# 3D SURFACE MODELLING OF TOMATO PLANTS USING CLOSE-RANGE PHOTOGRAMMETRY

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**ABSTRACT:**

The production of agricultural cultivates under intensive systems requires of big quantities of pesticides for fitosanitary control. Pesticides application is a major component of tomato production costs under greenhouse in Almería, Spain, and the excess in their applications have a great negative impact on the environment. 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. Our research group is working for the generation of a predictive and empiric model regarding non destructive estimation of LAI. This model will be based on the volume and density of tomato plants. This work seeks, as its main goal, the obtention of a Three-Dimensional (3D) accurate model of tomato plant canopies using close-range photogrammetry and 3D modelling tools. The 'real' volume of the plants can be measured accurately from the 3D model. Since the tomato volume can be measured by means of a simpler manual methodology, using plant measurements of width and height (e.g., Tree Row Volume or Unit Canopy Row), it is expected in the near future to outline a manual method for measuring tomato bush volume which presents a better fitting to the 'real' volume.

## 1. INTRODUCTION

The southeast of Spain, the part of Europe with the lowest rainfall and the highest number of sunlight hours per year, has been characterized in the last 40 years by the rapid growth of its plastic greenhouse surface dedicated to horticultural crops production. These greenhouses are concentrated in the coastal fringe of the Almería province, occupying at present an area of more than 30,000 ha. The area is therefore known as the 'kitchen garden of Europe', due to the fact that most of its production is exported to Central Europe, and even to USA and Canada.

This intensive horticulture is still affected by many problems related to spray applications of fitosanitary products. There is an increasing interest by growers to manage the variable groves site-specifically using variable rate technology which potentially resulting in more efficient use of inputs, increasing yields, and preventing environmental pollution by excess agrochemicals (Schumann and Zaman, 2005).

Thus, pesticides application is a major component of tomato production costs under greenhouse in Almería. Insecticides and fungicides have traditionally been applied to tomatoes plants as foliar sprays to control insects and diseases. The excess in the pesticides applications hold a great negative impact on the environment. At this point, it is necessary to clarify that 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).

There are different methods to fit the optimal volume of spray application to the vegetative development of the crop. Thus, manual methods to measure the volume of the vegetable mass to spraying, as Tree Row Volume (TRV) (Manktelow and Praat, 1997) or Unit Canopy Row (UCR) (Furness *et al.*, 1998), stand out for its facility of calculation. Both methods need as income the measurements of height and width of one row, and separation between rows of crop. Nevertheless, Bjugstad and Stensvand (2002) indicate that the previous parameters (TRV and UCR) do not define correctly the optimal volume rates for different indexes of LAI or plants with different shapes and sizes.

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.

Other authors use measurements on digital images acquired by digital cameras or video cameras to measure the density and spatial distribution of the vegetation in a certain growth stage (Tillett *et al*. 2001; Reyniers *et al*., 2004). Also, Ivanov *et al*. (1995) used the close-range photogrammetry to obtain the three-dimensional architecture of maize canopy.

Our research group is concerning for the generation of a predictive and empiric model for the non destructive estimation of LAI in tomato plants under greenhouse. This model will be based in volume and density of tomato plants. This work seeks, as its main goal, the obtention of a 3D model of tomato plant canopies, which is derived from real world measurements using close-range photogrammetry, and 3D modelling tools. Thus, the 'real' volume of plants can be measured accurately from the 3D model surface. Also, we studied the accuracy, in terms of object geometry, reached with the proposed methodology. Since the tomato volume can be measured by means of a more simple methodology, using plant measurements of width and height (e.g., TRV or UCR), in further works we will try to outline a manual method for measuring the tomato bush volume which presents the best fitting to the 'real' volume.

## 2. MATERIALS AND METHODS

In this work, we used a close-range photogrammetric package to obtain 3D points of the external surface of the each plant of tomato or surrounding surface. The accuracy of the close-range methodology used was computed by means a specific test. Afterwards, all 3D points obtained by close-range photogrammetry are introduced in a 3D scan modelling software oriented to point clouds management for obtain a mesh of triangular polygons. All these steps are extended below.

### 2.1 Points 3D by close-range photogrammetry

The close-range photogrammetric package used in this work was PhotoModeler Pro 5 (Eos System Inc., Vancouver, Canada). This software was employed to obtain a 3D model of the surrounding surface of some tomato plants under greenhouse. Approximately 400 3D points belonging to the canopy surface were measured using PhotoModeler with which a 3D CAD model of the tomato canopy surface may be obtained.

Five convergent photographs taken with an Olympus C5060 digital camera (5.0 Megapixels) were employed for the configuration of the network for the canopy restitution (Figure 1). The digital photographs have 2592 per 1944 pixels. The internal parameters of the Olympus C5060 digital camera had been previously calibrated with the aforementioned software package. Regarding this calibration process, twelve convergent photographs of a calibration grid given with the software were taken. The calibration grid has characteristic shapes which make the automatic pointing possible. In the figure 2, two of these photographs are showed. All twelve photos were taken to a distance of 1.5 m, similar to which we used in the greenhouse.

To obtain the exterior orientation with sufficient redundance, in every photo, at least six ground control points should appear, although this number depended of each photograph. These 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).

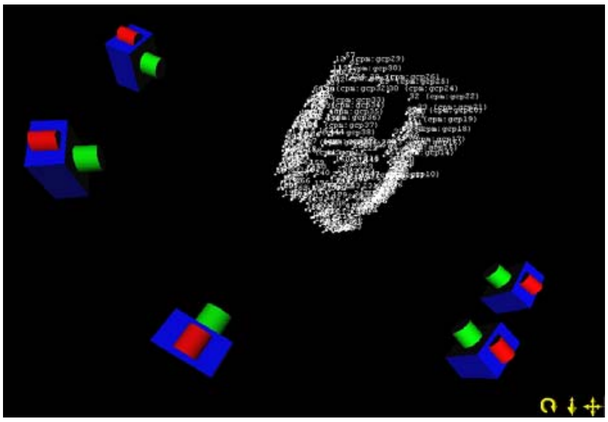

Figure 1. Location of all five positions of the digital camera in the photogrammetric network.

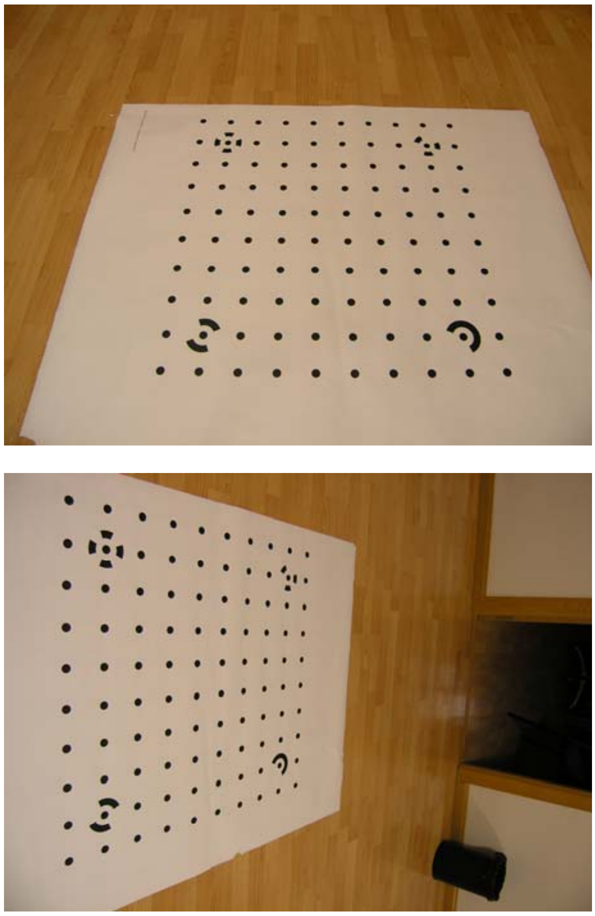

Figure 2. Two of the twelve photographs taken with the Olympus C5060 to calibration process.

To measure with PhotoModeler the *XYZ* coordinates of an important number of 3D points, which were surrounding tomato surface (Figure 3), around 400 target points of the tomato plant surface were marked with 0.6 mm diameter circular self-adhesive labels. These labels of different colours were used to improve the identification and matching of every target point taken in different photos. The labels were placed on a plastic mesh covering the tomato bush and in order to simulate its enclosing surface (Figure 4). To obtain these 3D points coordinates by means of close-range photogrammetry, every label must be pointed on at least two photographs, although almost all the points were appearing in three or more photos.

Figure 3. Situation of the plastic mesh and the self-adhesive labels on the surface of the tomato plants.

Figure 4. Detail of the self-adhesive labels on the surface of the tomato plants.

The necessary time to obtain the 3D coordinates of approximately 400 points on tomato surface with a network of five photographs, by means of PhotoModeler, was of nearly two hours. Besides, the time must be extended because a later and necessary point edition work must be done.

### 2.2 Close-range photogrammetry accuracy test

A previous test was carried out in our laboratory to know the accuracy of the employed methodology based on close-range photogrammetry to obtain 3D coordinates of tomato plant points. In this test, we measured thirty-five points with known coordinates inside the frame, using the same close-range methodology described before, although this network was composed by only three photos. The points were placed on metallic cylinders which height was known. The cylinders were placed on circles drawn on a flat paper. These circles were distributed over the nodes of a 100 mm by 100 mm grid, with a total of five rows and seven columns (Figure 5). The circles grid was printed in a plotter HP 1050C on acetate paper. In true, a very similar test was used by Deng and Faig (2001) for the accuracy evaluation of PhotoModeler.

Some parameters as number of control points and use of self-calibration, were tested in laboratory. In self-calibration PhotoModeler attempts to make minor adjustments regarding camera parameters to account for changes in focal length, principal point and lens distortion. Its main aim is to improve the bundle adjustment of network (Granshaw, 1980). PhotoModeler can only use this self-calibration process when there are sufficient 'good' points and photos in the project.

After these parameters had been modified (number of control points and use of self-calibration), the coordinates of the 35 points on the cylinders and the 40 ones on the rectangular frame were computed with PhotoModeler.

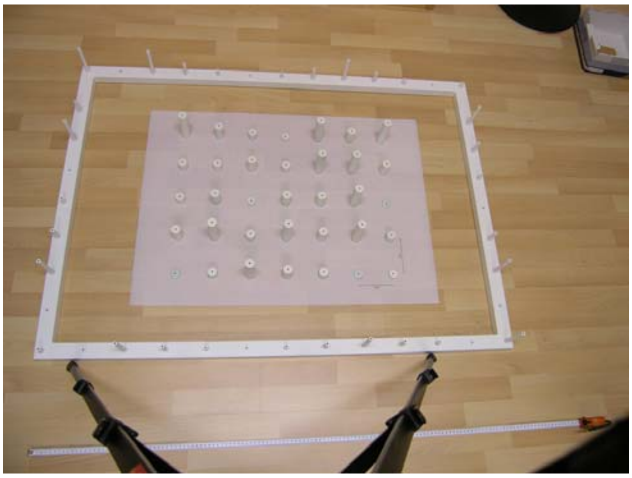

Figure 5. Laboratory test to study the accuracy of the methodology based on close-range photogrammetry.

### 2.3 Mesh generation

When a 3D CAD model, composed by approximately 400 points belonging to the canopy surface, is generated by PhotoModeler, it can be imported into RapidForm 2004 software (INUS Technology Inc., Seoul, Korea) as a DXF file. RapidForm 2004 is a 3D scan modelling software oriented to point clouds management. 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 canopy. 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.

## 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.

The automatic pointing generated a point marking residuals of 0.135 pixels, measured as root mean square error (RMSE), with a maximum value of 0.770 pixels and a minimum one of 0.012 pixels.

| | | |
|---|---|---|
| Focal Length | | 5.7033 mm |
| Format Size | Width | 7.0283 mm |
| | Height | 5.2849 mm |
| Principal Point | X | 3.5771 mm |
| | Y | 2.4502 mm |
| Radial Lens Distorsions | K1 | $3.168 \times 10^{-3}$ |
| | K2 | $4.419 \times 10^{-5}$ |
| | K3 | $-3.836 \times 10^{-6}$ |
| Descentering Lens Distorsions | P1 | $-7.239 \times 10^{-5}$ |
| | P2 | $2.496 \times 10^{-4}$ |

Table 1. Internal parameters for the Olympus C5060.

### 3.2 Close-range photogrammetry accuracy test

This accuracy test of these 40 known points on the rectangular frame and the thirty-five ones on the cylinders are showed in tables 2 and 3, respectively. They were computed as root mean square error (RMSE).

| Project | $RMSE_X$ (mm) | $RMSE_Y$ (mm) | $RMSE_Z$ (mm) | $RMSE_{3D}$ (mm) |
|---|---|---|---|---|
| 4 GCP | 1.163 | 1.798 | 2.756 | 3.490 |
| 4 GCP self | 1.395 | 1.352 | 1.777 | 2.633 |
| 8 GCP | 0.826 | 1.154 | 1.355 | 1.962 |
| 8 GCP self | 0.743 | 0.989 | 1.039 | 1.616 |
| 12 GCP | 0.783 | 1.096 | 0.949 | 1.648 |
| 12 GCP self | 0.919 | 0.761 | 0.607 | 1.339 |

Table 2. RMSE on the 40 points of the rectangular frame, with and without self-calibration. GCP stand for ground control points.

| Project | $RMSE_X$ (mm) | $RMSE_Y$ (mm) | $RMSE_Z$ (mm) | $RMSE_{3D}$ (mm) |
|---|---|---|---|---|
| 4 GCP | 0.932 | 1.004 | 0.716 | 1.546 |
| 4 GCP self | 0.696 | 1.047 | 0.545 | 1.370 |
| 8 GCP | 0.953 | 2.325 | 0.625 | 2.589 |
| 8 GCP self | 2.121 | 3.066 | 0.490 | 3.760 |
| 12 GCP | 1.045 | 2.756 | 0.593 | 3.006 |
| 12 GCP self | 1.301 | 2.442 | 0.746 | 2.866 |

Table 3. Root mean square error on the 35 points located on the cylinders, with and without self-calibration. GCP stand for ground control points.

When the number of GCPs grows, $RMSE_X$, $RMSE_Y$, $RMSE_Z$ and $RMSE_{3D}$ decreased in the check points located on the frame (table 2), although the opposite process happened in table 3, when the different RMSEs are computed in the check points on the cylinders.

This could indicate that some coordinates points of the frame do not have enough accuracy, probably because it has suffered some blow in the transport to the different projects for those who have been used.

As for the use of self-calibration, all these cases has demonstrated to improve the accuracies obtained in the check points.

The one dimensional RMSE in this test is ranging between 0.490 mm and 3.066 mm (tables 2 and 3). Thus, the relative error with regard to the size of the photographed object is ranging between 1/3000 and 1/480, 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.

Bearing in mind that with a focal length of 5.7 mm and taken the photographs since 1.5 m of height, the ground sample distance (GSD) was about 0.75 mm, and that the desired precision was related, among other things, to the dimension of individual pixels in the object space (desired precision should be about GSD size), the accuracies obtained in our test seem to be slightly bad.

### 3.3 Mesh generation

Once obtained the three-dimensional points by means of close-range photogrammetry (e.g., figure 6), 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 model was obtained. Figures 7 and 8 show the final 3D models of tomato plants photographed in October 2 and 8, 2007. Both models contain approximately 400 3D points and approximately 750 faces.

The calculated volumes were 571073163 $mm^3$ and 839631672 $mm^3$ for the 3D models generated for the first and the second plants, respectively.

The manual measurements obtained in field are showed in figure 9. Concretly, six measurements of width to three heights (width 1 left (w1l), width 2 left (w2l), width 3 left (w3l), width 1 right (w1r), width 2 right (w2r), width 3 right (w3r)) and two measurements of height (height right (hr), height left (hl)). Table 3 shows the obtained measurements of the first two generated models.

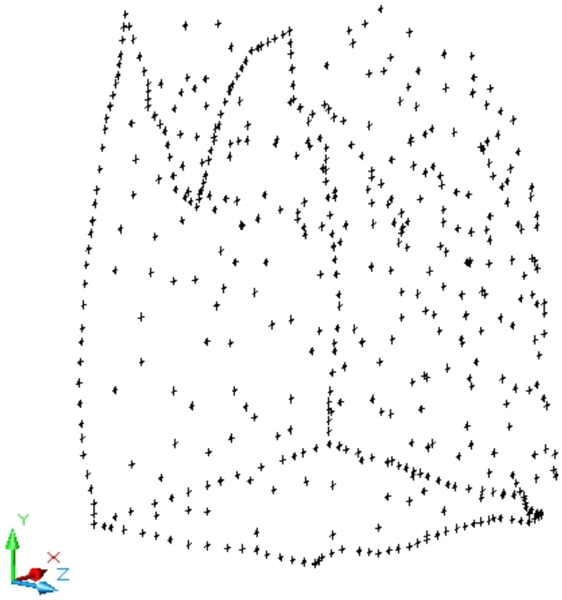


Figure 6. 3D model of the tomato plant.

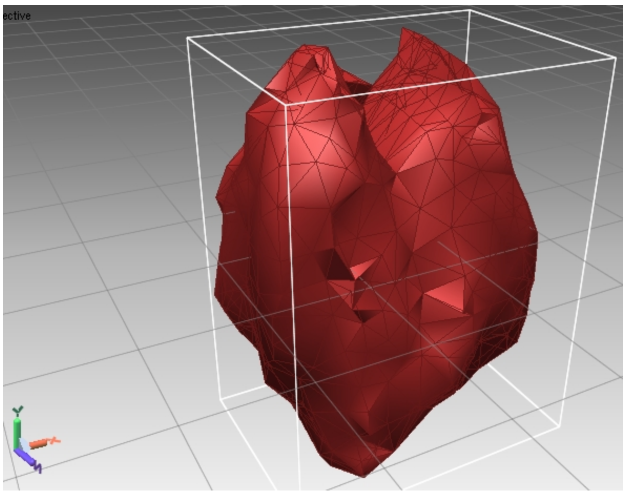

Figure 7. 3D model of the tomato plant.

Up to this moment, we have taken measurements of 17 plants of tomato along the development of the culture (from October to December, 2007). Nowadays, we are in process of obtaining the 3D model by close-range photogrammetry, of which we have only processed the first two.

The idea is, once completed all the models, to determine a simple method of manual measurements which has a good adjustment with the "real" volumes obtained by close-range photogrammetry.

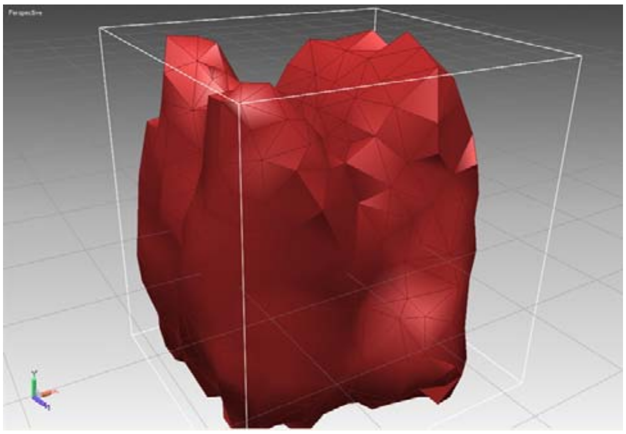

Figure 8. 3D model of the tomato plant.


Figure 9. 3D model of the tomato plant.

| | First model | Second model |
|---|---|---|
| w1-left (mm) | 500 | 510 |
| w2-left (mm) | 370 | 510 |
| w3-left (mm) | 300 | 310 |
| w1-right (mm) | 540 | 560 |
| w2-right (mm) | 440 | 490 |
| w3-right (mm) | 250 | 260 |
| h-left (mm) | 1040 | 1385 |
| h-right (mm) | 1125 | 1420 |

Table 3. Manual measurements taken on the first and second tomato plants.

## 4. CONCLUSIONS

In this communication, 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 a precise way, the volume of the cannopy.

Although the proposed method is perfectly applicable in field, it turns out to be very costly in time. We try to use the volume information obtained by close-range photogrammetry 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. Nevertheless, still we can not present the final results, though, the possibility of applying the proposed methodology has been demonstrated.

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