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Research on Three-dimensional Modeling of Urban Buildings based on CityGML

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Abstract

In the rapidly advancing wave of urbanization, 3D city modeling technology has gradually become a key means of urban planning and management. CityGML, based on XML, is a three-dimensional information modeling specification that covers various elements such as urban architecture and terrain. This article aims to explore the methodology of using CityGML to construct 3D models of urban architecture, elaborating on the modeling steps including data collection, feature selection, model refinement, and data storage. Key technologies such as geometric construction, semantic construction, texture matching, and data interaction are analyzed. With the standardized CityGML model, urban planning departments can more efficiently carry out tasks such as urban planning, building supervision, and disaster prevention, providing reference for promoting the application of CityGML in the field of urban model construction.

Keywords

Urban Modeling; 3D Modeling; Semantic Modeling; Geometric Modeling; Texture Mapping.

1. Introduction

With the continuous improvement of urbanization speed around the world, the complexity of urban governance and design is also increasing. 3D city simulation technology provides an efficient solution to address this complexity, which can present the spatial layout between buildings, streets, public facilities, and terrain in a three-dimensional manner. CityGML, as a universal urban information model specification, has been widely applied in the field of 3D city construction. Through consistent data formats and architectures, various information resources of the city are gathered, providing strong technical support for urban planning, building management, and disaster response. This article is based on the architectural 3D simulation method and core technology of CityGML, elaborating on the entire construction process from data collection to model refinement, and analyzing the outstanding advantages and technical details of CityGML in geometric and semantic construction.

2. Overview of City GML

2.1. Concept of CityGML

Urban Geographic Markup Language is a global standard established by the International Open Geospatial Information Alliance for the representation of three-dimensional urban structures. By integrating geometric and semantic construction standards, it is possible to provide detailed characterization of various objects and their features in urban environments. CityGML has the ability to display urban components such as architectural complexes, landforms, transportation systems, green vegetation, and underground structures in a three-dimensional space, integrate these elements with semantic data, and construct a comprehensive urban information

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architecture. Models can present the three-dimensional structure of buildings, revealing their usage properties, structural features, and interactions with the surrounding landscape. The main advantage of CityGML lies in the integration of geometric and semantic data, which plays an important role in multiple fields such as urban planning, governance, and evaluation. With the help of a unified expression system, CityGML can cross multiple platform and system boundaries, achieve data exchange and collaborative operations, and improve the integration and control efficiency of urban information. The model supports multiple models with different levels of detail, allowing users to select the appropriate level of detail based on specific application needs. Whether it is a macro city bird's-eye view or a micro building interior structure, CityGML can accurately display them.

2.2. Advantages of CityGML

As a standardized technology for urban 3D construction, CityGML has demonstrated advantages in semantic construction, standardized implementation, application of multi-level resolution, and data interoperability. Focusing on the three-dimensional structure of urban structures and landforms, integrating semantic information to showcase the functions, characteristics, and usage purposes of objects. By using semantics to construct CityGML, detailed explanations of the usage nature, construction materials, architecture types, and other details of buildings can be provided, which helps with more accurate urban governance and planning work. The standardization feature of CityGML ensures data sharing and good compatibility across different industries and system platforms. CityGML has created a cross platform and cross domain resource sharing tool for urban management teams, enhancing data consistency and visibility. CityGML can adapt to multiple resolutions and meet the different precision requirements of architectural and urban elements through multiple levels of detail from LoD0 to LoD4. Whether it is basic 2D floor plans or detailed 3D internal structures, they can be fully displayed within the CityGML framework. With the help of custom Application Domain Extension (ADE) components, CityGML is able to better match the application needs of specific industries.

2.3. Data Structure of CityGML

The data architecture adopted by CityGML is built on top of XML, achieving deep integration of spatial data and semantic information in the city, and constructing a comprehensive urban information architecture. The model mainly consists of two modules: geometry and semantics. In the geometry module, it is responsible for depicting the three-dimensional contours of urban elements, using polygons and topological relationships to display the shapes of buildings, streets, landforms, and other elements. The semantic modeling function of CityGML is extremely important, recording key information such as the functional characteristics, application status, and construction categories of urban entities. This model can clearly define the specific uses of buildings, such as residential, commercial and industrial uses, and can cover detailed information such as building materials, construction years, floor heights, etc. CityGML accurately presents the physical structure of urban buildings by integrating geometric and semantic models, mapping various functions and attributes in the urban environment. The design concept of CityGML is centered around modularity, allowing different elements in the city such as buildings, roads, and landforms to be effectively organized and managed through their respective modules. CityGML also has the function of expressing topological connections. Elements such as buildings, streets, and overpasses in the city can be connected through topological forms, displaying their mutual positions and connections in three-dimensional space [1].

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3. Process of 3D Modeling of Urban Buildings based on CityGML

3.1. Data Collection and Preprocessing

When using the CityGML standard for building modeling in the field of urban 3D modeling, data collection and preprocessing play a core role, directly affecting the quality and completeness of the model. Data collection covers aerial photography, LiDAR, satellite imagery, field surveying, as well as readily available computer-aided design (CAD) files and geographic information system (GIS) data. These diverse data resources provide detailed information on core elements such as the form, surface texture, and structure of buildings. Especially laser scanning technology, with its high-precision and high-density point cloud data, is often used to accurately capture the three-dimensional form of complex buildings. Aerial photography excels at capturing the appearance of buildings and their interaction with the surrounding environment. Data collection is not the end point of model construction, but a series of data preparation work must be carried out to ensure the accuracy and uniformity of information. Data cleaning is a crucial step in the process of data preparation, involving the removal of impurity information, correction of inaccuracies, and elimination of duplicate records. Due to the possibility of various biases in the collection process of data from different sources, especially when integrating multi-source data, achieving unified transformation of coordinate systems, accuracy calibration, spatial correspondence matching, and standardization of data formats are particularly crucial. In the process of building the CityGML model, it is essential to convert the collected data into a consistent coordinate system and structural format. The resolution and extraction frequency of the data must be adapted according to the different precision levels of the model (from LoD0 to LoD4) to meet the application requirements of different precision levels[2].

3.2. Extraction and Modeling of Architectural Elements

Extracting building elements for 3D modeling is an important step in the construction process of CityGML. Request to extract the three-dimensional structure, spatial attributes, and related semantic data of the building from preprocessed data. This extraction process relies on techniques such as point cloud information processing, image recognition, and vector transformation. The point cloud data generated by LiDAR technology can effectively draw the three-dimensional edge lines of buildings, while planar image data helps identify specific features of building surfaces, such as windows and doors. After extracting the architectural elements, geometric modeling can be carried out by converting these components into three-dimensional geometric models. CityGML provides multi-level detail representation from LoD0 to LoD4, allowing the complexity of the model to be adjusted according to specific application requirements. For example, in the field of urban planning, only the primary building block models of LoD1 or LoD2 are sufficient for use. When conducting detailed architectural analysis, LoD3 and LoD4 can showcase architectural details in detail, including roof construction, terraces, and indoor spaces. CityGML covers the geometric form of buildings and also enables modeling of building semantics, allowing the model to present both the appearance and functional characteristics of the building. In the process of building semantic models, it covers various aspects such as building functions, types of building materials, and construction units. This type of data has significant value for the subsequent analysis and governance of cities, in areas such as emergency response, transportation layout, and energy consumption assessment. Accurately extracting and constructing architectural elements is the core step in ensuring that the 3D model accurately reflects the architectural form in both geometric and semantic dimensions [3].

3.3. Model Integration and Optimization

The integration and optimization of CityGML models are crucial in maintaining the overall integrity and operational efficiency of the model during the key steps of constructing a three-dimensional model of urban architecture. Given that architectural three-dimensional drawings come from diverse data channels or multiple collections, these data sources may have issues such as information redundancy, positional deviation, or uneven accuracy that require integration. During the integration phase, it is necessary to calibrate, reconstruct, and merge various building components to ensure the precise positioning and coordination of all building elements within the three-dimensional space. The process covers geometric calibration, data deduplication, and filling in blank areas. Efficient optimization of models aims to enhance the efficiency of model construction and eliminate redundant information. When constructing large urban models, unoptimized models often lead to slow system operation and reduced rendering efficiency. The optimization methods adopted include simplifying geometric structures, eliminating duplicate data, and reducing file size. These measures have accelerated the operational efficiency of the model, making it more convenient to operate and display it on various platforms. The CityGML format supports models of different resolutions (LoD), and optimized models can smoothly transition between different levels of refinement, meeting diverse needs from macro level urban planning to specific architectural detail research. In the integration and optimization stage of the model, the spatial connections between buildings and other elements of the city (such as roads, landforms, public facilities, etc.) must also be maintained.

3.4. Data Storage and Management

In the 3D modeling process of urban buildings in CityGML, data storage and management play a core role, which is crucial for maintaining the long-term usability and smooth operation of the model. Given the rich geometric and semantic information embedded in the CityGML model, as well as the vast amount of complex topological correlation data between buildings, it is particularly crucial to develop appropriate storage solutions and management techniques. CityGML data can be saved in local file architectures or in database systems, which are particularly suitable for centralized management of large-scale urban models. When dealing with large-scale urban models, use spatial database management systems to save and maintain CityGML data. This type of database has efficient spatial data storage, index construction, and retrieval capabilities, and can perform advanced spatial analysis operations. Using a database for management enables the model to be quickly called and integrated with other management systems in the city, promoting collaboration efficiency between different departments. Maintaining version iterations, setting access permissions, and performing data backups constitute the core steps in the field of data processing. The CityGML model requires frequent upgrades and adjustments, and the version control function enables every update to be tracked to prevent data inconsistency issues[4]. The setting of access permissions ensures that only authorized users can access and modify model data, avoiding potential threats to data integrity from unauthorized operations. The data backup system can quickly recover in the event of data damage or system errors, ensuring the long-term stability of model data. With the advancement of cloud computing technology, many cities have begun to store CityGML data in the cloud, achieving synchronized online operations and collaboration among multiple users. Cloud storage has improved the convenience of data acquisition and provided convenience for cross departmental collaboration and data exchange. With efficient storage and management methods, the CityGML model can maintain high performance in various application scenarios, providing continuous support for urban planning and management.

4. Key Technologies for 3D Modeling of Urban Buildings Based on CityGML

4.1. Geometric Modeling Techniques

Geometric modeling technology is the foundation of CityGML 3D modeling, used to accurately describe the shape and spatial structure of urban buildings. Geometric modeling in CityGML is based on topological structure and polygon representation, and can present buildings at different levels of detail (LoD, Level of Detail).

The core formula for geometric modeling is as follows: $V = \frac{1}{3}Ah$

Among them ***V*** represents the volume of the building, ***A*** is the base area of the building, and ***h*** is the height of the building. In this way, the shape and physical properties of buildings can be calculated and represented in three-dimensional space. CityGML supports multi-resolution geometric modeling from LoD0 to LoD4, where LoD0 is only a two-dimensional representation and LoD4 can include the internal structure of buildings. Geometric modeling techniques allow for the construction of complex building forms, covering different types of building appearances such as straight lines, polygons, and even curved surfaces. Combining geometric models with the standard data format of CityGML in applications enables cross platform data sharing and analysis.

4.2. Semantic Modeling Techniques

Semantic modeling technology is crucial in the field of 3D modeling in CityGML, with the aim of injecting deep semantic connotations into building models, endowing them with basic geometric contours, and incorporating functional, structural details, and various attribute data of the building. With the help of this technology, buildings can be refined into multiple hierarchical components, such as walls, roofs, doors, and windows, each with its own unique properties and functions. These semantic data greatly enhance the readability of the model, supporting in-depth spatial analysis and retrieval. Semantic modeling technology has a wide range of applications in urban planning, disaster response, energy assessment, and other fields, providing strong support for various applications based on spatial data, making the 3D construction of urban buildings more accurate and easy to manipulate[5].

4.3. Texture Mapping Technology

Texture mapping technology in the field of 3D modeling is the core means to enhance the surface texture and realism of models. This technology accurately projects flat patterns or textures onto the surface of a three-dimensional building model, successfully reproducing the rich textures of diverse building materials such as stone, glass, and concrete. Under the CityGML technology framework, the application of texture mapping technology enhances the visual appeal of building models and significantly increases their potential for practical engineering applications, becoming a key tool in architectural display, urban planning, and virtual reality experiences. Texture mapping technology integrates the geometric information and texture coordinates of the model, and achieves seamless integration between texture and surface by implementing coordinate transformation and precise anchoring on the model surface. With the development of technology, texture mapping can optimize texture display and enhance the expressiveness of 3D models based on real-time factors such as changes in lighting and observation angles. The use of image compression and optimization methods in constructing large-scale urban building models ensures the portability of the models, reduces the consumption of system resources, and ensures smoother display and interaction of building models on different platforms[6].

4.4. Data Conversion and Interoperability Technologies

In CityGML's urban 3D modeling, data conversion and interoperability techniques are crucial to achieve seamless integration and sharing between different data formats and systems. Data conversion typically involves converting three-dimensional data in other formats (such as CAD or GIS data) into the CityGML standard format, ensuring that different systems and platforms can use the same set of data together. In this process, geometric, semantic, texture and other information must be accurately transformed to avoid data loss or errors.

Table 1. The main differences between different data formats when converting to CityGML format

Data type	raw format	CityGML support	data loss rate
Geometric information	CAD format	fully supported	0%
Semantic information	GIS format	partially supported	10%
Texture information	3D model format	fully supported	5%

Observing the table data, it can be seen that lossless effects can be achieved when converting geometric data. However, due to the different semantic and texture information between source formats, there is inevitably a certain degree of data loss during the conversion. In order to reduce errors during the conversion period, it is generally necessary to preprocess and improve the data beforehand. Interoperability technology refers to the ability of various software systems, hardware devices, and databases to achieve data interoperability and exchange. CityGML has adopted universal standards and achieved seamless integration with numerous GIS, BIM, and 3D design tools, greatly enhancing its applicability value in multi departmental and multi platform cooperation. With excellent data conversion and interaction technology, CityGML has been widely applied in various fields of urban management, planning, and evaluation, improving the efficiency and convenience of 3D city construction[7].

5. Conclusion

CityGML technology plays a key role in the three-dimensional construction of urban buildings, contributing standardized tools for urban planning, administrative management, and emergency response strategies. By utilizing geometric shape construction, semantic information encoding, texture mapping, and other methods, CityGML 3D models can comprehensively display the rich details of urban architecture and its surrounding environment, enhancing the informatization and meticulousness of urban management. It is necessary to deepen technological exploration and practical application, continuously improve modeling processes, enhance model accuracy and operational efficiency, and provide more solid technological support for urban management teams. Promote seamless integration between CityGML and various urban information management systems, further enhancing the practical value of 3D modeling in the field of urban planning and management.

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