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Use of digital images to disclose canopy architecture in olive tree

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ABSTRACT

The use of digital cameras for monitoring natural vegetation and agricultural ecosystems is particularly attractive since it necessitates neither expensive equipment nor extensive skill. In this study we tested the use of digital images (DIs) to generate 3D plant reconstruction for retrieving the main plant architectural features (leaf area, leaf inclination, leaf azimuth) of olive tree branches. High resolution image of tree branches were firstly used to generate 3D reconstruction of plant structures using a Structure From Motion approach; we therefore answered the question whether these 3D models may be segmented to discriminate main plant structures (leaves and branch) proposing a simple classification algorithm (Random Forest, RF) with saliency features and color indices as predictors. Finally, on the good and robust performances of the proposed classification algorithm, the single leaves were analyzed to retrieve the relevant area, inclination and orientation and compared to the relevant observed data. The calibration of the RF model indicated that color indices better discriminated leaves and stem than the sole use of saliency features. The classification performances were further improved by tuning the scale at which saliency features were calculated and by filtering the final result to reduce misclassified points. A RF model calibrated on a single plant was successfully applied to 5 others, indicating the robustness of the calibration strategy. The analysis of single leaves, as segmented after the classification process, indicated that plant architecture was satisfactorily reproduced with strong correlations obtained between measured and calculated values of leaf inclination and azimuth, while biases were observed for leaf area. These results emphasize the effectiveness of SFM in reproducing complex arrangements of leaves like on an olive tree. The use of such a system can be therefore suggested as a first step towards an improved low cost plant phenotyping platform to speed up our understanding of plant responses to environment. Further experiments are required to test the effectiveness of the approach also under outdoor conditions.

1. Introduction

An accurate estimate of plant architecture is of major importance for the ecological characterization of a natural or agricultural ecosystem, and digital images (DIs) have often been exploited for this purpose since the approach is not destructive, not time consuming and necessitates neither expensive equipment nor extensive skill (Li et al., 2014).

Many applications address the measurement of leaf area spatial distribution (Leaf Area Index, LAI), since this parameter plays a major role as plant interface with the atmosphere and determines biomass accumulation (Liu et al., 2013a; Macfarlane et al., 2007; Fuentes et al., 2008; Chianucci et al., 2014). The use of DIs is centered on the indirect estimation of canopy structural variables such as gap fraction (GF) or its complement (foliage cover, FC), clumping index (CI) and leaf inclination angles (LIA) (Ryu et al., 2010; Pisek et al., 2011; Liu et al., 2013b; Zou et al., 2014), which are then combined for LAI estimation according to the Beer-Lambert's law (Brantley and Young, 2007) The approaches generally used for the estimation of these indexes are based on single DIs taken by commercial cameras above or below the canopy depending on the ecosystem under analysis, the parameter to be estimated or the specific approach developed. E.g. for forest ecosystems Fuentes et al. (2008) estimated GF using horizontal upward-facing DIs, whereas Chianucci et al. (2014) obtained the same information using downward-facing DIs taken from above the canopy, while LIA was estimated using a digital leveled camera at several heights in the canopy. In agroecosystems, GF estimated using DIs acquired below the canopy have been proven to provide results for LAI estimation compara-

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ble to those obtained with commercial instruments (Confalonieri et al., 2013).

In a more comprehensive approach, DIs were taken orthogonally around a tree in the main directions, and GF analysis used for reconstructing tree crown volume and vertical profile of leaf area of isolated trees (Phattaralerphong and Sinoquet, 2005; Phattaralerphong et al., 2006). In other words, this system provides the basis to capture the third dimension (3D) in plant geometry that enables height and volumetric analysis, which cannot otherwise be calculated using traditional approaches.

The rapid technological development in DI-based photogrammetry made new tools and algorithms available for researchers that allow the 3D features of a scene to be obtained. Ivanov et al. (1995) proposed the first approach using stereo vision (SV) to reconstruct the 3D surface of a cultivar for measurement and analysis and this represents another step towards the fine quantification of plant geometry at spatial and temporal resolutions that are not easily achieved with a 2D image analysis. The SV system, often composed of two cameras aligned in a fixed structure, relies on the detection of corresponding points in the acquired stereo images. The analysis of relative positions of these points traced in the images provides the depth information (disparity) of the respective pixels. The resulting disparity map is then converted into a point cloud xyz with a given system of coordinates, which may be further classified and segmented to analyze plant structures. The framework described in Müller-Linow et al. (2015) provides evidence on the effectiveness of this approach in the estimation of LAI and LIA of herbaceous plant populations and single trees both in the laboratory and under field conditions.

Jay et al. (2015) pointed out that the structure from motion (SFM) approach, which simultaneously estimates the camera position and the structure and position of objects in the scene, is an alternative approach to retrieve a point cloud from DIs, which does not necessitate either expensive equipment or extensive skill. In practical terms, SFM solves the same problem as SV (i.e. seeking matching points from images and reconstruction of a 3D object), by processing a set of overlapping photographs of an object to create a 3D point cloud that represents the structure of the objects under analysis.

While SFM-based 3D models have been used extensively to reproduce urban features (Snavely et al., 2008; Pollefeys et al., 2004), natural vegetation (Dandois and Ellis, 2010; Turner et al., 2011) or agricultural areas (Mathews and Jensen, 2013; Zarco-Tejada et al., 2014; Díaz-Varela et al., 2015), their potential application in plant architectural analysis has still to be explored (Jay et al., 2015).

On these premises, in this study we tested the use of DIs as the core of a simplified phenotyping platform, which relies on the use of a SFM approach for retrieving the main plant architectural features (leaf area, leaf inclination, leaf azimuth) of olive tree branches. This test considers four basic steps: (i) high resolution image acquisition of olive tree branches under indoor conditions and generation of relevant point clouds via SFM; (ii) calibration of a classification algorithm (Random Forest, RF) to discriminate leaves and branch structures using saliency features (i.e. descriptors of shape) and color indices; (iii) segmentation of leaves and iv) analysis of single leaves to retrieve the relevant area, inclination and orientation. These steps are described and discussed separately.

2. Material and methods

2.1. Image acquisition

High-resolution TIFF images of a single branch of 6 potted 4-year old olive trees (*Olea europaea* L., var. *Frantoio*) were acquired in the laboratory in 2015 on 6 different plants, on days of year (DOY) 28, 37, 65, 79, 90, 118, 125, under natural indoor diffused radiation and used to reconstruct the relevant plant structures using an SFM approach (Table 1). A north-oriented vertical leveled panel with a grid of markers was placed behind the plant to mask surrounding objects and provide a grid for re-scaling the point clouds to a common reference system (Fig. 1 step 1).

Table 1
Description of branch under analysis. Legend: DOY = day of year of analysis, PStage = phenological stage (D = dormancy, SE = shoot elongation); TLN total leaf number on the branch; SL = sampled leaves; NOP = number of pictures taken for each branch. In plant 3 analysis were performed on both a subsample and total leaf number (indicated between brackets). In plant 4 analysis were performed only on the total leaf number.

Plant	DOY	PStage	TLN	NOP	SL
1	37	D	95	120	21
2	65	D	110	125	18
3	79	D	116	130	24 (116)
4	90	D	135	150	135
5	118	SE	140	150	39
6	125	SE	160	180	39

The number of DIs acquired was chosen bearing in mind that for a good 3D reconstruction the degree of overlap between two adjacent images should be at least 70% (James and Robson, 2012). In our specific case, the images were captured at a high resolution (5202 × 3465 pixels) using a leveled digital camera (CANON EOS D600) mounted on a tripod placed at as average distance of 0.5 m from the plant, which was moved spanning along the vertical and horizontal profiles of each branch. The final number of DIs depended on the dimension of the scene and the field of view (FOV) of the camera: considering as an example, an average focal length of 30 mm and a distance to subject of 0.5 m, the picture would have a horizontal FOV 37 cm and a vertical FOV of 25 cm. Considering an overlapping degree of 80% between pictures on both horizontal and vertical directions, this would result into pictures taken on a step of 7.5 cm and 5 cm respectively. When applied to a scene of e.g. 70 × 70 cm, this results into ∼10 pictures spanning the horizontal axis and 14 spanning the vertical one for a total of 140 pictures.

Given that SFM approach for 3D reconstruction relies on the identifications of points that are seen on several images, there is the need to keep in focus the objects of interest in the scene otherwise much information on the texture would be lost and the identification of points would be difficult. Accordingly, we increased the depth of field of the camera by reducing the aperture of the lens diaphragm (f. 22).

After the acquisition of DIs, azimuth, inclination and area of each leaf were measured. A digital compass installed on Apple IPhone 5 S® was used to measure leaf azimuth, which was computed clockwise as the angle between north and the horizontal projection of the vector lying on the leaf middle rib and centered on the leaf insertion. Leaf inclination was determined on DIs acquired by a leveled smartphone-camera application (LVL CAM) for each single leaf according to Pisek et al. (2011). In this case, the leveled camera was moved around each leaf manually until the leaf was found to be normally oriented to the camera's viewing direction. These operations (azimuth measures and acquisition of leaf images) were performed at a safe distance taking care not disturbing the original position of plant structures.

After azimuth measurement and acquisition of leveled DI of leaves on the plant, each leaf was removed, placed on a white background and photographed orthogonally from above for leaf area calculation (see next section).

On each sampling DOY, point clouds of plant were reconstructed, labelled leaves were identified on screen and the relevant inclination, azimuth and leaf area compared to measured values.