The Concept of Levels of Detail for 3D Niche Models in CityGML

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Abstract

Buddhist niches in grottoes can be represented in three-dimensional (3D) for their detailed geometries on surfaces by using triangular meshes generated from point clouds. However, not all applications require 3D models with high geometric detail. The mesh models of niches have drawbacks such as large data volumes, lack of semantic information, and absence of spatial relationships between structural components and members within niches. Those limitations make mesh models suitable only for visualization and challenging to use directly in tasks like spatial analysis, simulation experiments, mechanical analysis, and disease investigation. To address this problem, this study defines four Levels of Detail (LoDs) for Buddhist niches, ranging from LoD0 to LoD3, drawing on the concept of LoDs for urban buildings in CityGML 3.0. As the LoD level increases, 3D models contain more detailed geometries, including spatial points, bounding boxes, niche structural components, and component members. Those 3D models at different LoDs can represent niches with varying degrees of abstraction, making them suitable for different applications and guiding the production of standardized 3D semantic models. To validate the feasibility of the LoDs definition for Buddha niches, this paper reconstructs 3D models of niches at different LoDs based on high-precision mesh models. Finally, a comparison is made between the original mesh model and models at different LoDs in terms of data size and potential application scenarios.

1. Introduction

Buddhist niches are an important category in grottoes, widely distributed across East Asia and South Asia, holding immense historical and cultural value. Currently, the three-dimensional (3D) modelling of Buddhist niches with complex geometric shapes typically employs triangular mesh models generated using 3D laser scanning (Yastikli, 2007) and computer vision (Aicardi et al., 2018) technologies. The 3D mesh models produced by these technologies often have a large volume of data, easily reaching millions of vertices and faces (Remondino, 2003; Tommasi et al., 2016), consuming significant storage space, and requiring high computational power for interactive visualization. Moreover, triangular mesh models, primarily used for visualization (Lafarge and Mallet, 2012; Wang et al., 2018; Yang et al., 2022), lack the ability to integrate semantic information and struggle to model the spatial relationships of structural components within niches. Hence, these 3D models are unsuitable for applications requiring spatial analysis, simulation experiments, mechanical analysis, disease investigation, and virtual restoration (Yang et al., 2021; Yang et al., 2023). The required level of abstraction for 3D geometric models of niches varies across different studies, such as spatial distribution, geomechanical analysis, landscape design, and planning. Therefore, it is necessary to construct 3D models at different Levels of Detail (LoDs) according to actual application requirements to facilitate easy use by stakeholders in the digital environment (Biljecki et al., 2016c; Ergun et al., 2023). Although a study has virtual classified structural components and components members when constructing 3D semantic models of grotto scenes (Yang et al., 2024), there is still no clear definition of LoDs.

The Open Geospatial Consortium (OGC) CityGML standard is an interoperable data model for the representation of semantically enriched virtual 3D city models (Gröger and Plümer, 2012). One of the main characteristics of CityGML is the LoDs concept. Based on the CityGML standard, LoDs define a series of different abstract representations of real-world objects and suggest how thoroughly they are acquired and modelled (Biljecki et al., 2014). The models at different LoDs are employed to describe the intricacy of urban models currently in use and their appropriateness for specific applications. These models can differ significantly in terms of geometric and semantic intricacies, as well as the extent of their divergence from real-world counterparts. Levels of complexity result from specific methods of data collection or might serve to evaluate the relevance of data for certain applications (Löwner et al., 2016). Therefore, the concept of LoDs primarily serves to differentiate 3D models created by diverse production workflows, driven by semantics and geometry (Biljecki et al., 2016b).

In this study, four LoDs (i.e., LoD0-LoD3) are defined to represent Buddhist niches by analysing the need for the degree of abstraction of 3D models in practical applications. Furthermore, as an example, we constructed 3D models of a niche at LoD0-LoD3 and provided potential application scenarios for each LoDs. The definition of LoDs for niches not only improves the accessibility and utility of 3D representations but also helps enable more applications in the CityGML environment.

2. Related Work

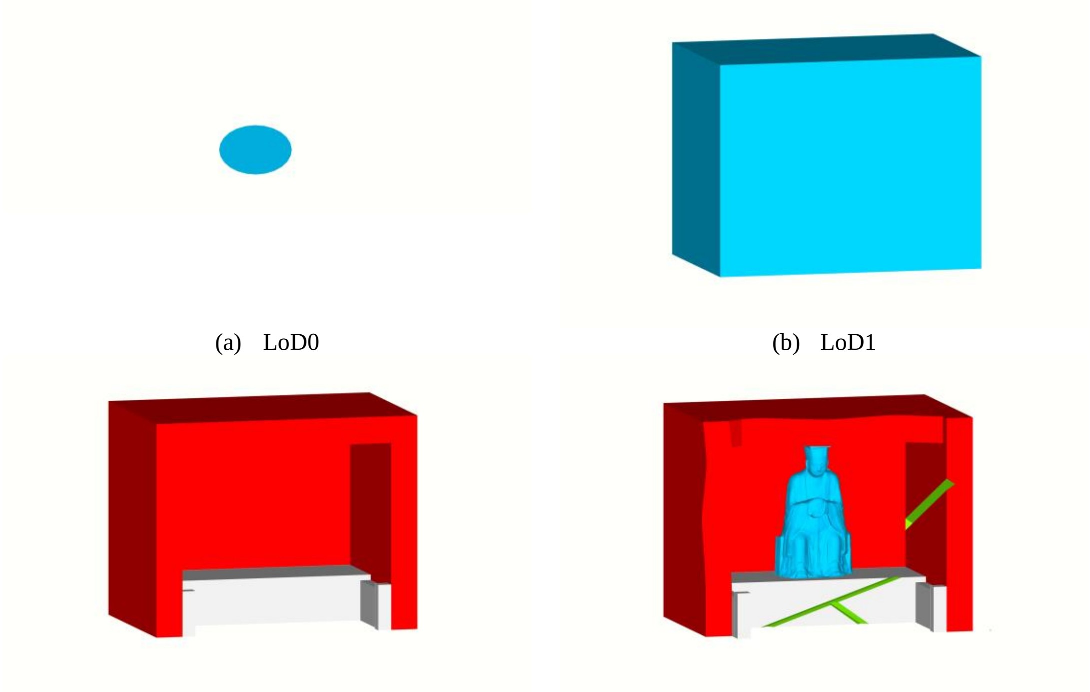
The development of CityGML has been a significant endeavour in the field of urban geographic information, providing a standardized data model for the representation and exchange of 3D city and landscape data. Originating as an initiative to address the need for a common model for 3D city modelling, CityGML has evolved to become a pivotal standard within the domain of geospatial data modelling (Biljecki et al., 2015; Kolbe, 2009).

Several key studies have contributed to the understanding and implementation of LoDs in CityGML. Biljecki et al. (2016a) were instrumental in proposing a procedural modelling engine called RANDOM3DCITY, designed to generate multi-LoD 3D city models in CityGML, addressing the gap in the availability of diverse LoDs datasets. This work facilitated the generation of detailed urban models and highlighted the potential of CityGML in supporting simulations and analyses across different scales of urban detail. Boeters et al. (2015) defined the LoD2+, which extends the CityGML LoD2 specification to make the indoor building geometries as complex as the exterior geometries. Labetski et al. (2018) proposed refinements to the network representation of roads in CityGML based on an analysis of the needs for transportation modelling, navigation, and road maintenance, to meet the application requirements of urban transportation. Liang et al. (2016) categorized 3D tree models into five LoDs considering the richness of the tree attributes and the cost of field data acquisition.

Currently, the definition of LoDs in CityGML mainly pertains to entities within urban scenarios. To the best of our knowledge, there has been no study on the concept of LoDs for modelling niches in 3D. Carved by humans into natural mountains, niches embody a blend of cultural and geographical elements, and their structural components differ significantly from urban objects. Similar to the demand for 3D models of multi-LoDs in urban scenes arising from urban management and public services, the LoDs of niche modelling are oriented towards the diverse needs of 3D models for cultural heritage conservation. The LoDs for niches in cultural heritage differ from objects in urban areas because their cultural values and preservation needs are distinct. For example, a replicated modern sculpture in an urban scene may not require much detail for representation, whereas sculptures in niches hold high historical and cultural value, necessitating disease investigation and preventive protection. Therefore, this paper defines LoDs for niches based on the demands for geometric detail in different applications.

3. Four LoDs for Niche

Although there exist obvious differences in form and structure between buildings and niches, the LoDs classification scheme for 3D building models in CityGML provides a useful reference for niches. Significant changes in the definition of LoDs have emerged from CityGML 2.0 to CityGML 3.0 (Kutzner et al., 2020). The latest 3.0 standard defines four LoDs (LoD0-LoD3) for city buildings. LoD0 represents a simple footprint, such as the projection of a building. LoD1 is a coarse prismatic (block) model, offers a basic volumetric shape. LoD2 introduces structural details, including roof shapes and major structural components. LoD3 provides a highly detailed geometric representation, featuring fine appearance details and architectural elements. This study categorizes the LoDs of niche models into four levels, highlighting the classification's rationality from the perspective of practical application requirements. Yang and Hou (2023) provided knowledge of niche structural components and component members in the context of knowledge graph-based grottoes knowledge representation, laying the foundation for LoD2 and LoD3 in this study. Figure 1 shows the defines of different LoDs for the niches.



(a) LoD0 (b) LoD1

(c) LoD2 (d) LoD3 (The green areas are diseases)

Figure 1. Representation of the same real-world niche in the LoD0-LoD3

3.1 LoD0

LoD0 is a spatial point with the geographical location, represented by latitude, longitude, and elevation. This level facilitates foundational information management (e.g., address, period, and theme), spatial distribution, and examination of spatiotemporal evolution patterns of Buddhist niches in the macro area of a large scene. For example, Runze (2023) explored the spatial distribution characteristics and evolution patterns of grottoes in Gansu, China, from the Wei-Jin dynasty to the Ming-Qing dynasty, discussing the main factors affecting their distribution. Xu et al. (2023) focused on the spatial distribution of grottoes in Anyue County, Sichuan Province, integrating various geospatial data such as water systems and elevation, and employing GIS spatial analysis methods to explore the distribution patterns.

3.2 LoD1

LoD1 represents a niche as a bounding box depicting its length, height, and depth. This level is used for disaster risk assessment, landscape design, and planning, where only the approximate sizes and shapes of niches are needed while their exact topologies and spatial extents are required. For example, employing 3D box models generated from building ground contours and height values can improve the efficiency of viewshed analysis in urban heritage conservation areas (Lopes et al., 2019). Utilizing hydrodynamic models for simulating flood scenarios in heritage areas shows that highly detailed 3D models are unnecessary to assess the flood impact on historical constructions (Li et al., 2017). Fanti et al. (2013) considered buildings as volumetric models to analyse the potential threat of rockfalls to the hilltop ancient towns.

3.3 LoD2

LoD2 represents a model with structural components such as niche eave, cliff wall, cliff wall footing, and ground, modelled as standardized shapes. This model can be applied to structural stability analysis and deformation detection without the need for geometric details of the components. For instance, Ursini et al. (2022) used point clouds from 3D laser scanning to create parametric Historic Building Information Modelling (HBIM) products and construct finite element models for dynamic simulations. Pepe et al. (2020) developed a pipeline from point clouds to structural analysis, applying it to historical structures. In these processes, point clouds were reconstructed to parametric 3D models, and geometric details that were not required were disregarded.

3.4 LoD3

LoD3 is a detailed model with components of a niche, namely, Buddha statues, geometric patterns with Buddhist significance, accessories (e.g., stone tablet), and diseases suitable for close observation scenarios such as disease investigation, virtual restoration, and knowledge dissemination. Hou et al. (2018) analyzed the spatial distribution of Avalokiteshvara's hands on a cliff wall for virtual restoration based on computing the similarity to restore missing areas. Hua et al. (2021) examined the similarity between Buddha statues on cliff walls, offering important references for assessing the preservation of Buddha statues. Documenting geometrically shaped diseases is crucial for cultural artifact conservation. Giaccone et al. (2020) discussed the impact of geometric models on the structural analysis of columns, where cracks are a critical factor affecting analysis. LoD3 can be utilized for detailed documentation of disease investigation, allowing for the determination of disease progression trends through long-term observation, thereby facilitating the development of corresponding conservation plans.

4. Niche LoDs Generation

This section describes how to derive 3D models at coarse LoDs from the most detailed 3D mesh model.

(1) From the most detailed 3D mesh model to LoD3

In the model reconstruction process, the first step involves segmenting all structural components, component members, and accessories from the original 3D mesh model. Depending on the geometric complexity of different elements, each geometric primitive undergoes mesh reconstruction to reduce the number of vertices and faces in the model. This step ensures that LoD3 retains detailed features while optimizing the model for efficiency.

(2) From LoD3 to LoD2

Based on LoD3, component members and accessories are removed, retaining only the structural components of the niche. These structural components are then reconstructed into more regular geometric shapes. This simplification helps in focusing on the main structural elements necessary for analysis while reducing model complexity.

(3) From LoD2 to LoD1

By calculating the 3D bounding box of the LoD2 model, the model is transformed into a rectangular prism, consisting of 8 vertices and 6 faces. This bounding box represents the 3D space occupied by the niche, providing a simplified volumetric representation suitable for applications where detailed geometry is not required.

(4) From LoD1 to LoD0

The 3D bounding box is converted into a spatial point, which represents the niche's spatial location in the real world. This point includes geographical coordinates (latitude, longitude, and elevation), facilitating the use of basic spatial data for foundational information management and broad spatial analysis.

5. An Example of LoDs Implementation

This section takes a specific Buddhist niche in the Anyue Grottoes of Sichuan Province, China, as a case study to construct 3D models of the niche at four LoDs (LoD0-LoD3). The high-precision irregular triangulated mesh model of the niche was created using computer vision techniques. As illustrated in Figure 2, the models from LoD0 to LoD3 were built in SketchUp Pro 2022, resulting in a set of 3D models at different levels of abstraction. Since SketchUp does not support standalone spatial points, LoD0 is represented by a small circular area as a substitute. Figure 3 shows the comparison of the data volume, vertices, and faces between the original mesh model and the different LoDs models. These 3D models at various LoDs can be easily integrated into the CityGML environment, significantly enhancing their utility in a wide range of application scenarios. Table 1 lists the potential applications for models at different LoDs.

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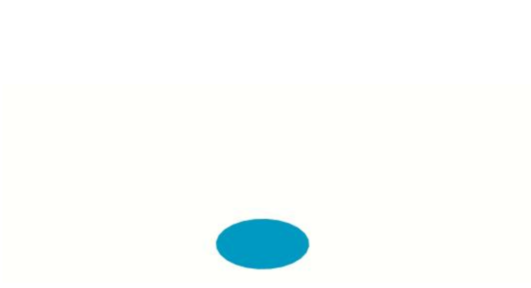
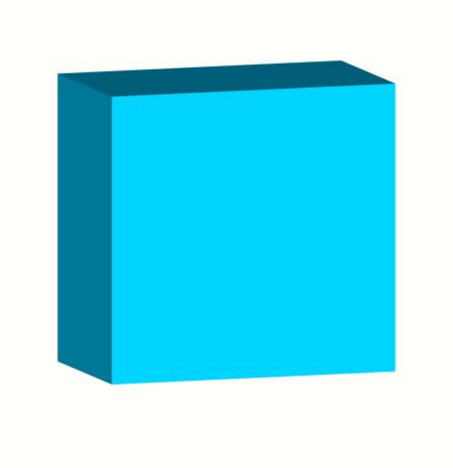
(a) Photograph of the Niche

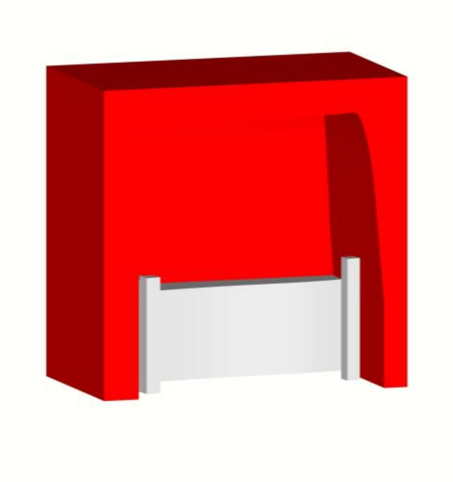
(b) Original model



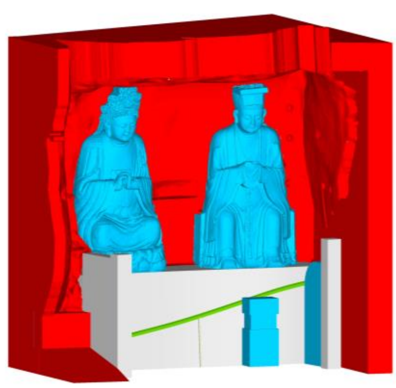
(c) LoD0



(d) LoD1



(e) LoD2



(f) LoD3 (The green areas are diseases)

Figure 2. A niche in Anyue grottoes modelled in LODs.

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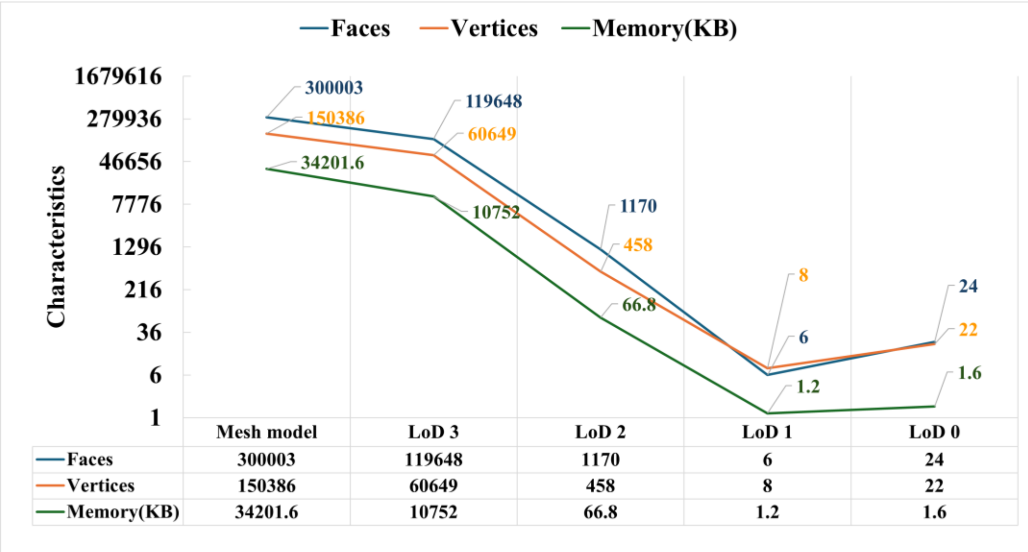

Figure 3. Characteristics of 3D mesh models with different LoDs

Family	Potential applications
Mesh model	Digital documentation, precise geometric analytics, high-fidelity visualization, video production, virtual tours.
LoD0	Spatial information querying, spatial pattern analysis, large-scale natural disaster impact analysis (e.g., tornado, rainstorm, sea level rise, earthquake impact range of cultural relics).
LoD1	Detailed disaster simulation (e.g., mudslides, floods, falling rocks), landscape planning and design (e.g., viewshed analysis).
LoD2	Structural stability assessment, rock mechanics analysis, structural deformation studies.
LoD3	Virtual restoration, detailed analysis of Buddha statues and geometric patterns, disease management, disease analysis and spatial distribution, digital archaeology report production.

Table 1. The potential applications of LoDs

6. Conclusion and Future Work

This paper proposes the concept of LoDs for Buddhist niches in grottoes and demonstrates the construction process of 3D models at different LoDs using a specific 3D niche model as an example. The high-detailed 3D models enable exceptional visualization, but the purpose of model creation goes far beyond that. Optimized 3D models tailored to specific application requirements not only enhance the rendering performance of application software and reduce latency caused by network transmission but also decrease the computational load during simulation and analysis processes, ensuring smooth operation across devices with varying performance capabilities. This is particularly important since not all cultural heritage institutions or individual users are equipped with high-performance computing resources. Moreover, defining LoDs appropriately provides explicit guidance for data production in the field of cultural heritage, aiding in the standardization and systematization of data processing work within this domain. In the future, we have three main tasks: (1) Separating structural components and members in point clouds is a very time-consuming task. Studying automatic semantic segmentation methods for Buddhist niches point clouds can speed up this process. (2) It is necessary to clarify the error tolerance between each level of LoDs and the real object (the original point cloud) and to integrate this into the workflow of multi-LoD 3D modelling. (3) Developing a method to automatically generate 3D models of each LoDs from the original point cloud will improve the efficiency of modelling.

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