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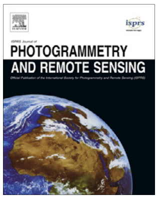

Terrestrial laser scanning in forest inventories

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ABSTRACT

Decision making on forest resources relies on the precise information that is collected using inventory. There are many different kinds of forest inventory techniques that can be applied depending on the goal, scale, resources and the required accuracy. Most of the forest inventories are based on field sample. Therefore, the accuracy of the forest inventories depends on the quality and quantity of the field sample. Conventionally, field sample has been measured using simple tools. When map is required, remote sensing materials are needed. Terrestrial laser scanning (TLS) provides a measurement technique that can acquire millimeter-level of detail from the surrounding area, which allows rapid, automatic and periodical estimates of many important forest inventory attributes. It is expected that TLS will be operationally used in forest inventories as soon as the appropriate software becomes available, best practices become known and general knowledge of these findings becomes more wide spread. Meanwhile, mobile laser scanning, personal laser scanning, and image-based point clouds became capable of capturing similar terrestrial point cloud data as TLS. This paper reviews the advances of applying TLS in forest inventories, discusses its properties with reference to other related techniques and discusses the future prospects of this technique.

1. Introduction

Forest resource information is gathered for planning and managing of various ecosystem services at various user-levels, from worldwide political decision making to operational forest management, and at various scales, from countrywide assessments to stand-level measurements. At the national and global scale, the main goal of the inventory is to collect information on forested area such as biomass, stem volume, biodiversity and changes in these attributes. At the regional and forest holding level, it is important to also collect information from timber harvesting potential and from forest operations. To meet the goals of the inventory, there are many different kinds of techniques depending on the available resources and the required accuracy. Most of the forest inventories are based on field samples. Field samples can be used to calculate means and totals over area of interest or to aid remote-sensing-based forest mapping. Therefore, the accuracy of the forest inventories depends on the quality and quantity of the field sample.

Forest sample plots are typically a small forest area, e.g., circular in shape with a radius varying from 4 m to 15 m. Tree information is usually collected in forest field inventories through tree-by-tree measurements. The main information consists of tree attributes such as species, diameter at breast height (DBH) and tree height. In the current inventory practices, tree-by-tree measures are mostly aggregated to plot-level means and totals. For example, the basal area per hectare is calculated from tree-level DBH measurements and the aggregation is based on the sample plot size. Conventionally, field sample has been measured using simple tools, such as calipers and clinometers, and the advancement of forest field inventories has been slow in the past. The situation experienced a dramatic change in the last two decades because of the introduction of terrestrial laser scanning (TLS), also known as ground-based Light Detection and Ranging (LiDAR).

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Three fundamental aspects shape the adaptation of any new technique in measuring tree-by-tree information in sample plots in forest inventories: (1) The cost of the data acquisition and data interpretation should be affordable. The costs originate mainly from the equipment, time consumption of data acquisition (e.g., field work) and post-processing of the data. (2) The accuracy of the tree attribute estimation should be at the same level or surpass the conventional technique, or the gained added value from the new technique should be significant. (3) The technique should focus primarily on tree attributes that are important for forest management decision-making at varying scales and time horizons. These three factors interact intimately. The minimized cost often leads to a smaller amount of tree attributes measured. The higher accuracy often requires better data and the measurement costs are on the increase consequently.

TLS automatically measures the surrounding three-dimensional (3D) space using millions to billions 3D points. The major advantage of using TLS in forest inventories lies in its capability to document the forest rapidly, automatically and in millimeter-level detail. The first commercial TLS system was built by Cyra Technologies (acquired by Leica in 2001) in 1998, and early works related to tree attribute estimation in forest inventories were reported around 2000 (Erikson and Karin, 2003; Lovell et al., 2003; Hopkinson et al., 2004; Parker et al., 2004; Thies et al., 2004; Henning and Radtke, 2006a). The initial motivation for using TLS in forest inventories was to improve the work efficiency in the sample plots, i.e., replacing manually measured tree attributes with those retrieved automatically from TLS data. Therefore, TLS has been used in collecting basic tree attributes in sample plots, such as DBH and tree position (Bienert et al., 2006; Maas et al., 2008; Vastaranta et al., 2009; Murphy et al., 2010).

More recently, TLS has been shown to be capable of determining high-quality tree attributes that are important but are not directly measurable in conventional forest inventories, such as stem volume and biomass components (total, stem and branches), with accuracy levels that are similar to the best national allometric models, such as in Yu et al. (2013), Kankare et al. (2013), Liang et al. (2014), Astrup et al. (2014) and Newnham et al. (2015). TLS data also permit time series analyses because the entire plot can be documented consecutively over time, such as in Liang et al. (2012a) and Srinivasan et al. (2014). With these latest research results, TLS has shown the possibility to improve the quality and quantity of the reference data collected in the forest inventories.

It is worth to note that TLS is also a popular tool in forest ecology. The use of TLS has been intensively studied, e.g., for the estimation of leaf area index (Hosoi and Omasa, 2006; Strahler et al., 2008; Jupp et al., 2009; Huang and Pretzsch, 2010; Hopkinson et al., 2013; Zheng et al., 2013), gap fraction (Danson et al., 2007; Seidel et al., 2012; Zhao et al., 2012; Cifuentes et al., 2014), canopy radiation (Van der Zande et al., 2011; van Leeuwen et al., 2013), crown structure (Moorthy et al., 2011; Bayer et al., 2013) and leaf area distributions (Béland et al., 2011). TLS studies aimed at forest ecology and forest inventories share certain common interests. For example, the basic tree attributes, such as the tree species, tree height, DBH and biomass, are collected in both research areas. However, most tree attributes that are intensively used in forest ecology are not measured in forest inventories, and vice versa, such as the leaf area index and the stem curve.

This paper reviews the advances of using TLS in forest inventories since TLS became available, discusses its properties with reference to other similar and competing techniques and highlights its future prospects. Section 2 describes the TLS system, data and measurement principles. Section 3 specifies methods and applications of TLS in forest inventories. Section 4 reviews studies reported in literatures. Section 5 reviews contemporary technologies that produce terrestrial point cloud and evaluates their advantages and disadvantages. Section 6 discusses the prospects of using TLS in forest inventories. The conclusions are summarized in Section 7.

2. TLS system, data and measurement principles

Laser measurements have been utilized in standard surveying application instruments for the past decades to measure object geometry. A total station, for instance, is used by a field surveyor to measure individual feature points with a high degree of accuracy. In the late 1990s, this manual and specific measuring mechanism was further developed into an automated and non-specific documentation of the entire surrounding 3D space by dense 3D measurements, i.e., terrestrial laser scanning.

2.1. TLS system

TLS is a laser-based instrument that measures its surroundings using LiDAR for range measurement and precise angular measurements through the optical beam deflection mechanism to derive 3D point observations from the object surfaces.

Two main techniques are used for the range measurement in current laser scanning systems: phase shift (PS) and time-of-flight (ToF) methods. PS ranging makes use of continuous laser illumination and amplitude modulation of the beam to discern the range at high frequency. ToF utilizes precise timing for determining the range from the pulse time of flight and the speed of light. In ToF, for each emitted laser pulse, the backscattered part of the laser signal may be recorded at the receiver as just one return exceeding the detection threshold or several returns (e.g., single, first, last and intermediate). A multi-return system typically produces a much denser point cloud in comparison with a single-return system, especially in a vegetated area, because the backscattered signals may arise from targets inside of and/or behind vegetation. Besides discrete returns, a backscattered laser signal may be consecutively digitized at the receiver, which gives a waveform data. Waveform includes data representing interactions between a laser pulse and targets in the laser beam direction, which can potentially be used to retrieve additional information with respect to discrete returns.

The scanning mechanisms enable TLS to capture very dense (e.g., currently one million points per second) measurements in a short period of time. In a typical TLS instrument, the scanner measures the surrounding environment stepwise using a fast vertical mirror rotation and a slower horizontal instrument rotation, as shown in Fig. 1. In the vertical direction, the laser beam starts, for example, from the scanner zenith and rotates to the lowest scanning position below the horizontal plane of the instrument. Then, the laser beam continues to the scanner zenith on the other side of the instrument. In the horizontal direction, the scanner turns 180° and scans both sides of the instrument simultaneously.

More details on the scanning mechanism and measuring technique of TLS scanners can be found in Petrie and Toth (2009), Reshetyuk (2009) and Vosselman and Maas (2011).

TLS hardware has experienced a rapid improvement in the last two decades. The price, the size and the weight of the laser scanners decreased rapidly, with the constantly increased spatial resolution and the measurement speed. Currently, scanners provided by manufacturers such as FARO, Leica Geosystems, Trimble and Zöller & Fröhlich can measure up to one million points per second at the range of 100–300 m and the ranging precision is at a millimeter level. A digital camera is also commonly integrated to the scanner to provide color information (in red, green and blue) for the measured point cloud. The weight of a scanner can be just a few kilograms, e.g., 5.2 kg in the case of the Faro Focus^{3D}X 330. Manufacturers typically have several options for the hardware,

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