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A semantics-constrained profiling approach to complex 3D city models

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ABSTRACT

A complex 3D city model contains detailed descriptions of both its appearance and its internal structure, including architectural components. Because of the topological complexity and the large volumes of data in such models, profiling is an effective method to present the internal structure, the distributed characteristics, and the hierarchical relationships of the model to provide intuitive visual information to the viewer and to reveal the relationships between the elements of the model and the whole. However, with commonly used boundary descriptions, it is difficult to comprehensively preserve the consistency of three-dimensional profiling using existing algorithms based on geometric constraints. This paper proposes a novel semantics-constrained profiling approach to ensure the consistency of the geometrical, topological, and semantic relationships when profiling complex 3D city models. The approach transforms the 3D model's boundary description, defined using the CityGML standard of the Open Geospatial Consortium (OGC), into a set of unified volumetric features described as solids. This approach is characterized by (1) the use of the concepts of semantic relationships, virtual edges, and virtual surfaces; (2) the semantic analysis of 3D models and the extraction of volumetric features as basic geometric analytic units; (3) the completion of structural connectivity and space coverage for each volumetric feature, which is represented as a solid model; and (4) the use of a reliable 3D Boolean operation for efficient and accurate profiling. A typical detailed 3D museum model is used as an example to illustrate the profiling principle, and the experimental results demonstrate the correctness and effectiveness of this approach.

1. Introduction

As the increasing complexity of a 3D city model makes the perception and understanding of the model more difficult (Glander & Döllner, 2009), profiling is an effective exploratory method used to present the internal structure, the distributed characteristics and the hierarchical relationships of the model to provide intuitive visual information to the viewer and to reveal the relationships between the elements of the model and the whole. Both geometrical and topological consistencies are important concerns when evaluating the effectiveness of profiling analysis. Consistency is not only an important aspect of spatial data quality (Gröger & Plümer, 2011a) but also a crucial prerequisite for many relevant applications of 3D city modeling (Gröger & Plümer, 2009). However, 3D city models that satisfy the CityGML standard are characterized by a unified multi-level representation of the geometrical, topological and semantic relationships (Zhao, Zhu, Du, Feng, & Zhang, 2012) with high coherence. The complexity of this coherence is greater at higher levels of detail (Stadler & Kolbe, 2007). For example, a 3D city model specified at the LoD4 level of detail of CityGML contains a detailed description of both the appearance and the internal structure, including the architectural components (Zhao et al., 2012). The profiling of such enriched 3D city models requires an integrative updating of the outer hull and the interior structures as well as the interior space; additionally, the profiling involves the joint updating of the geometry and its associated semantics as well as their relationships. Consequently, achieving consistent profiling is a basic and critical requirement for applications of complex 3D city models because the results produced by consistent profiling can support further analysis such as thematic queries and volume measurements.

CityGML provides three options for LoD4 models to represent the interior volumetric features: solids, independent discrete thematic boundary surfaces, and both solids and thematic boundary surfaces. The second option, termed as the 'boundary description' in this paper and typically obtained from CAD models, is most often used when a high degree of detail is needed in a model. The boundary description is commonly used not only because CAD models are an important data source for cyber GIS (Kofler, Rehatschek, & Gruber, 1996) but also because, compared to other modeling approaches using accurate measurement techniques, CAD models have advantages when displaying complex internal structures (Zhu & Lin, 2004). However, because this discrete representation is topologically complex, it is difficult to comprehensively preserve

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the consistency of the 3D profile when using existing profiling algorithms based on geometrical constraints, which are derived using computational geometry from vector models such as polygonal meshes and solids (Herring, 2001). Inconsistency in open structures (Fig. 1b) and insufficient topological connectivity between related elements (in this paper, complete topological connectivity means that a volumetric feature is represented by complete closed and continuous boundaries) (Fig. 1c) result in the computational problems of incomplete and inconsistent geometry and topology. These factors influence the completeness of the profiling of volumetric features such as rooms with openings for windows and doors.

Existing profiling algorithms based on vector models can be divided into two broad categories: cutting algorithms for polygonal meshes with open borders and profiling algorithms for solid models bounded by closed surfaces.

The first category, cutting algorithms for polygonal meshes with open borders, typically includes incremental algorithms based on edge swapping (Anglada, 1997), classic marching cubes (MC) algorithms (Hoppe, 1996; Lorensen & Cline, 1987; Zhou, Chen, & Tang, 1995), double-edge cutting algorithms (Tang, 1999) and active-points cutting algorithms (Nienhuys & Frank Van Der Stappen, 2004). These algorithms use a single continuous mesh with open borders as the main calculation unit and result in cross sections or split meshes. To calculate profiles, such algorithms require a consistency check of the outlines according to the geometrical topology of the cross sections. The drawbacks of these methods are their high computing cost, which results from the large volume of data, and the potential for topological ambiguity in the intersecting lines produced by complex models and scenes with a wide range of features, aggregate elements, complex topological relationships and mixed graphic element types. These methods are especially likely to produce logical errors because of their incomplete topological connectivity when highly detailed features composed of aggregating elements are profiled. Even when semi-automatic processing is used, degraded or approximately degraded intersecting lines are difficult to identify.

The second category of algorithms, which are always represented as 3D Boolean intersection predicates, addresses two key problems: spatial intersection and geometrical reconstruction. The related research focuses primarily on improving the efficiency of the intersection computation by providing collision detection through a special index (Gottschalk, 2000; Sun, Li, Tian, & Li, 2009; Yang, 2010); this approach has been used to reduce the dimension using projection (Zhang & Zhang, 2010), to simplify the intersecting objects using space partitioning (Yang, 2010) and to design a topological data structure to improve efficiency and stability (Granados et al., 2003). Although these methods can produce profiles with regular mathematical rules and clear topological relationships, they perform well only in cases in which a single model or model element is rigorously 2-manifold, and they cannot handle the diverse geometrical types in complex 3D city models, especially in complex building models such as LoD4 models. Consequently, the methods usually result in a series of discrete surfaces, and the methods have difficulty preserving volumetric features. Additionally, some effective algorithms used in mainstream modeling software, such as the Computational Geometry Algorithms Library (CGAL, 2010), are dependent on additional topological conditions that are not included in the records of general 3D city models.

As mentioned above, because of the complexity of 3D city models, the critical issue when using existing geometrical profiling algorithms is how to preserve the consistency of coherent geometrical, topological, and semantic relationships. Consistency refers not only to the coherent semantic-geometric representation designed using the principles of CityGML (Stadler & Kolbe, 2007) but also to complete space coverage using semantics with a specific demarcation of the geometry in 3D space (Gröger & Plümer, 2011b). Furthermore, consistency requires topological completeness in the 3D space, including a seamless topological connection within the closed boundary surfaces of each volumetric feature and all aggregating elements. However, each spatial element of a 3D city model can be defined as a corresponding volumetric feature, such as a wall or a room, in the semantic description, and also have a coherent and valid geometrical description for the purpose of modeling continuous and closed boundaries with specific demarcations. Therefore, the key problem in consistent profiling is to completely calculate correct profiles with specific and proper semantics and to preserve the correct model structures of all of the volumetric features, specifically avoiding the reduced dimensionality of geometric models resulting from incomplete boundaries. In this way, the ability to support further analyses, such as thematic queries, is maintained.

This paper proposes a novel semantics-constrained profiling approach to ensure the consistency of the geometrical, topological,

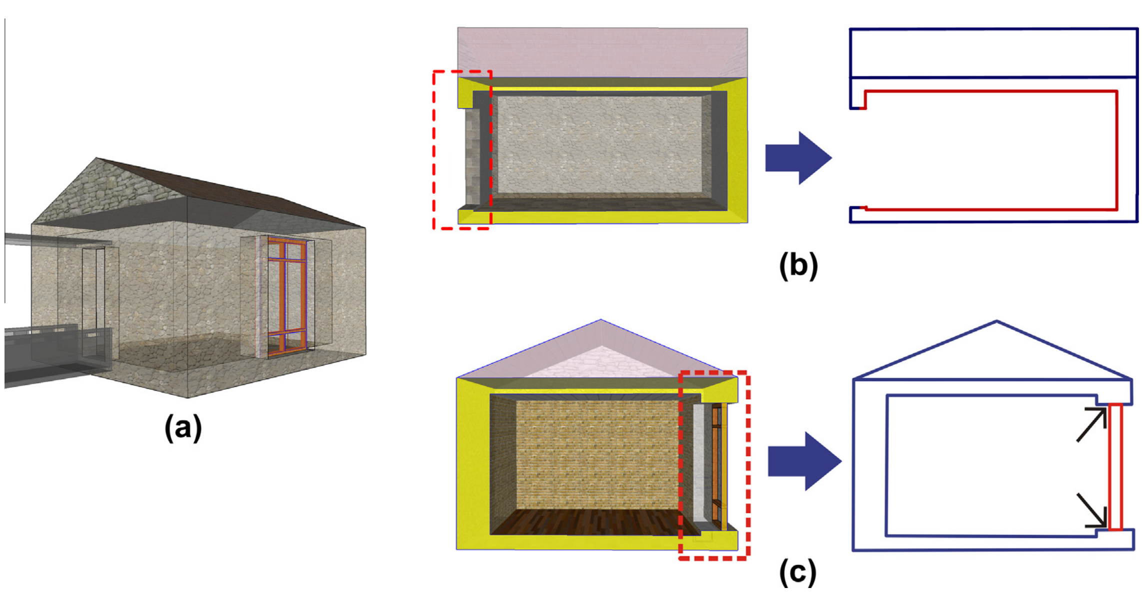

Fig. 1. Inconsistency problems in 3D building model profiling.