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Multiview range-image registration for forested scenes using explicitly-matched tie points estimated from natural surfaces

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Abstract

Range images collected from terrestrial laser scanners hold promise for characterizing forest canopies and facilitating research into linkages between forest structure and function. Applications that aim to make plot-level or canopy-level assessments may ultimately require combining range imagery from multiple viewpoints, a procedure of image co-registration that poses numerous challenges. We developed a method for simultaneously registering multiple range images using explicitly-matched, computer-estimated tie points from natural ground and tree-stem surfaces in two stages. Stage I involved registration using tie points estimated from ground-surfaces, while stage II involved tie points estimated from tree-stem centers. Eight range images were simultaneously aligned based on more than 3000 tie point pairs from ground surfaces, and more than 4000 tie point pairs from tree stems. Tie points were widely dispersed throughout the scanned volume, spanning a horizontal area of 750 m^2 and heights up to 22 m above ground. Results showed accurate image alignments at heights well above ground, with an average post-registration error, for tree-stem-based tie point pairs, of 0.16 cm. When linked to automated algorithms for identification and extraction of tree stems from point clouds, the method developed here should be useful for delivering an array of products related to the detailed assessment of forest canopies and stand structure.

Keywords: Alignment; Terrestrial laser scanning; Canopy structure; Point cloud; Ground-based lidar; Stem map; Stem profile; Digital terrain model

1. Introduction

Remote sensing technologies have substantially altered the way resource managers and scientists observe the attributes of forested ecosystems. Terrestrial laser scanners are among the remote sensing tools that have become increasingly available for making accurate, repeatable, and highly detailed assessments of forests and trees from close-range (Aschoff et al., 2004; Henning and Radtke, 2006a; Hopkinson et al., 2004; Tanaka et al., 2004; Thies et al., 2004; Thies and Spiecker, 2004). When operated from a fixed platform or tripod, a laser scanner produces "range images"—digital representations of the 3-dimensional (3D) positions of surfaces visible from the sensor's viewpoint. Range images of forested environments have been used to make detailed measurements of individual trees, including maps of stem positions and tree dimensions (Henning and Radtke, 2006a; Hopkinson et al., 2004). Plot-level attributes including the spatial distribution of canopy elements have also been quantified using range images (Henning and Radtke, 2006b). Such data allow for

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exploration of linkages between forest structure and function at scales and intensities that are impractical with current airborne remote sensing methods or traditional field measurements (Lovell et al., 2003).

A number of factors limit the utility of any single range image for the analysis of forest plot, canopy, or stand-level attributes. Vegetation or terrain in the foreground of a range image may occlude the lines of sight to more distant objects or surfaces. The natural variability of forests often limits the visibility of some surfaces of interest from any one vantage point (Hopkinson et al., 2004; Thies and Spiecker, 2004). Range-image point density and accuracy generally decrease with distance from the sensor, effectively limiting the range at which certain analyses can be carried out. Additionally, in multitemporal applications, two or more images must be taken at different points in time to measure change. Such applications depend on the existence of time-invariant features in scenes of interest to be carried out effectively.

Applications that combine multiple range images generally require registration of all images to a single coordinate system (Curless, 1999; Gagnon et al., 1999). A number of range-image registration algorithms are reported in the literature; however, their use in forested settings is limited due to the amount of occlusion, spatial variability, surface irregularities, and movement – especially of leaves and small branches – typical of forest vegetation. The registration techniques most applicable to range images acquired in forests were developed for surveying applications or architectural reverse-engineering. These registration algorithms typically select a number of common features from overlapping images to act as “tie points” or “registration surfaces,” then estimate transformation parameters that bring the corresponding features into best alignment (Goshtasby, 1998). Such algorithms can be broadly categorized as either automated or user-guided.

Automated registration techniques rely on computer algorithms to select tie points, although the ability of computers to perform this task in complex scenes has not been fully explored. The most well known of the automated class of registration algorithms is Besl and McKay’s (1992) iterative closest point (ICP) method. Other automated methods are similar to ICP, or extensions of it, so it serves as a useful example. The ICP algorithm determines matched points between two images as those that are “closest” or nearest in Euclidian space (Besl and McKay, 1992). Transformation parameters are then calculated that minimize the sum of squared distances between closest points. Following the transformation, a new set of closest-points is identified. The process is repeated iteratively until a transformation is attained that meets a specified termination criterion corresponding to the required transformation accuracy. The ICP algorithm is robust to single point measurement error and has been widely applied, with modifications, to achieve accurate fine scale registration of range images of engineered surfaces (Dalley and Flynn, 2002; Gagnon et al., 1999; Goshtasby, 1998). Reported limitations of ICP include the requirement of an accurate initial alignment prior to running the algorithm, occasional convergence on locally optimal transformation parameters, and the need to accurately determine which portions of scenes overlap (Dalley and Flynn, 2002; Goshtasby, 1998; Kim et al., 2004). Researchers have reported on the difficulty of determining appropriate initial alignments and devised methods to avoid convergence on local rather than global optima (Dalley and Flynn, 2002). Additionally, a number of attempts have been made to improve and generalize ICP through automated determination of overlapping regions between images and reduction of outliers in noisy data (Chetverikov et al., 2005; Estepar et al., 2004; Kim et al., 2004). However, the data used in most applications of these methods deal with images with significant overlap (often greater than 50%), images containing only one object or surface of interest, and images with relatively high point densities (Chetverikov et al., 2005; Estepar et al., 2004; Kim et al., 2004). Such characteristics are not typical with images of forested scenes.

User-guided algorithms rely on a human analyst to precisely match features or points in overlapping range images. Such features are sometimes created by the placement of artificial targets in range-image scenes (Gagnon et al., 1999; Goshtasby, 1998). Transformation parameters are calculated that minimize the squared distances between matched-point pairs. User-guided algorithms generally require no initial registration. They avoid convergence on local minima, so long as matched features are identified precisely enough. User-guided systems are sensitive to noisy data, especially when redundancy and reliability are poor due to low numbers of tie points. To minimize the effect of noisy data, the positions of corners or edges of engineered objects can be modelled using simple geometric primitives whose position and orientation define sets of matched tie points for subsequent alignment. Such features are generally not available for matching surface points that lie on vegetative surfaces such as the main stems of trees. Although tree branches, leaves or other features can be selected as tie points from an image, sufficiently precise manual matching of these features between images is hindered by the random and dispersed view occlusion of a natural scene and positional differences due to differing viewpoint perspectives. Further, in forests where many branches and leaves may be visible in a relatively small