ARTICLE IN PRESS

ISPRS Journal of Photogrammetry and Remote Sensing xxx (2018) xxx–xxx

Contents lists available at ScienceDirect

ISPRS Journal of Photogrammetry and Remote Sensing

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

# Three-dimensional building façade segmentation and opening area detection from point clouds

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ARTICLE INFO

Article history:
Received 2 October 2017
Received in revised form 31 January 2018
Accepted 16 April 2018
Available online xxxx

Keywords:
Point cloud segmentation
Three-dimensional model reconstruction
Feature detection
Light Detection and Ranging (LiDAR)
Laser scanning

ABSTRACT

Laser scanning generates a point cloud from which geometries can be extracted, but most methods struggle to do this automatically, especially for the entirety of an architecturally complex building (as opposed to that of a single façade). To address this issue, this paper introduces the Improved Slicing Method (ISM), an innovative and computationally-efficient method for three-dimensional building segmentation. The method is also able to detect opening boundaries even on roofs (e.g. chimneys), as well as a building's overall outer boundaries using a local density analysis technique. The proposed procedure is validated by its application to two architecturally complex, historic brick buildings. Accuracies of at least 86% were achieved, with computational times as little as 0.53 s for detecting features from a data set of 5.0 million points. The accuracy more than rivalled the current state of the art, while being up to six times faster and with the further advantage of requiring no manual intervention or reliance on a priori information.


## 1. Introduction

The ability to automatically generate three-dimensional (3D) urban façade models from point clouds has gained considerable importance across many fields including autonomous navigation (Zhang et al., 2016), vegetation management (Höfle et al., 2012), virtual reality creation (Bui et al., 2016) and environmental modelling (Singh and Laefer, 2015). Light Detection and Ranging (LiDAR) is a common remote sensing technology used to generate the point clouds that serve as input data sets for such models, as the technology has the ability to collect millions of points rapidly as x-, y- and z-positional coordinates. However, processing such a point cloud into a usable 3D solid model for computational analysis (Hinks et al., 2013) or Building Information Modelling (Laefer and Truong-Hong, 2017) continues to pose significant challenges and has largely been done only with individual facades. This is especially true, if the building includes non-rectilinear features (e.g. curved windows) and complex geometric elements (e.g. cornices).

Automated, 3D building model generation is highly relevant to many civil engineering applications, since, the vast majority of existing urban structures lack measured drawings, and the cost of producing them through traditional surveying methods is prohibitive when more than a handful of structures are involved (Laefer, 2016). While LiDAR offers a rapid and cost-effective alternative solution for documenting the external geometries of existing structures, the raw data are only positional in nature. Thus, an automated means for segmentation and feature extraction is required for further application-oriented usage. There are also the additional requirements of the final output needing to be both geometrically accurate and in a file format compatible with the selected modelling software (e.g. for finite element modelling in civil engineering). To automatically generate such models, the overall boundaries of each building must be established, and the opening areas across the façade must be located. These two issues are particularly challenging if: (1) a façade has protrusions; (2) there are non-rectilinear windows; (3) the roof-level features intersect non-orthogonally with the roof; (4) the use application requires multiple façades to be modelled; (5) the data set is very large; and/or (6) there is a desire to use the model for multiple domains. Finally, for any solution to be viable at a city-scale, it must be both scalable and robust. As will be discussed in the next section, most current approaches struggle with these issues.

This paper is organized as follows. Section 2 describes related work in for point cloud segmentation and feature extraction.

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https://doi.org/10.1016/j.isprsjprs.2018.04.004
0924-2716/

Please cite this article in press as: Zolanvari, S.M.I., et al. Three-dimensional building façade segmentation and opening area detection from point clouds. ISPRS J. Photogram. Remote Sensing (2018), https://doi.org/10.1016/j.isprsjprs.2018.04.004

Section 3 describes the theoretical framework for the study and develops the methodological pipeline. Section 4 tests the proposed method on two highly complex building and shows the experimental results. Then a comparative analysis is run to benchmarks the proposed method against a highly cited new technique. Subsequently, Section 5 presents a sensitivity analysis and discusses the influence of average density and other variables on the results. Section 6 expresses the conclusions drawn from the experimental results and the comparative analysis.

## 2. Related works

A raw LiDAR point cloud begins as an unclassified group of points. They are often massive in size [e.g. more than a billion points per square kilometre (Laefer et al., 2017)]. Arguably what is needed for 3D reconstructions for engineering-based applications is some form of segmentation followed by feature extraction. While, the concepts of building segmentation and feature extraction are relatively similar, as both processes aim to find relationships among the points, they are distinctive activities. Thus, this paper considers these two concepts separately by defining segmentation as the process of clustering a group of points belonging to a single surface or region at a building scale (e.g. a single building façade), while feature extraction is herein defined as identifying specific, smaller building features (e.g. chimneys and windows) typically from previously segmented patches.

### 2.1. Segmentation

Segmentation is often used to help classify portions of a point cloud. The action uses one or more criteria to group points into subsets (e.g. points belonging to the same plane, having a similar density, or being in a particular orientation). As described in the following paragraphs, three important strategies have been commonly adopted for this step: (a) geometric fitting; (b) region growing; and (c) clustering.

Geometric fitting-based approaches mostly use variants of the Random Sample Consensus (RANSAC) methods, as initially introduced by Fischler and Bolles (1981), to segment building façades by fitting planes or lines into denser point cloud areas (e.g. commonly seen with walls). As an example, Schnabel et al. (2007) employed RANSAC to fit several candidate shapes into the point cloud. For that purpose, an approximate surface normal for each point was computed, and then the number of compatible points for the candidate shape as a standard score function was counted. Although the method can detect the approximate shape of the scanned 3D object, even in the presence of up to 50% outliers, the shapes are strictly limited (i.e. planes, spheres, cylinders, cones and tori). Thus, the technique would not able to detect the shape of free-form objects. Boulaassal et al. (2009) used the fitting-based approach to extract planar clusters contours. RANSAC has been widely used in this capacity for more than a decade (e.g. Bendels et al., 2006; Awwad et al., 2010), as it is simple and applicable to many building styles and types. Yang and Förstner (2010), also applied a RANSAC-based algorithm integrated with a minimum description length to manually define the number of fitted planes in a point cloud. A limitation of RANSAC-based methods is that a tolerance threshold for the distance between the fitting plane and the searching points is always required. Defining this threshold value causes the methods to be case dependent. Another geometric fitting-based method is the Hough Transform (Hough 1962), which was introduced to recognise lines in images. Later this method was extended into 3D to identify positions of arbitrary planes (Maas and Vosselman, 1999; Vosselman and Dijkman, 2001), cylinders (Tarsha-Kurdi et al., 2007), and spheres (Rabbani and Van Den Heuvel (2005)). These methods extract surfaces with a relatively high level of success, as long as significant protrusions or intricate details are not part of a building's exterior architecture.

Region-growing is another common approach. This method divides the point cloud into large surface patches by grouping adjacent points or voxels (3D cells). Then, coarse groups identified with similar normal vectors or other residual values (e.g. distance to neighbours) can be refined. Next, the method considers only the points inside those groups/voxels that are related to a common feature (e.g. normal vector directions) and merges them as a segmented part. An early example employing region-growing was conducted by Woo et al. (2002) to simplify a larger dataset into smaller voxels via an octree-based method. The result generated a 3D surface for the target object by calculating all normal vectors. The neighbour voxels were then merged into leaf nodes as seed cells, and then these seeds were grown until the deviation of the voxels' normal vectors were less than the threshold. While the result can correctly estimate the surface of objects from a point cloud, the method needs two manually-assigned thresholds: voxel size and standard deviation of the voxels' normal vectors. The process of calculating normal vectors for all cells and other additional checks can be computationally expensive. To accelerate the procedure, Vo et al. (2015) introduced an octree-based algorithm that quickly extracts different planes of a building's façades from both Terrestrial Laser Scanning (TLS) and Aerial Laser Scanning (ALS) data. However, the scalability of that method has yet to be established. In general, while region-growing has been used widely in many state-of-the-art segmentation works (e.g. Deschaud and Goulette, 2010; Wang and Tseng, 2011; Nurunnabi et al., 2012), use of the approach always depends on at least one predefined criterion, which challenges its robustness as a universal solution.

Clustering is another major segmentation strategy. Clustering is the process of grouping points with similar feature vectors into a single cluster separate from points with dissimilar feature vectors. The method has been an integral part of many algorithms [e.g. Hierarchical Clustering (Pauly et al., 2002), the k-means algorithm (Shi et al., 2011), the fuzzy C-means algorithm (Lerma and Biosca, 2005; Biosca and Lerma, 2008)]. For example, Filin and Pfeifer (2006) performed a cluster analysis in a feature space for ALS data. For that, they employed a slope adaptive neighbourhood method that is based on a distance criterion and the geometrical content of the point cloud to detect the planar surfaces in the dataset. The method could successfully segment the coarse planes (e.g. roofs and ground plane around the building) from the airborne data, however, it is limited to segmenting only planar shapes.

Although the clustering method is similar to region growing and both are based on grouping points under common constraints, one of the major advantages of clustering over the region growing method is that no seed point(s) or regions are needed to initiate the characterization or grouping. Another benefit is that, unlike fitting-based methods, clustering can segment multi-planar and 3D façades. However, clustering is computationally expensive for 3D data sets and highly influenced by data density and quality, because the method must determine whether or not each point satisfies the clustering criteria. In addition, the approach may fail to properly segment edges, as edge points may meet the requirements of more than one cluster, especially if the criteria are based on point density or point distribution (e.g. Aljumaily et al., 2015; Aljumaily et al., 2017).

### 2.2. Feature extraction

After coarsely segmenting a building's façade planes and roof(s), feature extraction is typically needed for generating sufficiently detailed solid models. Recent contributions in the area mostly focus on detecting different opening areas (i.e. windows and door)