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Consistency constraints and 3D building reconstruction

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ABSTRACT

Virtual architectural (indoor) scenes are often modeled in 3D for various types of simulation systems. For instance, some authors propose methods dedicated to lighting, heat transfer, acoustic or radio-wave propagation simulations. These methods rely in most cases on a volumetric representation of the environment, with adjacency and incidence relationships. Unfortunately, many buildings data are only given by 2D plans and the 3D needs varies from one application to another. To face these problems, we propose a formal representation of consistency constraints dedicated to building interiors and associated with a topological model. We show that such a representation can be used for: (i) reconstructing 3D models from 2D architectural plans (ii) detecting automatically geometrical, topological and semantical inconsistencies (iii) designing automatic and semi-automatic operations to correct and enrich a 2D plan. All our constraints are homogeneously defined in 2D and 3D, implemented with generalized maps and used in modeling operations. We explain how this model can be successfully used for lighting and radio-wave propagation simulations.

1. Introduction

Before construction, buildings are often virtually represented in 3D so as to design a site and conduct studies related to lighting, heat transfer, radio-waves propagation, and so on. These environments are composed of a set of 3D geometric primitives with various types of additional information to expand their use: adjacency relationship between volumes, object types, or material properties used for building construction.

Many simulation programs cannot rely on commercial modeling software because their internal structure is not available. Consequently for each scene, the user has to manually pre-process the model in order to make it compatible with the required representation. This is why some integrated prototypes both build a 3D model and apply the simulation process [1]. However, the representation is not sufficiently generic for being used in different applications. To our knowledge, there is no common framework for both modeling indoor scenes and applying various types of simulations.

In this paper, our aim is to propose a representation of buildings homogeneous in 2D and 3D, taking geometry, topology and semantics consistency into account. The model should be generic enough to be used in as many applications and simulation systems as possible. To do this, we formally define a set of constraints adapted to most common buildings. Generalized maps (*G*-maps [2]) are used as a topological basis and our definitions rely on their terminology. We also propose a semi-automatic reconstruction pipeline for generating 3D buildings from 2D architectural plans (see Fig. 1). Our main contributions are:

- a formal description of constraints providing a generic representation of geometry, topology and semantics of architectural indoor environments;
- the use of these constraints for automatically reconstructing 3D buildings from 2D vector plans, including topology and semantics;
- a set of semi-automatic operations used to detect and correct errors in the 2D plans before 3D construction.

The resulting scenes can be edited with a general modeler based on *G*-maps [3]. In addition, cell and portal structures often used in the context of large buildings [4–8] can be naturally produced from our structure. We have also produced files for radio-wave propagation simulations used in our laboratory [9,10] (Section 7).

This paper is organized as follows. Sections 2 and 3 present the existing methods in 3D architecture and describe *G*-maps. Section 4 presents our consistency constraints. Section 5 provides the 2D processing of an architectural vector plan. Section 6 explains how we detect and correct errors. Sections 7 and 8 present and discuss our results.

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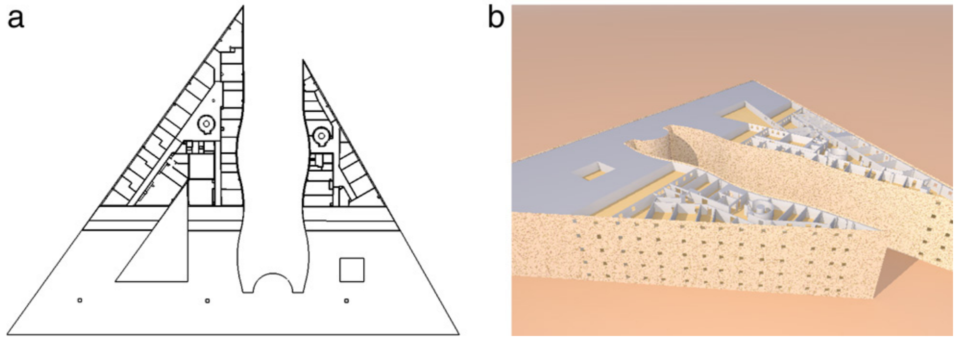

Fig. 1. (a) Building 2D plan; (b) 3D reconstruction with proper topology and semantics.

2. Related work

Topological models
We wish to represent large buildings, actually corresponding to 3D topological objects, made up of vertices, edges, faces and volumes which do not necessarily have regular shapes. Many topological models have been proposed in the literature for handling different classes of subdivisions (oriented surfaces, manifold, non-manifold, etc.) in any dimension. Examples of such structures are adjacency graphs [11], ordered models (as defined in [12]), 2D or 3D edge-based models [13–15] or higher-dimensional models [12,2].

Adjacency graphs (such as [11]) do not allow multi-incidence (see [2]). Moreover, the topological correctness of the model is difficult to express [16]. This is the reason why ordered models have been introduced. They are mainly defined with a single type of basic elements and links between these elements [12,2].

For the reasons explained above, we choose an ordered topological model. Complexity studies have shown that for 2D and 3D manifold (surface subdivisions or volume subdivisions), costs for representing an ordered model and an incidence graph are comparable [17]. This is even more true when taking geometry, photometry and other attributes into account.

Buildings are composed of volumes (floors, walls, rooms, etc.) sharing faces. Topologically speaking, it corresponds to 3D orientable manifolds. In [18], it has been shown that models defined to represent 3D manifolds are comparable either to 3D map (for orientable ones without boundaries) or to 3D Generalized maps (for orientable or not orientable ones, with or without boundaries). Generalized maps are defined homogeneously in any dimension, so that operations implemented in 2D can be naturally extended in 3D or in higher dimension.

Analysis of architectural bitmap images
Several methods have been proposed for reconstructing 3D buildings from existing images of 2D architectural plans (i.e. bitmap images) [19,20]. Bitmap images contain low-level geometrical and semantical information and before reconstruction, the first step is extracting richer information. However, the vectorization process usually employed to this task does not provide any topological information.

Even though the 3D reconstruction can be achieved with these methods, none of them does provide any topological information. However, these types of analyses are complementary to our work since much semantic information can be automatically deduced from images.

Google Earth [21], the French National Geographic Institute (IGN) [22,23] and other authors [24–26] also propose frameworks used to rebuild the geometry of real urban scenes based on various types of images (satellite, aerial, ground, etc.). Again, no topological information is produced with these approaches.

3D building analysis
Some authors have also proposed to extract topological information from a list of polygons, making it possible to reduce visibility calculations for lighting simulation and visualization. Airey et al. and Teller et al. [5,6] propose a binary space subdivision method (Binary Space Partitioning or BSP) while Meneveaux et al. [27] propose a method using rules for extracting rooms of buildings. These subdivision schemes produce a set of regions called *cells*, separated by openings (*portals*); the topological description corresponds to adjacency relations between 3D cells. However, this model does not provide any incidence/adjacency relations between lower-dimensional elements.

Building modelers
Fradin et al. [28] propose a building modeler for manually designing complex indoor scenes. The topological structure relies on *G*-maps, with hierarchy and multi-partitions, also adapted to various types of simulations [8,29]. The topological basis is also *G*-maps, but does not include any consistency constraints specifically related to architecture. Moreover, the operations defined in this modeler are designed so that the user has to construct the whole 3D building manually, without the benefit of using existing 2D data.

Several industrial software [30,31] propose to design 2D plans and/or 3D buildings. Many operations are provided such as: walls, stairs, or doors drawing; boolean operations; extrusion, revolutions and so on. However, even though those software allow us to construct 2D plan and 3D buildings simultaneously, they still do not provide any topological representation nor consistency control (superimposed walls, disjoint segments, and so on).

Many actors in architectural business need to share information for formalizing electronic documents. To this end, the IFC (Industry Foundation Classes) have been proposed recently. Since the first version appeared in 1997, more and more applications have employed this formalism. However, the associated file format essentially contains semantical information; it has not been defined for representing low-level topological relationships, which are necessary for many modeling operations such as those described in this paper.

Procedural modeling
Procedural systems which do not require any manual intervention have been used to produce urban scenes. Several authors propose applications for randomly constructing realistic (but not real) virtual cities and facades [32–35]. Unfortunately, these programs only produce cities and buildings geometry, without topology. In addition, reproducing a real environment is not possible due to the random processes applied.

Discussion
Many tools are dedicated to the (re)construction of 3D architectural environments. Some of them are dedicated to simulation, but