ISPRS Journal of Photogrammetry and Remote Sensing 64 (2009) 575–584

Contents lists available at ScienceDirect

ISPRS Journal of Photogrammetry and Remote Sensing

journal homepage: www.elsevier.com/locate/isprsjprs

Knowledge based reconstruction of building models from terrestrial laser scanning data

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ARTICLE INFO

Article history:
Received 19 August 2008
Received in revised form
15 April 2009
Accepted 16 April 2009
Available online 9 May 2009

Keywords:
Building reconstruction
Terrestrial laser scanning
Feature extraction

ABSTRACT

This paper presents an automatic method for reconstruction of building façade models from terrestrial laser scanning data. Important façade elements such as walls and roofs are distinguished as features. Knowledge about the features' sizes, positions, orientations, and topology is then introduced to recognize these features in a segmented laser point cloud. An outline polygon of each feature is generated by least squares fitting, convex hull fitting or concave polygon fitting, according to the size of the feature. Knowledge is used again to hypothesise the occluded parts from the directly extracted feature polygons. Finally, a polyhedron building model is combined from extracted feature polygons and hypothesised parts. The reconstruction method is tested with two data sets containing various building shapes.

1. Introduction

Various society fields demand realistic 3D city models. For urban planning, analyzing in a 3D virtual reality world is much more efficient than imaging the 2D information on maps. For public security, accurate 3D building models are indispensable to make strategies during emergency situations. Navigation systems and virtual tourism also benefit from realistic city models.

Manual creation of city models is undoubtedly a rather slow and expensive procedure, because of the enormous number of buildings and complexity of building shapes. The rapid development of cities also adds to the cost of manual city model updating. Nowadays, a lot of research has been done to automate the procedure of city reconstruction, and a number of approaches have been proposed. These approaches differ with respect to input data, automation level, and object representation.

Commonly used input data for city reconstruction include airborne images (Suveg and Vosselman, 2004; Taillandier and Deriche, 2004), close-range images (Dick et al., 2001; Schindler and Bauer, 2003), airborne laser scanning data (Maas and Vosselman, 1999; Haala and Brenner, 1999), terrestrial laser scanning data (Frueh et al., 2005; Pu and Vosselman, 2006; Beck and Haala, 2007) and video (Pollefeys et al., 2007). Airborne data usually covers large urban areas. Structures on roofs and grounds can be well recorded with airborne systems. In contrast, close-range systems, or terrestrial systems record information from building façades, but can hardly reach buildings' tops. A number of researches achieved promising reconstruction by integrating different data sources, where 2D map data is sometimes used to extract building outlines.

Some approaches (Suveg and Vosselman, 2004; Frueh et al., 2005; Beck and Haala, 2007) achieve fully automatic reconstruction processes. Commercial packages such as Cyclone, Phidias and CC-modeler provide semi-automatic reconstruction functionalities. Some examples of the manual operations are: selecting key vertices for a pre-defined geometry model, selecting tie points for image matching, and intersecting of two faces to determine an edge.

The geometry of a reconstructed model can be described with boundary representation, constructive solid geometry (CSG) and spatial enumeration (Brenner, 2005). Compared to a spatial enumeration model, the size of a boundary representation model is far smaller, because only the vertices and their topology relations are stored. This in turn makes the visualization of boundary representation models much faster than spatial enumeration models. With CSG, a building model can be represented by combining some fixed primitives with Boolean operators (union, difference, and intersection). CSG guarantees the model is watertight, and requires fewer parameters than boundary representation. However, it is hard to represent complex buildings with CSG, because they are not easily composed from shape primitives. Only a few methods (Suveg and Vosselman, 2004; Haala and Brenner, 1999) fit CSG building models.

In this paper, we present a knowledge based approach which automatically reconstructs building façade models using terrestrial

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doi:10.1016/j.isprsjprs.2009.04.001

laser scanning data. As humans primarily perceive buildings from the ground, many structures (balcony, stairway, etc.) on building façades should be included in a realistic building model. Our approach takes the high density point cloud from terrestrial laser scanning as input data. Planar features are first extracted as segments from raw laser point cloud. They are further classified into various semantic features (wall, door, window, etc.) using generic knowledge of building façades. A concave or convex polygon of each semantic feature is then generated, which are also used to assume the geometry of occluded parts. A polyhedron building façade model, which contains both detailed geometry and semantic meaning, is finally combined from directly generated polygons and assumed polygons.

1.1. Previous work

Despite the slow data acquisition of terrestrial systems, a few building façade reconstruction methods have been proposed. From close-range images or terrestrial laser points, façade structures such as outlines and protrusions/intrusions can be automatically extracted and modeled. There are also attempts to recover façade structures from airborne images (Zebedin et al., 2006). However, as the airborne cameras have limited visibility of vertical facade planes, airborne images are more suitable for recovering structures on roofs than façades. In the following, three automatic methods which generate façade models are briefly discussed.

Frueh et al. (2005) present an early attempt which integrates terrestrial laser scanning and digital image to generate façade meshes. Laser point clouds are first used to generate depth images, and foreground (occlusion objects) and background (building façades) are distinguished by histogram analysis. TIN mesh models are generated from background points, and textured with selections from photos. The texture holes caused by occlusions are filled in with textures from similar areas. This approach achieves very high automation and realistic results, but no simple geometry shape (such as polygon) is reconstructed. The generated huge amount of triangles (every street contains millions of triangle and texture pieces) results in slow visualization.

Pu and Vosselman (2006) present an automatic approach to extract building façade features from a terrestrial point cloud. The method first defines several important building features based on knowledge about building façades. Then the point cloud is segmented to planar segments. Finally, each segment is compared with building feature constraints to determine which feature this segment represents. The feature extraction method works fine for all façade features except for windows, because there are insufficient laser points reflected from window glass. Therefore a hole based window extraction method is developed (Pu and Vosselman, 2007). Pu (2007) further explains the fitting of polygons to extracted feature segments and the merging of polygons to a complete façade model. An advantage of this approach is that semantic feature types are extracted and linked to the resulting models, so that (i) it is possible to get faster visualization by sharing the same texture for same feature type; (ii) polygons can be associated with various attributes according to its feature type. However, this approach still cannot extract features from complex buildings.

Beck and Haala (2007) reconstruct polyhedron models by integrating terrestrial laser points and digital photos. To achieve registration between laser point clouds and digital photos, intensity images generated from laser point clouds are used as a bridge. This turns the problem into an image–image registration problem, which is solved by the SIFT (scale invariant feature transform) algorithm (Lowe, 2004). Assuming that no laser points are available from windows, laser points on window edges can be determined, and horizontal and vertical window border features are further extracted. Edges extracted by a Sobel filter from digital photos are used to refine the windows edges. The resulting model contains window frames with even window crossbars, which looks quite realistic. Problems may arise when the laser point density is too low to reliably match digital images. Also the window shapes are limited to rectangles.

1.2. Presented approach

Our approach aims at reconstructing highly detailed polyhedron models from terrestrial laser scanned buildings, with a largely automatic process. Mainstream terrestrial laser scanning systems are able to record building façades with a density of hundreds of laser points per square meter or more, which is obviously dense enough to recover both façade contours and small details.

Reconstruction of buildings starts with recognition of structures in the raw data. Usually, the recognized structures are geometry features such as points, lines, or planes. In our approach, a higher level feature, the semantic feature, is defined, because we believe that understanding the meaning of each segment will support the façade reconstruction in several aspects. First, a point cloud often contains points which do not belong to the building façade (for example people walking by), or points of objects on the building which we do not want to include in the final model (for example flower pots behind windows). These points can be filtered out if we know that they do not belong to the building. Second, laser scanning can hardly scan a building completely. There are always occluded areas which cannot be reached by the laser beams. Knowledge can be used to fill these gaps by understanding the relations between the features surrounding the gaps, and guarantee a water-tight model. Third, a semantically labelled building model enables better visualization ability, by sharing the same texture in all polygons with the same feature, or assigning a pre-defined texture to a certain semantic type. Finally, a semantic labelled building model can be associated with more attributes (name, owner, floor, etc) according to the semantic types, which helps integration with object based geo-databases.

Fig. 1 shows our reconstruction process. This bottom-up process starts with segmenting a raw terrestrial laser point cloud, so that the first level of features: "geometry features", are extracted as segments. Then with the recognition rules defined from human knowledge, semantic features such as walls, windows, and doors are extracted from the geometric features. A polygon is then fitted to each semantic feature, which represents the contour polygon of this feature. Because there are always some occluded parts missing from the point cloud, the directly fitted contour polygons are insufficient for a complete solid model for a building. To fill in the occluded parts, assumptions are made based on generic knowledge about building shapes. The hypothesized polygons, together with directly fitted contour polygons, combine to the final polyhedron model of a building.

This paper is structured as follows: Section 2 explains the geometric and semantic feature extraction as well as the hole detection algorithm which is developed specially for window extraction. Section 3 first elaborates on how to generate outlines from extracted features and then describes the strategy for hypothesizing models of occluded parts. Our approach has been tested with two terrestrial laser data sets containing buildings. The results and quality analysis are given in Section 4. Some discussions are given in Section 5.

2. Feature extraction

In this section, we aim at extracting semantic features from terrestrial point clouds. The six semantic features are wall, door, roof, protrusion, intrusion and window, which are the most important elements on building façades.