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An adaptive approach for the segmentation and extraction of planar and linear/cylindrical features from laser scanning data

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ABSTRACT

Laser scanning systems have been established as leading tools for the collection of high density three-dimensional data over physical surfaces. The collected point cloud does not provide semantic information about the characteristics of the scanned surfaces. Therefore, different processing techniques have been developed for the extraction of useful information from this data which could be applied for diverse civil, industrial, and military applications. Planar and linear/cylindrical features are among the most important primitive information to be extracted from laser scanning data, especially those collected in urban areas. This paper introduces a new approach for the identification, parameterization, and segmentation of these features from laser scanning data while considering the internal characteristics of the utilized point cloud – i.e., local point density variation and noise level in the dataset. In the first step of this approach, a Principal Component Analysis of the local neighborhood of individual points is implemented to identify the points that belong to planar and linear/cylindrical features and select their appropriate representation model. For the detected planar features, the segmentation attributes are then computed through an adaptive cylinder neighborhood definition. Two clustering approaches are then introduced to segment and extract individual planar features in the reconstructed parameter domain. For the linear/cylindrical features, their directional and positional parameters are utilized as the segmentation attributes. A sequential clustering technique is proposed to isolate the points which belong to individual linear/cylindrical features through directional and positional attribute subspaces. Experimental results from simulated and real datasets demonstrate the feasibility of the proposed approach for the extraction of planar and linear/cylindrical features from laser scanning data.

1. Introduction

Over the past few years, laser scanning systems (airborne, static terrestrial, and mobile terrestrial systems) have been adopted as popular tools for the direct acquisition of high density and accurate spatial data. These systems provide 3D point clouds over the scanned surfaces. However, no interpretation and scene classification is performed during data acquisition. Accordingly, the collected point cloud should be processed to extract the required information for different applications, such as 3D city modelling, transportation planning, emergency response, cultural heritage documentation, structural health monitoring, and industrial site modelling. Segmentation and identification of low-level geometric primitives are considered as the fundamental steps in laser scanning data processing. This step is crucial since the accuracy of further laser scanning data processing activities depends on the validity of the segmentation results (Vosselman et al., 2004). Planar and linear/cylindrical features are the most important primitives that can be encountered in laser scanning data, especially those collected in urban areas, industrial sites, and electrical substations. These features include building rooftops, road surfaces, urban furniture, light poles, traffic poles, electrical transmission lines, and other urban and suburban features. Therefore, automated and efficient methods should be utilized for the segmentation and extraction of these features from point clouds collected by different laser scanning systems.

1.1. Background

To date, various approaches have been developed for the classification and segmentation of primitive features – planar and linear/cylindrical – from laser scanning data. In this section, these approaches are reviewed while highlighting their specific advantages and limitations.

1.1.1. Planar feature segmentation approaches

The existing approaches for the segmentation of planar features can be generally categorized into two groups: (1) spatial-domain segmentation approaches, and (2) parameter-domain segmenta-

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tion approaches. In the spatial-domain segmentation approaches, the point cloud is segmented based on the proximity of the points and the similarity of locally estimated surface characteristics. These approaches are mainly implemented in two steps: In the first step, a set of nearby points is selected as seed region, and in the second step selected seed regions are augmented by their adjacent points while considering their proximity, similarity, and continuity (Hoover et al., 1996; Lee and Schenk, 2001). In other words, the points which are located at the vicinity of the seed region and have similar properties to those within the seed region are clustered into the same group. Several research efforts have been conducted to introduce applicable similarity measures for the segmentation of the point cloud in the spatial domain. These similarity measures can be summarized as the proximity of the points and planarity or roughness of the surfaces (Tovari and Pfeifer, 2005; Pu and Vosselman, 2006; Rabbani et al., 2006; Wang and Tseng, 2010; Al-Durgham and Habib, 2013). Spatial-domain approaches are widely utilized, since they are easy to implement and computationally efficient for large point clouds. However, the performance of these methods depends heavily on the selection of the seed regions. It is usually difficult to judge if the selection of one set of seeds is better than the other. Therefore, spatial-domain segmentation approaches are computationally efficient; however, they are not generally considered as robust methods (Wang and Shan, 2009).

The second group of segmentation approaches – parameter-domain methods – aggregate points with similar attributes into clusters in the parameter domain (or attribute space). In the first step of these approaches, the segmentation attributes associated with each laser scanning point are derived based on the characteristics of its local neighborhood. Since these approaches are highly dependent on the quality of the derived attributes, they should be precisely computed to produce the best separation among different surfaces. The segmentation attributes can be estimated as the parameters of the tangent plane defined through the points neighboring a certain point (Axelsson, 1999; Maas, 1999; Filin, 2002), normal vectors derived from a slope adaptive neighborhood (Vosselman et al., 2004; Filin and Pfeifer, 2006), magnitudes of the normal vectors to locally estimated surfaces from two defined origins (Kim et al., 2007), and/or reflectance properties of laser scanning points (Nobrega and O'Hara, 2006). Once the segmentation attributes are computed, an n-dimensional attribute space is constructed (where n is the number of the estimated attributes for the individual laser points). In the second step of these approaches, clusters of the estimated attributes are detected and extracted in the parameter domain. The cluster detection procedure is usually carried out in a tessellated accumulator array (attribute space) that keeps track of the frequency of computed attributes for the individual cells. The points whose attributes belong to the same cluster – i.e., share similar attributes – are grouped into one segment in the spatial domain. The main advantage of parameter-domain segmentation approaches is that they do not involve seed points. However, they suffer from the lack of computational efficiency when dealing with multi-dimensional attribute spaces and a massive amount of points. The outcome of these approaches is also sensitive to the cell size utilized for the tessellation of attribute space. The other drawback of parameter-domain segmentation techniques is that the points belonging to coplanar but spatially disconnected planes are segmented into the same cluster.

So far, we have reviewed the established approaches for the segmentation of planar features from laser scanning data. It should be noted that the performance of the majority of the aforementioned segmentation methods is affected by the noise in the laser scanning datasets and local point density variations (Filin and Pfeifer, 2006) which have not been addressed in previous research work. These methods also require tuning of different parameters depending on the nature of the data and the application type (Rabbani et al., 2006).

1.1.2. Linear/cylindrical feature segmentation approaches

As yet, different approaches have been developed for the segmentation and extraction of linear/cylindrical features from laser scanning data. These methods can be mainly categorized into three groups: (1) spatial-domain approaches, (2) parameter-domain approaches, and (3) hybrid methods. The methods in the first category are usually divided into region-growing based methods (Belton and Lichti, 2006; Gross and Thoennessen, 2006; El-Halawany and Lichti, 2011) and model-fitting methods (Lukács et al., 1998; Marshall et al., 2001). In the region growing-based approaches, a Principal Component Analysis of the local neighborhood of individual laser points is initially conducted to classify the points which belong to linear/cylindrical features and estimate their geometric properties. A region growing algorithm is then implemented utilizing arbitrary seed points to aggregate neighboring points which potentially belong to linear/cylindrical features. The region-growing based methods are able to reliably classify and extract the linear/cylindrical features. However, their outcome is highly sensitive to the size of the established local neighborhoods and the location of seed points. Model-fitting methods are usually implemented in two steps. In the first step, a segmentation technique is utilized to group the laser points into different surfaces while selecting appropriate models to represent the segmented surfaces (planes, lines, spheres, cylinders, and cones). In the second step, a non-linear least squares procedure is utilized to define the best fitted lines/cylinders to the segmented linear/cylindrical surfaces. The drawback of these methods is that the quality of extracted linear/cylindrical features is highly dependent on the quality of the initial values of the parameters that will be estimated using non-linear least squares procedure.

In the parameter-domain approaches, the geometric attributes which describe linear/cylindrical features – seven parameters (Lukács et al., 1998) or five parameters (Rabbani, 2006) – are initially estimated for the local neighborhoods of each point. A seven/five-dimensional attribute space is then established for the extraction of linear/cylindrical features. In such an attribute space, the detection and extraction of linear/cylindrical features will be time and memory consuming. In order to optimize the computational cost of this procedure, the linear/cylindrical features are detected in the direction and position/radius attribute subspaces, respectively (Kimme et al., 1975; Vosselman et al., 2004; Rabbani and van den Heuvel, 2005; Rabbani, 2006). For the linear/cylindrical features represented by five parameters, a Gaussian sphere of the point cloud is initially constructed and a 2D Hough transform is performed to identify the features which have similar axis direction in the established Gaussian sphere. In the second step, a 3D Hough transform is carried out to identify these features based on their position and radius parameters. Although this sequential procedure greatly improves the performance of the parameter-domain linear/cylindrical feature extraction procedure, it is still computationally inefficient to process a massive amount of points. The other problem of parameter-domain segmentation approaches is that the points belonging to collinear/coaxial cylindrical features which are spatially disconnected are segmented into the same cluster.

In the existing hybrid approaches, the linear/cylindrical features are initially classified in the parameter domain and then precisely modelled using least squares line/cylinder fitting procedure in the spatial domain (Bolles and Fischler, 1981; Fischler and Bolles, 1981; Chaperon and Goulette, 2001; Schnabel et al., 2007). These methods usually employ a RANdom SAmple Consensus (RANSAC) algorithm on a Gaussian sphere to approximate the axis direction of linear/cylindrical features. The estimated directional parameters

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