Research and Practice in Three-Dimensional City Modeling

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Abstract The way we interact with spatial data has been changed from 2D map to 3D Virtual Geographic Environment (VGE). Three-dimensional representations of geographic information on a computer are known as VGE, and in particular 3D city models provide an efficient way to integrate massive, heterogenous geospatial information and georeferenced information in urban areas. 3D city modeling (3DCM) is an active research and practice topic in distinct application areas. This paper introduces different modeling paradigms employed in 3D GIS, virtual environment, and AEC/FM. Up-to-date 3DCM technologies are evolving into a data integration and collaborative approach to represent the full spatial coverage of a city, to model both aboveground and underground, outdoor and indoor environments including man-made objects and natural features with 3D geometry, appearance, topology and semantics.

Keywords 3D city model; multiscale representation; 3D data acquisition; integrated database management

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Introduction

More and more online tools, led by the Google Earth virtual globe, are dramatically changing the way we interact with spatial data from 2D map to 3D virtual geographic environment (VGE)[1, 2]. Up to now, three-dimensional representations of geographic information in computers are known as VGEs, which are of increasing importance in urban areas and provide us more accurate and flexible mathematical models, effective tools and user interface for geospatial communication. This paper therefore focuses on the creation of 3D virtual city environment which provides essential information for different aspects of urban life, from professional to public. There are two kinds of virtual worlds, the mirrored world and imaginative world[3]. Herein, only the mirrored virtual city, i.e., the replicas of the real physical city, is considered. The creation of a uniform, seamless conceptual and technical geospatial information framework of such kind of virtual city is known as 3D city modeling (3DCM). Because buildings can no longer be considered in isolation from one another, or from the transportation and provisioning systems that support them, 3DCM must provide permanent, evolving and completely integrated models of our cities, which can form the basis for urban planning, operational decision making, and response to everything from terrorist attacks to threats to environmental security. Different from the computer-based simulated imaginative virtual city, not only the photorealistic appear-
People’s recognition of an urban built environment is no longer constrained to the 2D planar or 2.5D surface world. There is an increasing need for intuitive 3D-descriptions of urban areas in various applications such as urban planning, emergency response, environment or microclimate investigation, as well as game (meaning the ability to simulate and to interact with the 3D virtual world in the same manner as one interacts with the real world - with the same physical constraints and dynamics). While significant progress has been made in processing 2D data, and numerous solutions to rapid 3D visualization are also available, the acquisition, management and analysis of 3D data remains a major challenge. It is urged to enhance the technologies to improve accuracy, resolution and detail of 3DCM as well as the lower cost and higher efficiency.

This paper is organized as follows: after introducing the multidimensional characteristics of 3DCM, up-to-date technologies such as data acquisition and database management are presented and analyzed. Finally, several practical examples are illustrated to support the conclusion with thoughts on the future prospects.

1 Three-Dimensional city models

The 3D city model is a 3D representation of the urban area in computer compatible form (geometry and semantics), and focuses on common urban objects and structures. According to the investigation of the Organisation Europeenne d’Etudes Photogrammetriques Experimentales (OEEPE), aboveground city objects of interest in general include buildings, traffic network, vegetation, waterways and public utilities\(^4\). At present, both the underground objects such as the geological formations, utilities and construction, and interior facility objects within buildings are demanded to be modeled and analyzed.

According to the geometrical elements of 3D city models, the 3D data hierarchy/complexity can be described as follows:

1. 2D digital orthoimage map (DOM), the texture of terrain surface, multiresolution DOMs from high resolution satellite imagery to aerial imagery provides the real world details and offers a time stamped record of land use, urban development and the general environment;
2. 2.5D DEM, a digital representation of ground surface topography or terrain, is the most common foundation of 3D city models;
3. 2.5D linear elements, the boundaries or centerlines of road, rivers, railways and landuse, represent the outline of an object;
4. 3D solid objects, external and/or internal surfaces of buildings, bridges overpasses, pipelines, stratum, etc., represent the entire volume of an object.

For geometrical purpose, only the point clouds may be enough, but the topology needs a line model, while surface and body model for semantics.

Different modeling paradigms are employed in 3D geographical information systems (3D GIS), computer graphics, architecture, engineering, construction, and facility management (AEC/FM). Whereas in 3D GIS the focus is put on the management of multi-scale, large area, and geo-referenced 3D models, the AEC/FM domain addresses more detailed 3D models with respect to construction and management processes, and computer graphics are rather concentrated on the visual appearance of 3D models\(^5\). A common information model named CityGML is available as candidate OpenGIS implementation specification for a multi-purpose and multi-scale representation for the storage of and access to 3D city models, including their semantic properties (http://www.citygml.org/). Spatial and semantic properties are structured in five consecutive levels of detail (LoD), where LoD0 defines a coarse regional model and the most detailed LoD4 comprises building interiors resp. indoor features. CityGML is still on the way to perfect a common definition of the basic entities, attributes and relations that can be shared over different applications.

Aiming at the limitation of existing road network models based on the 2D link-node of roadway centrelines for lane-oriented network flow analysis and multi-dimensional inventory management in complicated 3D urban environments, a hierarchical lane-
oriented 3D road network model (HL-3DRNM) is now available[6]. HL-3DRNM is a non-planar topological model with the support of 3D lane topologic elements and lane ribbon polygon features.

Aiming at the increasing critical issues of existing 2D plans and map-based methodology for integrated management of advanced buildings and related dynamic property rights in complicated 3D built environments, a semantics-based 3D dynamic house property model with hierarchical levels of detail is proposed[7]. This model provides an integrated representation of 3D geometry, topology and semantics of both house and property rights.

2 Multisource and multiscale 3D data acquisition

The latest technology developments clearly show the improvement (resolution and accuracy) in 3D data collection techniques: aerial and close range photogrammetry, airborne or ground-based laser scanning, mobile mapping and GPS surveying[8]. Even 3D scanners are becoming a standard source for input data in many application areas, but image-based modeling still remains the most complete, economical, portable, flexible and widely-used approach[9]. However, there are still big obstacles to current 3D city model reconstruction from map, point clouds and imagery, such as the manual correspondence or extensive computation for texture mapping. Therefore, a lot of researches have been conducted toward the automation of 3D object reconstruction[10].

3D city models have become one of the most important and attractive products of photogrammetry and remote sensing. These models comprise the topologic and geometric information of urban features. At present, the fully automatic production of DEM, DOM and specific building models with rectilinear shapes and flat roofs give a significant boost to the 3DCM. However, the photogrammetric reconstruction of complicated objects with various forms and shapes still faces the problems including image understanding, automatic control of LoD and topology generation[11]. Above all, we have to think about more efficient semi-automated approaches for practice. Commercial digital photogrammetric systems assist the human operator in measuring 3D objects in combination with the registration of attribute data in a semi-automated mode.

Recently, airborne or terrestrial LIDAR has become a rather important information source for generating high quality digital surface models (DSMs). It offers an accurate, expedient and cost-effective way of capturing wide-area elevation information to produce highly detailed DSMs. It contains vast amounts of information like buildings, trees, streets, streams and so on. Planar faces are detected reliably in laser data. Laser scanning techniques depend on point density due to its poor quality on the object edge. Because of the complementary characteristics of laser scanning data, photographs and GIS maps, by integrating knowledge from the images and the GIS map, the complexity of the building reconstruction process can be reduced, and the modeling tools for combined measurement processes in laser scanning data and imagery or map are to be developed[12].

Because of the inability of photogrammetry and remote sensing technology in the reconstruction of the underground utilities and indoor facilities, 3DCMs require data from a number of different domains, such as building information models (BIM) and the CAD models. Even the aboveground data-collection techniques have progressed from manual measurement to remote sensing and photogrammetry, but the difficulties in surveying underground geologic structure and sub-surface constructions are very distinct. Boreholes, cross-sections, geological maps and seismic data are, therefore, the main data sources for 3D geological modeling, and the best effort is to develop new algorithms to model the sub-surface geometry and properties (http://www.gocad.org).

On the other hand, the fidelity requirements of different objects are dramatically different. Modern digital photogrammetric systems, LIDAR and CAD enable an efficient recovery of 3D surface details, and generate the models with architectural details and roof morphology. The fully textured buildings present a real challenge because of the amount of data that can be visible in a single scene. To improve performance, multiple levels of detail for the building models are created. There are three reasons to transform the most detailed model to lower levels of detail: (1) time
is the biggest enemy in capturing and visualizing scenes of the real world, (2) the data sets' sizes and processing also demand model simplification, and, (3) perception is a kind of multiresolution hierarchies as LOD. Most of the existing methods in computer science are focused on consecutive free curved surfaces like terrain. It is difficult to locate the components and primitives of a complex building that has to be simplified, perception-driven simplification methodology is therefore potential[13].

Integrating the above-mentioned multisource and multiscale 3D data to create a complete seamless virtual city environment faces great challenges: different scopes, different semantics and different formats. On the other hand, due to the manual labor required, modeling 3D buildings and city models has been a very expensive and time-consuming process. Based on the CityGML, standard flexible tools still need to be developed for editing and database creating with fusion of multi-source data consistently and accurately. In fact, the post modeling problems such as facade texture mapping, discrete LoD models generation, model editing and database updating are the main bottleneck of fast 3DCM over large-scale urban areas.

3 Integrated database management and applications

The integration of different 3D data is closely related to the construction of the 3D scene. As we recognized, not only the reconstruction and representation of the 3D shape of buildings and other objects of the city are the issue, but also the description of surface properties and material parameters have become part of the database. Different types of data are integrated in the 3D scene, through a process called data-fusion. The constructed 3D scene can be stored in Relational Database Management Systems (RDBMS). Approaches of integration are usually at the following four levels[14].

(1) Syntax level: merged by transforming the data into a single format, regardless of possible mismatches, overlaps, inconsistencies, etc. CityGML is a good standard format for the storage and sharing of relevant 3D geodata.

(2) Semantics level: share the same semantics and fulfill common properties and constraints, even with different formats.

(3) Model level: merged by transforming the data into a common, shared object model.

(4) Visualization level: merged by mapping the data during visualization into a common, shared virtual 3D space. For example, the OGC implementation standard KML2.2 provides a standard approach to code and share visual geographic content in existing or future web-based online maps and 3D geospatial browsers like Google Earth (http://www.opengeospatial.org/standards/kml/).

2.5D DEM data is served as the base layer or foundation for the placement and alignment of aerial photography and other geospatial layers. Multisource and multiresolution DOMs are draped over a three-dimensional foundation to create a unique and accurate user viewing experience. The data required to visualize the whole world at the resolution we desired was many tens of terabytes in size. So it was immediately obvious that we would not be able to host all the data locally on the user's PC. An effective way is to host on a large server or distributed cluster server and transmitted to the client as needed.

To get the best quality for a given texture size, new image formats are available in Windows Imaging Components to compress textures for transmission, such as the DDS format for mipmap texture mapping especially. Image data can be stored in the same compression format(s) that hardware currently uses (DXT1, DXT3, DXT5).

Compared to 3D vector models, it is still very easy to manage the very large DEM and DOM databases even of the whole world[15] because the techniques of image tiling and pyramid structure are mature enough for the management and real time applications of raster data. SDO_GEORASTER object of Oracle 11g already provides similar functions. However, due to the irregular distribution and various complexity of discrete 3D objects, there are many big obstacles for large-scale 3D city models database management and related multi-user on-line applications, such as spatial data declustering and full 3D spatial index with concern of LoD geometry and texture[16].

Because most users will tend to view their own city most often, caching is a very effective way to improve
performance on subsequent visits. Once the data is downloaded, the textures are kept in system memory to render to the screen. Therefore, load-balanced configurations have to be considered more comprehensively.

The applications of 3D city models are manifold. Currently, the major users in China are in the field of urban planning. Other fields include environmental studies and simulations, location-based services, risk routing and analysis, car navigation, real estate business, virtual tourism, and microclimate studies. Interesting markets are expected in the entertainment and infotainment industries, e.g., for video games, movies for TV and cinema, news broadcasting, sports events, animations for traffic and crowd behavior, and so on. The visualization of 3D models is an essential function, and more than 550 software packages are now available just for terrain visualization[11]. The interactive and real-time visualization of large-scale complete 3D city models with detailed texture still has problems. Therefore, large urban database contents are usually organized by a special data structure, which supports LoD and spatial data retrieval to allow fast access and real-time visualization for fly-over and walk-through applications.

4 Case study

Like most 3DCM efforts, current web services, such as Google Earth typically, provide only graphic or geometric models, neglecting the semantic and topologic aspects, and are used for visualization purposes but not, in most cases, for thematic queries, analytical tasks or spatial data mining.

Different from the hand-made Google Earth 3D models created by SketchUp, Microsoft updates its Virtual Earth 3D. Cities are much more densely modeled with higher resolution textures by the new Version 2, thus, delivering a truly impressive mirror world experience. Microsoft is aiming at making 500 worldwide 3D city models in a scalable fashion available in Virtual Earth this year, alongside works to make Virtual Earth "more real and more precise" (virtualearth.com). The models and their texturing are generated from aerial imagery generally captured at a 15 cm ground sample distance (GSD) by planes flying roughly 5 500 feet over the target city and capturing a minimum of 5 views for each building (top and 4 sides).

UK aerial surveying specialist Bluesky also has launched a new range of highly accurate and detailed 3D city models for UK cities (www.bluesky-world.com). Bluesky 3D city models is created from the most up-to-date, high-resolution, stereo aerial photography, and to map every building over 140 cubic metres, accurate to ±60 cm.

In China, increasing megacities like Wuhan and Guangzhou are building 3D city models covering whole urban areas for urban planning, construction and management. At the same time, comprehensive data standards and technical specifications for 3DCM including levels of detail and accuracy are designed. For example, there are 4 levels of details in Wuhan city: the 2.5D geometric block models with accuracy of 1m provide a framework for the whole city areas of 8 549km², 2.75D basic models with geometry and appearance over 2m, 3D standard models with detailed roof structures and real facades for each specific building over 0.5m in built areas of 425.03km², 3D finest models with exterior and interior structures over 0.2m for buildings in special districts of 80km². Fig.1 illustrates part of Wuhan 3D city models.

3DCM techniques also play an important role in digital cultural heritage documentation. For example, in order to protect the Mogao Caves of China effectively, a world cultural heritage, digital Mogao Caves is created for researches of resuming and repairing, as well as for the tourism instead of the locale. 3D reconstruction is an essential content of it, including the inside (as shown in Fig.2) and outside of all the 492 grottoes and the whole environment around it, nearly 220 km². Another successful example is the digital Chi Lin Nunnery of Hong Kong finished in 2007, which provides a virtual architecture environment with 3D manual measurement data of the wooden components in detail for researching the arts and crafts of timber-frame buildings of the Tang Dynasty, as well as for accurate documentation, digital preservation and restoration, virtual tourism, and research or education. Especially, such 3D models with semantic information of construction process were effectively used for the quality control within the entire
construction lifecycle, like the single-component supervision and assembly supervision. Fig.3 illustrates the overall view and local details.

Fig.1 A screenshot of 3D city models of Wuhan, China

Fig.2 3D cave models reconstructed from laser scanning and imagery

Fig.3 3D virtual environment of digital Chi Lin Nunnery

5 Conclusion and perspectives

Because the 3D city models provide us better ways to represent, understand, manage, and communicate our natural world, every industry requiring 3D models for the urban environment will benefit from the innovative cost-effective product designed to meet a range of customer needs and requirements. Time sensitive industries, in particular security & defence, disaster management and the emergency response sector can greatly benefit from the rapid and reliable delivery of detailed 3D city models in an attempt to optimize the decision making process in the most critical
events.

Advanced information technologies, especially the geotechnologies, bring us increasing facilities of geo-data processing. Almost everything can be digitized now. The GIS enables integrated database management and virtual environment provides photorealistic visualization and natural interaction. However, because of the complexity of the reality, the 3DCM tasks still cannot be fulfilled by any kind of stand-alone technology. Multiple platforms such as satellite, space vehicles, stratosphere balloons, aerial and terrestrial vehicles, and multiple sensors with higher resolution (geometrical and spectral) are evolved to accelerate the technology-driven 3DCM towards near real-time and integrated systems for more flexible products.

Of course, building a parallel and augmented virtual city environment still faces great challenges in full automated, real-time and accurate 3D data acquisition, seamless and interoperable massive database management.

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