahedrons or polyhedrons. This presents topology as a solid composed of tetrahedrons, surface composed of triangles, a line is composed of arcs and points are also nodes. The unified geometric-semantic model as shown in Fig. 6.

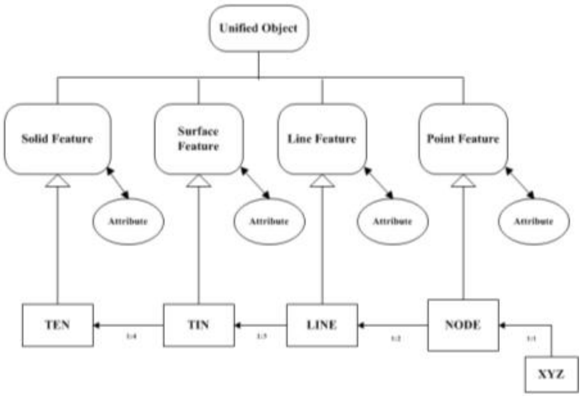

Fig. 6 3D Unified Object Model

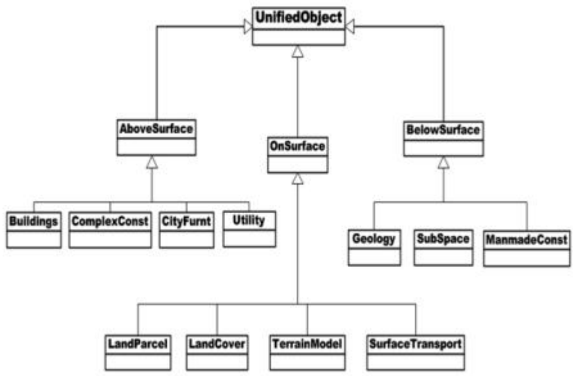

Fig. 7 A UML Diagram for the top classes in 3D Objects

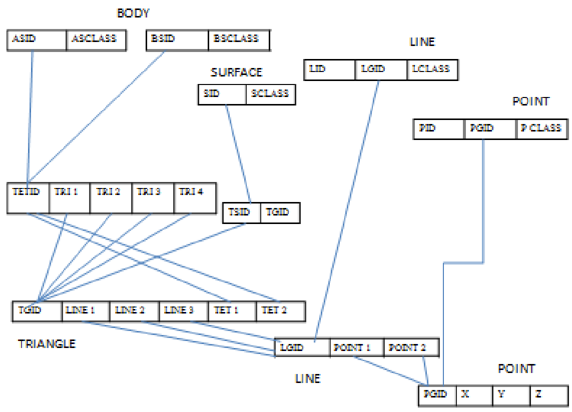

Fig. 8 Logical Model for 3D Objects

Above surface objects include buildings and city furniture which could be made up of trees, lamp posts etc. On surface objects are composed of the terrain model, land use and land lots or parcels. Objects below the surface will constitute geology and man-made objects such as parking areas, storage facilities, tunnels, rail lines, basements etc. Buildings are 3D objects above the surface, humans and other living things use above surface objects as places of abode, work, storage, car parks and for other activities. A building consists of facades from all the sides, the roof and its footprint which intersects the terrain model and can be represented from LoD0 to LoD4 as described by Kolbe (2009). Fig. 7 is the Unified Modelling Language (UML) diagram for the top object classes for the 3D object model, and Fig. 8 is the logical model for the conceptual model adopted.

5 Simulation for 3D Objects

Implicit geometry is used to form the nodes with appropriate identifiers, the line identifier will have a beginning node and an ending node with the topological relationship of is on, is in, point and solid, line and solid, line and surface, point and surface being used to form the relationship for the unified model. The tetrahedron is formed by four nodes, six lines and four triangles, to form solids (see Fig. 1) for both the surface and subsurface. Six regular tetrahedrons form the basic cube which is the basic volume primitive in 3D GIS. The methodology adopted in achieving the frameworks discussed, was the development of codes using Microsoft Visual C++ version 2010 and OpenGL and Qt libraries as the graphical user interface (GUI), the workflow for the simulated data is shown in Fig. 9.

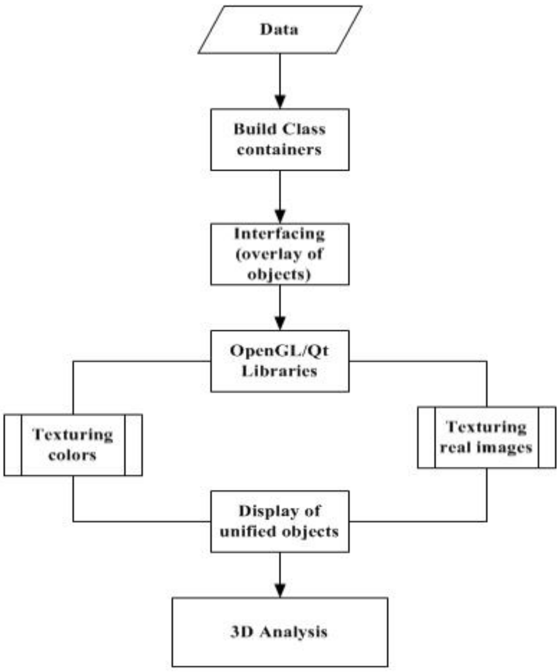

Fig. 9 Workflow for the Unified Model

The merit of such an algorithm is that no special equipment is required as these data sources already exist in the form of AutoCAD data, orthophotos, orthoimagery, GPS data, mine data and data from Light Detection and Ranging (LIDAR) equipment. Texturing is the technique of increasing the Level of Realism (LoR) of 3D objects which requires Photogrammetry in the capture of the appropriate images of the various components of a building such as window type, colour type etc to make images real. In this research texturing using colour codes was adopted to the 3D objects.

5.1 Results and Discussions

The unified model for a complex man-made construction in LoD1 (see Figure 2) is modelled. Figure 10a is the original building located in Malaysia and Figure 10b is the complex building with a road under the building and a below subsurface man-made construction such as a rail system. This is a complex cadastral problem as it raises questions such as who owns the flats above the road? Who owns the land parcel under the road? What are the tax liabilities of these owners? What is the size of cavities created or occupied beneath the surface by mining companies? What are their liabilities? The unified model can provide answers to such queries.

Fig. 10a Snapshot of Original Building (Hassan and Abdul Rahman, 2010)

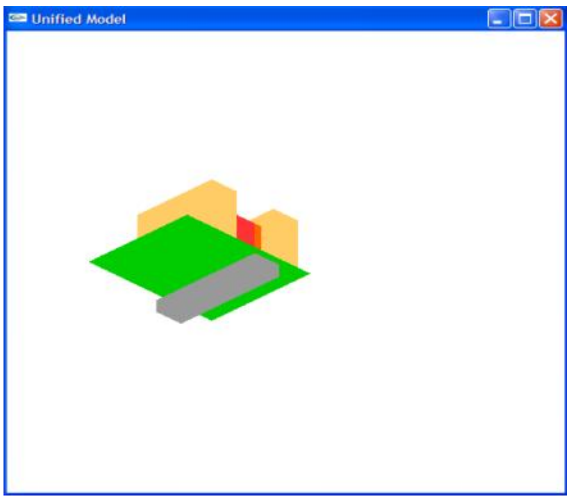

Fig. 10b 3D Unified Object

6 Concluding Remarks and Further Work

3D TIN has been adopted as the underlying model for most of the models used for the subsurface. The concept for a new unified model seeks to integrate above surface objects and below surface geology and man-made objects. The UML diagram seeks to show the conceptual model followed by the logical model which can be implemented in a database such as Oracle 11g. If this model is adopted, a whole district or town where mining is intensive could be monitored constantly to avoid disaster in the area. The underground mine works cuts across a lot of surface parcels within the mining area.

The unified model will be improved in the areas of 3D topology and 3D analysis. Real textures to show the combination of LoD3 for above surface and LoD4 for below surface objects is on-going. An algorithm to fully integrate the above framework in a database will be part of the next phase of this research. Finally the applicability of the model generated will be applied in the areas of 3D analysis for 3D buildings, 3D cadastre and a direction for the implementation of this model for a 3D mining model will be presented.

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