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Roof planes detection via a second-order variational model

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ABSTRACT

The paper describes a unified automatic procedure for the detection of roof planes in gridded height data. The procedure exploits the Blake-Zisserman (BZ) model for segmentation in both 2D and 1D, and aims to detect, to model and to label roof planes.

The BZ model relies on the minimization of a functional that depends on first- and second-order derivatives, free discontinuities and free gradient discontinuities. During the minimization, the relative strength of each competitor is controlled by a set of weight parameters. By finding the minimum of the approximated BZ functional, one obtains: (1) an approximation of the data that is smoothed solely within regions of homogeneous gradient, and (2) an explicit detection of the discontinuities and gradient discontinuities of the approximation.

Firstly, input data is segmented using the 2D BZ. The maps of data and gradient discontinuities are used to isolate building candidates and planar patches (i.e. regions with homogeneous gradient) that correspond to roof planes. Connected regions that can not be considered as buildings are filtered according to both patch dimension and distribution of the directions of the normals to the boundary. The 1D BZ model is applied to the curvilinear coordinates of boundary points of building candidates in order to reduce the effect of data granularity when the normals are evaluated. In particular, corners are preserved and can be detected by means of gradient discontinuity.

Lastly, a total least squares model is applied to estimate the parameters of the plane that best fits the points of each planar patch (orthogonal regression with planar model). Refinement of planar patches is performed by assigning those points that are close to the boundaries to the planar patch for which a given proximity measure assumes the smallest value. The proximity measure is defined to account for the variance of a fitting plane and a weighted distance of a point from the plane.

The effectiveness of the proposed procedure is demonstrated by means of its application to urban digital surface models characterized by different spatial resolutions. Results are presented and discussed along with some promising developments.

1. Introduction

1.1. The detection roof planes

The identification of roof planes from the analysis of three dimensional (3D) point clouds and Digital Surface Models (DSMs) is an active research and application topic (Rottensteiner et al., 2014). The representation of building volumes in 3D city models can be improved when roof planes are properly included in the models. City models and DSMs of urban areas are widely used in several applications, e.g. acoustic and energy studies (Jochem et al., 2009), environmental and pollution modeling, visualization, cadastre updating and building volume estimates, urban and land planning, cultural heritages studies, telecommunication networks design and orthophoto generation in urban contexts (Habib and Kim, 2006; Barazzetti et al., 2010).

From a general point of view, the processing of elevation data of urban areas based on the so-called data-driven approach involves data segmentation, enforcement of topological consistency if needed, object detection and reconstruction. Many different strategies have been proposed to tackle the mentioned tasks (Haala and Kada, 2010). The model-driven approach is an alternative to the use of data-driven methods (Tarsha-Kurdi et al., 2007b).

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For example, Huang et al. (2013) used a generative model based on a primitive library for roof detection and reconstruction. Works mixing the bottom-up and the top-down approaches have also been presented (e.g. Satari et al., 2012) along with strategies involving the integrated processing of different types of data, such as topographic maps or imagery data (Brenner, 2005; Rottensteiner, 2010; Demir and Baltsavias, 2012; Awrangjeb et al., 2013).

In this work, a procedure for the detection of roof planes in gridded data is presented. As suggested by Vitti (2012b), regions with homogeneous gradient (i.e. planar patches) and their boundaries (i.e. roof edges and ridges) can be detected by exploiting the global variational model of the second order proposed by Blake and Zisserman (1987). The application of the model to DSMs was investigated in two preliminary works by Zanetti and Vitti (2013) and Benciolini and Vitti (2015); recently Zanetti et al. (2016) presented numerical results useful for practical purposes. This work presents a complete procedure for accomplishing the specific goal of detecting and labeling roof planes.

The paper is organized as follows. In the remainder of this section references to know solutions which have some kind of relationship with the propose procedure are provided and the main features justifying the procedure based on variational segmentation are introduced. The BZ model and its numerical implementation are presented in Section 2. A detailed step-by-step description of the automatic roof-detection procedure is given in Section 3. Other models involved in the procedure are also presented therein. To illustrate the procedure outputs a sample application to a DSM (1 m spatial resolution) of an urban area of the city of Trento, Italy, is considered. Section 4 presents a detailed application of the procedure to a DSM (25 cm spatial resolution) of an urban area of the city of Vaihingen, Germany. Final remarks and perspectives on further developments are given in the Section 5.

1.2. Known solutions

The segmentation of 3D point clouds and DSMs can be addressed applying different data-driven methods directly to height values, normals or other features derived from height values. Strategies based on clustering, region growing, edge and contour based methods have been proposed along with others based on parametric or statistical models. In this context, interesting examples are proposed in the following works. In (Ohtake et al., 2004) edge detection on triangle meshes is performed by analyzing the principal curvature and its derivatives. In (Rottensteiner, 2003) a region growing model is applied to normal vectors for the generation of 3D building models. In (Wang et al., 2013) normal vectors are treated as points on the unit sphere and then clustered to detect planes and other regular surfaces. Filin and Pfeifer (2006) proposed a feature-based approach to cluster Airborne Laser Scanning (ALS) data, capable of detecting planar elements; in that work, normal vectors were computed according to a slope adaptive neighborhood mechanism. Biosca and Lerma (2008) used the fuzzy clustering method and the so called possibilistic c-means mode-seeking algorithm to detect planes in point clouds. Sampath and Shan (2010) proposed a procedure for the segmentation and reconstruction of polyhedral roofs based on the eigen-analysis to filter planar and non-planar (set of) points and on a fuzzy k-means method to cluster planar points.

Other works present conceptual or operational resemblances. For example in (Lavoué and Dupont, 2009) a polygonal mesh is approximated by a set of semi-sharp surfaces built after the detection of the main linear features of the analyzed object; in the same work a global model based on the Variational Shape Approximation by Cohen-Steiner et al. (2004) is used to produce a piecewise smooth surface segmentation with sharp edges. In (Goebbels and Pohle-Fröhlich, 2016) the reconstruction of complex roofs is achieved starting from an *ad hoc* interpolated height map and using image processing techniques to avoid shortcomings of standard geometric methods for plane detection. Lin et al. (2014) applied the principal component analysis to a weighted covariance matrix with a geometric median to compute local geometric characteristics less sensitive to data noise and partial sampling. Jochem et al. (2012) applied a 3D k-nearest neighbors based region growing model to normals for the segmentation of planes in large ALS data set. Chen et al. (2012) applied a region growing algorithm based on a plane-fitting technique to select building points in ALS data followed by an adaptive implementation of the RANSAC algorithm (Fischler and Bolles, 1981) to segment building rooftops. Plane detection can also be performed by means of the Hough transform (Hough, 1962), (e.g. Tarsha-Kurdi et al., 2007a, 2011). Kim and Shan (2011) based the modeling of building roofs on the application of the level set method to the normals for the segmentation of planes in ALS data. Recently, Yan et al. (2014) adopted a global plane-fitting approach based on the works by Delong et al. (2012) and Hossam and Boykov (2012) for roof segmentation in LiDAR point clouds.

1.3. A novel approach based on 2nd order variational segmentation

The rationale of the proposed approach can be understood by considering that roof planes are basically planar surfaces and that buildings have regular shapes, e.g. polygonal footprints. In fact, a complex roof can be thought of as a piecewise smooth surface with edges and creases, i.e. surface discontinuities and surface gradient discontinuities respectively (see Fig. 1(a) and (b)). The projection of the roof boundary on the ground is the building footprint and it can be identified as an area surrounded by a closed curve made up of edge points (see Fig. 1(c)). Within a building footprint, edge and crease (edge&crease) discontinuities allow for the representation of the closed boundary of each planar patch that comprises the complex roof (see Fig. 1(d)). In real cases, noisy data and discrete sampling affect the quality of LiDAR point clouds and gridded DSMs. The noise affecting data should be reduced without altering edge and crease structures that would help the detection of planar patches. Due to the spatial granularity of the data, the detection of regular shapes is difficult and modeling a boundary with a smooth approximation with sharp corners would be very useful in this case. An example of a convenient piecewise linear approximation of the gridded points representing a building boundary is given in Fig. 2.

The proposed approach to building and roof plane detection exploits an elliptic approximation of a variational model by Blake and Zisserman (1987). The model is applied in 2D to approximate a DSM by piecewise nearly-linear surfaces and in 1D to approximate footprint boundaries by piecewise nearly-linear curves.

The 2D BZ applied to an input DSM returns a piecewise nearly-linear approximation of data and the graphs of two auxiliary functions mapping the discontinuity of the smooth approximation and of its gradient (edges and creases). Such outputs provide the ideal starting point for a further process that implements the concepts given above. The discontinuity map is first processed to isolate building footprint candidates. The candidates are then filtered according to their area and the direction of the normals to the boundary. The DSM sampling-interpolation noise can significantly affect the distribution of the normals, therefore the 1D BZ is applied to each building footprint candidate in order to model its boundary by means of a piecewise nearly-linear approximation with sharp corners (see Benciolini and Vitti, 2015). The rejection of a candidate is performed on the assumption that buildings have, in general, polygonal footprints with right angles. Both the use of discrete differential operators and the smoothing of building