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DTM extraction under forest canopy using LiDAR data and a modified invasive weed optimization algorithm

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ABSTRACT

The penetration ability of Light Detection and Ranging (LiDAR) pulses into vegetation cover makes it a valuable tool in forest inventory. Extraction of a Digital Terrain Model (DTM) using LiDAR data is a challenging topic, especially in steep and complex terrains with forest canopy. This paper presents some approaches for ground filtering and interpolating the point cloud to generate DTM in forested terrains. Interpolating the points in dense forests that have high attitude variation is very difficult and make the popular interpolation methods unsatisfactory. This paper proposed a modified Invasive Weed Optimization (IWO) method for finding the optimized coefficients of the polynomial interpolation method. This method had a good performance with 0.210 mm *RMSE* value in the forested terrains. The interpolated point cloud was used as the input of the proposed ground filtering method for detecting the non-ground pixels. The proposed ground filtering method was structured with two main sections including, iterative geodesic morphology and scan labeling. In the iterative geodesic morphology, some geometric and structural parameters were introduced to investigate the quality of extracted points in each iteration. The scan labeling searched the data pixel by pixel in four directions and labeled the pixels with the high slope value in all directions. The non-ground pixels were obtained by integrating the result of iterative geodesic and scan labeling. Assessment of the ground filtering results using the International Society for Photogrammetry and Remote Sensing (ISPRS) showed 3.92% total error compared to the other reported algorithms. This demonstrated the ability of the proposed approach in recognition of the non-ground pixels. The extracted pixels were removed and the DTM was generated by filling the gaps using the proposed IWO and polynomial interpolation. Some forested regions with various characteristics such as sparse and dense trees on the hills and steep slopes were utilized to evaluate the accuracy of the generated DTM. The computed *RMSE* in the test areas was 0.463 m, on average, which was acceptable for the complex and forested terrains.

1. Introduction

In the last decade, an airborne Light Detection And Ranging (LiDAR) technology has greatly progressed and gradually turned into an effective tool in photogrammetry and remote sensing for collecting the 3D point cloud from the earth surface (Chen et al., 2013). The airborne LiDAR is an active sensor that measures the distance to the earth using laser light and processes the global positioning system (GPS) and inertial measurement unit (IMU) data of the platform to acquire a point cloud with 3D coordinates (Wallace et al., 2012). The laser pulse of LiDAR can penetrate into the trees' canopy and this special characteristic increases the frequency of using LiDAR in forestry applications (Reutebuch et al., 2005). Moreover, LiDAR can record full-waveform of each laser pulse that provides the capability of collecting more information about the reflecting objects' features. These features turn LiDAR into a powerful sensor with the potentiality of generating the digital terrain models (DTM) with the high accuracy in forest regions (Ullrich et al., 2007).

1.1. *Ground filtering*

Nowadays, LiDAR data is widely used for estimating various forest parameters such as tree height (Wang and Glenn, 2008), volume and biomass, as well as delineating the individual tree boundaries (Van Leeuwen and Nieuwenhuis, 2010). Estimation of the carbon saturation in the high biomass tropical and subtropical forests made the capability of LiDAR pulses feasible to penetrate in the dense and multilayer canopies (Detto et al., 2015; Lim and Treitz, 2004). Previous researchers

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demonstrated the high potential of LiDAR data for estimating biomass in temperate (Lim and Treitz, 2004), boreal (Kankare et al., 2013; Næsset et al., 2013), tropical as well as subtropical forests (Asner et al., 2010). As mentioned, LiDAR calculates the distance between the platform and earth objects; hence, this data directly produces a digital surface model (DSM). A common step for estimation of forest parameters is the generation of the DTM that indicates the Bare Earth (BE) elevation without any non-ground objects. The Canopy Height Model (CHM) is a useful model that can be derived by computing the difference of DSM and DTM. This model contains the non-ground objects with their height values (Takahashi et al., 2005). Some researchers do not generate the CHM to estimate the trees' height. They suppose the surface that fits on top of the forest trees is approximately parallel to the BE with an elevation difference set to the computed mean height (Yamamoto et al., 2011). This procedure does not lead to generate an accurate DTM because their hypothesis was not correct in every scenario, and the BE surface is significantly different from the hypothetical surface of the top of the trees.

Accordingly, generation of DTM using DSM is a challenging research topic in photogrammetry and remote sensing. The proposed DTM extraction approaches consist of two main steps. The first step is ground filtering that separates the non-ground points from the ground points. In the second step, the DTM is generated by interpolating and retrieving the elevation of the removed point in the filtering step (Axelsson, 2000; Kraus and Pfeifer, 1998). Some researchers only focused on the ground filtering algorithms (Arefi, 2009; Arefi et al., 2011; Axelsson, 2000; Kraus and Pfeifer, 1998) and some others combined these two steps to improve the results (Maguya et al., 2013, 2014; Pingel et al., 2013). The ground filtering approaches can be categorized into three groups including morphology-based, slope-based, and interpolation-based approaches (Pingel et al., 2013).

The mathematic morphology filter has the potential of recognizing the non-ground points using a structuring element (Kilian et al., 1996). Kilian et al. (1996) utilized the simple opening operator with specified structuring element to detect the non-ground points. In the morphological filter, the size of the structuring element is important to eliminate the non-ground points (Kilian et al., 1996). The small size of the structuring element is not successful to remove the large objects like building and dense trees, and the big size leads to pick some parts of the ground, wrongly (Zhang et al., 2003). Accordingly, the progressive procedures have been suggested to modify these problems (Chen et al., 2007; Meng et al., 2009; Pingel et al., 2013; Zhang et al., 2003). In these approaches, the size of the structuring element is determined by consideration of the region's characteristics and is increased, gradually. For example, the suitable structuring size in a steep hillside is different from a flat region (Chen et al., 2007; Zhang et al., 2003).

Pingel et al. (2013) proposed a simple morphological filter and used a linearly increasing window to detect the non-ground points. Mongus et al. (2014) constructed the connectivity of a grid over the LiDAR point cloud for performing multi-scale data decomposition. A top-hat scale-space was formed using differential morphological profiles on the points' residuals from the approximated surface. In order to extract the non-ground points, some geometric attributes are estimated by mapping characteristic values of differential morphological profiles (Mongus et al., 2014). Hui et al. (2016) utilized a morphological opening operation with the filtering window that gradually was downsized. Moreover, the kriging interpolation can be applied at different levels by consideration of the different filtering windows (Hui et al., 2016). Some researchers specified the elevation threshold in each iteration according to the size of the structuring element (Chen et al., 2007; Pingel et al., 2013; Zhang et al., 2003). Chen et al. (2013) proposed an edge-based morphological approach that simplified the calculation and reduced the number of tunable parameters (Chen et al., 2013). Li et al. (2014) proposed an improved top-hat transformation with a sloped brim while the intensity difference between them was inspected as the omission error. The brim filter that was extended outward was employed to recognize the non-ground points (Li et al., 2014).

In the slope-based approaches, for each point, the slope value was computed using its adjacent points. The points with high slope value are potentially non-ground. Hence, considering the slope value in a constant distance can be a suitable criterion to detect the non-ground points (Vosselman, 2000). Specifying the slope threshold in these approaches is a challenging issue; because a constant threshold is not appropriate for dealing with various regions (Meng et al., 2010). In other words, the threshold should be slope-adaptive and should be specified according to the slope of the area (Liu, 2008; Sithole and Vosselman, 2001; Susaki, 2012). As sometimes the BE points have height jumps similar to the non-ground points, employing only the slope parameter in the steep and complex terrain with dense coverage is not enough and does not lead to an acceptable result (Sithole and Vosselman, 2004). Shao and Chen (2008) introduced two parameters such as slope increment and maximum slope beside the slope parameter to improve the shortages of using only the slope parameter (Shao and Chen, 2008).

The interpolation-based approaches have an iterative procedure that gradually improves the DTM. Actually, at first, a primary surface is generated using a few local minima; then the surface is updated by analyzing the residual of the primary surface (Maguya et al., 2013). The weight of the point for updating the surface pertained to their residual value (Maguya et al., 2013). The points with negative residual value probably belong to the BE, hence they were given greater weight rather than the other points (Kraus and Pfeifer, 1998). The procedure of generating the surface, computing the residuals, weighing the points as well as updating the surface was repeated until the surface does not change and is stable (Kraus and Pfeifer, 1998). Chen et al. (2013) proposed a multi-resolution hierarchical approach with three levels based on the residual point from the interpolated surface. At each level, the cell resolution and the residual threshold were increased, gradually. The generated surface was updated in each iteration until no ground points were classified (Chen et al., 2013). Axelsson (2000) proposed a Triangulated Irregular Network (TIN) based approach that generates a surface with the lowest points and gradually increased the terrain points considering to the point angle and distance to the generated surface. In each iteration, the points that compiled the specified criteria were added to the BE points (Axelsson, 2000).

Generally, the mentioned categorized approaches have some limitations and cannot fulfill all expectations. The slope-based approaches do not have a suitable performance in steep and complex terrains (Li et al., 2014). The interpolation approaches are time-consuming and have difficulties dealing with break lines, steep terrain as well as highly variable terrains. Although the morphology-based approaches are very fast and simple to implement, the points of the protruding terrain are not satisfactory for morphology-based approaches (Hui et al., 2016). Accordingly, modification of the morphological approaches for dealing with the protruding terrain provides a fast, practical and accurate approach.

Despite the development of the DTM extraction approaches in the last decade, these approaches still face some challenges in forested terrain (Maguya et al., 2014). The dense forest canopy limits the penetrating the LiDAR pulses and this makes the DTM extraction procedure difficult (Kobler et al., 2007; Kraus and Pfeifer, 1998; Mongus and Žalik, 2012). Some factors such as flight attitude, canopy thickness, season, scan angle and terrain slope have a direct effect on the pene-