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Bottom-up delineation of individual trees from full-waveform airborne laser scans in a structurally complex eucalypt forest☆

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ABSTRACT

Full-waveform airborne laser scanning (ALS) is a powerful tool for characterizing and monitoring forest structure over large areas at the individual tree level. Most of the existing ALS-based algorithms for individual tree delineation from the point cloud are top-down, which are accurate for delineating cone-shaped conifers, but have lower delineation accuracies over more structurally complex broad-leaf forests. Therefore, in this study we developed a new bottom-up algorithm for detecting trunks and delineating individual trees with complex shapes, such as eucalypts. Experiments were conducted in the largest river red gum forest in the world, located in the south-east of Australia, that experienced severe dieback over the past six decades. For detection of individual tree trunks, we used a novel approach based on conditional Euclidean distance clustering that takes advantage of spacing between laser returns. Overall, the algorithm developed in our study was able to detect up to 67% of field-measured trees with diameter larger than or equal to 13 cm. By filtering ALS based on the intensity, return number and returned pulse width values, we were able to differentiate between woody and leaf tree components, thus improving the accuracy of tree trunk detections by 5% as compared to non-filtered ALS. The detected trunks were used to seed random walks on graph algorithm for tree crown delineation. The accuracy of tree crown delineation for different ALS point cloud densities was assessed in terms of tree height and crown width and resulted in up to 68% of field-measured trees being correctly delineated. The double increase in point density from ~12 points/m^2 to ~24 points/m^2 resulted in tree trunk detection increase of 11% (from 56% to 67%) and percentage of correctly delineated crowns increase of 13% (from 55% to 68%). Our results confirm an algorithm that can be used to accurately delineate individual trees with complex structures (e.g. eucalypts and other broad-leaves) and highlight the importance of full-waveform ALS for individual tree delineation.

1. Introduction

Forests provide a multitude of ecosystem services to both humans and the surrounding natural environment. The loss of healthy forests can degrade crucial ecosystem services, such as carbon storage in biomass and soils, the regulation of water regimes, the modulation of regional climate and conservation of biodiversity (Lindberg, Staff, & Black, 1997). Therefore, accurate and up-to-date forest inventories including health condition information are of importance to the preservation of ecological environments and the wellbeing of both humans and wildlife (Liu, Shen, Zhao, & Xu, 2013). In the past years, a substantial effort has been put into decreasing costs of forest inventories by minimizing labor-intensive field-based surveys and developing inventory systems that are based on remote sensing.

One of the most prominent remote sensing tools used in forest studies so far is airborne laser scanning (ALS), which measures distances by precisely timing a laser pulse emitted from a sensor and reflected from a target (Lefsky, Cohen, Parker, & Harding, 2002). In early discrete return ALS systems a sensor was able to record multiple returns (up to 4); however, they have a dead zone of about 3 m in which no returns can be recorded (Reitberger & Krzystek, 2009; Korpela, Hovi, & Morsdorf, 2012). The advances in ALS technology in the form of introduction of full-waveform scanners allowed the acquisition of much richer datasets. Whereas discrete return ALS systems record, for each laser pulse, the time of travel and intensity of every return, full-waveform ALS systems record the entire waveform of the returning laser pulse as a function of time (Heritage & Large, 2009; Weng, 2011). By applying adequate modeling (e.g. Gaussian decomposition) of the recorded waveform it is possible to extract additional information to that of discrete return ALS systems such as denser vertical distribution of laser returns. Moreover, apart from intensity, the returned pulse width attribute could be extracted, both of which are a function of object characteristics like the reflectivity and the cross section (Wagner, Ullrich, Ducic, Melzer, & Studnicka, 2006; Weng, 2011). This additional information enables

☆ This research deserves to be honored as a highlighted student paper because of its novelty and far reaching implications for forest health assessment and conservation.

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even more accurate characterization of forest structure over large areas at the individual tree level (Reitberger, Schnörr, Krzystek and Stilla, 2009; Vega et al., 2014), which in turn benefits management decisions to enhance forest health and biodiversity conservation (Höfle, Hollaus, Lehner, Pfeifer, & Wagner, 2008; Heinzel & Koch, 2011).

However, algorithms for individual tree trunk detection and crown delineation are usually site specific as they tend to not extrapolate from the site where they were fit. Lu, Guo, Li, and Flanagan (2014) provided a literature review of more than 20 existing algorithms for individual tree detection and delineation from ALS, which showed overall accuracies (F_{score}) ranging from 42% to 96% depending on ALS point density, forest complexity and reference data used. Highest accuracies of tree detections were achieved over coniferous forests, while most of the algorithms have lower accuracies over more structurally complex forests, such as broadleaves (Vauhkonen et al., 2011; Lu et al., 2014). The majority of existing algorithms (Lee, Slatton, Roth, & Cropper, 2010; Li, Guo, Jakubowski, & Kelly, 2012) use top-down approaches and work best for trees with a distinct top. This is usually true for coniferous, cone-shaped trees, while most of the broad-leaf trees including eucalypts are asymmetrically-shaped, often have complex structures and thus require a bottom-up approach for delineation. Furthermore, the accuracy of tree detections and delineations is usually higher for algorithms that directly process an ALS-derived point cloud, rather than algorithms based on canopy height models (CHM) describing the outer canopy surface (Vega et al., 2014). This is because CHM based algorithms such as inverse watershed segmentation (Chen, Baldocchi, Gong, & Kelly, 2006; Edson & Wing, 2011) and local maxima growing algorithms (Tiede, Hochleitner, & Blaschke, 2005; Popescu, 2007) are ineffective in detecting suppressed trees.

To overcome the drawbacks of CHM based algorithms, it is now common to directly process an ALS-derived point cloud. In Li et al. (2012), a method to segment trees sequentially starting from the global maximum and taking advantage of the relative spacing between trees was proposed. Vega et al. (2014) developed the PTtrees segmentation that processes a 3D point cloud multiple times from the highest to the lowest point, using point kernels of varying size to identify potential trees. Lahivaara et al. (2014) used 3D model matching to approximate the geometries of trees with simplified surface models, which have been shown to work well (detection rates of 70%) in a conifer dominated forest. Lindberg, Eysn, Hollaus, Holmgren, and Pfeifer (2014) delineated tree crowns based on ellipsoidal tree crown models approximating the shapes of the hemi-boreal forest trees. Overall, even though the majority of recently developed algorithms take full advantage of a point cloud, they still represent either top-down or model matching approaches commonly developed for coniferous forests and expected to have lower accuracies when used for tree detection in natural broad-leaf forests, as shown in Vega et al. (2014) and Vauhkonen et al. (2011).

To segment individual trees from ALS, novel bottom-up approaches were proposed, which have only been implemented very few times (Reitberger, Schnörr et al. 2009; Lu et al., 2014). Both Reitberger, Schnörr et al. (2009) and Lu et al. (2014) made use of horizontal spacing between ALS points to detect tree trunks. While in the former method (Reitberger, Schnörr et al. 2009) results were refined using random sample consensus (RANSAC) based 3D line adjustment to detect individual trunks, the latter method (Lu et al., 2014) filtered out points reflected from small branches and withered leaves based on intensity values prior to the tree trunk detection. Both methods successfully detected tree trunks in their respective study areas. However, the problem of applying only a horizontal threshold means that tree trunks that have spacing of less than the pre-defined threshold (0.5 m to 2 m in the above mentioned studies) will be clustered together. In our study, we suggest that by looking at the spatial arrangement of points in both horizontal and vertical space, the problem of over-clustering tree trunks could be overcome. While Lu et al. (2014) assessed the performance of their algorithm using reference trees manually delineated from the point cloud, the study by Reitberger, Schnörr et al. (2009) detected 58% of field-measured trees using normalized cut segmentation. However, in Reitberger, Schnörr et al. (2009) 46% of the reference trees were conifers, which are known to be more easily delineated as compared to broad-leaved trees due to their cone-shaped structure. It is also important to note that in Reitberger, Schnörr et al. (2009) and Lu et al. (2014) only the accuracy of tree trunk detection but not the accuracy of segmented trees was assessed (e.g. in terms of crown width).

For some algorithms used for individual tree delineation from ALS it was reported that point density of ALS has a minor effect on accuracy of tree delineations after densities reach 10 points/m^2 (Reitberger, Schnorr, Krzystek, & Stilla, 2008; Yao, Krull, Krzystek, & Heurich, 2014). In contrast Wallace, Lucieer, and Watson (2014) showed that increases in point density (from 5 to 50 points/m^2) lead to significant improvements (of up to 8%) in the rate of omission for algorithms that made use of the high density of the data. This suggests that both algorithm and point density are important considerations in the accuracy of the detection and delineation of individual trees, and should be considered prior to ALS survey.

In ALS-based individual tree delineation studies the accuracy assessment of segmented tree crowns is usually validated using tree trunk to crown allometry (Vauhkonen et al., 2011; Duncanson, Cook, Hurtt, & Dubayah, 2014), tree height measurements (Yao, Krzystek, & Heurich, 2012; Lindberg et al., 2014) or tree crown width measurements (Persson, Holmgren, & Söderman, 2002; Popescu, Wynne, & Nelson, 2003). While the tree trunk to crown allometry based approach is skewed due to a weak relationship between trunk diameter and crown area for many forest sites, the tree height measurements based approach is prone to over- or under-segmentation of the crown extent. The high accuracy of tree trunk detections suffices for the needs of most forest studies; however, an accurate delineation of tree crowns is needed to allow its use with other remote sensing datasets, crown structural characterization or to accurately estimate tree volumes. Therefore, in this study we propose a new method for assessing tree crown delineation accuracy that takes advantage of both field-measured crown width and tree height.

For a more detailed description, accuracies achieved and examples of studies readers are referred to Lu et al. (2014) and Jakubowski, Li, Guo, and Kelly (2013) where the need for a reliable tool for delineating broad-leaf trees from ALS is also highlighted. In this respect, the full-waveform ALS is of special interest as it provides a higher point density and additional information about the reflecting properties of trees, such as returned pulse width and intensity (Yao et al., 2014). Previous research showed that surface roughness is the most influential factor affecting the returned pulse width and may be useful for identifying tree branches and trunks (Lin, 2010). It was reported that returned pulse widths on smooth surfaces (e.g. asphalt or tree trunks) were close to that of the emitted pulse, while forest canopies, representing rough surfaces, exhibit larger values of returned pulse widths (Wagner, Hollaus, Briese, & Ducic, 2008; Lin, 2010). It was also shown that the foliage material provides returns with lower intensity as compared to the woody material at 1500 nm wavelength, while they have similar intensity values at 1064 nm (Côté, Widlowski, Fournier, & Verstraete, 2009; Li et al., 2013). The wood–leaf separation approach is usually based on identifying an appropriate intensity threshold value and requires that the intensity values be normalized at least for range (Béland, Baldocchi, Widlowski, Fournier, & Verstraete, 2014) and could be estimated using a trial-and-error method (Côté et al., 2009) or by minimizing misclassifications in a point cloud (Béland, Widlowski, Fournier, Côté, & Verstraete, 2011). While most of these approaches utilize terrestrial laser scanners (TLS) in first return acquisition mode with extremely small footprints (~15 mm) allowing to eliminate transmission loss problem of secondary laser returns and to minimize the problem of partial laser hits, we believe that approximate leaf–wood separation could be achieved for airborne systems with larger footprints (~15 cm) as well. In our study to differentiate