Obtaining the three-dimensional structure of tree orchards from remote 2D terrestrial LIDAR scanning.

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ABSTRACT

In recent years, LIDAR (Light Detection and Ranging) sensors have been widely used to measure environmental parameters such as the structural characteristics of trees, crops and forests. Knowledge of the structural characteristics of plants has a high scientific value due to their influence in many biophysical processes including, photosynthesis, growth, CO_2-sequestration and evapotranspiration, playing a key role in the exchange of matter and energy between plants and the atmosphere, and affecting terrestrial, above-ground, carbon storage. In this work, we report the use of a 2D LIDAR scanner in agriculture to obtain three-dimensional (3D) structural characteristics of plants. LIDAR allows fast, non-destructive measurement of the 3D structure of vegetation (geometry, size, height, cross-section, etc). LIDAR provides a 3D cloud of points, which is easily visualized with Computer Aided Design software. Three-dimensional, high density data are uniquely valuable for the qualitative and quantitative study of the geometric parameters of plants. Results are demonstrated in fruit and citrus orchards and vineyards, leading to the conclusion that the LIDAR system is able to measure the geometric characteristics of plants with sufficient precision for most agriculture applications. The developed system made it possible to obtain 3D digitalized images of crops, from which a large amount of plant information -such as height, width, volume, leaf area index and leaf area density- could be obtained. There was a great degree of concordance between the physical dimensions, shape and global appearance of the 3D digital plant structure and the real plants, revealing the coherence of the 3D tree model obtained from the developed system with respect to the real structure. For some selected trees, the correlation coefficient obtained between manually measured volumes and those obtained from the 3D LIDAR models was as high as 0.976.

Key words: Terrestrial LIDAR, Laser measurements, 3D Plant structure, Tree volume, Geometrical characteristics of plants, Plant modelling.

1. Introduction

Considering the structural aspects of a canopy is important at different scales: individual tree, crop, forest and ecosystem. Foliar spatial arrangement determines the possibilities for resource capture and atmospheric exchange (Phattaralerphong and Sinoquet, 2004). Plant structure influences many biophysical processes including, photosynthesis, growth, CO_2-sequestration and evapotranspiration (Li et al., 2002; Pereira et al., 2006). At the forest level, structure plays a key role in the exchange of matter and energy between plants and the atmosphere, and affects terrestrial, above-ground, carbon storage (Van der Zande et al., 2006). Aspects of structure can indicate stand developmental stage and its potential for growth, and may also help to predict attributes that are important in stand management, such as stem density, basal area, and above-ground biomass (Parker et al., 2004). Vegetation structure and diversity are also essential factors that influence habitat selection for animal species in forest ecosystems (Bradbury, 2005).

In recent decades, several innovative remote sensing methods have been developed to characterize the 3D structure of individual trees or tree canopies. The use of ultrasonic sensors (Giles et al., 1988; Zaman and Salyani, 2004; Zaman and Schumann, 2005; Solanelles et al., 2006), photography (Phattaralerphong and Sinoquet, 2004, Leblanc et al.,2005), stereo images (Rovira-Más et al., 2005; Andersen et al., 2005, Kise and Zhang, 2005), light sensors (Giuliani et al., 2000), high-resolution radar images (Bongers, 2001) and high-resolution X-ray computed tomography (Stuppy et al., 2003) offers innovative solutions to the task of structural assessment, although most of these methods pose practical problems under field conditions (Van der Zande et al., 2006).

LIDAR (**Li**ght **D**etection **a**nd **R**anging) laser technology potentially provides a relatively novel tool for generating a unique and comprehensive quantitative description of plant structure**.** LIDAR is a non-destructive remote sensing technique for measuring distances. The distance between the sensor and the target (e.g. leaf, branch) can be measured by two alternative methods: i) measuring the time that a laser pulse takes to travel between the sensor and the target (*time-of-flight LIDAR*) or ii) measuring the phase difference between the incident and reflected laser beams (*phase-shift measurement LIDAR)*. A LIDAR system is able to create 3D structural datasets with high point densities from which structural variables can be extracted in a computer environment. Many published studies have been based on LIDAR measurements of forest canopy structure, ranging from terrestrial systems beneath the canopy (Fleck et al., 2004; Fröhlich et al., 2004, Aschoff et al., 2004; Pfeifer et al., 2004), to airborne systems (Naesset, 1997a,b; Blair et al., 1999; Lee et al., 2004; Solberg et al., 2004; Tanaka et al., 2004; Yu et al., 2005; Houldcroft et al., 2005; Coops et al., 2007; Naesset, 2008, 2009).

Forestry was one of the first disciplines to use 3D information extracted from remote sensing data (aerial photographs) to produce three-dimensional models of trees and canopies. Since 1933, stereo-photogrammetry has been known as a suitable technology not only for assessing large forest areas and mapping or opening new forest land, but particularly for measuring individual trees and stands in order to derive quantitative measurements required for forest management, such as tree height and crown diameter. Investigating the potential applications of airborne laser scanner data is another important focus of current research. Other methods have also been used to measure 3D data, including optical stereo and radar systems.

Most of the work carried out to date has focused on forestry (Lim and Honjo, 2003; Disney et al., 2006; Simard et al., 2008; Ling and Jie, 2008; Kushida et al., 2009). However, 3D models may also be valuable in agricultural landscapes, with some applications being similar to those used in forest areas and others being specific to agricultural subjects. The special characteristics of agricultural crops make it difficult to apply some techniques to forest plantations. One basic difference relates to the accessibility of the zones of study for people and vehicles. Forest areas are often difficult to access for people and especially for vehicles. However, the transit of both people and machinery within agricultural plantations is guaranteed in most cases. This is highly relevant as, it largely determines the kinds of instrumentation that can be used in each case. This explains the use of 3D LIDAR sensors in ground-based laser studies for forest applications.. The main advantage of using these sensors is that they provide a three-dimensional cloud of points of the measured object. However, the high cost of these instruments limits their use.

In agricultural applications, however, it is possible to use two-dimensional (2D) terrestrial LIDAR sensors, which are much cheaper to use (Walklate et al.,2002; Palacín et.al., 2007). 2D LIDAR sensors obtain a cloud of points corresponding to a plane or section of the object of interest. Sensor position, when well-determined (for example, with a constant known-speed linear movement) allows the registration of measurement results corresponding to different planes or cross sections of the object, generating a 3D point cloud.

The objective of this work is to explain how to use 2D terrestrial LIDAR to obtain the 3D structure of agricultural plants, trees and canopies in a digital format.

2. Materials and methods

2.1. System description

The scanner used was a general-purpose Sick LMS200 model: a 2D divergent laser scanner with a maximum scanning angle of 180º, with a selectable lateral resolution of between 0.25º, 0.5º and 1º and an accuracy of ±15 mm in a single-shot measurement and a 5 mm standard deviation in a range of up to 8 m. The distance between the laser scanner and the object of interest was determined by measuring the time interval between an outgoing laser pulse and the return signal reflected by the target object. Fig. 1 shows a scheme with the main components of the experimental LIDAR system, while Table 1 summarizes the outstanding characteristics of LMS 200 LIDAR.

2.2. Development of measurement software

Specific software was developed to control the LMS200 laser scanner and to collect, store and process the data measured by the sensor. In the initial development stage, the LIDAR was interfaced to a computer through a RS232 serial port for data recording and offline processing using a graphic interface developed in MatLab (The Mathworks Inc, Natick, MA). In the final test stage, the LIDAR was interfaced to a Compact FieldPoint programmable automation controller (National Instruments Corporation, Austin, TX) for real time operation.

The LIDAR was used to obtain vertical slices of the tree surface. Each vertical slice was composed of the points of intersection between the laser beam and the vegetation. The distance between slices when the system runs at 1 $km.h^{-1}$ is of 20 mm. With a lateral resolution of 1º, the vertical distance between consecutive measurements lies within a range of 10 to 50 mm, depending on the distance between the LIDAR and the measured object. Raw data generated by the LMS-200 LIDAR can be configured in two different modes: i) only by distance or ii) by distance and reflectivity. For the proposed application, the LIDAR was configured in the distance only mode, and the sensor data were composed of the radial distance corresponding to each angular direction of laser beams (polar coordinates).

The integration of sensor data measured at different LIDAR positions into one coordinate system for obtaining the 3D structure of plants was carried out as explained below. Firstly, the spatial coordinates of the point of intersection of each laser beam with the plant were measured with respect to the LIDAR. For each LIDAR position, the intersection points corresponding to a full 180º LIDAR scan gave the slice contour of the plant for that position. The exact position of each slice contour along the tree row (y-axis, Fig 2) was determined by the time between slices and from the forward travel speed of the LIDAR (which was attached to a mobile structure or tractor), which was kept constant in each trial.

In the case of field tests, the speed of the tractor was kept constant by means of its manual velocity control, and its real value was determined by GPS measurements. As a result, the accumulation of the slice contour set of points along the tree row produced a cloud of plant intersection points. Although the LMS200 LIDAR is a 2D laser scanner, the software that has been developed has made it possible to use it as a 3D scanner by moving the sensor in a direction parallel to the row of trees at a known speed. After subsequently converting the polar coordinates of the intersecting points supplied by the LIDAR to Cartesian coordinates, the program exported the x,y,z Cartesian values of each data point in a file format ready to be used by the most common CAD, GIS, statistical and computational software, thereby making 3D modelling and data processing very simple. One of the options of the program allowed us to georeference the data obtained by introducing the real-time coordinates of the LIDAR sensor measured using a GPS system. However, this option is only useful if the GPS system to be used offers precision to within only a few cm.

2.3. Laboratory tests.

The developed system was tested in a laboratory. The laser scanner was fixed to a mobile structure suspended from the ceiling and its linear velocity could be selected by the user. In this way, the LIDAR was able to follow a straight path at a known speed when scanning the object being studied. The first laboratory tests produced 3D measurements of the geometric dimensions (width, height and thickness) of solid objects, such as a PVC tube and a steel frame. The results obtained with the LMS200 LIDAR system were then compared with manual measurements of the same objects. Laboratory measurements of a medium size tree (a *Ficus Benjamina Variegata* approximately 2 m. high, 0.7 m. wide and with a foliage density similar to that of common Mediterranean fruit trees) were subsequently carried out in order to test the performance of the measurement system in a controlled and reproducible environment. The *Ficus* was placed inside a steel frame with vertical and horizontal wires that made it possible to divide the plant into 36 cubes for subsequent defoliation. The laser moved in a straight line, with minimum distance of at least 1 metre between the trunk of the plant and the path of the LIDAR sensor. Laboratory tests were carried out at two LIDAR angular resolutions (1º and 0.5º) and three advance speeds (0.5, 1, and 1.5 $km.h^{-1}$). Both the front and rear of the Ficus were scanned using the laser system.

2.4. Measurements with real crops

Field measurements with real tree crops were made in 2004 and 2005. Before that, a device was designed that made it possible to accommodate the LMS200 laser scanner on a vertical axis at different heights above the soil surface. This device had four wheels so that it could be moved manually. Alternatively, the system could be mounted in the back of a tractor. Fig. 2 shows the experimental system used for field measurements.

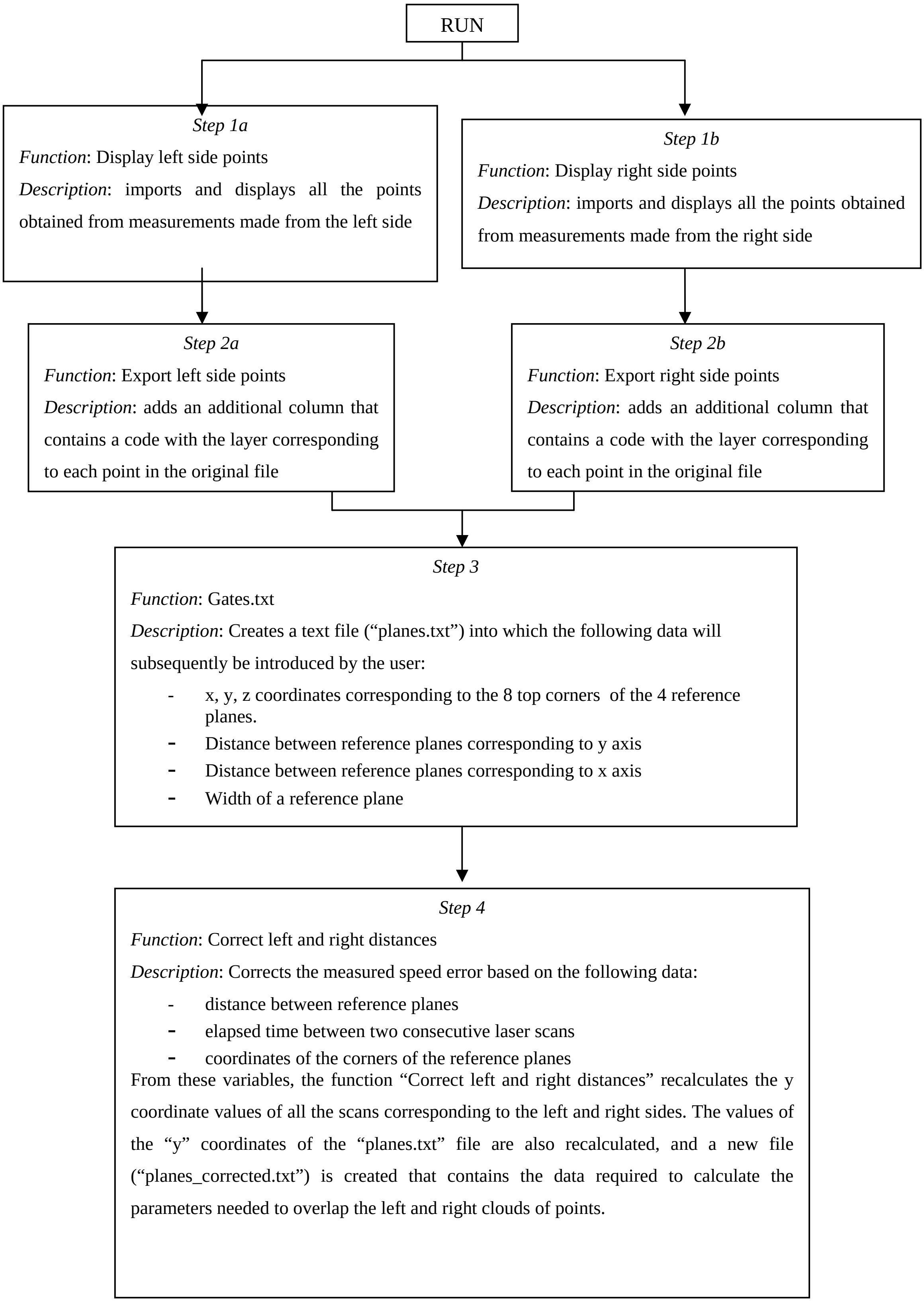
Each field test consisted of several runs (measurements) along either side of the row, with the LIDAR mounted in the back of a tractor and moving in a straight line at a constant known speed (between 1 $km.h^{-1}$ and 2 $km.h^{-1}$) and a distance of between 1 m and 3 m from the trees axis, depending on the crop measured, as shown in Fig. 3. The interval of the scanning angle of the LIDAR was between 0º and 180º, and two different (0.5º and 1º) angular resolutions were used. For each crop, the laser sensor was placed at three different heights, depending on the geometric characteristics of the plants in question (0.9 m, 2.1 m and 3.3 m, in the case of fruit trees and 1.2 m, 1.6 m and 2.0 m, in the case of vineyards). The ground surface of the travel path was quite smooth due to frequent tractor travel and compaction. The measured area contained several trees and had a total length of between

1.2 and 40 m, depending on the crop. Some known objects were placed, for reference (reference planes), at the exact points where measurements began and ended. These were wooden structures with flat surfaces that the LIDAR detected correctly and they served as references for analysis and the subsequent processing of data. By joining together each cloud of points obtained from the scanner measurements made on both sides of the trees, and following the procedure described in the next paragraphs, it was possible to obtain 3D images of the crops.

2.5. Construction of 3D models of plants

Each cloud of points obtained from LIDAR measurements corresponding to a side (left or right) of the trees was independent. Each cloud of points therefore had its own coordinate origin, which coincided with the position of the sensor when measurement started. In order to build 3D models of plants, it was necessary to overlap the points of the two sides of the plants. This implied that all the points obtained had to be registered in a single coordinate system and that the points obtained from one of the measured sides had to be transferred to the coordinate system of the other. The superposition and display of the two clouds of points corresponding to the two sides of the plants was carried out using an automated procedure followed by a manual adjustment.

In the automated phase, the clouds of points were processed using specific software that automatically overlapped them. This software was developed by the authors in VBA (Visual Basic for Applications), making use of the programming resources of AUTOCAD (Autodesk, Inc.). The following flow chart explains how this software works:


RUN
Step 1a
Function: Display left side points
Description: imports and displays all the points obtained from measurements made from the left side
Step 1b
Function: Display right side points
Description: imports and displays all the points obtained from measurements made from the right side
Step 2a
Function: Export left side points
Description: adds an additional column that contains a code with the layer corresponding to each point in the original file
Step 2b
Function: Export right side points
Description: adds an additional column that contains a code with the layer corresponding to each point in the original file
Step 3
Function: Gates.txt
Description: Creates a text file ("planes.txt") into which the following data will subsequently be introduced by the user:
- x, y, z coordinates corresponding to the 8 top corners of the 4 reference planes.
- Distance between reference planes corresponding to y axis
- Distance between reference planes corresponding to x axis
- Width of a reference plane
Step 4
Function: Correct left and right distances
Description: Corrects the measured speed error based on the following data:
- distance between reference planes
- elapsed time between two consecutive laser scans
- coordinates of the corners of the reference planes
From these variables, the function "Correct left and right distances" recalculates the y coordinate values of all the scans corresponding to the left and right sides. The values of the "y" coordinates of the "planes.txt" file are also recalculated, and a new file ("planes_corrected.txt") is created that contains the data required to calculate the parameters needed to overlap the left and right clouds of points.

In order to illustrate this procedure, the upper part of Fig 4 shows two clouds of points corresponding to the left and right side measurements of a crop, with each in its own coordinate system. The lower part of Fig 4 shows the superposition of the two clouds of points corresponding to both sides of the plants in the same coordinate system.

Some additional errors could be produced in field tests as a consequence of inaccuracies in the following experimental steps: positioning the vertical bar that holds the LIDAR sensor; levelling the LIDAR; setting the reference planes; keeping the speed and trajectory of the sensor constant and keeping its path straight. Other external factors, including: vibration of the sensor due to soil irregularities; changes in slope and soil roughness; the movement of leaves and branches caused by the tractor and/or the wind also influenced measurements.

In some cases, such human and environmental influences factors had a detrimental effect on the overlap of the two side measurements and therefore subsequent fine adjustments were needed to improve it. Such errors were corrected after the automated superimposition had been completed by making fine manual adjustments to the superimposed figures. This manual adjustment involved four movements of the cloud of points on the left-hand side:

- y axis rotation
- (Vertical) displacement on the z axis
- (Horizontal) displacement on the x axis
- (Horizontal) displacement on the y axis

The quantification of these movements was based on the locations of common elements that were present in measurements made on both sides of the plants: the soil, the lower part of the trunk, the leafless areas of plants, poles, wires, and individual branches, etc.

Figs. 5a) and 5b) illustrate the fine adjustment process. The clouds of points corresponding to the left and right sides are respectively represented in red and green. The example has been deliberately exaggerated in order to facilitate understanding of the fine adjustment process. The magnitude of this kind of error is usually much smaller.

The manual process starts when an unsatisfactory overlap (upper left corner of Fig. 5a) needs a more precise adjustment. Taking the common soil zones shown in the images obtained from the two as a reference, we carried out an anti-clockwise rotation of 3º around the y axis on the left side of the figure (upper right corner of Fig. 5a). We then carried out a displacement of 73 mm on the left side of the figure, along the z axis (lower left corner of Fig. 5a). Subsequently, based on the reference planes, a displacement of 50 mm of the left side figure along the x axis is done (lower right corner of Fig. 5a). In this example, due to the low foliage density of the plants, the LIDAR sensor (despite being located on the left side) measured points corresponding to laser impacts on the reference planes located on the right side, and vice versa. This also makes it possible to correct the x axis. Finally, the upper part of Fig. 5b) shows a front view of the same crop, just before the adjustment along the y axis. Based on the perimeter contours of the leafless areas of plants, displacing the left side figure 125 mm along the y axis produced the definitive cloud of points, with a front view which is represented in the lower part of Fig. 5b).

The previously mentioned corrections affect the following systematic errors (which are constant during the tests): a) position in height and levelling of the LIDAR sensor, b) lack of precision in the reference planes position, and c) different tractor speeds when scanning the left and right sides. The correction of non-systematic errors, such as soil irregularities, the zigzagging of the tractor, the variations in speed during measurement etc., requires the use of more sensors in the system, such as clinometers, gyroscopes or high precision GPS. It is also necessary to create new software to automatically identify and correct these errors.

After obtaining the preliminary results of tests carried out in 2004, the LIDAR system was applied in the 2005 season to characterize some common Spanish tree crops. The species analyzed were: pear trees (*Pyrus communis* L. ‘Conference’ and ‘Blanquilla’), apple trees (*Malus communis* L. ‘Red Chief’ and 'Golden'), vineyards (*Vitis vinifera* L. ‘Cabernet Sauvignon’ and ‘Merlot’) and citrus (*Citrus reticulata Blanco* ‘Oronules’ ‘Fortune’ and ‘Marisol'; and *Citrus sinensis* L. cv. Osb Navelate).

3. Results and discussion

There was a good degree of agreement between the results corresponding to solid objects obtained with LIDAR and by manual measurements. This can be seen from comparisons between the real dimensions of the steel frame (Fig. 6) used in the laboratory tests and those extracted from LIDAR measurements. The width and height of the steel frame were measured by both the manual and LIDAR procedures at several points in the structure. Differences between the real dimensions of the steel frame and those obtained using

LIDAR were within ± 15 mm. This was compatible with the system error stated in the technical specifications of the LMS 200 laser scanner (Table 1).

The same system error was found for LIDAR measurements of individual vegetation components (leaves and branches) under both laboratory and field conditions. However, a detailed study of laser beam characteristics and its interaction with leaves showed that when the laser beam partially impacted on two leaves, under certain conditions, instead of giving the distance to the first object, it provided an intermediate distance between the two. A laser beam is able to simultaneously impact on two (or even more) plant components because it is several centimetres wide. In fact, due to laser beam divergence, its cross section (and therefore the probability of partial simultaneous impact) tends to increase with distance (for example, transversal beam width increased from 2 cm to 3 cm when the distance from the LIDAR increased from 2 m. to 4 m.). Whether or not the sensor gave the distance to the first object or to an intermediate value depended on the distances between the LIDAR, first, and second object, and also on the distribution of laser intensity. Thus, despite the previously explained restrictions, from the results obtained from laboratory tests, it is possible to conclude that the LIDAR system was able to measure the geometric characteristics of plants with sufficient precision for most agriculture applications. Fig. 8 shows an example of a 3D image obtained from a laboratory test.

As a result of the developed work, a system capable of obtaining the three-dimensional structure of trees and plantations was obtained and used to characterize real crops. The results of field measurements, undertaken in 2004 and 2005 seasons, which were conducted for several types of tree crops (pear trees, apple trees, citrus and vineyard crops) made it possible to obtain 3D digitalized images of crops, from which a large amount of plant information -such as height, width, volume, leaf area index and leaf area density- could be obtained. Figs. 7 and 8 show some examples of the images obtained, which were taken with a digital camera and the developed LIDAR system. These figures show great concordance between the physical dimensions, shape and global appearance of the 3D digital plant structure and real plants and reveal the coherence of the 3D tree model obtained from the developed system with respect to the real structure. This high level of agreement is shown more explicitly in Fig. 9, where the concordance of the physical dimensions and shape of both foliated branches and leafless areas is very high. The top of Fig. 9 shows the volume occupied by the cloud of points. For some selected trees, the correlation coefficient obtained between manually measured volumes and those obtained from the 3D LIDAR models was as high as 0.976 (e.g. in the case of pear trees, *Pyrus communis* L. 'Blanquilla'). Furthermore, repetitions of these measurements produced similar results. For example, a second test for pear trees produced a correlation coefficient for manual versus laser-estimated volumes of 0.974: very similar to the previous value.

As explained, the methodology developed made it possible to obtain a satisfactory three-dimensional structure of trees and crops in an appropriate format for multiple uses. There is, however, still room to improve the procedure for obtaining 3D images. Indeed, as previously expounded, these images are obtained from known, fixed reference points (the reference planes) and by subsequently overlapping the measurement results corresponding to each side. This procedure is, however, very time-consuming, as several steps must be carried out manually. Much effort is currently being made to achieve measurements and results that can be obtained automatically and without the need to use the planes of reference. This will be possible as soon as GPS systems provide the required level of accuracy at a moderate cost. If, in addition, it is possible to incorporate precision inclinometers into the system, it will also be possible to convert it into a portable 2D ground LIDAR system for the 3D characterization of plantations.

Likewise, as far as the software is concerned, tools for automatically differentiating between herbs, trunks, branches, leaves and the ground are being developed. At present, this task has to be carried out manually. The same occurs with determinations of the plant volume and other parameters of interest: the newly developed tool will allow these determinations with precision, but still manually and in a time consuming way. Future efforts must therefore also focus on developing tools that can carry out these determinations faster and more automatically.

4. Conclusions

This paper examines the use of a 2D LIDAR scanner in agriculture to obtain three-dimensional characteristics of trees and crops. The results obtained for fruit orchards, citrus orchards and vineyards show that this technique could provide fast, reliable, and non-destructive estimates of 3D crop structure. As a result, it was possible to obtain a three-dimensional cloud of points, drawn by CAD software. This format facilitated data handling for both qualitative and quantitative studies of the geometric parameters of plants. There was a great degree of concordance between the physical dimensions, shape and global appearance of the 3D digital plant structure and the real plant. The correlation coefficient between manually measured plant volume and that obtained using the 3D LIDAR model was also high. The precision and repeatability of the measurements obtained led us to the conclusion that the newly developed LIDAR measurement system would be suitable for a wide range of applications in agriculture. This tool could constitute a valuable instrument for scientists, since it makes it possible to introduce the ground-based remote measurement of the three-dimensional structure of plants (geometry, size, height, cross-section, etc) as a complementary variable in their research. Once the 3D structure has been obtained, numerous applications are possible. The geometric (height, volume, etc) and structural (Leaf Area Index -LAI-, Leaf Area Density, etc) characteristics of plants, as well as their temporal evolution, can therefore be determined with this non-destructive remote sensing technique. Reliable and objective estimations of Leaf Area Density and Leaf Area Index (LAI) are essential for accurate estimations of canopy carbon gain by trees. A 3D representation of tree-covered fields can also help to improve our knowledge of their characteristics and offer a valuable aid for making decisions and extracting conclusions as well as helping to improve the representation of plant-related information in Geographical Information Systems.

Future research will be directed towards developing tools to differentiate between herbs, trunks, branches, leaves and the ground and towards quickly and automatically constructing GPS-supported 3D models of plants and 3D maps of tree crops. In this way, the physical characteristics of a crop that has been measured with the LIDAR system could be compared and integrated with other geo-referenced information relating to the same crop (satellite data, disease distribution maps, yield maps, etc).

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Table 1. Characteristics of LMS200 laser scanner (SICK AG, 2002)

Wave length	905 nm
Maximum range	8 or 80 m
Angular resolution	0.25º / 0.5º / 1º
Response time	53 ms / 26 ms / 13 ms
Measurement Resolution	±10 mm
System error **(environmental conditions: good visibility, T_a=23ºC, reflectivity ≥ 10%)**	Typ. ± 15 mm, range 1 …8 m Typ. ± 4 cm, range 1 …20 m
Statistical error, standard deviation (1 sigma)	Typ. ± 5 mm (at range ≤ 8m / ≥10 % reflectivity / ≤ 5 kLux
Temperature	0ºC 50ºC
Data transmission rate	9.6 / 19.2 / 38.4 / 500 kBauds
Weight	4.5 kg

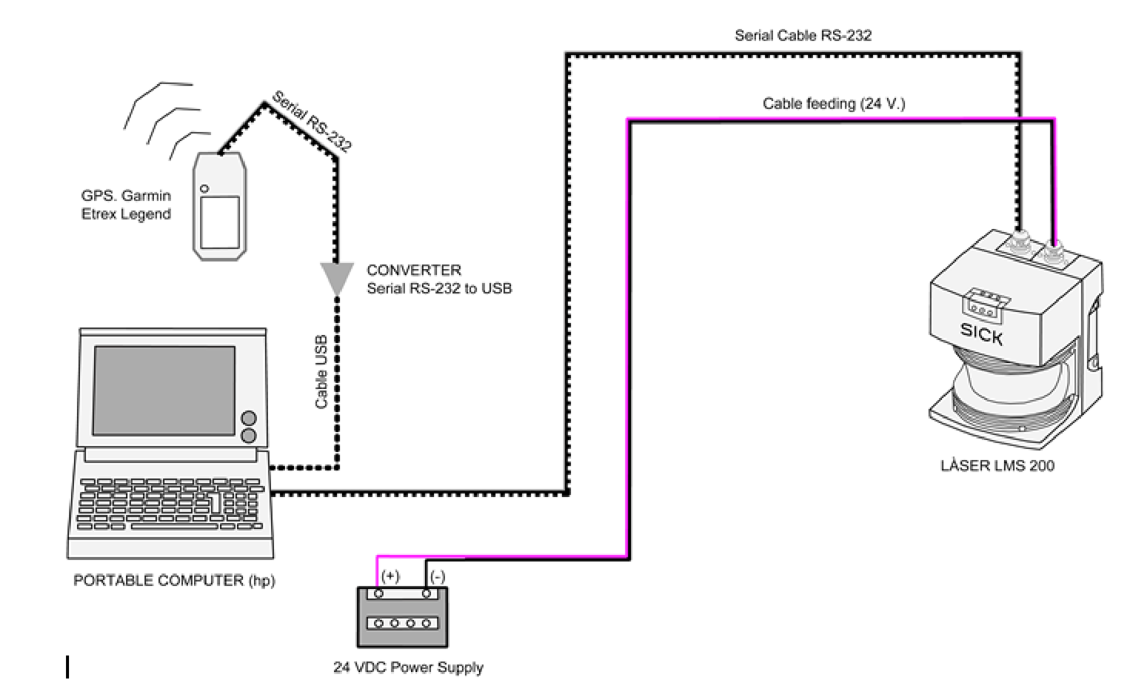


Fig. 1. A scheme of the main components of the experimental LIDAR system

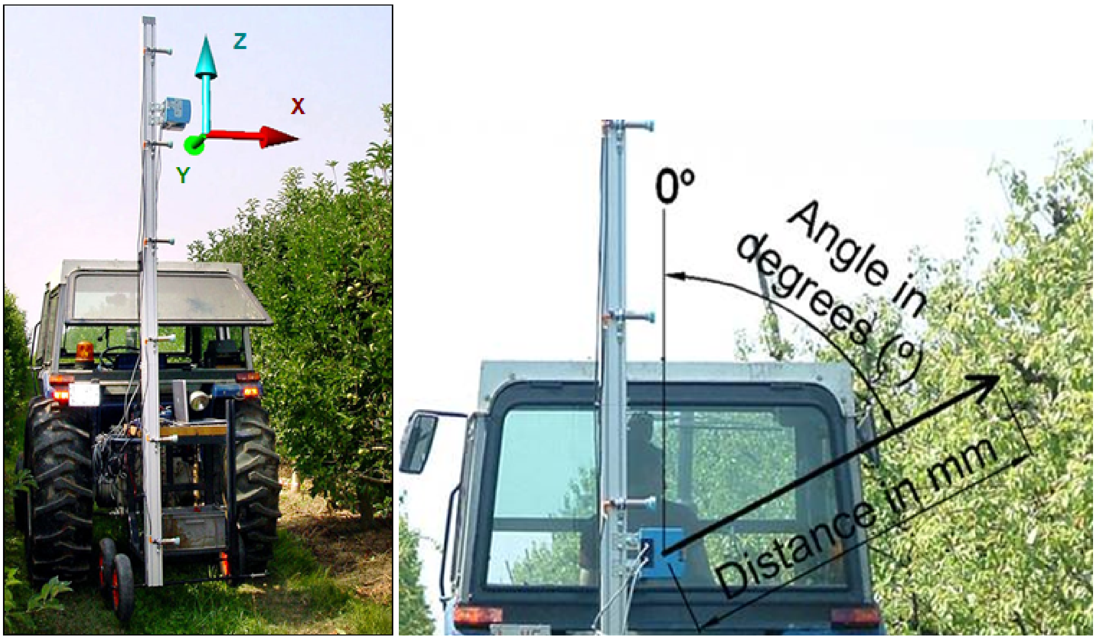


Fig. 2. The LIDAR measurement system, mounted on a tractor, carrying out an experimental test in a pear orchard. Six ultrasound distance sensors are also shown. The height of the laser sensor above the ground was between 0.9 m and 3.3 m, depending on crop characteristics and the purpose of the test. The measurement data formats are also shown. *Left*: data in Cartesian coordinates: x, y, z (the y coordinate corresponds to the tractor displacement axis). *Right*: data in polar coordinates (distance and angle).

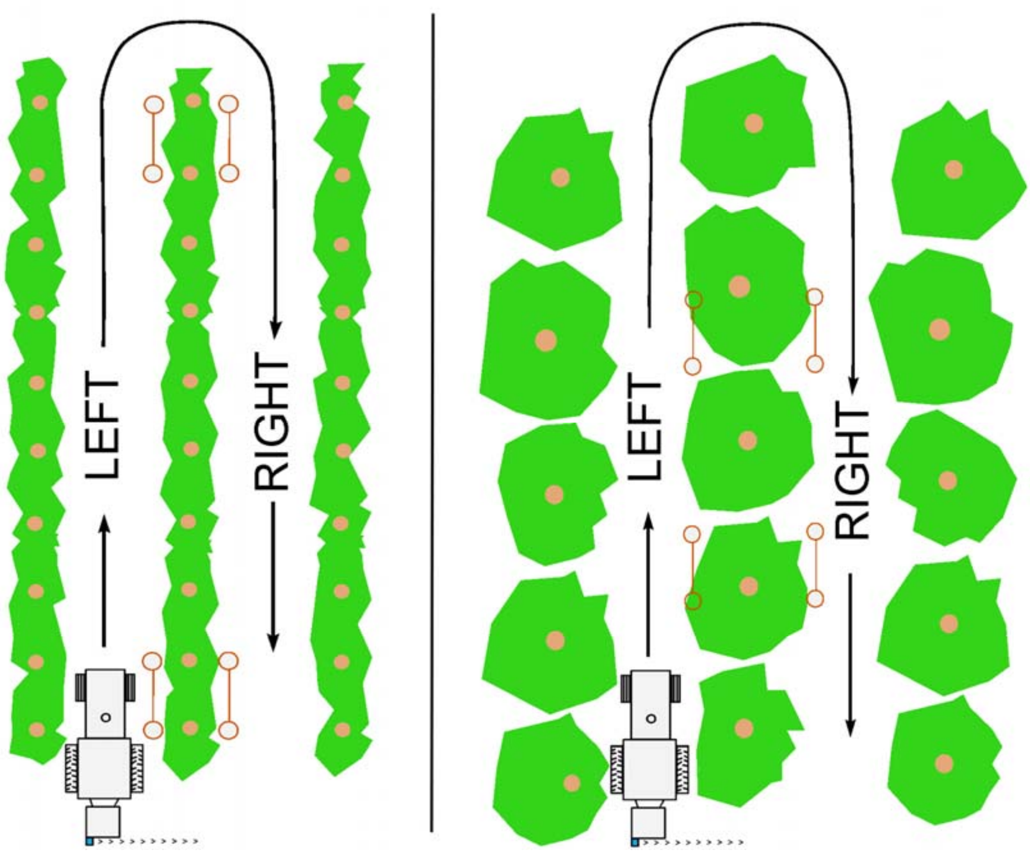


Fig. 3. Trajectory of the LIDAR measurement system on both sides of the tree rows. *Left*: fruit trees and vineyard orchards (almost continuous vegetation). *Right*: Citrus orchards and isolated trees (discontinuous vegetation).

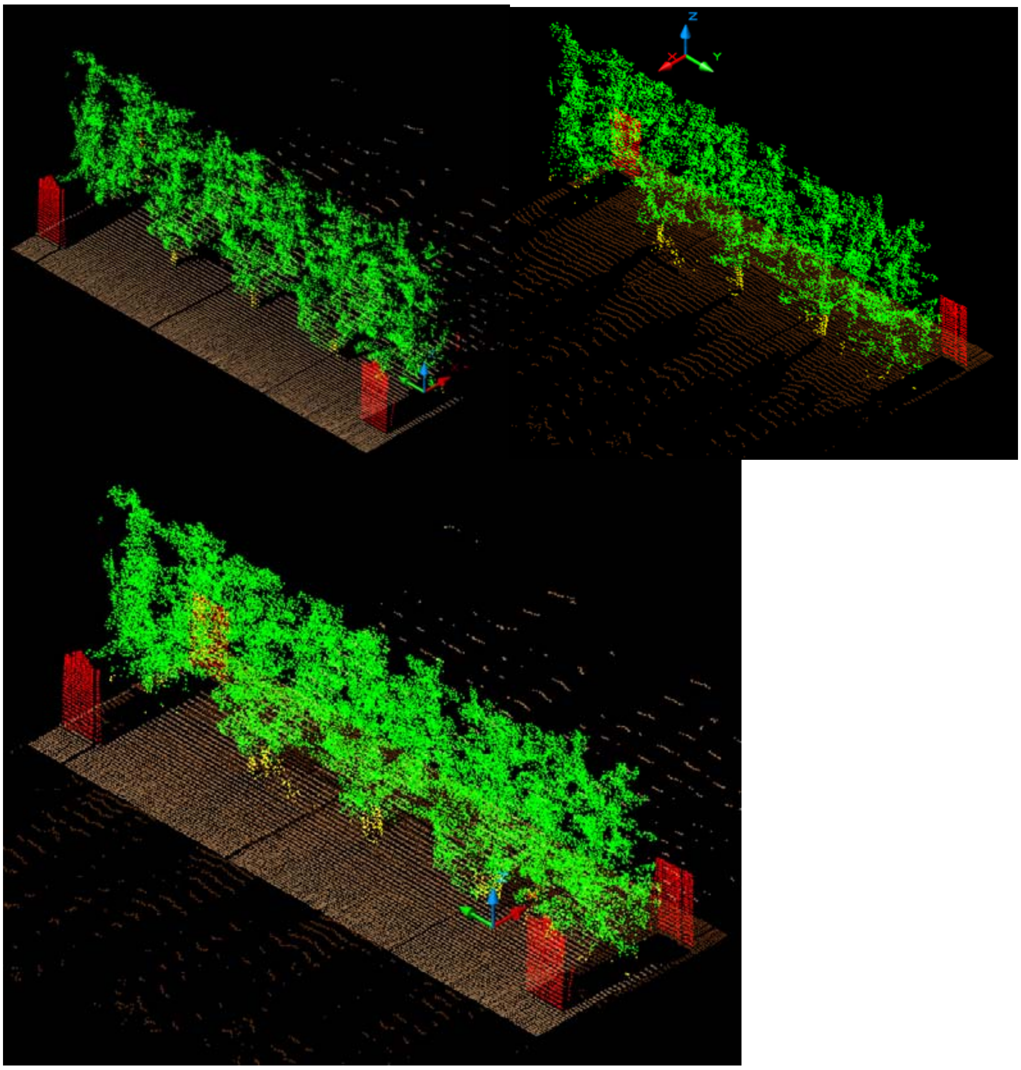
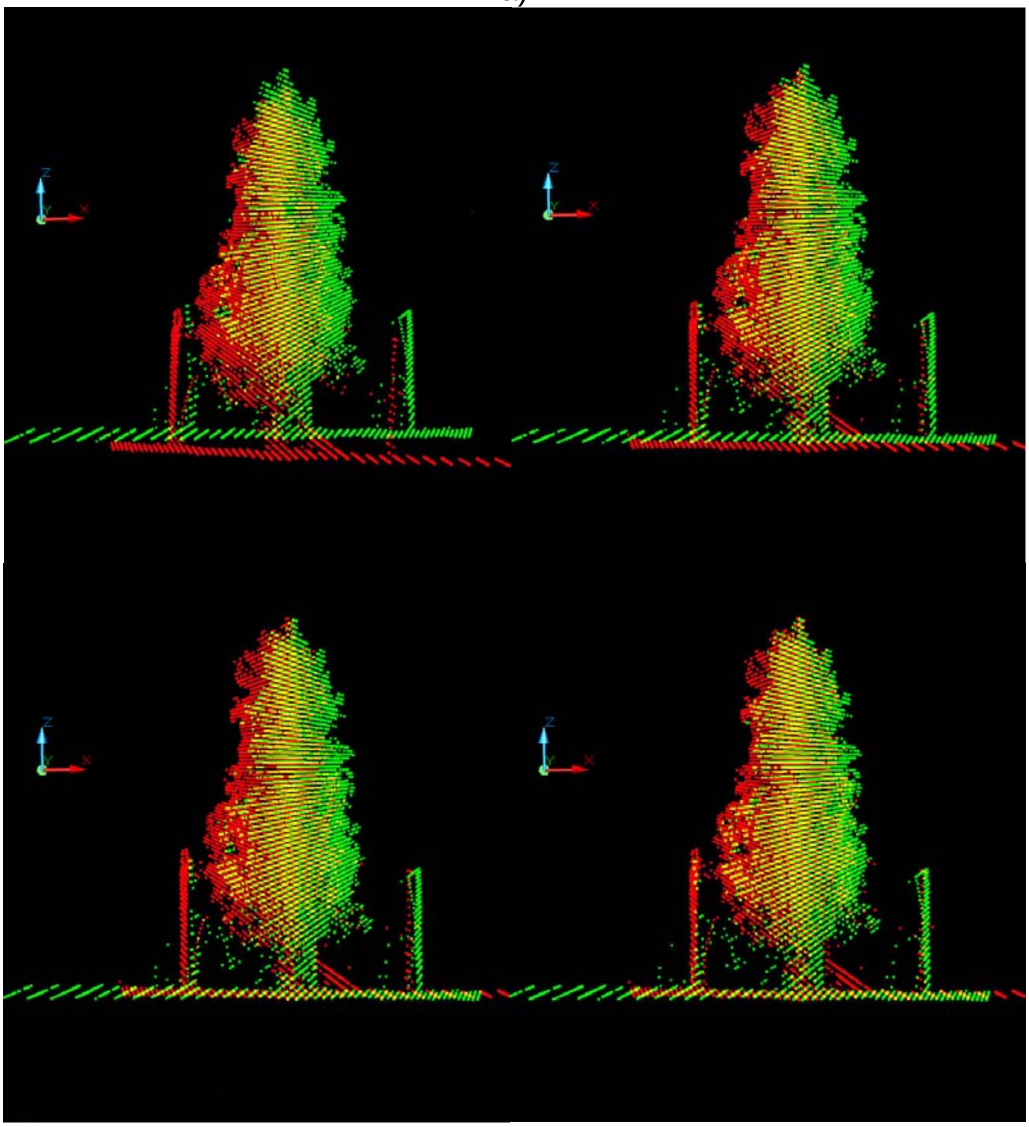


Fig. 4. *Top left*: cloud of points corresponding to LIDAR measurements of a crop from the left side. *Top right*: cloud of points corresponding to LIDAR measurements of a crop from the right side. *Bottom*: superposition of the two clouds of points corresponding to the two sides in a single system of coordinates.

a)



b)

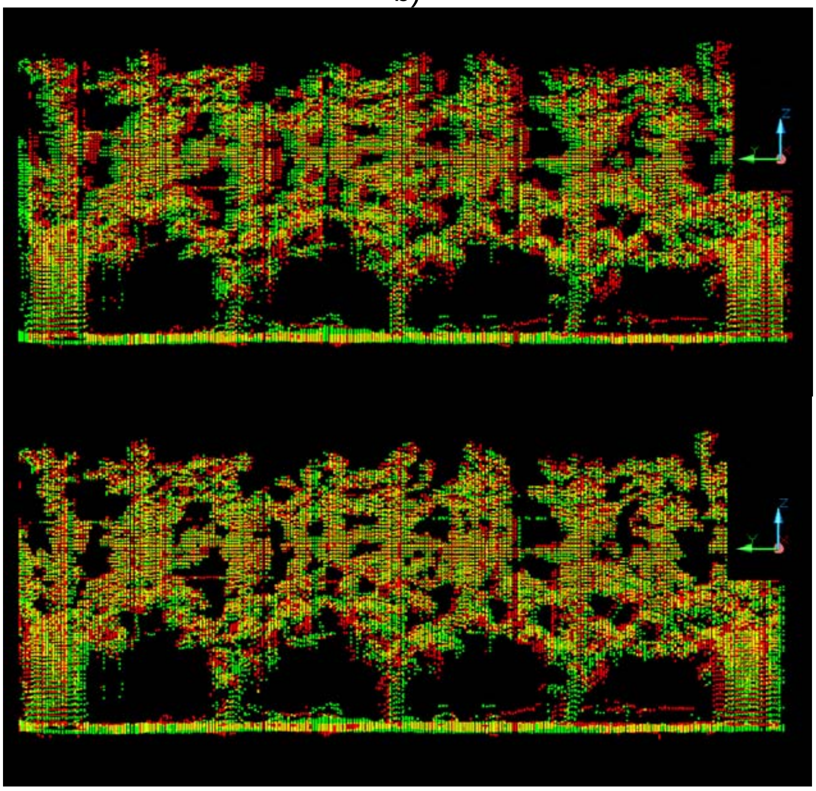


Fig. 5. ***a)*** Side view of a crop to illustrate the fine adjustment process. The clouds of points corresponding to the left and right sides are represented in red and green, respectively. Yellow points are the result of the visual confluence of red and green points. This figure shows the first three steps of the fine adjustment process for improving the overlap of the two clouds of points corresponding to the two sides of the plants. *Top left*: Initial situation of a fictitious example before any correction is implemented. *Top right*: The cloud of points after completing an anti-clockwise rotation of 3º around the y axis of the left side figure. *Bottom left*: The cloud of points after displacing the left side figure 73 mm along the z axis.

Bottom right: The cloud of points after displacing the left side figure 50 mm along the x axis.

b) Front view of a crop to illustrate the last step of the fine adjustment process. The clouds of points corresponding to the left and right sides are represented in red and green, respectively. *Top*: a front view of the clouds of points corresponding to both sides of the crop just before displacement along the y axis. *Bottom*: a front view of the definitive clouds of points after displacing the left side figure 125 mm along the y axis.

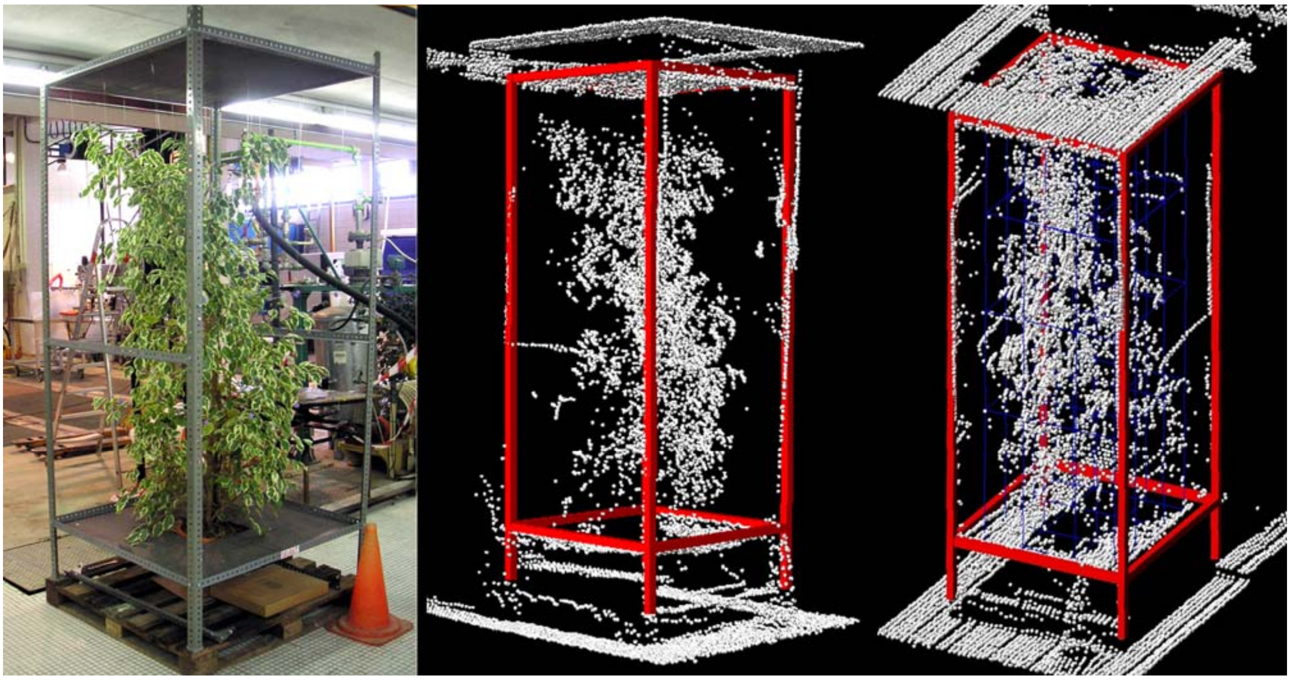


Fig. 6. Photography (*left*) and two 3D images (corresponding to different views) of a *Ficus Benjamina Variegata*, obtained with a LMS200 laser scanner in a laboratory environment.

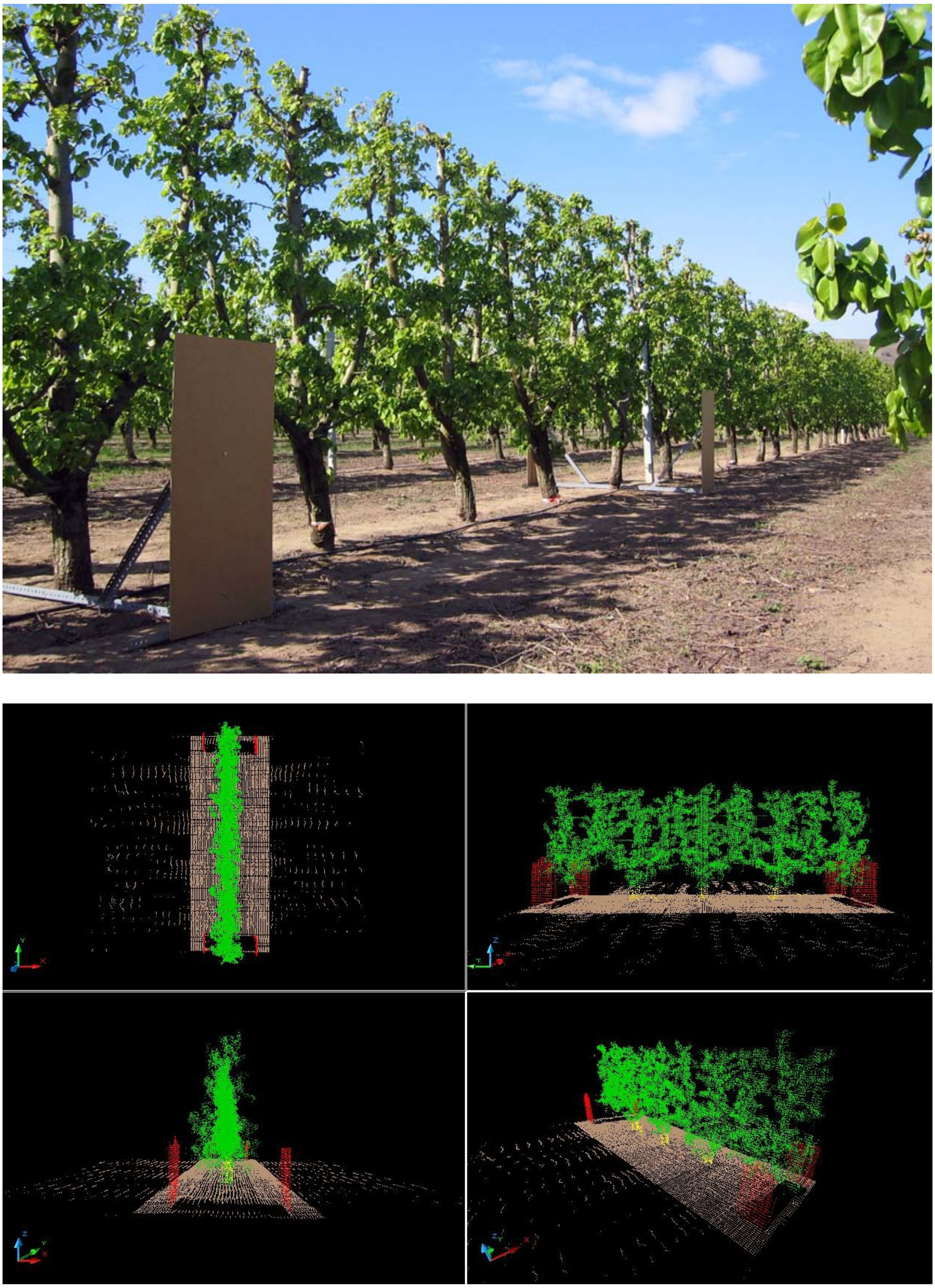


Fig. 7. Different views of the 3D structure of the pear orchard shown in the upper picture.

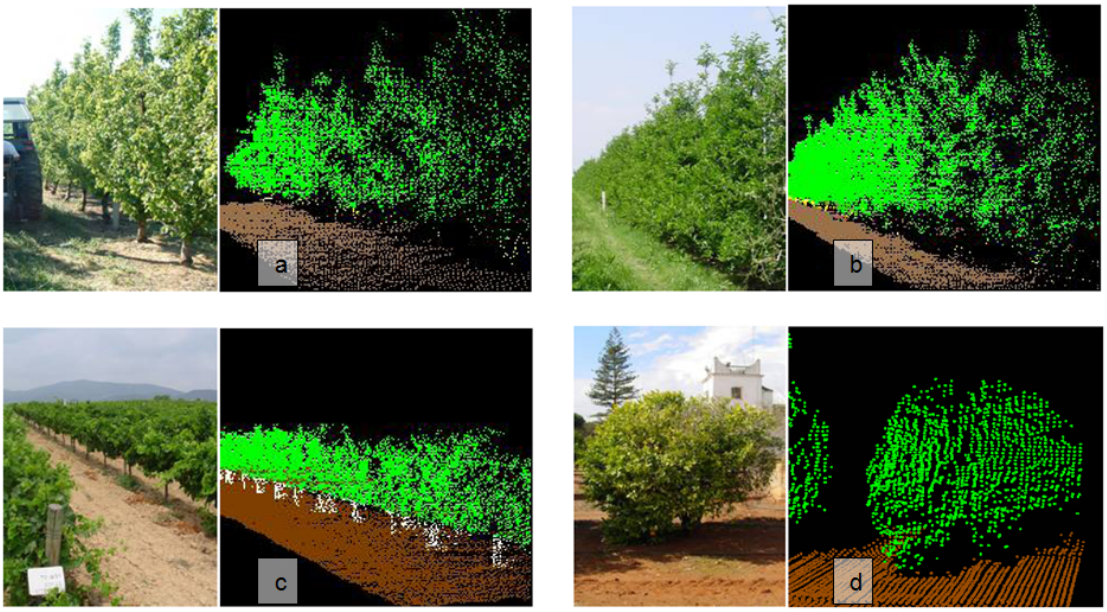


Fig. 8. Pictures and 3D images of pear trees (a), apple trees (b), vineyards (c) and citrus trees (d).

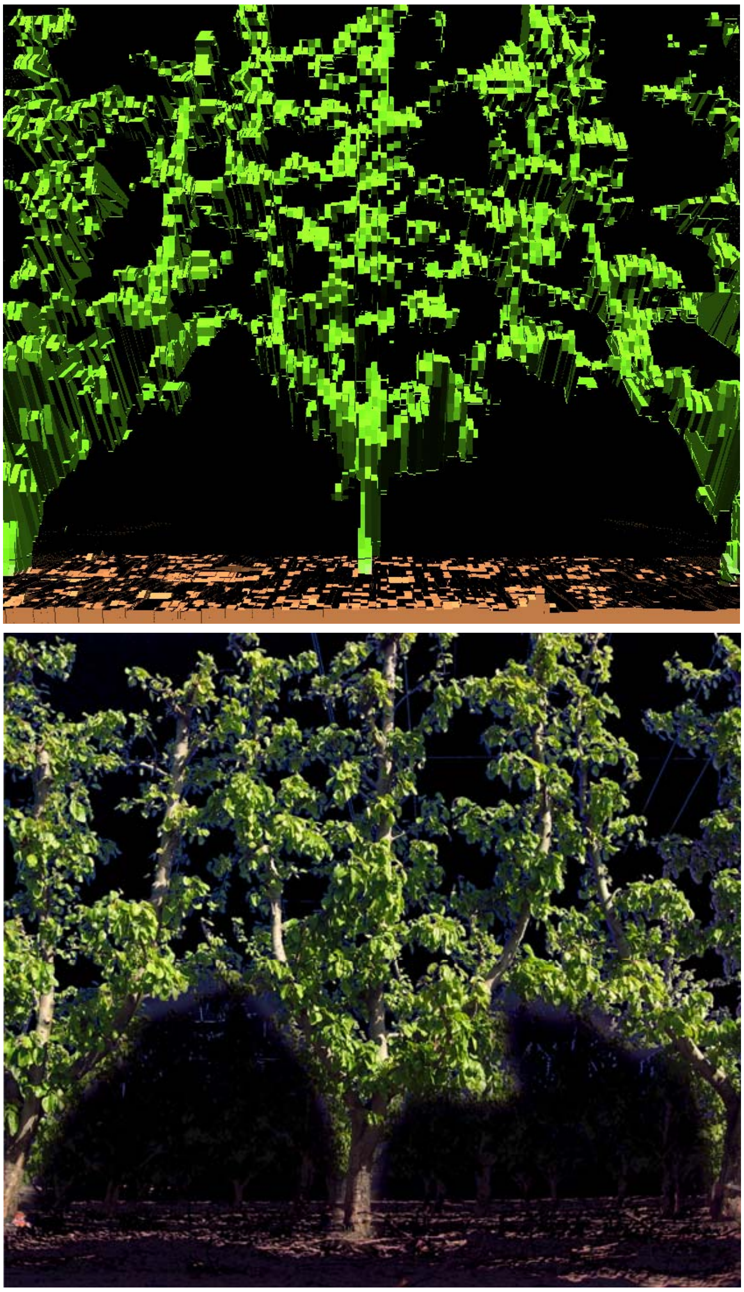


Fig. 9. 3D model of pear trees (*Pyrus communis* L. ‘Blanquilla’) obtained from LIDAR measurements (*Top*) and digital photography of the same real trees (*Bottom*), evidencing the great degree of concordance between the two. The upper figure shows the volume occupied by the cloud of points.