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Large-scale road detection in forested mountainous areas using airborne topographic lidar data

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ABSTRACT

In forested mountainous areas, the road location and characterization are invaluable inputs for various purposes such as forest management, wood harvesting industry, wildfire protection and fighting. Airborne topographic lidar has become an established technique to characterize the Earth surface. Lidar provides 3D point clouds allowing for fine reconstruction of ground topography while preserving high frequencies of the relief: fine Digital Terrain Models (DTMs) is the key product.

This paper addresses the problem of road detection and characterization in forested environments over large scales (>1000 km^2). For that purpose, an efficient pipeline is proposed, which assumes that main forest roads can be modeled as planar elongated features in the road direction with relief variation in orthogonal direction. DTMs are the only input and no complex 3D point cloud processing methods are involved. First, a restricted but carefully designed set of morphological features is defined as input for a supervised Random Forest classification of potential road patches. Then, a graph is built over these candidate regions: vertices are selected using stochastic geometry tools and edges are created in order to fill gaps in the DTM created by vegetation occlusion. The graph is pruned using morphological criteria derived from the input road model. Finally, once the road is located in 2D, its width and slope are retrieved using an object-based image analysis. We demonstrate that our road model is valid for most forest roads and that roads are correctly retrieved (>80%) with few erroneously detected pathways (10–15%) using fully automatic methods. The full pipeline takes less than 2 min per km^2 and higher planimetric accuracy than 2D existing topographic databases are achieved. Compared to these databases, additional roads can be detected with the ability of lidar sensors to penetrate the understory. In case of very dense vegetation and insufficient relief in the DTM, gaps may exist in the results resulting in local incompleteness (∼15%).

1. Introduction

1.1. Motivation

Accurate road location, use and condition in forested environments is an invaluable input for many ecological, economical purposes, and in particular for evaluating adequate spatial indicators related to public policies (Coffin, 2007; Robinson et al., 2010). It concerns forest management or biodiversity issues, wildfire protection, animal movement, leisure activities etc. In mountainous areas, such knowledge is highly necessary since it can have a negative impact on water quality, habitats and can cause landslides (Sidle and Ziegler, 2012).

In addition, for a cost-effective wood supply, mobilization conditions (both harvesting and accessibility) is a prerequisite for setting up adequate chains for the timber industry. Road location knowledge is coupled with planning models and decision-making tools implemented in geographic information systems (Sačkov et al., 2014): forest harvesting, logging and investments in forest infrastructures can be optimized, while taking current and scheduled accessibility of forest resources into account. For those purposes, both 2D road location and geometrical characteristics (slope, width, radius of curvature) are required in order to evaluate which kind(s) of vehicules can go down a given road. The related

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information should also be updated in a yearly basis (Gucinski et al., 2001).

Various solutions exist for forest road database (DB) generation and updating: existing DB integration, human photo-interpretation, GPS field surveys, crowdsourcing web-based solutions, and automatic remote sensing data analysis. The four first solutions exhibit significant advantages in terms of road centerline completeness albeit lacks can be noticed under dense canopy cover. However, limitations exist in terms of 2D location accuracy and geometrical characterization: the road width remains most of the time the unique available feature. This is not sufficient since (i) only coarse values may be provided, (ii) smaller and narrower roads (e.g., trails and haul roads) may not be described, and (iii) no solution has been developed for the updating task yet.

In this paper, the issue for large-scale road detection and characterization in forested mountainous areas is addressed. For that purpose, the airborne topographic lidar technology is adapted. This is due to its ability to provide reliable and accurate terrain altitude even under forest cover. It offers a mature and realistic solution since forest massifs are now acquired over large areas in many countries (Maltamo et al., 2014).

1.2. Related work

A large body of literature has addressed the problem of (semi-) automatic road detection for more than 30 years. However, existing studies are mainly focused on urban and peri-urban areas using geospatial optical imagery (Mena and Malpica, 2005; Amo et al., 2006; Mayer et al., 2006). A majority of techniques was designed for specific data and environment. Main differences stem from the selected road model, which is highly correlated to the spatial resolution of the input images.

For spatial resolutions superior to 1 m, roads are considered as thin elongated objects. Top-Down methods based on a line extraction procedure are privileged (Lacoste et al., 2005). In structured man-made environments, this allows to directly generate networks by solving graph problems (Hinz and Baumgartner, 2003; Türetken et al., 2013). Top-Down methods are also adopted in peri-urban areas in order to cope with occlusions and missing information issues, such as vegetation and shadows (Rochery et al., 2004). They are often embedded into a hierarchical multi-scale approach (Laptev et al., 2000). Initial detections are frequently refined with a radiometric profile tracking step (Hu et al., 2007) in order to improve the centerline estimation. These latter methods are all the more relevant than they can be integrated into workflows with already available initial road information (Fujimura et al., 2008; Miao et al., 2013): existing 2D topographic DBs are the main data source.

Very High Resolution images (<1 m) are considered for urban areas, where roads are seen as homogeneous areas in terms of geometry, topology, texture, and color. Thus, Bottom-Up approaches, based on classification methods, are prefered (Grote et al., 2012; Mnih and Hinton, 2012; Ziems et al., 2012). The most recent techniques allow the integration of contextual information. This aims to limit the false detection rate, correlated to the high spectral variability of road areas (cars, road marks etc.). Similarly to Top-Down approaches, they are often followed by a network generation and vectorization step (Unsalan and Sirmacek, 2012; Matkan et al., 2014), which enforces additional regularization constraints.

Finally, Top-Down and Bottom-Up strategies are merged both at the feature and the decision levels in the most recent techniques (Chai et al., 2013; Montoya et al., 2014; Poullis, 2014). This permits to benefit from advantages of both approaches.

Airborne topographic lidar data features three main advantages for the design and the performance of road detection methods. First, the ability to acquire ground points beneath vegetation canopy permits to generate very high resolution Digital Terrain Models (DTMs) in forested areas. Accurate height information can be extracted (Hatger, 2005; Matkan et al., 2014). DTM morphological analysis gives access to terrain geometrical features unseen with standard optical sensors (Rieger et al., 1999; Sherba et al., 2014) and without any occlusion and shadowing issue (Hu et al., 2014) In mountainous environments, this corresponds to breaklines and road edges (Rieger et al., 1999; White et al., 2010).

Second, raw 3D lidar point clouds can be directly processed in order to retrieve the vertical distribution of the objects above the ground (Hatger, 2005). In forested areas, this indicates the presence of low vegetation and it helps predicting occlusion areas (Lee et al., 2005). Finally, 3D points are accompanied with an intensity information, more and more often extracted from full-waveform data (Djuricic and Hollaus, 2013). This spectral information is helpful for discriminating many surfaces (roads from buildings in (Clode et al., 2007), roads from bare earth in (David et al., 2009; Azizi et al., 2014)). Nevertheless, it cannot be assumed that road shoulders always exhibit a distinct spectral behavior from road centers for precisely defining the road areas. Furthermore, classification techniques based on the intensity feature cannot be straightforwardly transferred to forested areas since correction and calibration methods are not mature enough.

In this paper, we aim to develop a fast and efficient method that is able to extract roads in mountainous forested environments at large scales. Consequently, main existing recent methods (David et al., 2009; White et al., 2010; Djuricic and Hollaus, 2013) do not fit to these requirements since they were not tailored for large-scale processing or/and involve too complex data (namely lidar waveforms).

2. Methods

2.1. Overall strategy

Our road detection and characterization strategy is based on the two-dimensional analysis of a lidar-based 1 m DTM. This allows to provide a solution efficient at large scales, without complex 3D processing techniques. We acknowledge that advanced point cloud classification methods may improve the discrimination accuracy of pathways. However, it would be to the detriment of the computing time and the scalability of the approach.

We do not aim to extract a network but road patches, for two main reasons. First, solutions that exist in the literature are efficient but to the detriment of the processing time, in particular since a priori knowledge on mountainous areas cannot be straightforwardly integrated in such solutions. Second, our pipeline is also designed for topographic database updating and refinement, which do not necessarily need to handle road junctions and correct topology.

Here, the DTM generation process (off-ground point filtering and surface reconstruction) is not considered and no DTM evaluation is performed. We rely on the adaptive Triangulated Irregular Network solution (Axelsson, 2000). It is commonly adopted in the literature, implemented in various softwares, and known to be efficient at large scales. DTM quality may vary with the area of interest: artifacts (outliers or coarse surface interpolation) can exist, but their knowledge is not integrated in our process.

Clode et al. (2007) and David et al. (2009) integrate lidar echo intensity information for road discrimination but, it was decided here to discard these values. First, intensity calibration without sufficient metadata, partly stemming from full-waveform data, is very difficult (Wagner, 2010), in particular for large areas with significant slopes and height range. Second, to the best of our