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Virtual 3D City Models as Foundation of Complex Urban Information Spaces

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1 INTRODUCTION

Virtual 3D city models represent spatial and geo-referenced urban data by means of 3D geovirtual environments that basically include terrain models, building models, vegetation models as well as models of roads and transportation systems. In general, these models serve to present, explore, analyze, and manage urban data. As a characteristic element, virtual 3D city models allow for visually integrating heterogeneous geoinformation within a single framework and, therefore, create and manage complex urban information spaces.

An increasing number of applications and systems incorporate virtual 3D city models as essential system components such as for urban planning and redevelopment, facility management, logistics, security, telecommunication, disaster management, location-based services, real estate portals as well as urban-related entertainment and education products. Consequently, a large number of potential users and usages require an efficient and effective access to and tools for virtual 3D city models and their contents.

The requirements on virtual 3D city models vary between different applications. On the one hand, in the context of tourism, entertainment, or public participation, a high degree of photorealism is required (Fig. 1 left). For instance, if the aim is to give a realistic impression of a planned environment, the quality of a 3D visualization is directly related to the similarity between the virtual city model and the actual result after implementation of the planning.

On the other hand, in applications that attempt to provide analytical and exploratory functionality, visual details of buildings are not of primary interest. Instead, the 3D representation of a city model serves as a medium to convey spatial-related thematic information in a comprehensive way. In the context of urban planning, e.g., thematic building information such as vacancy, ownership, or year of construction have to be considered. As an example, the illustration (Fig. 1 right) created by the Senate Department of Urban Development, Berlin, shows a 3D overview of the ownership structure of an urban area. While in 2D GIS applications exploration and analysis of thematic spatial-related objects and associated thematic information is a common practice, the potential of virtual 3D city models as a medium to communicate complex urban information spaces has not been explored extensively.

Fig. 1: Different design requirements on 3D city model visualization: Photorealistic visualization to give an intuitive impression of existing or planned environments (left) and abstract visualization to encode thematic information (right).

2 GEODATA FOR VIRTUAL 3D CITY MODELS

In practice, the creation and maintenance of virtual 3D city models is based on a number of independent data sources since the sustainable management of 3D city models requires tight links to existing administrative work flows and databases. As a major challenge, these data sources have to be integrated in a systematic and pragmatic way and include:

- Cadastral Data: The cadastral databases deliver the official footprints of buildings and land parcels as well as ownership and address information. Although typical cadastral databases do not contain 3D data, they provide essential input for 3D building models and a kind of official foundation for virtual 3D city models.
- Digital Terrain Models and Aerial Photography: These data sources include, e.g., grid-based DTMs and true-ortho photos. DTMs are used as a reference surface for all geometric objects of a virtual 3D city model, whereas aerial photography provides essential data for photorealistic visualization, e.g., land coverage images and roof textures.
- 3D Building Models: 3D building geometry can be captured and processed by laser-scanning and photogrammetry-based methods. The buildings are represented at various levels of detail (Kolbe et al. 2005), including block-models (LOD-1), geometry-models (LOD-2), architectural models (LOD-3), and detailed indoor models (LOD-4). In addition, continuous level-of-detail buildings as needed during incremental refinement processes are supported, e.g., by SmartBuildings (Döllner et al. 2005). For capturing and processing 3D geodata, several cost-effective methods have been developed (Ribarsky et al. 2002, Förstner 1999).

- Architectural Models: In addition to 3D building models, architectural models can be incorporated such as historic or future ensembles and redevelopment plans. In general, these models include not only buildings but also their surrounding environment at a high level of detail.

There is no widely accepted standardized convention for encoding virtual 3D city models. A first proposal for virtual 3D city models, CityGML, is currently discussed by the Open Geospatial Consortium (OGC). In general, the following data standards are used in practice:

- CityGML, in particular, for building models
- 3D-Studio MAX object files and VRML files
- ESRI Shapefiles with 2D footprint polygons and height values for each building
- ESRI Shapefiles containing an explicit geometric description of each building in the form of boundary polygons.

Apart from the geodata listed above, virtual 3D city models also store or reference classical georeferenced 2D raster-data sources (e.g., land use information) and vector-data sources (e.g., road network, public transportation networks). These data sets are visualized, for example, as an image layer superimposed on the digital terrain model.

Complex urban information spaces refer to virtual 3D city models integrating thematic and application-specific georeferenced information that is jointly presented and related to the geometric entities of virtual 3D city models. For example, a real-estate portal may want to visualize vacancy, year-of-construction, and average monthly rent of buildings within the virtual 3D city model using façade color, façade texture, and roof colors as visual variables to indicate that information.

3 THE LANDXPLORER SYSTEM

In this paper, we introduce the software architecture and system components of a new system for creating, managing, securing, and distributing complex, large-scale virtual 3D city models, called LandXplorer. It has been developed at the Hasso-Plattner-Institute as common software platform for 3D geovisualization techniques and systems. Based on LandXplorer, a number of products for urban planning and city models have been created, including the LandXplorer Studio (3dgeo 2005).

The system supports 3D terrain models, 3D building models, 3D street space models, and 3D vegetation models as so-called first-class objects, that is, they represent primary components in contrast to first-generation, graphics-oriented virtual 3D city solutions. The system facilitates the automated transformation of traditional vector-based 2D planning information into a 3D model based on a heuristic-algorithmic approach.

Besides core functionality for importing, instantiating, and modifying components of virtual 3D city models, the system concentrates on functionality to control usage of distributed virtual 3D city models and to transform contents of virtual 3D city models into a number of different media. For example, the system supports the automated extraction of customer-specific spatial regions and thematic information layers into a self-contained, ready-to-use viewing application, e.g., for Internet download or DVD production. This process relies on a geospatial digital rights management, which enables and simplifies the broad use of digital model contents.

The system architecture is modeled as an open platform to facilitate diverse applications of the virtual 3D city model both in administration and industry. In contrast to previous systems, LandXplorer is considered to act as an integration platform for 2D and 3D geodata and georeferenced data instead of being only a 3D graphics system. Its main objectives encompass the management of the underlying 3D geoinformation and its integration into administrative workflows by a central 3D geo-database; the on-demand, on-the-fly integration of georeferenced thematic data with (parts of) the virtual 3D city model, and the dissemination and distribution of the virtual 3D city models through a number of digital media such as Internet, imagery, video, and DVD. This way, LandXplorer creates complex urban information spaces based on virtual 3D city models.

3.1 System Components

The overall architecture of the system is outlined in Fig. 2. In the project, we identified the following principal system components:

- 3D Authoring System: It is responsible for creating, editing, and versioning of the 3D city models and its components, e.g., importing, exporting, grouping, and annotating buildings, vegetation plans, landscape plans, etc. Technically, it provides an interactive access to the 3D geo-database.
- 3D Geo-Database System: The database for storing and managing 3D city models is based on the logical structure of CityGML, which represents a first XML and GML-based format for storing and exchanging virtual 3D city models (Kolbe et al. 2005). It also supports semantic and thematic properties, taxonomies and aggregations. Its principal object, the city object, represents geo-referenced, geometric entities. Specialized classes of city objects include buildings, green spaces, street spaces, transportation networks, water bodies, vegetation, and plants. It is implemented as an independent subsystem, and it does not provide visualization functionality.
- 3D Editor Systems: These systems are responsible for creating and editing specific 3D objects such as architectural building models or 3D landscape models. We apply both the ArchiCAD editor for architectural models and 3D Studio Max as general-purpose 3D modeler. This approach allows us to support a broad spectrum of digital 3D contents and to fulfill needs of specific applications and users with respect to 3D digital contents.
- 3D Presentation Systems: The presentation systems provide real-time visualization of and interaction with the virtual 3D city model. In contrast to the 3D authoring system, the presentation systems are targeted at specific media (e.g., Internet, DVD) and specific user groups (e.g., general public, experts, and politicians). For example, within a showroom, a large-screen projection can give impressive presentations tailored to the specific needs of clients based on pre-defined 3D points-of-interests.

- Geospatial Digital Rights Management System: As a complementary functionality, a geospatial digital rights system allows for enclosing, compressing, and controlling digital contents of the virtual city model. Technically, a virtual city model can be serialized into a single data stream, compressed, and encrypted for export. In addition, a number of visualization techniques, such as adaptive visual watermarks and user interaction restrictions complement the DRM repertoire.

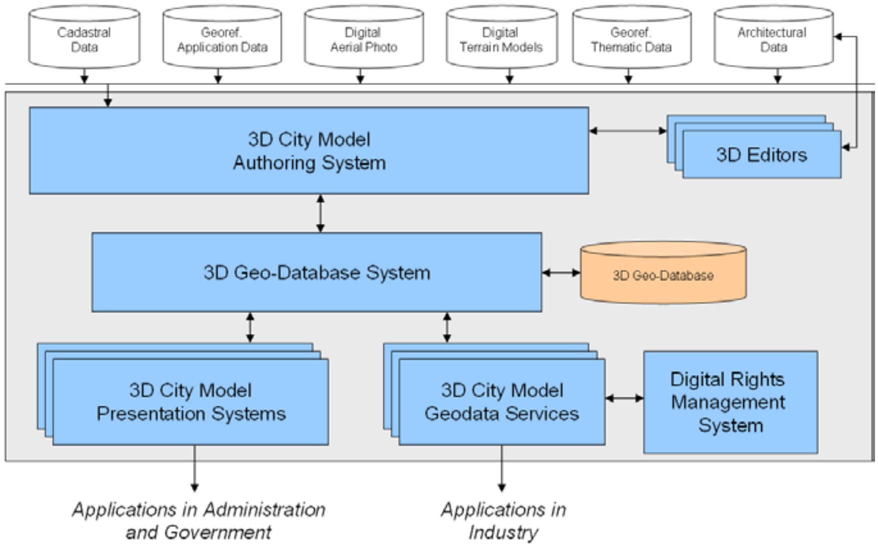

Fig. 2: Architecture and principal components of a virtual 3D city model system such as LandXplorer.

3.2 System Functionality

The LandXplorer functionality can be divided into the following categories:

- Editing Tools: These tools allow for the direct creation and manipulation of 2D vector graphics and 3D graphics objects. As a unique feature, 2D vector objects (points, lines, polygons, etc.) are edited "in situ", that is, in the 3D view. With the building modeler, the footprints can be directly edited and extruded to 3D block models. As advanced tool, the smart building editor can be applied, which manages LOD-1 to LOD-4 building models based on a per-storey representation.
- Navigation Tools: Include metaphor-based interactive controls such as virtual helicopter, airplane, and pedestrian as well as gaming controls and classical 2D modes such as panning and zooming. The tools are complemented by a list-based selection of points-of-interest.
- Spatial Analysis Tools. Include tools to blend in distance grids and distance concentric circle around a specified location as well as tools to measure height and distance along paths. In addition, the morphology of the digital terrain model (e.g., slope, exposition, form) can be analyzed and visualized by superimposed terrain textures.
- Animation Tools: These tools allow for designing and recording animation sequences within virtual 3D city models. The basis elements represent 3D bookmarks, which capture a camera position and its parameters. A movie is implicitly defined by an ordered sequence of 3D bookmarks that are interpolated in pairs.
- Printing Tools: The system supports high-resolution snapshot generation based on a tiled production of images, e.g., used for poster printing. In addition, virtual panorama images and movies can be generated.
- Import and Export Tools: To transfer common 2D raster data and 2D vector data, the system supports standard GIS and computer graphics formats. For 3D graphics, models given as CityGML, 3DS, VRML, and X3D can be processed. Selected areas and model parts can be exported in common GIS formats and CityGML.

4 VISUALIZATION OF URBAN INFORMATION

Virtual 3D city models, in general, have become generic tools for an increasing number of application areas in administration and industry. For that reason, the requirements made on visualization vary. LandXplorer explicitly supports several visualization strategies and techniques.

4.1 Photorealistic Visualization

In the context of tourism, entertainment, or public participation a high degree of photorealism is required (Fig. 3). For instance, if the aim is to give a realistic impression of a planned environment, the quality of a 3D visualization is directly related to the similarity between the virtual city model and the actual result after implementation of the planning. To enable real-time rendering of large-scale 3D city models, their geometric complexity has to be reduced in order to guarantee high and constant frame rates. For virtual environments, geometry or texture related optimization and multiresolution algorithms and data structures can be applied to achieve real-time rendering even for complex virtual 3D city models (e.g., Beck 2003, Willmott et al. 2001).

Fig. 3: Example of a photorealistic representation of virtual 3D city models. The Berlin 3D model contains true-ortho photography and LOD-3 and LOD-4 building models. The colored lines show part of the underground network.

To extend the scope of photorealistic rendering, the LandXplorer system also provides a specialized rendering engine for 3D vegetation, the LandXplorer Lenné3D module, which also includes a library of 3D plant models. Plant and vegetation modeling represents a challenging task, particularly because botanical knowledge is required and manual processes are involved, for example, to collect images of plant parts, to scan leaf textures, to produce variants of a single plant, and to set up properties for a plant type. To achieve interactive frame rates, we have to solve a non-trivial problem: reduction of the massive geometric complexity. The complexity results from two facts: 1) A single plant model, e.g., a typical tree, commonly contains between 50,000 and 150,000 textured triangles, whereby large parts are spent for tree leafs. 2) The human experience in seeing and realizing plants is highly developed.

The Lenné3D project (Paar 2003) has developed new level-of-detail rendering techniques (Coconu & Hege 2003; Deussen et al. 2005) that drastically reduce the geometric complexity, e.g., by point-based and line-based simplification schemata. Consequently, with Lenné3D technology a high amount of photorealism for vegetation elements in virtual 3D city models becomes possible.

4.2 Information Visualization

For applications in information visualization and data mining, visual details of buildings are not of primary interest (Fig. 4). Instead, the 3D representation of a city model serves as a medium to convey spatial-related thematic information in a comprehensive way (Müller & Schumann 2002). In the context of urban planning, e.g., thematic building information such as vacancy, ownership, or year of construction has to be considered.

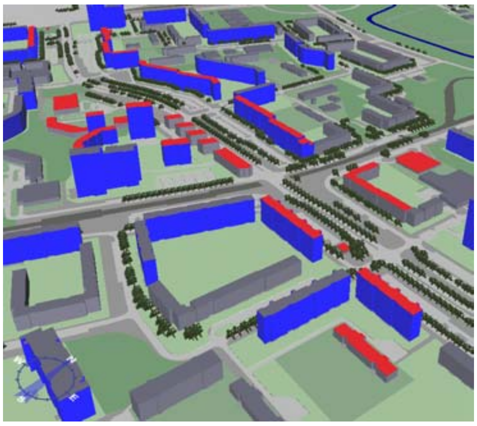

Fig. 4: Example of urban information visualization within 3D city models. Facades and roofs are used to project two independent information variables.

4.3 Illustrative Visualization

Non-photorealistic, interactive 3D city maps lead to a number of new solutions for effective and comprising visual display and user interfaces overcoming restrictions and transcending mindsets of photorealistic approaches (Strothotte & Schlechtweg 2002). Primary application areas include urban data mining, city and landscape planning, cartoon worlds in computer games, urban visual analytics, decision-support systems, and urban information systems. They all benefit from abstracted map-like depictions (Fig. 5) of 3D city models to get insights into complex geospatial and georeferenced urban information spaces. This approach is inspired by the tradition of depictions typically found in bird's-eye views and panoramic maps, and it combines related principles in cartography, geographic information systems, visualization, and arts (Döllner et al. 2005).

Fig. 5: Example of illustrative visualization for virtual 3D city models. Stylized and sketched buildings and facades provide a comprehensive, abstracted view to contents of 3D city models.

5 VISUAL DATA MINING

LandXplorer has been primarily motivated by the requirements of visualization in the context of urban planning and development. For example, in public participation processes such as public discussions between city planners, political decision makers, and the public, 3D city models can be applied to communicate ideas, e.g., where buildings and streets shall be removed, constructed or modified; and to discuss feasibility and consequences of certain plan ideas, e.g., how many people would be affected or which housing companies would be involved if a plan would be implemented.

5.1 Communicating Complex Information Spaces

Classical media such as 2D maps or 3D maps do not provide sufficient support for decision-making because they can only show prepared views. An effective tool for decision-support should permit dynamic adaptation of thematic views to the currently focused aspects of a discussion. That is, there are generally more information dimensions than dimensions currently visualized, and we cannot generally assume that specific dimensions are more important than others, in particular, if experts and non-exports want to explore parts of the information space for the first time. In the case of large-scale data sets, we furthermore need to be able to vary the scales in the visualization to support both locally and globally focused investigations.

As a basis for decision-support tools and other applications requiring insight to thematic data, LandXplorer supports visual data mining in large-scale 3D city models. As stated by Eidenberger (2004) "The main aspect of visual data mining is allowing direct communication of the user with the data space through flexible and easy to understand user interfaces". The key characteristics of our system are interactivity and flexibility. As Müller and Schumann (2002) point out, "Interaction is crucial for effective visual data mining. The data analyst […] must be able to interact with the presented data and to change the visualizations and the mining parameters". For this, we support navigating in the virtual space as well as controlling the mapping of thematic information to the city model's appearance in real-time. Photorealistic detail information such as photo-textures for building facades are not excluded by our system but photorealistic views represent only one of several possible views on an underlying data set.

5.2 Visual Data Mining Using Building Models

For visual data mining, building objects are primary components used to visualize thematic information. Each building object consists of two components: a geometry description and a building-related attribute table storing application-specific information related to the building.

The geometry description contains different parts, each of which can be managed separately for information display. The standard parts include facade, roof, and unknown. The unknown category is used for buildings whose source specification does not provide the required information to separate facade geometry and roof geometry, e.g., if the whole building geometry is defined by a single set of polygonal faces.

The attribute table of a building is a set of key-value pairs. Keys are specified by strings; values can be strings as well, but also floating point, integer, or Boolean values, where all values for a certain key must be of equal type. The attribute table is the representation of thematic information within the 3D city model. These tables are created by filtering, importing, and merging one or more data sets into the 3D city model. The reason for the table is that we require a direct and efficient access to thematic information that potentially has an impact on the appearance of building models.

Each categorized geometric part of each building forms an own entity that can be accessed separately and can therefore be changed independently in its appearance. To be useful for visual data mining, 3D city model visualization must fulfill two fundamental requirements:

- It must provide means to make non-graphics building information visible, e.g., year of construction, vacancy, state of repair, or the importance of buildings.
- Changing the appearance of buildings must be possible interactively.

To meet the first requirement, we consider the graphics variables available for building models, which include:

- Building height
- Facade material, color, and texture
- Facade elements such as doors and windows
- Roof material, color, texture, and type.

These variables can be modified according to thematic data but are frequently needed to support orientation within a city. By integrating different rendering techniques, we obtain additional graphics variables that have no equivalent in photorealistic presentations and, therefore, can easily be perceived as variables for abstract thematic data. Examples include:

- Edge styles applied to facades and roofs
- Transparency of buildings
- Highlights using haloing effects.

For instance, we can map the status of buildings as planned, existing, or torn off by different edge styles to outline the walls of a building. This kind of graphics variables allow for illustrative depictions known from many classical presentations in urban planning and architecture.

To meet the second requirement, visual data mining requires the functionality to interact with a 3D city model in three different ways:

1. Explicit selection: The user can select one or more individual buildings explicitly.
2. Spatial selection: The user can select a group of buildings within a certain area by drawing a polygon onto the terrain.
3. Rule-based selection: The user can specify a selection of buildings by defining a filter condition based on the attribute table of each building. All buildings whose attribute table meet the given filter condition are selected for editing.

A group of selected buildings can be edited simultaneously, either by manipulating their appearance or by changing the attribute table. As a shortcut of rule-based selection and editing, the system also allows for the definition of a color legend: For a certain key of the attribute table, an individual color can be mapped to each occurring value for the key.

6 CASE STUDY: THE BERLIN 3D CITY MODEL

In a three-year case study, we developed and applied the LandXplorer system to visualize complex urban information spaces for a number of cities. The core application areas are business location marketing and urban redevelopment. In our largest project, the virtual 3D city model of the city of Berlin, the LandXplorer system has been deployed by the Business Location Center, which supports companies considering relocating to Berlin-Brandenburg by presenting all key decision-making factors within the 3D geovirtual environment as well as in the Senate Department of Urban Planing, for exploring and evaluating redevelopment plans.

7 CONCLUSIONS

Virtual 3D city models represent a key component for geoinformation infrastructures and serve as basis for urban 3D decision support systems. Advanced virtual 3D city technology enables and provides tools for handling complex urban information spaces, going beyond classical graphics-only applications of 3D city models. 3D city model systems cover functionality such as managing, integrating, and distributing complex geoinformation based on a uniform communication metaphor, the virtual 3D city model.

In our experience, the decoupling of the system's functionality into subsystems for content authoring, editing, storing, and presentation leads to an open, extendible 3D city model system as exemplified by LandXplorer. As a fundamental concept, CityGML as well as a number of identified standard formats provide a high degree of interoperability. Innovative visualization techniques beyond photorealism, such as information visualization and illustrative visualization, allow us to address new application areas and improve the quality and usability of graphics display.

In our current activities, we are developing 3D geodata services to further extend the ways city models can be accessed by third-party applications and systems. In addition, techniques for the automated mapping of 2D landscape plans and architectural plans to 3D geovirtual environments based on a heuristic-algorithm approach are investigated.

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