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An update on automatic 3D building reconstruction

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ABSTRACT

The development of tools for the generation of 3D city models started almost two decades ago. From the beginning, fully automatic reconstruction systems were envisioned to fulfil the need for efficient data collection. However, research on automatic city modelling is still a very active area. The paper will review a number of current approaches in order to comprehensively elaborate the state of the art of reconstruction methods and their respective principles. Originally, automatic city modelling only aimed at polyhedral building objects, which mainly reflects the respective roof shapes and building footprints. For this purpose, airborne images or laser scans are used. In addition to these developments, the paper will also review current approaches for the generation of more detailed facade geometries from terrestrial data collection.

1. Introduction

The automatic reconstruction of urban 3D models became an important part of photogrammetric research almost two decades ago (e.g. Grün et al., 1995, 1997). Since these early beginnings numerous research papers on different reconstruction methods were published with quite a number of approaches emerging to commercial services and software (Brenner, 2005). As e.g. documented by the EuroSDR Building Extraction project (Kaartinen and Hyyppä, 2006), which aimed at a comprehensive test of commercial products and services, areas covering sets of 3D building models are commonly collected from photogrammetric 3D measurement using airborne stereo imagery or LiDAR. Some systems additionally support the extraction of building outlines as 2D map data. Available methods usually record the roof shapes and building footprints at the required detail and accuracy and then use this information to generate a geometric representation of the building in a subsequent step.

However, as Habib et al. (2010) point out: “digital building model generation of complex structures still remains to be a challenging issue”. Since fully automatic image understanding is very hard to solve, semi-automatic components are usually required to at least support the recognition of very complex buildings by a human operator. The difficulties of aerial image interpretation also motivated the increasing use of 3D point clouds from laser altimetry as an alternative data source. By these means, the interpretation task can be restricted to explicit geometric information, which helps to facilitate the development of automatic tools for 3D building reconstruction. In the past, the success of approaches based on elevation data was also supported by the continuously increasing density and accuracy of point clouds as a result of the fast evolution in LiDAR technology. Meanwhile, suitable image matching software can alternatively generate 3D point clouds and 2.5D raster representations at an accuracy, reliability and amount of detail, which was only feasible by LiDAR measurements. This is especially true if high quality imagery from digital airborne cameras is used, which usually provides good radiometric quality and high redundancy due to large image overlap (Haala, 2009; Hirschmüller and Bucher, 2010). The 3D city model of Las Vegas in Figs. 1 and 2 is e.g. automatically generated from high-resolution images. As can be seen from Fig. 2, the result is a detailed 3D surface mesh, which can be textured with the images accordingly (Fig. 1).

If image based surface reconstruction is applied, both geometric and radiometric information is available from one sensor. The integration of these two complementary data types can then be used for the extraction of three dimensional features or for large scale classification as pre-processing for 3D urban modelling (Vosselman, 2002; Zebedin et al., 2006). The joint availability and combination of geometric and radiometric information are also required for visualization applications. There the building geometry as provided from dense elevation data is enriched by surface texture from aerial imagery.

The interactive visualizations of 3D city models were opened to a general public mainly by applications such as Google Earth and Bing Maps (Leberl et al., 2009). Such visualizations at large and medium scale are feasible by relatively coarse building models, which are usually limited to roof structures and planar facades.

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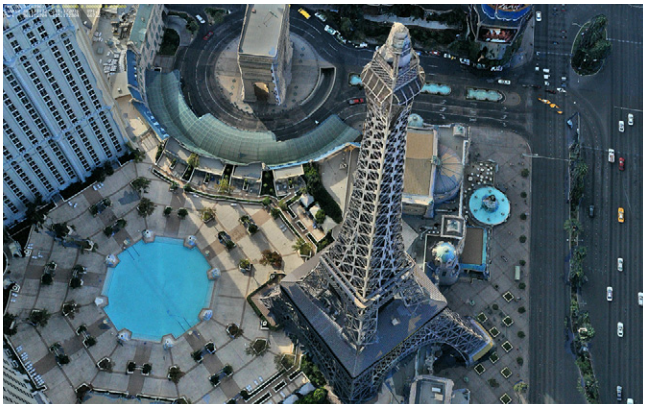

Fig. 1. 3D city model of Las Vegas, USA (courtesy of C3 technologies).

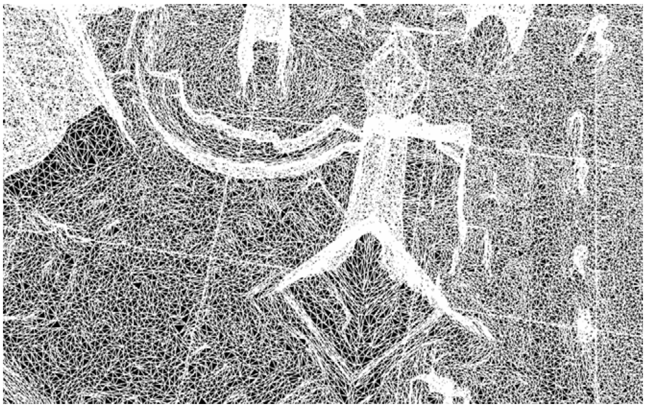

Fig. 2. Wireframe version of the 3D city model of Las Vegas, USA (courtesy of C3 technologies).

Thus, polyhedral models are sufficient, which represent the building shapes by rather simple planar surfaces. Since a number of operational tools have been developed for the automatic reconstruction of such polyhedral models from airborne data, large areas can be captured by fully automatic city modelling systems while interactive components can usually be limited to relatively complex landmark buildings or highly detailed reconstructions. Within Section 2, these developments on the automatic reconstruction of building shapes from elevation data – either provided from airborne LiDAR or automatic matching of highly overlapping imagery – are grouped according to the underlying principles of the respective approaches and discussed in detail.

While the outcome of these approaches can for example be used very well for visualizations of large areas from elevated viewpoints, an increasing demand for ground based presentations is currently evolving. This presumes very detailed geometric reconstructions including the building facades, which are frequently made available from terrestrial data collection. In this context, terrestrial images are e.g. used by suitable texturing methods to improve the visual appearance of the respective building facades. However, as discussed in Section 3, a number of approaches also aim at an explicit geometric modelling of features like doors or windows in order to enrich the respective facades. In addition to pleasing visualizations, such representations also allow for ''location-aware'' applications of city models. Such more complex search and navigation applications within urban environments require fully interpreted urban scenes with knowledge of doors and windows, but also roads, sidewalks, trees or parking spaces. Thus, technologies and algorithms are required to automatically describe urban areas in much higher detail, maybe even the building's interior. This will be discussed in the final part of the paper.

2. Roof shapes from elevation data

In this article, we want to focus primarily on the developments of the last couple of years with the purpose to close the gap between today and the thorough overviews given by Brenner (2005) and Baltsavias (2004) and the EuroSDR project on building extraction (Kaartinen and Hyyppä, 2006). A great number of approaches have since then been presented, which will briefly be described and put in context to one another in order to show both the past and present trends in building roof reconstruction from elevation data. As mentioned in the introduction, this type of input data can originate from various sources like LiDAR or image matching. Also, it is assumed that footprints are available or can be automatically extracted beforehand. Footprints have recently been derived from digital elevation models (DEM) e.g. based on marked point processes (Ortner et al., 2007), by combining them with aerial images (Li and Wu, 2008) or high-resolution satellite images (Sohn and Dowman, 2007). They are then delineated by a graph-based point reduction of the segmented building points (Neidhart and Sester, 2008), hierarchical least squares with perpendicularity constraints (Sampath and Shan, 2007). An evaluation of different methods on the detection of building footprints for the update of 2D databases is given by Champion (2009). Especially in Western European countries, footprints are available nationwide as cadastral data and the governmental authorities more and more request from the data providers to deliver 3D building models that are consistent with them.

One has to keep in mind that the point density greatly increased during that time period, but there is still a huge difference between what data is available for large area production purposes and what current sensor technology is able to deliver. While no one expects anything better to result from low density data other than rough and generalized roof shapes, the expectations are increasing along with the quality of the input data. Also the architectural style varies among rural, suburban, and inner city areas and geographical regions. Therefore, many different procedural methods are still being proposed, motivated by previous work, their planned application area, quality of input data or just by the urge to follow new ideas. But it seems that at least for high density data, the reconstruction of building roofs converges towards a uniform process that is based on a segmentation process of the elevation data (see Section 2.2).

The remainder follows the developments from simple parametric buildings, their combination to more complex ones (Section 2.1) to the construction of general roof structures that are based on point cloud segmentation (Section 2.2). Also an alternative reconstruction approach is discussed (Section 2.3), which does not assemble or construct building models in the traditional sense, but rather simplifies the meshed raw data until it suffices certain geometric and semantic criteria. As we will see from the reported results, detailed roof shapes that are close to reality are already within grasp.

2.1. Reconstruction with parametric shapes

A great number of buildings in rural and suburban areas are rather simple. They can be approximated by rectangular footprints and parameterized standard roof shapes. Most common are the saddleback roof, sometimes with hip ends on one or either sides, pent, flat, tent, and mansard roof. A description of common roof shapes are e.g. given in Milde and Brenner (2009) and Kada (2009). Our experience is that if roof details like dormers and chimneys are not required, these buildings can be automatically and reliably recognized and their parameters exactly determined even from low density data since the early works on building reconstruction; e.g. with the approach described in Brenner and Haala (1998).