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Tree height quantification using very high resolution imagery acquired from an unmanned aerial vehicle (UAV) and automatic 3D photo-reconstruction methods

P.J. Zarco-Tejada [a,b,*], R. Diaz-Varela [a,c], V. Angileri [a], P. Loudjani [a]

[a] European Commission, Joint Research Centre, Institute for Environment and Sustainability, Via E. Fermi 2749, I-21027 Ispra, VA, Italy
[b] Instituto de Agricultura Sostenible (IAS), Consejo Superior de Investigaciones Científicas (CSIC), Córdoba, Spain
[c] Department of Botany, GI-1934-TB, IBADER, University of Santiago de Compostela, Escola Politécnica Superior, Campus Universitario s/n, E-27002 Lugo, Spain

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ABSTRACT

This study provides insight into the assessment of canopy biophysical parameter retrieval using passive sensors and specifically into the quantification of tree height in a discontinuous canopy using a low-cost camera on board an unmanned aerial vehicle (UAV). The UAV was a 2-m wingspan fixed-wing platform with 5.8 kg take-off weight and 63 km/h ground speed. It carried a consumer-grade RGB camera modified for color-infrared detection (CIR) and synchronized with a GPS unit. In this study, the configuration of the electric UAV carrying the camera payload enabled the acquisition of 158 ha in one single flight. The camera system made it possible to acquire very high resolution (VHR) imagery (5 cm pixel^{-1}) to generate ortho-mosaics and digital surface models (DSMs) through automatic 3D reconstruction methods. The UAV followed pre-designed flight plans over each study site to ensure the acquisition of the imagery with large across- and along-track overlaps (i.e. >80%) using a grid of parallel and perpendicular flight lines. The validation method consisted of taking field measurements of the height of a total of 152 trees in two different study areas using a GPS in real-time kinematic (RTK) mode. The results of the validation assessment conducted to estimate tree height from the VHR DSMs yielded R^2 = 0.83, an overall root mean square error (RMSE) of 35 cm, and a relative root mean square error (R-RMSE) of 11.5% for trees with heights ranging between 1.16 and 4.38 m. An assessment conducted on the effects of the spatial resolution of the input images acquired by the UAV on the photo-reconstruction method and DSM generation demonstrated stable relationships for pixel resolutions between 5 and 30 cm that rapidly degraded for input images with pixel resolutions lower than 35 cm. RMSE and R-RMSE values obtained as a function of input pixel resolution showed errors in tree quantification below 15% when 30 cm pixel^{-1} resolution imagery was used to generate the DSMs. The study conducted in two orchards with this UAV system and the photo-reconstruction method highlighted that an inexpensive approach based on consumer-grade cameras on board a hand-launched unmanned aerial platform can provide accuracies comparable to those of the expensive and computationally more complex light detection and ranging (LIDAR) systems currently operated for agricultural and environmental applications.

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1. Introduction

Canopy height is an important parameter required for inventory, monitoring, and modeling activities (Selkowitz et al., 2012). In particular, it is an ecological measure that provides essential information related to ecological, hydrological, biophysical, micrometeorological, and agronomic processes in natural vegetation and agricultural crops. However, existing spatial datasets provide little information on canopy height. An accurate and automatic estimation of tree height is also important for the identification and monitoring of certain features of agricultural lands in the framework of the European common agricultural policy (CAP). In this regard, since 2005 farmers have had to comply with common rules and standards regarding the environment as well as public, animal

Abbreviations: AAT, automatic aerial triangulation; AGL, above ground level; AHRS, attitude heading reference system; ALS, airborne laser scanner; BBA, bundle block adjustment; CAP, common agricultural policy; CIR, color-infrared; COTS, commercial off-the-shelf; DSM, digital surface model; EFA, ecological focus areas; GAEC, good agricultural and environmental condition; GPS, global positioning system; GSD, ground sampling distance; LIDAR, light detection and ranging; MAMSL, meters above mean sea level; MVS, mutiview-stereo; NDVI, normalized difference vegetation index; RGB, red-green-blue; RMSE, root mean square error; R-RMSE, relative root mean square error; RTK, real-time kinematic; SfM, structure-from-motion; TOW, take-off weight; UAV, unmanned aerial vehicle; VHR, very high resolution.

* Corresponding author at: Instituto de Agricultura Sostenible (IAS), Consejo Superior de Investigaciones Científicas (CSIC), Córdoba, Spain. Tel.: +34 957499280; fax: +34 957499252.
E-mail address: pablo.zarco@csic.es (P.J. Zarco-Tejada).

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and plant health and animal welfare in order to obtain full 'single farm payments.' Such standards are known as 'cross-compliance' (Council Regulation EC No. 73/2009). As a component of cross compliance, farmers are obliged to keep the agricultural land in good agricultural and environmental condition (GAEC) by respecting a number of minimum requirements in issues such as the prevention of soil erosion, the conservation of soil organic matter and structure, and the maintenance of habitats and landscape features. Further measures are under discussion in the proposal of the 'greening' of direct payments, which may require the need for identifying and characterize landscape features.

One of the measures proposed for the 'greening' of payments establishes that farmers shall ensure that a certain amount of their agricultural land is kept as 'ecological focus areas' (EFA), which refers to a set of elements that delivers environmental benefits. Several types of landscape features such as hedges and trees, either in groups or isolated, are among the elements taken into account in both the GAEC and the EFA proposals. All these elements generally show a distinct contrast in their dimensions and physiognomy (i.e. height) with their surrounding agricultural matrix. Therefore, the estimation of their height is a key input for their automatic identification and monitoring (Bork and Su, 2007), particularly in cases where the spectral responses of landscape features and surrounding crops are often similar. In this regard, the standard multispectral indices currently obtained from passive remote sensors, such as the normalized difference vegetation index (NDVI) calculated from near infrared and red spectral regions (Rouse et al., 1974), are quite limited for mapping vegetation canopy height. This is because reflectance data are primarily sensitive to canopy cover and vegetation density rather than height and thus can only capture canopy height indirectly (Chopping et al., 2008).

For this reason, remote quantification of canopy structural parameters such as canopy height must rely on the development of very high resolution digital models to enable the identification and retrieval of the height of each single tree crown or canopy plot. Such standard methodologies used for the generation of digital surface models (DSMs) usually focus on photogrammetric methods and more recently on the use of active sensors such as light detection and ranging (LIDAR) laser scanners. Both require expensive cameras, well-trained personnel, and precise technology to obtain accurate results. Several examples can be found in the literature regarding the retrieval of canopy height using multi-angle/multiview passive imagery from both airborne platforms (Waser et al., 2008; Wallerman et al., 2012) and satellite platforms (Takahashi et al., 2012) and also from active laser systems (Kaartinen et al., 2012). In a study, researchers obtained 34% error when retrieving canopy height from aerial DMC imagery in a forest area (Wallerman et al., 2012). Other authors obtained errors ranging between 0.09 m and 1.2 m (i.e. from over 5% to over 10%) when estimating individual tree height from an airborne laser scanner (ALS) (Kaartinen et al., 2012; Ma et al., 2012; Edson and Wing, 2011; Pirotti, 2010; Tesfamichael et al., 2010a,b; Gratziolis et al., 2010). Depending on the segmentation methodology used to process the ALS data, reported errors when quantifying individual tree height ranged between 0.09 and 0.56 m, depending on the type of forest canopy under study such as young conifers and forested plots (Edson and Wing, 2011). Nevertheless, we are not aware of the existence of any other studies on canopy height quantification using very high resolution DSMs obtained from passive sensors.

New progress in the miniaturization and cost reduction of GPS devices, embedded computers, and inertial sensors has opened new possibilities for remote sensing applications using commercial off-the-shelf (COTS) instrumentation (Berni et al., 2009a). Such miniaturization has provided high flexibility in terms of potential applications based on the development of unmanned aerial vehicles (UAVs). In fact, recent studies have demonstrated the feasibility of conducting quantitative remote sensing for vegetation monitoring using miniaturized thermal cameras on board lightweight UAV platforms (Berni et al., 2009a,b; González-Dugo et al., 2012), acquiring narrow-band multispectral imagery (Zarco-Tejada et al., 2009; Suárez et al., 2010; Guillén-Climent et al., 2012), and using micro-hyperspectral imagery for crop stress detection (Zarco-Tejada et al., 2012, 2013a,b).

Nevertheless, miniaturized cameras installed on board unmanned vehicles are usually a compromise between size, weight, specifications, and cost. They tend to produce poorer quality imagery than the metric systems generally used on board manned aircraft with regard to radiometric integrity, sensor signal-to-noise characteristics, and optical geometry deformations. For this reason, specific methodologies are required to perform image calibration and corrections when the aim is to derive accurate remote sensing products from low-cost cameras operated from lightweight platforms. In fact, the use of consumer-grade cameras for field operations and for use on board UAVs has generated a promising research avenue regarding the development of very high resolution DSMs. Structure-from-motion (SfM) and mutiview-stereo (MVS) algorithms are the methods generally proposed when consumer-grade cameras are used as opposed to expensive laser scanners and rigorous photogrammetric methods that require high expertise (Küng et al., 2011).

The assessment of traditional photogrammetric methods as compared to SfM and MVS algorithms has demonstrated comparable results and an 80% time reduction in data collection when applied to 3D reconstruction of surfaces and topography using consumer-grade SLR cameras (James and Robson, 2012). In other studies, researchers have compared MVS algorithms against LIDAR data as a reference for benchmarking camera calibration methods (Strecha et al., 2008) or performed such comparisons using data obtained from consumer-grade camera installed on board lightweight UAVs (Vallet et al., 2011). In such studies, cheap cameras on board ultra-light UAV platforms with a take-off weight under 1 kg generated DSMs with errors below 15 cm using multi-angle correlation methods when compared to a reference digital model.

In this study we explored the use of low-cost UAV imagery and automatic DSM generation methods for canopy height quantification using an inexpensive non-metric consumer-grade color infrared (CIR) camera. We assessed the spatial resolution effects of the VHR imagery used as input for the DSMs generated through automatic processing methods in the context of tree height quantification in orchard fields.

2. Materials and methods

2.1. Study site description and airborne campaigns

The study was performed in an area of 148 ha planted with olive orchards (*Olea europaea* L.) in Alcolea, Cordoba, southern Spain (37° 44′ N, 4° 36′ W, altitude 150 MAMSL) in summer 2012. The area comprised orchards with various canopy densities cultivated either in rows or in patterns and had a gradient in tree crown sizes and heights, as required for the validation methods conducted (Fig. 1).

The airborne campaigns were conducted in summer 2012 using an unmanned aerial vehicle (UAV) operated by the Laboratory for Research Methods in Quantitative Remote Sensing (QuantaLab, IAS-CSIC, Spain) (Berni et al., 2009a; Zarco-Tejada et al., 2012, 2013a,b). For this study, the UAV carried a consumer-grade camera modified in the laboratory for color-infrared (CIR) detection by removing the internal infrared filter. The camera was a Panasonic Lumix DMC-GF1 with a 4000 × 3000 pixel detector that captured images at f/3.2 and 1/2500 s with an angular FOV of 47.6° × 36.3°

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