APPLICATION OF CLOSE-RANGE PHOTOGRAMMETRY AND DIGITAL PHOTOGRAPHY ANALYSIS FOR THE ESTIMATION OF LEAF AREA INDEX IN A GREENHOUSE TOMATO CULTURE

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ABSTRACT:

The excess in the applications of pesticides have a great negative impact on the environment, besides, when these pesticides are used inside the greenhouse, they might have an important repercussion on the health of the farmers. A pesticide application is ideal if the spraying coverage is presented as evenly distributed over the whole crop canopy and, if the product application is correctly adjusted for minimizing the losses towards the soil or the environment. It is proved that for a certain crop stage, there is an optimal volume of application. This ideal volume is related by the canopy Leaf Area Index (LAI), which is the ratio of total upper leaf surface of a crop divided by the surface area of the land on which the crop grows. In this work a predictive and empiric model regarding non destructive estimation of LAI has been generated. This model is based on the volume and density of tomato plants, i.e., LAI=function (Density, Volume). Volume was obtained first by close-range photogrammetry (Volume 'Real') which was used later to choose a manual method for measuring tomato bush volume which presents a better fitting to the 'real' volume. Plant densities were derived by digital image analysis. Finally, the LAI 'Real' was measured by a destructive method using a leaf area meter. The LAI empiric model presented a coefficient of determination close to 83 %.

1. INTRODUCTION

A pesticide application is ideal if spraying coverage is presented as evenly distributed over the whole crop canopy and, also, product application is correctly adjusted for minimizing the losses towards the soil or the environment (Camp *et al.*, 2006).

One fundamental element in the design of pesticide application on tomato plants is the volume of liquid applied (l ha^{-1}). It is proved that for a certain crop stage, there is an ideal volume of application. This ideal volume and chemical rates are related by Three-Dimensional (3D) canopies (Manktelow and Praat, 1997; Furness *et al.*, 1998) and the canopy Leaf Area Index (LAI) (Zhu *et al.*, 2004; Siegfried *et al.*, 2007). LAI is defined as a dimensionless variable representing the leaf area per unit ground surface area (Jonckheere *et al.*, 2004).

Many researchers have realized more accurate measurements of the canopy volume in fruit trees by means of laser (Cross *et al.*, 2001; Holownicki *et al.*, 2002), ultrasonic sensors (Solanelles *et al.*, 2006; Gil *et al.*, 2007). Tumbo *et al.* (2001) realized comparisons between different methods (laser, ultrasonic and manual) to measure the citrus tree canopy volume. Working with tomato plants, Wang *et al*. (2007) proposed combining laser scanning, CAD and crop growth mathematic model for crop modelling. Terrestrial Light Detection and Ranging (LIDAR) is also being very used lately (Palacin *et al*., 2007; Rosell *et al*., 2009a; Rosell *et al*., 2009b).

This work seeks, as its main goal, the generation of a predictive and empiric model for the non destructive estimation of LAI in tomato plants under greenhouse. This model is based in volume and density of tomato plants, which are estimated from real world measurements using close-range photogrammetry, 3D modelling tools and digital photographs analysis respectively.

The 'real' volume of plants can be measured accurately from the 3D model surface obtained by photogrammetry, nevertheless, in order to the model is more usable in the field, directly for the farmers, the tomato volume can be measured by means of a more simple methodology. The volume finally applied in the model will be a manual method for measuring the tomato bush volume which presents the best fitting to the 'real' volume (photogrammetry).

2. MATERIALS AND METHODS

This work was carried out in a greenhouse belonging to the "Palmerillas" experimental farm located in El Ejido, Almería (Spain) from October to December of 2007.

2.1 Points 3D by close-range photogrammetry and 3D model generation

In order to compute the 'real' volume for the tomato plants canopies, a close-range photogrammetric package called PhotoModeler Pro 5 (Eos System Inc., Vancouver, Canada) was

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used to obtain 3D points of the external surface for the 17 groups of tomato plant in different states of growth (for more details, Aguilar *et al*., 2008; Pozo, J.L., 2009). Afterwards, all 3D points obtained by close-range photogrammetry for each plant were introduced in a 3D scan modelling software oriented to point clouds management for obtain a mesh of triangular polygons. From this model, the ‘real’ volume of each group of plans could be computed.

Approximately 400 3D points belonging to each canopy surface were measured using PhotoModeler with which a 3D CAD model of the tomato canopy surface may be obtained. From five to 14 convergent photographs taken with an Olympus C5060 digital camera (5.0 Megapixels) were employed for the configuration of the 17 network for the canopies restitution. The internal parameters of the Olympus C5060 digital camera had been previously calibrated with the aforementioned software package. This task was carried out four times during the test.

To obtain the exterior orientation, ground control points were marked on a white portable metal rectangular frame of 3 mm diameter black dots with 3D known coordinates. A very similar portable frame was employed by Aguilar *et al*. (2005).

To measure with PhotoModeler the *XYZ* coordinates of an important number of 3D points, which were surrounding tomato surface, target points of the tomato plant surface were marked with 0.6 mm diameter circular self-adhesive labels. The labels were placed on a plastic mesh covering the tomato bush and in order to simulate its enclosing surface. This methodology is extended in Aguilar *et al*. (2008).

When a 3D CAD model, composed by approximately 400 points belonging to the canopy surface of each plant, is generated by PhotoModeler, it can be imported into RapidForm 2004 software (INUS Technology Inc., Seoul, Korea) as a DXF file. This software allows us to convert a dense point clouds obtained by close-range photogrammetry into polygon meshes, and then, computing the ‘real’ volume of the tomato canopies.

2.2 Manual volumes

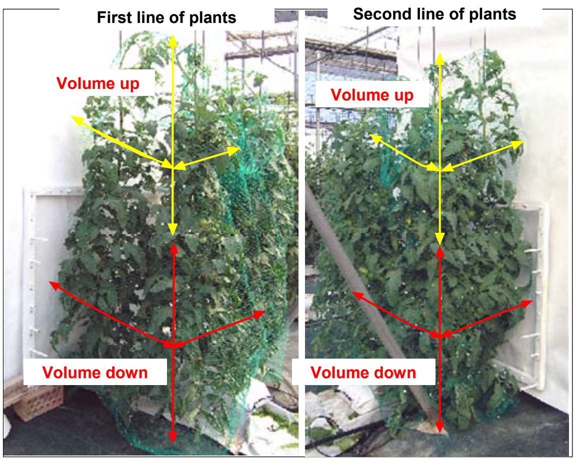


Figure 1. Detailed scheme for the obtention of the manual volume of tomato plants in the initial states of growth.

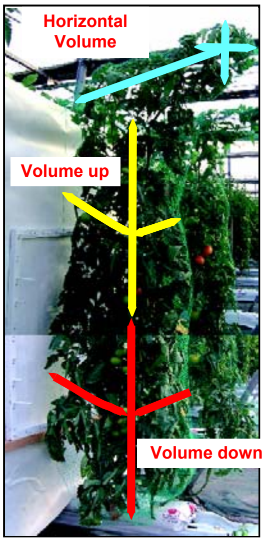


Figure 2. Detailed scheme for the acquiring of the manual volume of tomato plants in the final states of growth.

The manual volumes of these 17 plants were computed by means of a more simple methodology, basically using plant measurements of width and height. The best manual volume was obtained when the shape of the plants were considered as two rectangular prism (Figure 1) in the initial states and as three prism in the final states of growth (Figure 2). The hypothesis is that when an important number of tomato plants are modelled, a mathematical relationship between the ‘real’ volume and the manual one could be found.

2.3 Plant density

To determine the plant density, the same digital camera Olympus C-5060 was used. A white screen of 850 per 1200 mm with a hollow or square window of 300 mm of side (Figure 3) was placed ahead of the plants. Three or four photographs (depending on the size of the plant) were taken at different heights. The analysis of the images was realized by means of SigmaScan Pro software as can be seen in Figure 4.

Figure 4 shows different steps for acquiring the plant density by image analysis. First, a photograph with 300x300 mm window size is taken (Figure 4a). After, blank areas, which there are not vegetable are measured and eliminated (Figure 4b). The last thing is to measure the area occupied by the leaves and stems of the tomato plant using digital image analysis (Figure 4c). The relation (in percentage) between the area occupied by pixels representing vegetable and the area of pixels representing gaps is the density of this window. The plant density is computed as the mean or the densities of the three or four windows taken per each plant.

Figure 3. Photograph of the 300x300 mm window for plant density computing.

a) b) c)

Figure 4. Methodology for acquiring plant density.

2.4 Computing LAI

After the above measurements were done, the plant was cut and LAI was computed for each group of plants. A destructive method based on the obtention of the area occupied for the 25% in weight of the leaves from each group of tomato plants was used. This is a simple method and is adapted to calibrate other methods (Sinoquet and Adriew, 1993). The area of each leaf was measured by a leaf area meter 'Delta-T Devices Ltd' (Figure 5).

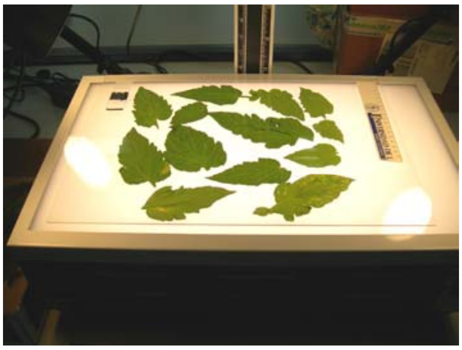


Figure 5. Photograph of leaf area meter.

3. RESULTS

3.1 Internal parameters for the Olympus C5060

The internal parameters for the Olympus C5060, computed by the Camera Calibration module of PhotoModeler, are showed in table 1. Camera calibration is a method for accurately obtain values for these interior camera parameters. Once a camera is calibrated, it will provide accurate measurements. As the internal calibration can change with the time, four calibration projects were done along this work.

		Mean (mm)	SD (mm)
Focal Length		5.678	0.036
Format Size	Width	7.001	0.041
	Height	5.260	0.034
Principal Point	X	3.562	0.021
	Y	2.437	0.017
Radial Lens Distorsions	K1	3.448×10^{-3}	1.877×10^{-4}
	K2	2.988×10^{-6}	4.24×10^{-5}
Descentering Lens Distorsions	P1	-5.112×10^{-5}	2.36×10^{-6}
	P2	2.416×10^{-4}	1.02×10^{-6}

Table 1. Internal parameters for the Olympus C5060. Mean and Standard Deviation for the four calibration projects.

3.2 Close-range photogrammetry accuracy

The three dimensional RMSEs (Root Mean Square Errors) in 17 photogrammetric projects are ranging between 1.330 mm and 3.651 mm (tables 2). Thus, the relative error with regard to the size of the photographed object is ranging between 1/1130 and 1/410, considering as maximum object dimension diagonal of the reference system rectangular frame. In any case, this accuracy is more than enough for our objectives. Relative error of 1/2400 was reported by Aguilar *et al*. (2005). As well, Deng and Faig (2001) obtained relative errors of 1/1635 and 1/1684, working with two different digital cameras (Kodak CD-50 and Fujix DS-100) on two different scales, whilst with a Olympus OM 35mm camera, the relative errors were 1/781.

Tests	RMSE 3D (mm)	Nº points	Processing error (σ)
Plant 1	3.040	363	0.690
Plant 2	1.330	330	0.625
Plant 3	1.870	316	0.660
Plant 4	3.450	322	1.034
Plant 5	2.740	324	0.927
Plant 6	3.179	326	0.799
Plant 7	2.717	282	0.844
Plant 8	3.030	366	0.797
Plant 9	3.180	367	0.712
Plant 10	2.825	325	0.990
Plant 11	3.450	473	0.892
Plant 12	3.512	519	0.791
Plant 13	3.651	558	0.879
Plant 14	3.480	486	0.722
Plant 15	3.524	622	0.711
Plant 16	3.309	511	0.750
Plant 17	3.351	396	0.743

Table 2. Accuracy values in the photogrammetric projects.

3.3 Mesh generation and volumes

Once obtained the three-dimensional points by means of close-range photogrammetry, they are imported to RapidForm and the triangulation process was realized. Quite often, it is necessary to edit the mesh to cover some holes or to create some new point in zones with lack of information. Thus, the final 3D models and its 'real' volumes were obtained (Figure 6).

The manual measurements obtained in field were used for computing the volumes of each plant by the manual method explained in methodology section.

3.4 Empiric model for the estimation of LAI

The final plant density, 'real' and manual volumes, and LAI values are showed in table 3. The first step was to determine a simple method of manual measurements which has a good adjustment with the "real" volumes obtained by close-range photogrammetry. The best manual method was measuring the volume like two or three rectangular prism (it was explained in methodology section). As can be seen in Figure 7, Manual and 'Real' volumes present a very good fit, with a R^2 of 0.75.

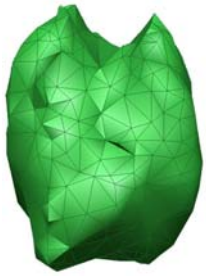
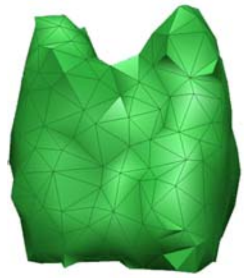
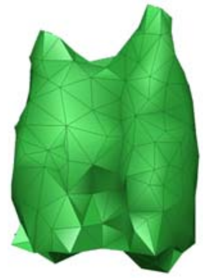
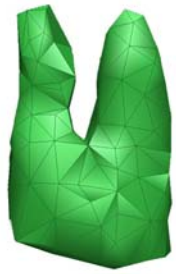
 **Plant 1**: October 2 Volume 0.571 m^3	 **Plant 2**: Oct. 8 Volume 0. 840 m^3	 **Plant 3**: Oct. 8 Volume 0. 879 m^3	 **Plant 4**: Oct. 15 Volume 0. 747 m^3	 **Plant 5**: Oct. 15 Volume 0. 828 m^3
 **Plant 6**: Oct. 22 Volume 0. 999 m^3	 **Plant 7**: Oct. 29 Volume 1.354 m^3	 **Plant 8**: Nov. 5 Volume 1. 117 m^3	 **Plant 9**: Nov. 12 Volume 1. 482 m^3	 **Plant 10**: Nov. 23 Volume 1. 497 m^3
 **Plant 11**: Nov. 26 Volume 1. 547 m^3	 **Plant 12**: Nov. 30 Volume 0. 949 m^3	 **Plant 13**: Dic. 7 Volume 1.201 m^3	 **Plant 14**: Dic. 10 Volume 1.024 m^3	 **Plant 15**: Dic. 13 Volume 1. 283 m^3
 **Plant 16**: Dic. 17 Volume 1. 215 m^3	 **Plant 17**: Dic. 20 Volume 0.623 m^3	 **Plant 1 photograph**	 **Plant 17 photograph, down part**	 **Plant 17 photograph, up part**

Figure 6. 3D models of 17 tomato plants obtained by close-range photogrammetry, volume and some photographs of real plants.

	Plant density (%)	Volume 'real' (m^3)	Volume manual (m^3)	Leaf Area Index (LAI)
Plant 1	82.72	0.571	0.541	1.267
Plant 2	79.04	0.840	0.995	1.841
Plant 3	73.03	0.879	0.966	1.713
Plant 4	78.62	0.747	0.964	2.614
Plant 5	81.13	0.828	0.934	2.687
Plant 6	78.84	0.999	1.500	2.942
Plant 7	68.65	1.354	1.280	2.529
Plant 8	75.05	1.117	1.257	2.679
Plant 9	76.20	1.482	1.883	3.654
Plant 10	82.60	1.497	1.697	3.452
Plant 11	80.67	1.547	1.846	2.961
Plant 12	87.46	0.949	1.462	3.742
Plant 13	86.65	1.201	1.718	3.493
Plant 14	88.45	1.024	1.754	3.781
Plant 15	80.90	1.283	2.053	4.433
Plant 16	90.40	1.215	1.713	3.345
Plant 17	80.43	0.623	0.943	2.286

Table 3. Plant density, 'real' and manual volumes, and LAI values used for computing the empirical model.

LAI values measure by leaf area meter can be predicted from Manual Volumes of tomato plants with a high correlation (R^2=0.817), as can be seen in Figure 8. On the other hand, plant density is related with LAI values weakly (Figure 9).

Bearing in mind Figures 8 and 9, the proposed empirical model had the follow form:

$$LAI=(A\cdot Density^2 + B\cdot Density + C) \cdot (D\cdot (Manual\ Volume)^E)$$

where A, B, C, D and E are coefficients for the non-linear regression, Density values are expressed in %, and Manual Volume in m^3.

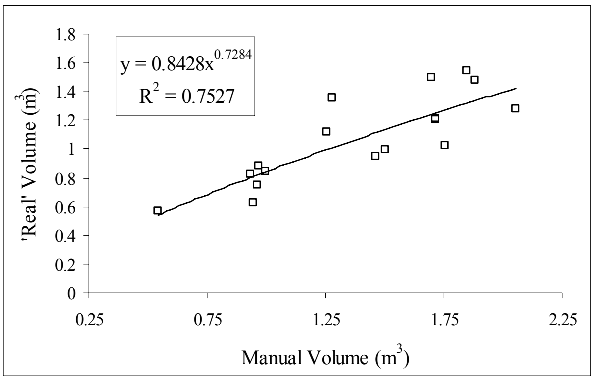


Figure 7. Relation between Manual and 'Real' Volume.

After doing the non-linear regression by means of Marquardt's method and StatGraphics 5.1 software, the coefficients were estimated (A = -0.0259588, B = 5.90108, C = -103.471, D = 0.0113628, and E = 0.739597). By means this empirical model, the LAI values can be predicted with a R^2 of 82.71 %. In Figure 10 the graphic form of this model is presented.

Similar coefficient of determination (R^2) of 84.22% was related by Rosell *et al*. (2009a) between total foliate area and volume of pear trees obtained by LIDAR. When the comparison was done between leaf area versus volume, R^2 reached a value of 81.4%.

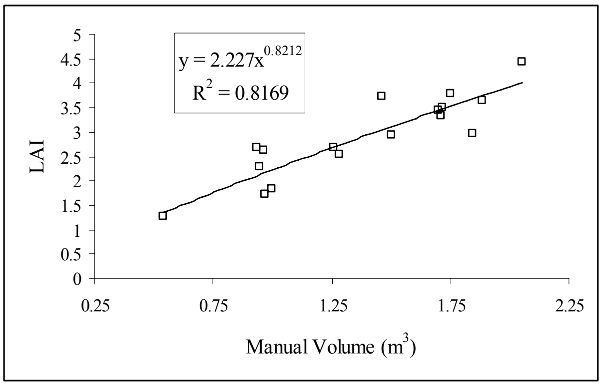


Figure 8. Relation between Manual Volume and LAI.

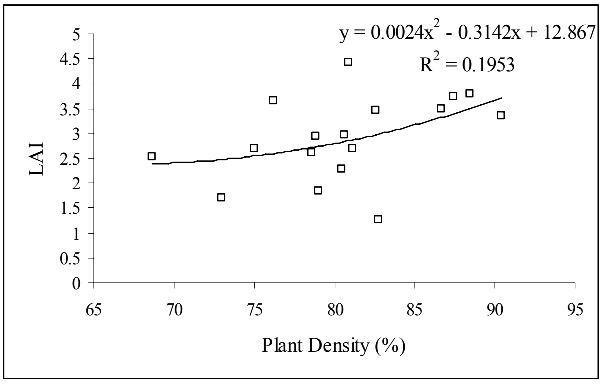


Figure 9. Relation between Plant Density and LAI.

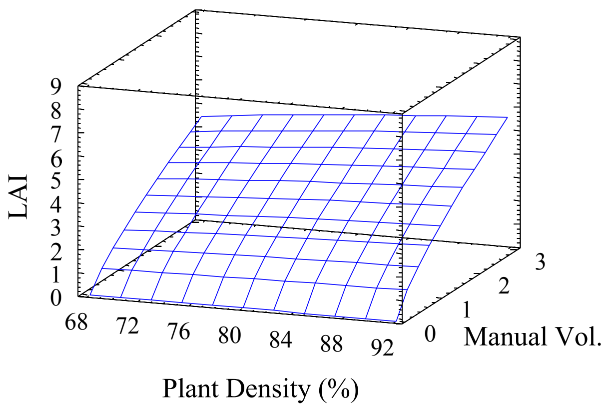


Figure 10. Graphic 3D of the empiric model computed for LAI.

4. CONCLUSIONS

In this work, a methodology based on close-range photogrammetry has been applied to obtain, with the higher possible accuracy, the exterior surface of tomato plants inside of a greenhouse. The obtained results indicate the possibility of representing the surrounding surface of a tomato plant with approximately 400 3D points and compute, in an accurate way, the volume of the canopy.

Although the proposed method is perfectly applicable in field, it turns out to be very costly in time. The volume information

obtained by close-range photogrammetry was used to find a simple manual method of volume measurement for the surrounding surface of tomato canopy, which adjusts of the best possible way to this information.
The generation of a predictive and empiric model for the non destructive estimation of LAI in tomato plants under greenhouse was the main goal of this communication. This model was based in volume and density of tomato plants, which are estimated from real world measurements using close-range photogrammetry, 3D modelling tools and digital photographs analysis respectively. The LAI empiric model presented a coefficient of determination of 82.71 %.

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