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Slicing Method for curved façade and window extraction from point clouds

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A B S T R A C T

Laser scanning technology is a fast and reliable method to survey structures. However, the automatic conversion of such data into solid models for computation remains a major challenge, especially where non-rectilinear features are present. Since, openings and the overall dimensions of the buildings are the most critical elements in computational models for structural analysis, this article introduces the Slicing Method as a new, computationally-efficient method for extracting overall façade and window boundary points for reconstructing a façade into a geometry compatible for computational modelling. After finding a principal plane, the technique slices a façade into limited portions, with each slice representing a unique, imaginary section passing through a building. This is done along a façade's principal axes to segregate window and door openings from structural portions of the load-bearing masonry walls. The method detects each opening area's boundaries, as well as the overall boundary of the façade, in part, by using a one-dimensional projection to accelerate processing. Slices were optimised as 14.3 slices per vertical metre of building and 25 slices per horizontal metre of building, irrespective of building configuration or complexity. The proposed procedure was validated by its application to three highly decorative, historic brick buildings. Accuracy in excess of 93% was achieved with no manual intervention on highly complex buildings and nearly 100% on simple ones. Furthermore, computational times were less than 3 sec for data sets up to 2.6 million points, while similar existing approaches required more than 16 hr for such datasets.

1. Introduction

Laser scanning, also known as Light Detection and Ranging (LiDAR), has become a common and reliable tool in applications related to Civil Engineering like urban planning (Wu et al., 2015), disaster coordination (Vetrivel et al., 2015), vegetation management (Ferraz et al., 2016), and auto-navigation (Vo et al., 2015a). Automatically transforming these largely visual models into forms readable by finite element programmes remains a challenge, unless significant manual intervention is involved. Thus, their value is hampered for use in the engineering community for district-level and city-scale topics as such tunnel damage prediction (Laefer et al., 2010) and microclimate modelling (Singh and Laefer, 2015). In general, having a geometrically accurate, three-dimensional (3D) building model is an essential component for computational analysis. This is complicated to achieve economically, because the geometry for the vast majority of urban structures is undocumented and the expense of collecting that data through traditional surveying methods is likely to be prohibitive. In such cases, remote-sensing technologies can offer a cost-effective alternative (Abayowa et al., 2015). Prominent amongst these is laser scanning, which furnishes a rapid means to collect the relevant data from three-dimensional (3D) objects, including Cartesian coordinates in the *x*-, *y*- and *z*-directions, intensity of the reflected laser beam, plus digital camera, colour values [(red-green-blue (RGB)] when there is an integrated camera. These 3D points are collectively referred to as a point cloud. The difficulty then becomes the extraction of geometries of interest in a way that is accurate and technically meaningful and in a format that ultimately is compatible with computational modelling software.

Extracting relevant geometrical façade components from LiDAR data is challenging, in part due to data collection imperfections

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including occlusions and general noise. Currently, the majority of relevant approaches, while highly effective for visualisation, have acute limitations with respect to generating input for computational models. Prominent limitations are as follows: (1) having applicability only to simple, rectilinear structures; (2) requiring a priori knowledge (e.g. a reference library); (3) necessitating significant manual user involvement; and/or (4) being computationally expensive. Presently, these issues are impediments to using laser scanning to generate city-scale computational models. To begin to addresses these issues, this paper introduces the Slicing Method, a new means to rapidly and automatically detect a façade's overall geometry and its openings, even in the presence of non-rectilinear shapes and significant façade complexities.

2. Related works

Building façade extraction tends to encompass two major components: segmentation and feature extraction. Segmentation is the process of segregating a group of points belonging to a single surface or region. Building segmentation often separates walls from roofs and different sides of a building from each other. In contrast, feature extraction involves identifying building features (e.g. doors and windows) from patches that resulted from segmentation. Segmentation is typically a precursor to feature extraction. Both are long-standing research topics in remote sensing, as described below.

2.1. Segmentation

Segmentation has an essential role in the reconstruction of 3D models from laser scanning data. While a wide variety of strategies have been developed, the majority use some form of model fitting approach (e.g. Schnabel et al., 2007 and Awwad et al., 2010), such as the well-established Random Sample Consensus (RANSAC) technique introduced by Fischler and Bolles (1981). As an example, Boulaassal et al. (2009) integrated the use of RANSAC for wall segmentation of planar surfaces. RANSAC iteratively calculates parameters of a potential plane through a dataset with the goal of fitting a surface. Accuracy depends upon the number of iterations and the dataset size. Since walls have much higher point densities than openings or outliers, this method can extract walls, roofs, and doors that are located on a segmented plane. The method successfully extracts planar surfaces of building façades, as long as substantial protrusions or complex details are not present. Boulaassal et al. (2009) showed that this technique can also be used for boundary detection of segmented planes.

Another highly influential technique is that proposed by Wang and Tseng (2004), which is based on an octree indexing structure. In that approach, planar clustering was employed for 3D segmentation by splitting points into small planes (based on characteristics such as average height, average intensity, and shape orientation) and by subsequently merging neighbouring planes that have similar normal vectors. Although the method is relatively successful for rough segmentation, it proved unsuitable for complicated façades. Another octree-based approach was introduced by Vo et al. (2015b), in which a region-growing algorithm was introduced to segment points into large, coarse surface patches by incrementally grouping adjacent voxels (3D cells) based on them having similar normal vectors and residual values (the quadratic mean of the orthogonal distances from the points to their best-fit plane). The procedure then considered the points inside the voxels, rather than outliers or unwanted points. To accelerate the process, only points belonging to voxels adjacent to incomplete segment boundaries (around each group of voxels) were considered as candidates for merging. That segmentation method was able to quickly extract different planes of a building's façades for both terrestrial and aerial laser scanning data. However, the scalability and robustness of the method have yet to be demonstrated.

Contemporaneous to that, Chen et al. (2014) proposed an automatic and threshold-free evaluation system that offers an object-based technique for roof extraction. The enhanced algorithm performs well, even in the presence of noisy data and roofs covered in vegetation. However, the method has to date not been applied to façades, which are arguably often geometrically much more complicated than roofs. Also in 2014, Lari and Habib (2014) used principal component analysis to identify the points that belong to unique planar, linear, or cylindrical surfaces. Next, they automatically selected the proper representation model of the detected elements. Then, the results were corrected by implementing cylindrical neighbourhoods that utilised estimation of local point density variations along their surfaces. Finally, the outputs were improved by employing the characteristic attributes of the segmented elements. This work introduced a robust and new approach for the identification, parameterization, and segmentation of walls, roofs, and other groups of points having the same geometrical features. However, the segmented features are too rough and general for detecting openings and overall façade boundaries with great accuracy.

2.2. Feature detection

After successful segmentation, feature extraction is often pursued. This is a popular topic. So, the following represents only a sampling of recent contributions. For this, Wang and Tseng (2004) used a simple classification method based on planar attributes, which was limited to horizontal and vertical planes (e.g. roofs, ground surfaces and walls). Later Bendels et al. (2006) attempted to detect holes in point clouds by calculating the distance of each point to all of its neighbouring points by combining an angle and a shape criterion. The proposed approach was successful for holes that were either a part of a small object or that happened due to occlusions, reflectance, or transparency during data acquisition. The method's main drawback is its computational intensity due to its need to calculate all of the points' distances to each other and to find the normal that is determined as the eigenvector corresponding to the smallest eigenvalue of the weighted covariance matrix of the points. The method also needs some human intervention for such things as window frame removal.

Simultaneously, Pu and Vosselman (2006) proposed a fully automatic approach to extract building façade features from terrestrial LiDAR, which involved first segmenting a point cloud into planar patches, then applying a set of rules (i.e. ontologies) based on common construction attributes (e.g. size, position, direction and topology). After this, each segment was compared by fitting polygons to these constraints for feature classification. The method works well, except for windows, because of insufficient data. Therefore, the authors developed a subsequent hole-based window extraction method (Pu and Vosselman, 2007), which is effective, as long as the buildings are relatively simple and conform to the architectural styles from which the matching rules were derived.

Shortly thereafter, Becker and Haala (2007) introduced a method for solid model reconstruction, which involved integrating terrestrial images with laser scanning data. The resulting models were highly realistic – returning even the crossbars of window frames. The technique, however, requires a sufficiently high density of laser scanning data to have a resolution comparable to that of a photograph. Otherwise, an unstable matching and orientation process is likely to occur.

Subsequently, Pu and Vosselman (2009) identified façade features (e.g. doors and windows) for building façade reconstruction from terrestrial LiDAR by extending their ontological work (e.g.