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UAV lidar and hyperspectral fusion for forest monitoring in the southwestern USA

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ABSTRACT

Forest vegetation classification and structure measurements are fundamental steps for planning, monitoring, and evaluating large-scale forest changes including restoration treatments. High spatial and spectral resolution remote sensing data are critically needed to classify vegetation and measure their 3-dimensional (3D) canopy structure at the level of individual species. Here we test high-resolution lidar, hyperspectral, and multispectral data collected from unmanned aerial vehicles (UAV) and demonstrate a lidar-hyperspectral image fusion method in treated and control forests with varying tree density and canopy cover as well as in an ecotone environment to represent a gradient of vegetation and topography in northern Arizona, U.S.A. The fusion performs better (88% overall accuracy) than either data type alone, particularly for species with similar spectral signatures, but different canopy sizes. The lidar data provides estimates of individual tree height ($R^2 = 0.90$; RMSE = 2.3 m) and crown diameter ($R^2 = 0.72$; RMSE = 0.71 m) as well as total tree canopy cover ($R^2 = 0.87$; RMSE = 9.5%) and tree density ($R^2 = 0.77$; RMSE = 0.69 trees/cell) in 10 m cells across thin only, burn only, thin-and-burn, and control treatments, where tree cover and density ranged between 22 and 50% and 1–3.5 trees/cell, respectively. The lidar data also produces highly accurate digital elevation model (DEM) ($R^2 = 0.92$; RMSE = 0.75 m). In comparison, 3D data derived from the multispectral data via structure-from-motion produced lower correlations with field-measured variables, especially in dense and structurally complex forests. The lidar, hyperspectral, and multispectral sensors, and the methods demonstrated here can be widely applied across a gradient of vegetation and topography for monitoring landscapes undergoing large-scale changes such as the forests in the southwestern U.S.A.

1. Introduction

Many forests across the world are becoming increasingly susceptible to fire, drought, insect outbreak, and disease due to climate change (Foley et al., 2005; Trumbore et al., 2015). In response to this, forest managers are proactively undertaking targeted, yet widespread forest treatments such as thinning and prescribed burning to make forests more resilient to climate change effects (Mast et al., 1999; Fulé et al., 2001; Reynolds et al., 2013; Stephens et al., 2013). Remote sensing-based classification of forest vegetation and measurement of forest structure are fundamental and necessary steps for planning, monitoring, and evaluating forest treatments (Roberts et al., 2004; Wulder et al., 2004; Hyde et al., 2006; Hyyppä et al., 2001; Van Leeuwen and Nieuwenhuis, 2010). Since many of the treatments are conducted at the scale of individual trees within forests that contain many species, remote sensing tools need to be spatially and spectrally sufficient to classify and measure vegetation at the level of individual species and canopies.

Here we focus specifically on the use of high spatial and spectral resolution data from UAVs to classify vegetation at the species level and to measure structural characteristics of individual plant canopies in ponderosa pine forests of Arizona, USA. The US Forest Service (USFS) is launching a regional restoration effort in Arizona, known as the Four Forest Restoration Initiative (4FRI), the first and largest restoration project in US history, which will soon be adopted in other states across the southwestern USA. The 4FRI will restore over a million hectares of ponderosa pine forests in northern Arizona via thinning and prescribed burning over the next 20 years (USDA, 2015) to mimic historic low density forests. As 4FRI modifies the forests, land managers must monitor the treatments and evaluate their effectiveness. In particular, managers need to measure changes in tree cover, density, and spatial distribution and how they in turn influence other ecological processes such as evapotranspiration, snow accumulation and melt, soil and groundwater recharge. Satellite images in many cases cannot provide enough spectral and spatial detail to classify and measure individual plants at the species level for these types of forest treatments (Sankey and Glenn, 2011).

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Lidar data can be used for high-resolution estimates of tree cover and density (Popescu et al., 2003; Bork and Su, 2007; Asner et al., 2010; Koch, 2010) as well as individual tree height and diameter (Hyyppä et al., 2001; Popescu, 2007; Sankey et al., 2013). Hyperspectral data have been commonly used to classify vegetation at the species level and detect target species (O'Neill et al., 2000; Root et al., 2004; Parker Williams and Hunt, 2002; Noujdina and Ustin, 2008). Taken together, lidar and hyperspectral data can offer unique and synergistic capabilities leveraging the vertically and horizontally explicit estimates from each data source. Previous efforts have integrated lidar derivatives with hyperspectral and multispectral data (Anderson et al., 2008; Dalponte and Burzzone, 2008; Wulder et al., 2009; Ke et al., 2010). While some of these fusion efforts have resulted in marginal improvements in classification accuracies for forested environments (Hyde et al., 2006), the fusion has been found particularly useful in rangeland environments (Bork and Su, 2007; Sankey et al., 2010), which can contain a mixture of trees, shrubs, forbs and grass species and where vegetation structural characteristics therefore often vary among species. A fusion of UAV-based lidar and hyperspectral images might further improve these benefits due to the finer spatial and spectral resolution of UAV data.

1.1. Unmanned aerial vehicles

The use of UAVs is rapidly expanding and is expected to revolutionize remote sensing for the natural sciences (Anderson and Gaston, 2013; Vivoni et al., 2014). In this study, we use and evaluate an octocopter UAV and a fixed-wing UAV, two of the first platforms permitted to operate in the USA by the Federal Aviation Administration (FAA). UAV platforms provide a unique opportunity for acquiring low-cost imagery at fine spatial and temporal resolutions, from local to regional scales (Anderson and Gaston, 2013; Bryson et al., 2014). Furthermore, they can avoid some complications associated with other platforms, such as plane flight logistics, satellite return times, cloud cover, and atmospheric effects on imagery (Anderson and Gaston, 2013). Specific applications of UAV images include analysis of vegetation patterning and orientation (Wallace et al., 2014; Paneque-Gálvez et al., 2014; Lin et al., 2015; Chianucci et al., 2016), detecting plant stress and disturbance (Zarco-Tejada et al., 2012; Getzin et al., 2014; Lehmann et al., 2015), biodiversity monitoring (Vas et al., 2015), land cover change detection (Koh and Wich, 2012), precision agriculture (Hunt et al., 2010; Guillen-Climent et al., 2012; Matese et al., 2015), and water resource management (Vivoni et al., 2014; DeBell et al., 2015).

Recent advances in UAV sensors include lidar (Lin et al., 2015; Wallace et al., 2012) and hyperspectral sensors (Zarco-Tejada et al., 2012; Hruska et al., 2012), although visible (RGB) and near-infrared (NIR) imagery have been most commonly used on UAV platforms (Valavanis and Vachtsevanos, 2015) along with multispectral (Nebiker et al., 2008) and thermal sensors (Berni et al., 2009). Hyperspectral sensors aboard UAVs is expected to enhance remote sensing research in the natural sciences (Anderson and Gaston, 2013; Valavanis and Vachtsevanos, 2015). Similarly, UAV-based lidar scanners will provide high-resolution topographic models and key measurements necessary for geomorphic, hydrological, and geomorphological modelling (Sankey et al., 2010; Sankey et al., 2012). The 3D individual tree canopy estimates can provide inputs for total aboveground biomass measurements and carbon estimates for carbon sink and source calculations at the landscape scale (Lefsky et al., 2002; Patenaude et al., 2004; Sankey et al., 2013). UAV-based 3D models have thus far provided "synthetic" data generated from simple RGB and multispectral images using photogrammetric methods including structure from motion (SfM) (Neitzel and Klonowski, 2011; Niethammer et al., 2012; Guillen-Climent et al., 2012; Dandois and Ellis, 2013; Lisein et al., 2013; Harwin et al., 2015). SfM-derived 3D models, however, can have errors too large for applications such as topographic and vegetation change detection due to geomorphic processes and vegetation growth, respectively (Niethammer et al., 2012; Dandois and Ellis, 2013), although they have accuracies adequate for many other applications compared to traditional laser-derived models (Neitzel and Klonowski, 2011; Niethammer et al., 2012; Fonstad et al., 2013).

1.2. Objectives

We use the octocopter UAV lidar and hyperspectral sensors and the fixed-wing UAV multispectral sensor to classify and measure the structural characteristics of individual canopies in ponderosa pine forest and ecotone vegetation in northern Arizona. Using the individual datasets from the octocopter UAV, we first estimate: 1) presence and sub-pixel abundance of eight different cover types including tree, shrub, and herbaceous species in 12-cm resolution hyperspectral data, 2) individual tree canopy height and diameter along with 3D tree segmentation and bare earth DEM using the lidar data, and 3) tree canopy cover and density (number of trees) per 10-m cells among different forest treatment types using the lidar data. We then fuse the hyperspectral classification and lidar-derived canopy height estimates to produce a final land cover type map. We hypothesize that the fusion of lidar and hyperspectral data would perform better than either data type alone for classifying multiple vegetation species in areas where spectral signatures between species are similar, but their sizes are different. We also assess the spectral and geometric accuracies of the hyperspectral and lidar data by comparing them to field-based GPS (Trimble GeoXH), ground-based spectroradiometer (ASD), and terrestrial laser scanner (Riegl VZ-1000 georeferenced with TOPCON GR3 RTK-GPS) data.

Secondly, we estimate tree canopy cover in 10-m cells using the fixed-wing UAV multispectral data with 15-cm resolution and generate a structure from motion (SfM) 3D point cloud to estimate tree density, individual tree height and diameter, and bare earth DEM. We then evaluate the SfM-derived 3D vegetation models and DEMs to determine if the commonly used, more affordable fixed-wing UAV SfM-derived models perform equally well compared to the octocopter UAV lidar-derived models.

2. Methods

2.1. UAV platforms and sensors

The octocopter aircraft (Service-Drone, Germany) weighs 5.5 kg and was developed to carry an additional heavy payload of up to 6.5 kg (Fig. 1). The flight duration is relatively limited at 9 min per mission due to the heavy payload and battery capabilities. The octocopter is controlled via a hand-held remote control transmitter and a ground control station with navigation data link, which sends waypoint navigation information to the aircraft from a laptop computer. Pre-programmed flight mission plan is made in a software known as GroundStation, where the flight path, flight altitude, and speed are user defined. The flight path information is converted and transferred as waypoint navigation data to the UAV GPS. For additional safety, the octocopter UAV is launched and landed manually with the remote control transmitter, although it automatically navigates to the waypoints once it reaches the pre-defined flight altitude. The platform has a redundant design and is stable in windy conditions up to 15 m/s. The octocopter was custom-designed to carry an inertial navigation system (INS), a lidar scanner, and a hyperspectral sensor with a data storage unit on a 3-axis gimbal. The INS has an integrated survey-grade Global Navigation Satellite System (GNSS) and an inertial motion unit (IMU) that correct for errors associated with pitch, roll, and heading (0.05°, 0.05° and 0.5° RMS, respectively) (SBG Systems North America, Inc., Chicago, IL). The hyperspectral sensor is a pushbroom nano-sensor with 272 spectral bands ranging 400–1000 nm (Headwall Photonics Inc., Fitchburg, MA). The hyperspectral sensor can operate at a large range of flight altitudes resulting in various spatial resolutions and image extents depending on flight altitude. The hyperspectral sensor was integrated with the onboard data storage, GNSS INS/IMU, and a Velodyne HDL-32E lidar