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Automatic building information model reconstruction in high-density urban areas: Augmenting multi-source data with architectural knowledge

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ABSTRACT

Many studies have been conducted to create building information models (BIMs) or city information models (CIMs) as the digital infrastructure to support various smart city programs. However, automatic generation of such models for high-density (HD) urban areas remains a challenge owing to (a) complex topographic conditions and noisy data irrelevant to the buildings, and (b) exponentially growing computational complexity when the task is reconstructing hundreds of buildings at an urban scale. This paper develops a method - multi-Source recTification of gEometric Primitives (mSTEP) - for automatic reconstruction of BIMs in HD urban areas. By retrieving building base, height, and footprint geodata from topographic maps, level of detail 1 (LoD1) BIMs representing buildings with flat roof configuration were first constructed. Geometric primitives were then detected from LiDAR point clouds and rectified using architectural knowledge about building geometries (*e.g.* a rooftop object would normally be in parallel with the outer edge of the roof). Finally, the rectified primitives were used to refine the LoD1 BIMs to LoD2, which show detailed geometric features of roofs and rooftop objects. A total of 1361 buildings located in a four square kilometer area of Hong Kong Island were selected as the subjects for this study. The evaluation results show that mSTEP is an efficient BIM reconstruction method that can significantly improve the level of automation and decrease the computation time. mSTEP is also well applicable to point clouds of various densities. The research is thus of profound significance; other cities and districts around the world can easily adopt mSTEP to reconstruct their own BIMs/CIMs to support their smart city programs.

1. Introduction

City reconstruction in 3D digital format emerges popularity in the era of information [19]. A city information model (CIM) contains spatial data and virtual representations of all objects of interest in an urban area. A well-developed CIM can facilitate the work of city planners and urban designers in addressing urban problems such as traffic congestion, accessibility, connectivity, and the potential impact of natural disasters [1]. From a city administrator's perspective, a CIM with rich information can be useful for city governance, while at the individual citizen level, a CIM enables applications such as transportation navigation, emergency response, and many other location-based services. Cities such as New York, London, Berlin, and Adelaide have all created their CIMs to support many of the applications cited above [14,31,39].

Buildings are the most important manmade objects in the urban scene [18]. Many studies, over the years, have focused on the reconstruction of building information models (BIMs) (*e.g.* [40,45]) which can be stitched together to form a CIM. Another approach is to create CIMs using Geographic Information Systems (GIS) [24] and remote sensing [15,26]. In these CIMs, individual buildings could be roughly represented by prisms or “boxes” without precise information on the “as-is” condition. With the advancements of data acquisition and processing technologies, the trend is to reconstruct BIMs that contain detailed geometric features of roofs and rooftop objects (so termed as Level of Detail 2 [LoD2] defined by the [30] to extend CIM applications, *e.g.* green roof development [8] and energy performance improvement [47]. However, the reconstruction of BIMs, particularly those with greater details, is labor-intensive, time-consuming, and error-prone [42]. The process requires a considerable amount of manual rectifications and computational power, and this becomes extremely burdensome when the task is at the urban scale [25,39,44].

Researchers have attempted to improve the efficiency of BIM reconstruction by introducing automatic or semi-automatic approaches. Images, 3D laser scanning point clouds, and total station surveying data are commonly used for model reconstruction (*e.g.* [4,25,44]). Algorithms have been developed to process different types of data and

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reconstruct BIMs (*e.g.* [19,45]). In addition, with data from multiple sources become affordable, it is now possible to use multi-source data to overcome some of the inherent problems (*e.g.* inaccurate/“noisy” data, incomplete information) associated with single-source data (*e.g.* [7,12,16]). Acknowledging considerable achievements in the field of BIM/CIM reconstruction, BIM/CIM reconstruction in high-density (HD) urban areas remains an open problem [29]. Firstly, city features such as trees, roads, and terrain introduce a lot of noise that undermines the quality of the measurement data. Secondly, densely-distributed buildings make it difficult to segment data for generating individual BIMs. Lastly, reconstructing thousands of buildings at an urban scale exponentially increases the computational complexity, bringing many difficulties for methods which rely on general object recognition approaches to derive geometric primitives to form the building models.

This study aims to improve automatic BIM reconstruction in HD urban areas by proposing a reconstruction method called multi-Source recTification of gEometric Primitives (mSTEP). mSTEP harnesses the data from multiple sources and makes use of architectural features (*e.g.* parallels and symmetries) to reduce the noisy data and fine-tune the geometric primitives to reconstruct LoD2 BIMs automatically. The data employed in this study comes from the Hong Kong governmental agencies, comprising digital topographic map and light detection and ranging (LiDAR) point clouds. Given the fact that such types of data are extensively available in many cities and districts around the world, mSTEP can be applied to reconstruct their BIMs/CIMs in an efficient manner.

The organization of the paper is as follows: Section 2 reviews the state-of-the-art studies on BIM reconstruction. Section 3 describes the overall research progress, the subject area and characteristics of the corresponding topographic map and LiDAR point clouds. Section 4 details the BIM reconstruction method - mSTEP. Section 5 provides a comprehensive discussion of the evaluation results, discusses the parameter configuration of mSTEP, and shows the compatibility of mSTEP with a denser point cloud. Section 6 concludes with a summary and highlights future research directions.

2. Literature review

Previous studies on the generation of BIMs in the urban environment can be reviewed from two different perspectives: (1) the raw data used for BIM reconstruction; and (2) the methods employed in processing the data. While the two perspectives are related, the discussion deals with each perspective separately for the sake of clarity.

2.1. Original datasets

Aerial and satellite images are typical data sources for large-scale BIM reconstruction. Spaceborne sensors like IKONOS, QuickBird, and GeoEye-1 have provided 1 m-resolution satellite images for 3D building reconstruction [22,33]. Aerial image resolution can be even higher than that of satellite images, in some cases, reaching decimeter accuracy. Owing to their high image resolution as well as the widespread use of unmanned aerial vehicles (UAVs), the uses of aerial images to create 3D models of individual buildings or even to reconstruct the entire urban scenes are increasing [25].

LiDAR point clouds have also been widely used for BIM reconstruction. It typically utilizes laser light which is projected on surfaces and its reflected backscattering is captured for generating 3D point clouds. Heo et al. [19] used LiDAR point clouds to develop the models of 29 buildings. Other studies including Sun and Salvaggio [39], Xiong et al. [43], and Yan et al. [46] used airborne LiDAR point clouds to model a limited number of buildings with roofs of various shapes. With the availability of city-scale LiDAR point clouds, Poullis and You [34] created simplified BIMs within a large city area.

Topographic maps, which describe urban objects in terms of geometry, land use, and other attributes, are another important data source for BIM reconstruction at city- or district-scale. In addition to the topographic maps produced by government agencies, recent years have seen the emergence of open-access geographic datasets. For example, OpenStreetMap (OSM) – a prominent volunteered geographic information service – has been used for BIM reconstruction [31]. However, without official verification, the common problem of open-access geographic datasets is their completeness and accuracy.

The use of single-source data for BIM reconstruction, be it aerial images or LiDAR point clouds, is prevailing but still poses problems such as “noise” data caused by complex urban features and incomplete information [7]. These drawbacks have given rise to increased use of multi-source data for BIM reconstruction. A number of studies have confirmed that using multi-source data can overcome some of the problems associated with the use of single-source data [2,17,35,48–50].

2.2. Data processing methods

Various data processing methods have been proposed for BIM/CIM reconstruction [15,29]. Aerial or satellite images can be processed into digital elevation model (DEM) [22,33] from which building models can be extracted by applying height thresholds. With the further development of image matching, an alternative way is to generate colored point clouds from a number of aligned aerial images and then processed the generated point clouds into textured BIMs, which are formed by a large number of small geometric primitives [38]. This method, however, requires careful selection of images and manual interpretation to adjust the building models is often needed. Li et al. [25] also generated point clouds from images and proposed an object-level point cloud segmentation and roof extraction. However, their method was only tested on buildings with flat roofs.

Processing LiDAR data starts with segmentation of the point clouds of individual buildings. This can generally be achieved using semantic segmentation approach [27], classification or clustering algorithms [6,50] or the reflectance value captured by the LiDAR sensors [39]. LiDAR point clouds can also be integrated with other datasets. For example, building footprints retrieved from a topographic map can provide a reference for segmenting the point clouds of buildings [2,23]. The segmentation of LiDAR point clouds can also be improved with aerial images that provide regions of homogeneous gray level or color distribution [35]. Once segmented, the point clouds are used to model the buildings with roofs and rooftop objects by various methods. A typical method is to decompose the roof shapes into simple pre-defined ones by 2D plans [17] or graph matching technique [43], but the reconstruction may fail if the roof shape is not pre-defined in the model library. Connecting the extracted primitives to form the roof features is also widely-used due to its flexibility [34,46,49]. However, such kind of method is sensitive to noise [13] and so far have only been used for specific roof forms.

Although it is difficult to directly compare all these reconstruction methods since they are developed under different context with their own emphasis, our review has revealed that existing data processing methods usually require much time for noise filtering and assume buildings with flat or other simplified roof structures. Those methods that can generate more differentiated building and roof structures require considerable manual interpretation for pre- or post-processing. Actually, architectural designs commonly exhibit some conventional features such as parallels, symmetries or other structural regularities, which are not accidental, but often the result of economical, manufacturing, functional, or aesthetic considerations [28]. Parallel and perpendicular features have been used as the constraints to segment the point clouds to extract planar segments that constitute approximate building roof structure [9,36]. However, few studies have systematically applied architectural rules to reconstructing BIMs of densely-distributed buildings in large-scale urban areas. As will be demonstrated in this study, rules derived from architectural conventions can help reduce the noise in the collected data and improve the efficiency of