Research Paper

Accuracy of tree diameter estimation from terrestrial laser scanning by circle-fitting methods

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ABSTRACT

This study compares the accuracies of diameter at breast height (DBH) estimations by three initial (minimum bounding box, centroid, and maximum distance) and two refining (Monte Carlo and optimal circle) circle-fitting methods The circle-fitting algorithms were evaluated in multi-scan mode and a simulated single-scan mode on 157 European beech trees (*Fagus sylvatica* L.). DBH measured by a calliper was used as reference data. Most of the studied circle-fitting algorithms significantly underestimated the mean DBH in both scanning modes. Only the Monte Carlo method in the single-scan mode significantly overestimated the mean DBH. The centroid method proved to be the least suitable and showed significantly different results from the other circle-fitting methods in both scanning modes. In multi-scan mode, the accuracy of the minimum bounding box method was not significantly different from the accuracies of the refining methods The accuracy of the maximum distance method was significantly different from the accuracies of the refining methods in both scanning modes. The accuracy of the Monte Carlo method was significantly different from the accuracy of the optimal circle method in only single-scan mode. The optimal circle method proved to be the most accurate circle-fitting method for DBH estimation from point clouds in both scanning modes.

1. Introduction

High-density point clouds from terrestrial laser scanning (TLS) open up new possibilities for accurate measurement of tree parameters and detailed three-dimensional modelling of forest stands. New TLS devices are small and lightweight; therefore, they can be easily used in a forest environment.

Trunks of all diameters can be detected and measured in high-density TLS point clouds. Studies have been carried out with a focus on deriving diameter at breast height (DBH), tree height (Király and Brolly, 2007; Liang and Hyyppä, 2013), and plot basal area (Seidel and Ammer, 2014). Point clouds completely cover the trees and canopy. This fact allows researchers to derive the shape and size of the tree crown (Moorthy et al., 2011), crown volume (Fernández-Sarría et al., 2013), and tree biomass (Kankare et al., 2013; Saarinen et al., 2017) from TLS data. Analysis of the amount and spatial distribution of reflected laser beams can be used in gap analysis (Ramirez et al., 2013) and estimation of leaf area index (Culvenor et al., 2014).

The prospective applications of TLS in forestry include 3D modelling of trees (Hackenberg et al., 2014), 3D modelling of tree root systems (Smith et al., 2014), and derivation of forest canopy fuel properties (García et al., 2011). Multi-temporal TLS of a forest stand was used to evaluate the influence of skidding operations on soil disturbance (Koreň et al., 2015).

DBH is one of the most important parameters required for forest inventory. Callipers or girth tapes are used to measure DBH in forest practices. TLS data offers new opportunities to derive tree diameter not only at breast height but potentially at any height above ground.

Trunk circumference is usually represented by a circle. The position and diameter of the circle are estimated by circle-fitting algorithms from a spatial cluster of points. Other geometric approaches approximate tree sections with cylinders (Brolly and Király, 2009), free-form curves (Pfeifer and Winterhalder, 2004), polygons (Wezyk et al., 2007) or skeletonization (Pál, 2008). Procedures based on three-dimensional rasters (Moskal and Zheng, 2012), Hough transformation (Aschoff and Spiecker, 2004) and morphological analysis (Maas et al., 2008) are under development.

Circle-fitting methods for deriving DBH from point clouds are based on horizontal cross-sectional slices. Horizontal cross-sectional slices of a point cloud are created at a given height above the ground. The thickness of the horizontal cross section is chosen according to the density of a point cloud to include the sufficient number of points

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needed for a reliable identification of trunks and measurement of their DBH. Cross-sections of individual trunks are identified by spatial clustering. Spatial clusters are also used for noise filtering. Spatial clusters with a low number of points are excluded from the subsequent data processing.

The accuracy of DBH estimated from a TLS point cloud is influenced by the technical parameters and settings of the scanner, scanning mode, positioning of the scanner, and data processing techniques. Most previous works studied the accuracy of one preferred DBH estimation algorithm. The results of these studies are difficult to compare because experiments were carried out in different forest stands and point clouds were processed by different methods. In our study, the accuracy of DBH estimation using different circle-fitting algorithms has been analysed in the same point cloud.

The aim of this work was to compare the results of DBH estimation using five circle-fitting methods from cross-sections of a TLS point cloud of European beech (*Fagus sylvatica* L.). The circle-fitting methods were evaluated by bias, precision, and accuracy of DBH estimation in a multi-scan and a single-scan mode. The results of DBH estimation by five algorithms have been statistically tested. Our findings provide deeper insight into the performance of the studied circle-fitting algorithms.

2. Material and methods

2.1. Research plot and field measurements

The research plot was established on the property of the University Forest Enterprise of the Technical University in Zvolen, central Slovakia. The research plot (Fig. 1) was located in a monoculture of European beech (*Fagus sylvatica* L.). The size of the research plot was 50 × 50 m. The forest stand was 80 years old with 160 beech trees, four European hornbeams (*Carpinus betulus* L.) and one European silver (*Abies alba* Mill.). To eliminate the influence of tree species on the results, only DBH estimation of beech trees was studied.

Terrestrial laser scanning and field measurements of the research plot were performed on the same day. DBH of trees was measured by digital BT Caliper (Masser Oy, Finland) with measurement accuracy 1 mm. DBH of trees was measured in a slope direction and in the perpendicular one. The resulting DBH of each tree was calculated as the arithmetic mean of the measured diameters. Distribution of DBH measured by calliper on the research plot is presented in Fig. 2.

The phase-shift laser scanner FARO Focus3D 120 (FARO Technologies, Inc., USA) was used for terrestrial laser scanning. Distance range of the scanner is 0.6–120 metres. The horizontal angular range of the scanner is 360° and the vertical angular range is 305°. The density of the scan can be set to 9 levels ranging from 1.5 to 49 mm at a
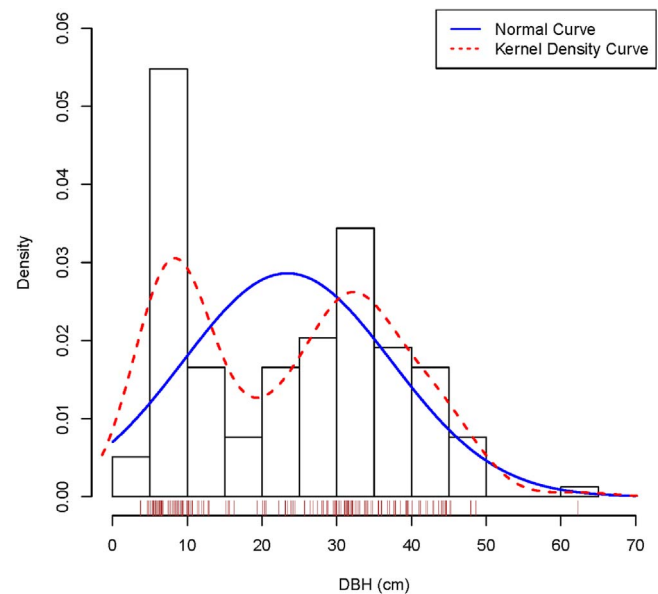
Fig. 2. Distribution of DBH measured by calliper on the research plot.

distance of 10 m. At the highest resolution, a single point cloud contains up to 699 million points. The scanning quality can be set to one of 6 levels. Higher scan quality means more effective noise removal and longer scanning time. Scanning time for the highest quality and resolution is approximately 2 h.

Terrestrial laser scanning of the research plot was completed in late autumn (23/10/2012). The research plot was scanned with quality 3 and resolution 6 mm/10 m. With this combination of settings, the time for one scan was approximately 8 min, which is an appropriate length of time for the forest environment. We scanned the research plot 22 times in total (Fig. 3).

18 reference spheres of the standard size 14.4 cm were used to register the point clouds to a local coordinate system. The central scan was chosen as a reference scan. The y-axis of the local coordinate system was oriented in the uphill direction. The other scans were registered with the reference scan.
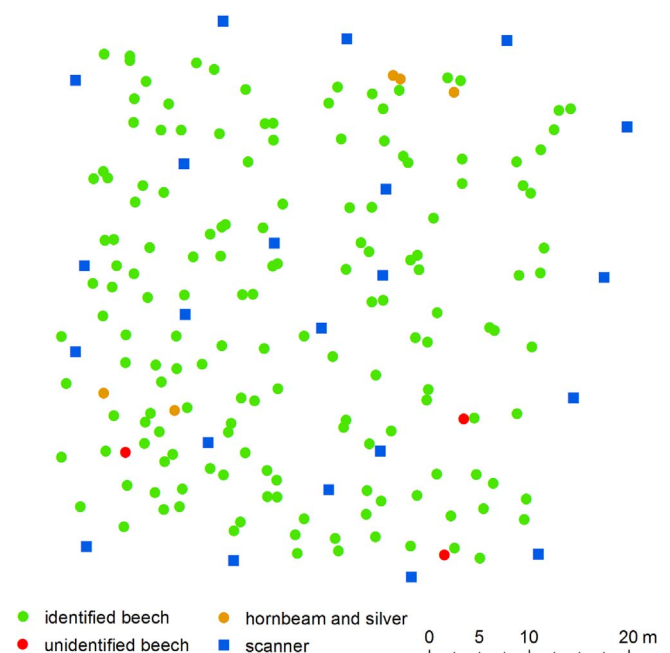
Fig. 1. Beech stand on the research plot.

Fig. 3. Scanning scheme of the research plot.