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RESEARCH ARTICLE

2D LiDAR-Based System for Canopy Sensing in Smart Spraying Applications

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ABSTRACT The efficient application of phytochemical products in agriculture is a complex issue that demands optimised sprayers and variable rate technologies, which rely on advanced sensing systems to address challenges such as overdosage and product losses. This work developed a system capable of processing different tree canopy parameters to support precision fruit farming and environmental protection using intelligent spraying methodologies. This system is based on a 2D light detection and ranging (LiDAR) sensor and a Global Navigation Satellite System (GNSS) receiver integrated into a sprayer driven by a tractor. The algorithm detects the canopy boundaries, allowing spray only in the presence of vegetation. The spray volume spared evaluates the system's performance compared to a Tree Row Volume (TRV) methodology. The results showed a 28% reduction in the overdosage of spraying product. The second step in this work was calculating and adjusting the amount of liquid to apply based on the tree volume. Considering this parameter, the saving obtained had an average value for the right and left rows of 78%. The volume of the trees was also monitored in a georeferenced manner with the creation of a occupation grid map. This map recorded the trajectory of the sprayer and the detected trees according to their volume.

INDEX TERMS Agricultural robotics, canopy characterization, precision spraying, robotics.

I. INTRODUCTION

Using pesticides in agriculture is a conventional and necessary practice to avoid crop yield losses. However, these practices have secondary negative effects on human health and negative environmental impact. In regular practices, a significant amount of product is applied out of the target, contaminating the air, water and soil [1].

Precision spraying is a method that reduces drift by controlling the amount of water and pesticides used according to canopy characteristics [2].

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The first proposed solutions applied spatially variable herbicide doses [3]. However, it later evolved to control the amount of water and pesticide used based on factors such as foliage shape and volume [4].

Over the years, many works have been done to quantify the reduction of spray volume applied using systems that adjust the applied quantity according to the target structure.

In the early stages, the perception of the canopy was based on techniques using ultrasonic sensors [5]. In 2008, tests were carried out in a dormant orchard using a commercial target-sensing spray system. This technique was compared with a conventional air-blast sprayer application to understand the benefits. The results showed dose reductions of 40%

in the product application rate, 41% in ground deposition, and 44% in surface water runoff [6].

In other work, the tree structure was detected by ultrasonic sensors, resulting in a 48% decrease in the pesticide applied [7].

Later in 2015, an automatic toward-target sprayer was designed based on infrared and hall effect sensors for canopy perception [8]. The system was limited to a tractor speed of 1.5m/s, and the sensors range operation of 70cm, unable to detect trees outside this zone.

The work [9] proposed a pesticide spraying system with a single nozzle with a variable opening and an automatically adjustable spraying angle, colour camera and distance sensors. The method consists of directing the spraying to the target centre and defining the diameter of the spraying.

The approach [10] presented a low-cost pesticide sprayer based on ultrasonic sensors. This technology has allowed abstaining from spraying in spaces without a canopy, saving 26% of the product. In this work, the sprayer was evaluated with two different nozzles.

Tree canopy parameters are relevant for decision-making related to crop management, irrigation, pesticide application and crop load management.

The data collected by sensors integrated into tractors have extra difficulty in its analysis due to the irregularities of the displacement. This way, the authors collected LiDAR sensor data on sliding rails, a tree at a time [11]. With this data, it was possible to measure the canopy volume, showing the ability of this method to be integrated into precision sprayers.

Work was also carried out using a LiDAR sensor to measure the density and volume of tree canopies [12]. The data collected from the orchard is then processed on a cloud system, which can generate a map for VRT. However, this implies data collection before the application.

The system [13] included a 2D LiDAR to detect tree height and canopy leaf density, two cameras for image classification, fruit detection and counting, a GNSS sensor and two flow meters. The sprayer adjusts the spraying rate according to tree height and health status. This work noted errors in detecting dead trees, as most have mature trees in the background. This type of error can be mitigated if there is information about the distance to the tree being analysed. In this way, only the canopy on the nearest row is considered.

Recently, an approach was presented [14] that used LiDAR-based 3D point clouds of cherry trees to indirectly, based on the estimation of the leaf area, calculate the water interception and precipitation at individual tree levels. The method can support precise irrigation management.

Another work based on LiDAR 3D point clouds [15] developed a method to analyse the spray drift in real-time spraying operations.

In another work, an autonomous spraying robot was developed using a 3D LiDAR sensor [16]. They combine autonomous navigation with precision spraying utilising the sensor to sense the trees around the robot. The results showed a 32% reduction in pesticide application.

Although a 3D LiDAR sensor can provide more information than a 2D LiDAR sensor, it is much more expensive and requires more processing power. In the case of this work, the use of this sensor in front of the robot makes perfect sense. However, the integration of such a sensor in a sprayer that is attached to a tractor would mean that a large part of the FOV of the sensor would be occluded by the tractor in front of it.

Analysing all the work that has been presented here, some missing points or mistakes have been identified:

- choice of a position for the LiDAR sensor that causes parts of the canopy to be occluded in certain situations;
- no detection of the start and end of trees, i.e. the canopy is treated as a whole;
- tree by tree scanning, instead of continuous scanning with tree limits detection;
- does not show how the algorithm would be applied to a spraying process and the impact it would have.

In this way, the system developed in this work is expected to encompass all the aspects presented.

With the development of this work, we intend to contribute to a system capable of processing data obtained by a 2D LiDAR sensor integrated into a sprayer attached to a tractor. The data is collected continuously along one row of an orchard without stopping at each tree. This data collection makes detecting the tree limits and volume possible. This real-time processing has a direct impact on the application being carried out. And there is also the possibility of saving information that can be used in future applications, with more information about the state of the vegetation. The calculations performed, which represent significant savings in the spray volume to be used, are also presented.

The principal objective of this work is to make a characterisation of the canopy of fruit trees that can support precision spraying. There are three steps to achieving this goal:

- detecting the start and end of the canopy, which allows spraying only where there is vegetation;
- making it possible to decide the spray volume (and pesticide dose) to apply based on the volume of the trees to make spraying even more precise and economical;
- monitoring the tree volume, which is georeferenced to the sprayer's trajectory, obtaining more information on each tree to carry out the process.

II. MATERIALS AND METHODS

This section presents the materials and methods applied in this work. The methodology used can be divided into three main parts, as illustrated in figure 1. First, how data collection was carried out is presented. Next, the different processing techniques are presented to obtain a plane, tree boundaries, and volume. Finally, the way used to show the performance of our system is demonstrated by creating a map and calculating the percentage of spray volume that can be saved with this approach.

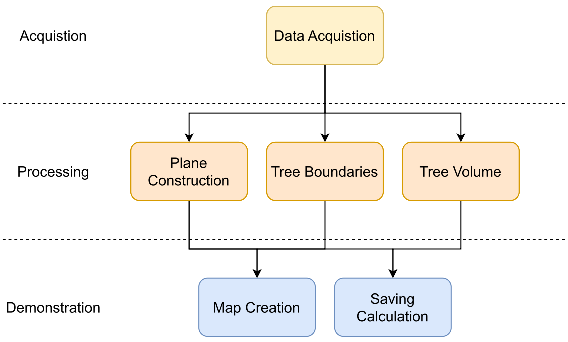

FIGURE 1. **Methodology used and division into three main parts: Acquisition, Processing and Demonstration.**

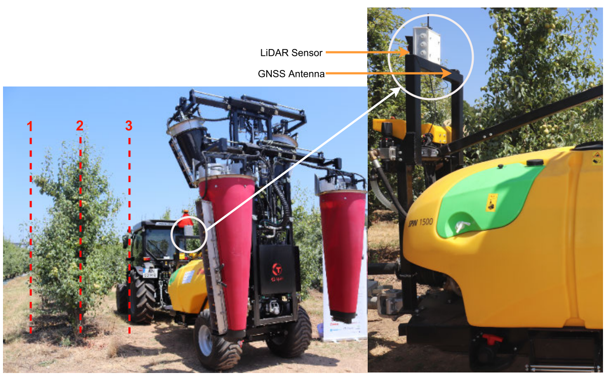

FIGURE 2. **Tractor and sprayer used for data collection (left). Identify of the 2D LiDAR sensor and GNSS antenna (right). Line 3 in the left image represents the canopy area closest to the sensor. Line 2 marks the tree trunk, and line 1 represents the canopy area furthest from the sensor.**

A. DATA ACQUISITION

The data acquisition was performed in a "Rocha" pear orchard, planted in 1998, trained in central leader and grafted on BA29, the most vigorous used rootstock in commercial orchards. It also features a tree density of 1111 trees/ha with a configuration 4.5 × 2.0 (meaning a 4.5 meters inter-row width and 2.0 meters distance between consecutive trees in a row), located in Alcobaça, Portugal (39.551392, -8.959871). Figure 2 shows the tractor with the sprayer and the sensors used. The LiDAR sensor model is the Hokuyo UST-10LX [17], with a 270° field of view, a 0.25° angle resolution and a detection range of 0.06 m to 10 m. The GNSS receiver belongs to the ANN-MB series from Ublox [18].

The LiDAR sensor was on the sprayer at 2.05 meters from the ground. The sensor's height was adjusted to position it approximately at the midpoint of the trees' height while also considering the available fixing points on the sprayer. The LiDAR is mounted so that the front, the x-axis, points towards the ground. In this manner, correspondingly, the y-axis's positive and negative sections indicate the trees located to the right and left of the sprayer. With just one sensor, it is possible to cover the trees on both sides of the sprayer. The tractor was driven between the rows at approximately 6 km/h to collect data.

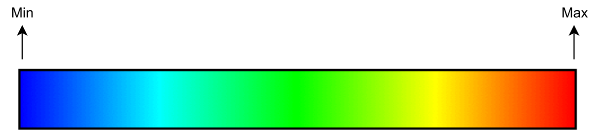

FIGURE 3. **Colour map used to set the colour as a function of a given parameter.**

Some measurements were taken to define the thresholds used in the algorithm. Figure 2, on the left image, represents the zones where these measurements were performed. This way, the distance obtained between the sensor and the canopy beginning measured in zone three was 1.5 meters. The distance between the sensor and the tree trunk, represented by zone two, was 2.3 meters, and between the sensor and the canopy end in zone one was 3 meters.

B. PLANE WITH THE LiDAR SENSOR POINTS CONSTRUCTION

The LiDAR data is projected in two different planes, one for the tree row to the left of the sprayer and the other to the right. Each plane has four meters in height and ten meters in width and has a resolution of four centimetres.

The LiDAR data is initially in polar coordinates and needs to be converted to cartesian coordinates. The x coordinate gives the height from the ground, and the y coordinate is the distance from the sensor to the tree.

Some threshold values for the distance are defined to consider just points in the closest row and not some noise close to the LiDAR.

In this way, each point is converted to cartesian coordinates. It is verified if the distance (y) is within limits, and it is also verified if the height (x) is inside the boundaries of the projected plane.

The sign of the distance value defines which plane the point belongs to. If the value is positive, it refers to the right plane; if it is negative, it concerns the left plane. Each LiDAR sample of points represents a column in the projected plane.

Figure 3 displays a colour map representing the points obtained on the plane. The colour of the points corresponds to their distance from the sensor, which is based on the defined minimum and maximum values. The colour scheme ranges from blue to cyan, green, yellow, and red in ascending order of distance.

C. DETECTION OF TREE BOUNDARIES

The plane is equally divided into three horizontal sections. As the plane is being created, the idea is to detect the beginning and end of each tree. The detection of the tree boundaries is based on a moving average calculation (figure 4). The green window, with width W, is used to store, in each position, the number of points in a section in a given iteration. This window

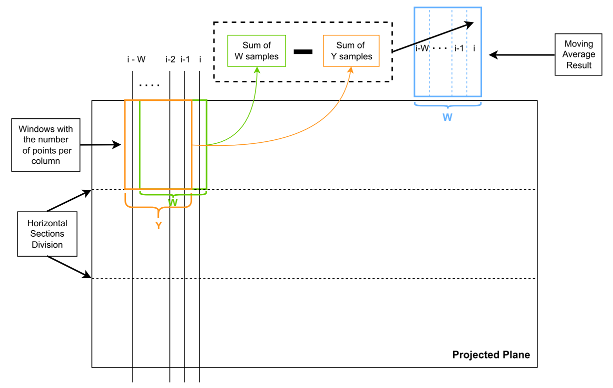

FIGURE 4. Representation of the tree detection calculation based on a moving average calculation.

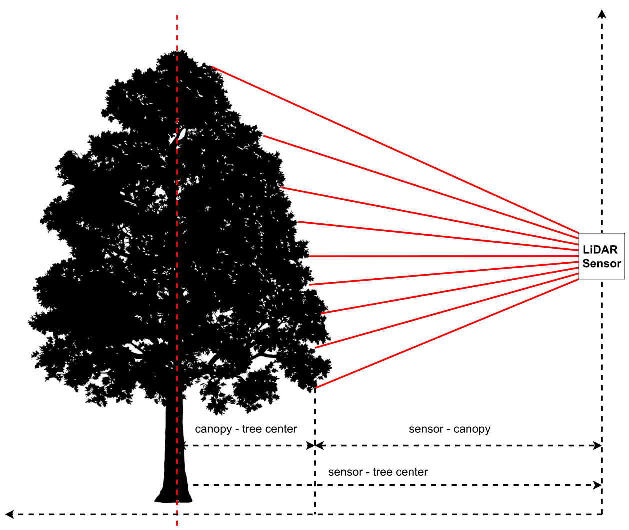

FIGURE 5. Representation of the distances considered in the calculation of the canopy volume.

keeps the total points in the last W samples. In each iteration, these W different values are summed. Then the difference between the actual sum (green window) and the previous one (orange window) is calculated. The result is stored in the blue window with width W. This window has the variation of points in the last W samples. The sum of these values results in the slope. The slope from the current and previous iterations is used to detect the tree start and end.

When a specific variation is detected between these slopes, defined experimentally, a tree limit is considered to have been detected. The bottom of Figure 10 shows the evolution of the sum of points along the plane. The beginning and end of the trees coincide with the zones in which the slope sign is altered.

D. TREE VOLUME CALCULATION

The volume is calculated for each tree's horizontal section. For each sample of sensor points, the distances of the points within the plane boundaries are stored.


```
{
"map_type":"prescription",
"units":"kg",
"lat_up":"41.4306",
"lon_up":"1.7129",
"lat_down":"41.429",
"lon_down":"1.711",
"topic_map":"/nodered/maps",
"topic_overlay":"prescription",
"map":",iVBORw0KGgoAAAAN......"
}
```


FIGURE 6. PNG JSON format to store the map. The latitude and longitude values are merely illustrative, not referring to the place where this work was carried out.

The volume calculation for each tree is performed based on the scheme shown in figure 5. The sensor gives the distance to the tree's canopy at a given point. The distance between the tree's canopy extremity and the centre is needed to calculate the tree's volume.

This value is obtained through the difference between the distance from the sensor to the tree's centre and the sensor to the canopy extremity.

If we multiply this value by the area of a square with three centimetres on a side, which is the resolution used in the plane, we get the volume corresponding to each point. A volume value is stored for each horizontal section, incremented with each iteration.

The detection of canopy limits, beginning and end, is used to assign the calculated volumes to the different trees.

The algorithm assumes symmetry between the side of the tree being detected and its opposite side. This way, the calculated volume is multiplied by two at the end of each tree.

In this way, each section volume is obtained at the moment when the end of the tree is detected. The volume is reset at the canopy beginning and is calculated iteratively until the tree end is detected again.

E. MAP WITH SPRAYER TRAJECTORY AND TREES

The trajectory of the sprayer is recorded on a map that is stored in json format (figure 6). The fields "lat_down", "lon_down", "lat_up" and "lat_down" are the limits for latitude to be represented on the map. The fields "topic_map" and "topic_overlay" will promote the map's publication on a specific topic. The field "map" must contain the base 64 map image. This map is presented in the World Geodetic System 1984 (WGS84) referential.

Each detected tree is plotted on the json map, along with the sprayer trajectory (figure 7). The sprayer sensing system measures the features in the metric space. To project this on the json map, we need to convert the sprayer position to the Universal Transverse Mercator (UTM) referential (metric space) [19].

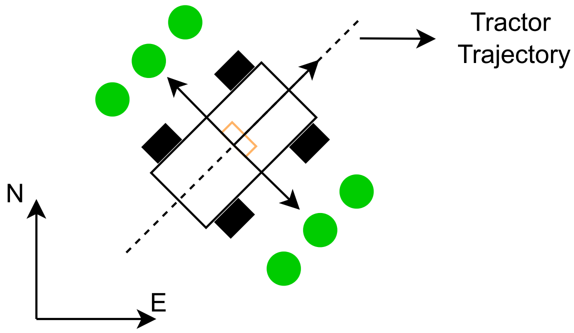

FIGURE 7. Tree position calculation related to the sprayer trajectory.

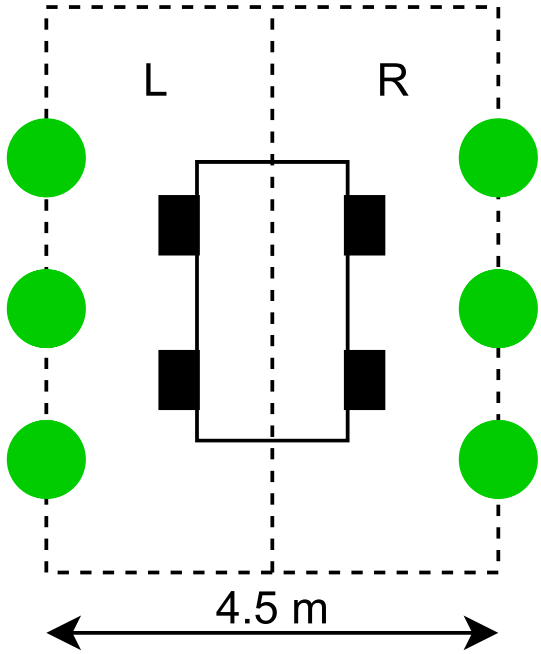

FIGURE 8. Covered area in the left (L) and right (R) row along the sprayer trajectory.

The tractor heading (trajectory bearing) is estimated with equation 1 considering equations 2, 3 and 4.

$$B = atan\frac{Y}{X} \tag{1}$$

$$Y = sin(dLon) * cos(lat2) \tag{2}$$

$$X = cos(lat1) * sin(lat2) - sin(lat1) * cos(lat2) * cos(dLon) \tag{3}$$

$$dLon = lon2 - lon1 \tag{4}$$

where:

- lon1 - longitude of the previous sprayer position
- lon2 - longitude of the actual sprayer position
- lat1 - latitude of the previous sprayer position
- lat2 - latitude of the actual sprayer position

A vector representing the distance between the tractor and the trees is added to the UTM reference system for the sprayer's position. This vector's length is then rotated 90 degrees relative to the tractor's heading, obtained from the trajectory. In this way is used the equation 5 for the right tree and the equation 6 for the left tree.

$$X_{tree}^{UTM} = X_s^{UTM} + R(h_s + 90°)\vec{d} \tag{5}$$

$$X_{tree}^{UTM} = X_s^{UTM} + R(h_s - 90°)\vec{d} \tag{6}$$

where X_{tree}^{UTM} is the tree position, X_s^{UTM} is the sprayer position, both in UTM referential. R is the rotation matrix, h_s is the trajectory bearing, and $\vec{d}$ is the vector that represents the distance to the tree.

Then the result is converted from UTM to WGS84 coordinates. The tree coordinates are plotted on the map with a colour related to the tree volume.

F. SPRAY PRODUCT SAVING CALCULATION

The performance of this work is evaluated according to the amount of spray volume that is spared.

According to work [20], a unit volume expresses the volume of spray liquid per one cubic meter of canopy volume, which is biologically effective in covering the target. For the orchards in Poland, this unit volume takes the value of 0.033 l/m3. Similar values are used in Portugal [21].

In this way, assuming the sprayer is always on, the volume of liquid used is obtained by calculating the volume occupied by the row as if it were a parallelepiped, based on the TRV methodology [20]. The canopy volume is obtained using equation 7. Where k is the unit volume (l/m^3), RH is the average height of trees in the row (m), RW is the tree width (m), and D is the meters the tractor travelled in the trajectory.

$$V[ON] = k * RH * RW * D \tag{7}$$

The first iteration for saving on the amount of product used is to switch off the sprayer when no trees are detected. In this situation, the volume spent is determined by the equation 8. Instead of considering the total displacement, only the metres travelled in which trees are detected are considered.

$$V[ON/OFF] = k * RH * RW * DWT \tag{8}$$

Finally, the volume to be applied is calculated, considering the volume of trees obtained in the row using the equation 9. Where TV is the total canopy volume of all trees detected in the row.

$$V[TreeVolume] = k * TV \tag{9}$$

The spray volume values are typically presented in l/ha. As the tractor only travelled one row, it is necessary to estimate the area covered by the sprayer. The distance between rows is 4.5 metres. Since the rows to the left and right of the sprayer are processed individually, a division into two areas is considered, as shown in figure 8. In this way, it is just considered half of the vegetation on each row side since the width of the area is obtained between the tree trunks of the two rows. The covered area (CA) by each side of the sprayer is obtained by multiplying the displacement performed by 2.25, half the distance between rows.

TABLE 1. Parameters obtained for the right and left plane.

Methodology	Parameters	Row Side	
		Rigth	Left
Field Facts	Planted Trees	45	45
	Tree Step Spacing (m)	2.00	2.00
	Distance between Rows (m)	4.50	4.50
	Total Displacement (m)	92.00	92.00
	Typical Spraying Volume (l/ha)	**700**	**700**
Tree Row Volume (TRV)	Total Row Volume (m^3)	522.91	481.43
	Spray Liquid ON (l) (equation 7)	17.26	15.89
	Spray Liquid ON (l/ha) (equation 10)	**417**	**384**
Perception algorithm proposed	Tree Count	44	43
	Tree Average Spacing (m)	2.01	2.05
	Tree Average Height (m)	3.79	3.49
Algorithm ON/OFF	Displacement with Tree (m)	65.93	65.68
	Spray Liquid ON/OFF (l) (equation 8)	12.37	11.34
	Spray Liquid ON/OFF (l/ha) (equation 10)	**299**	**274**
	Saving with ON/OFF (%)	**28.34**	**28.61**
Algorithm considering tree canopy volume	Total Tree Row Canopy Volume (m^3)	123.52	100.33
	Spray Liquid Tree Volume (l) (equation 9)	4.08	3.31
	Spray Liquid Tree Volume (l/ha) (equation 10)	**99**	**80**
	Saving with Tree Volume (%)	**76.38**	**79.16**

The equation 10 is used to convert the values, in litres, obtained in equations 7, 8 and 9 to litres per hectare. Only half the volume in litres is considered, as the area presented in figure 8 only considers half the trees canopy.

$$V(l/ha) = \frac{V(l)/2}{CA(m2)} * 10000\ m2/ha \qquad (10)$$

III. RESULTS AND DISCUSSION

Table 1 presents results that will be discussed throughout this section.

Figure 9 shows the planes obtained from the LiDAR sensor data. With a single sensor, is possible to get data for trees on the left and right of the sprayer. The represented colours follow the colour map referred to in figure 3. To perform this colour map, minimum and maximum values were defined for distances of one and three metres, respectively.

These values were defined knowing that the trees are about one and a half metres from the sensor and that the distance to the end of the canopy is no more than three metres. This way, detecting objects beyond the closest row to the sprayer is avoided.

In the lower part of figure 9, referring to the right plane, it is still possible to verify the detection of a post. This pole is about three centimetres wide and was in the field due to other tests with the sprayer. This detection demonstrates the detail obtained with this type of sensor.

A fault can be observed in the central region of both planes. The cause of this issue is attributed to the sensor providing consistently zero values in this particular area during all data collections, indicating a potential defect in the sensor.

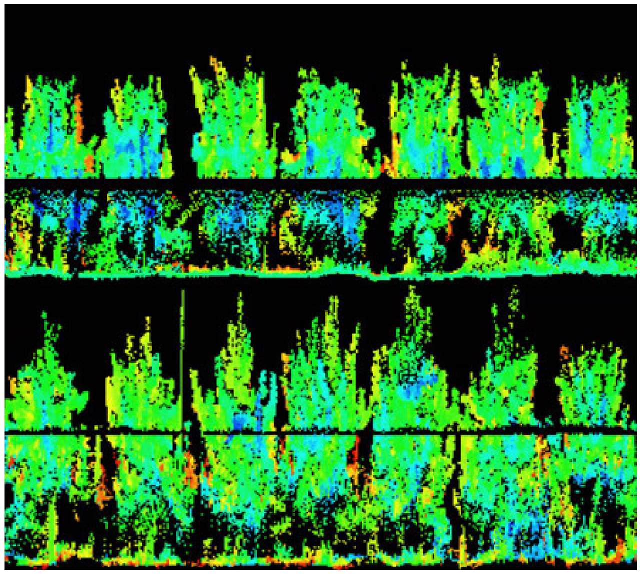

FIGURE 9. Left plane (up) and right plane (down).

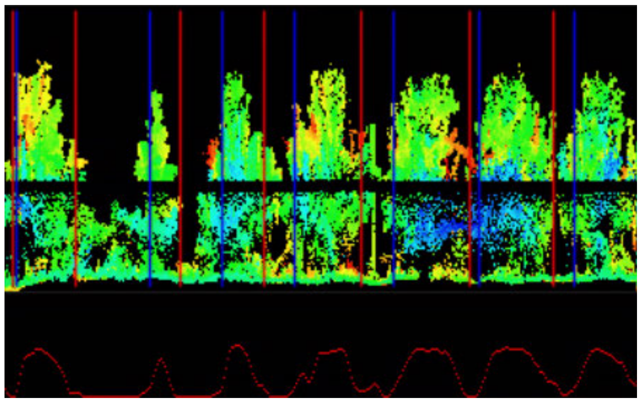

FIGURE 10. Results of the detection of canopy limits. The blue line is the beginning, and the red line is the end. The bottom part shows the variation in the number of points along the plane.

During data processing, 44 trees were counted on the row to the sprayer's right, with an average height of 3.79 meters, and 43 trees with an average height of 3.49 meters on the left row. Although 45 trees were expected to be detected in each row within the data collection area, this was not the case. One or more trees in both rows were absent, likely due to not surviving in the orchard.

Figure 10 shows the results of detecting canopy limits. The blue line is the beginning, and the red line is the end. In the lower part of this figure, it is possible to observe the variation of the number of points along the plane, which, as presented in II-C, assists in calculating tree boundaries. In this example, the limits of the seven trees were detected correctly.

The average value obtained for tree spacing was 2.01 meters on the sprayer's right and 2.05 meters on the left. These values are very close to the two-metre spacing, corresponding to the spacing at which the trees were planted.

Since the total displacement was 92 meters, each sprayer side (L and R in figure 8) covered an area of 207 m^2.

FIGURE 11. Representation of the trajectory performed by the sprayer.

FIGURE 12. Representation of the trajectory and the canopy volume calculated for the lower section of trees.

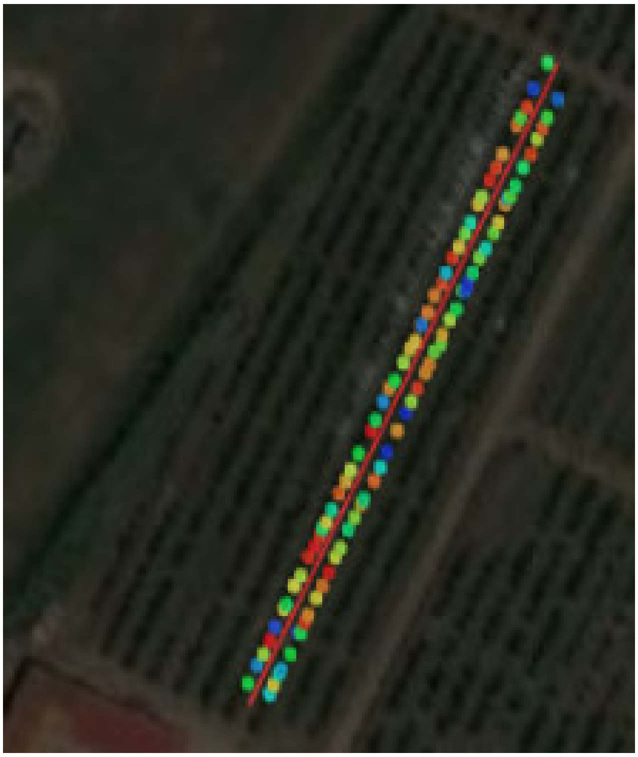

FIGURE 13. Representation of the trajectory and the canopy volume calculated for the middle section of trees.

Considering this value and the volume value obtained from equation 7, the spray volume was calculated using equation 10, obtaining values of 417 and 384 l/ha for the right and left rows, respectively.

With the value of the total sprayer displacement and the value of the displacement in which trees are being detected, it is possible to calculate the amount of liquid spray that could be saved if it were possible to switch off the sprayer when there were no trees. In this case, the value obtained was 299 l/ha for the right row and 274 l/ha for the left one, representing a saving of 28% in the volume of product required.

Figure 11 shows the trajectory performed by the tractor with the sprayer. All the results presented in table 1 were obtained in this same trajectory.

This collection resulted in the occupation maps shown in figures 12, 13 and 14. The coloured circles represent the trees detected along the trajectory, and their colour represents the volume of each tree section. This colour was obtained through the colour map in figure 3, where 0 m^3 and 1.5 m^3 were values for the minimum and maximum volume, respectively.

The saving in the required product volume is even more significant when considering the tree volume in calculating the liquid spray to be applied. In this case, there is a big difference between the row volume, considering the row as a parallelepiped, and the tree volume calculated by the algorithm. In this case, the value obtained was 99 $l/hafor$ the right row and 80 l/ha for the left one, representing a saving of 76% and 79%, respectively.

To compare the performance of our algorithm with the existing literature, we observed the savings rate obtained

FIGURE 14. Representation of the trajectory and the canopy volume calculated for the upper section of trees.

in other works. Most works in the introduction section don't present these values. But we can compare work [13], which reduced the spraying volume by 28%. In the case of work [16], this rate was 32%. These values are around our results obtained with the ON/OFF method, 28%. However, considering the tree volume, we get a much higher savings rate than the ones presented. It is important to note that the results were obtained based on predictions and not on the actual realization of the spraying process.

IV. CONCLUSION

This work developed a 2D LiDAR-based system for canopy sensing in smart spraying applications. This system was validated by acquiring a LiDAR sensor and GNSS antenna data. These sensors were fixed on a sprayer driven by a tractor. This configuration allowed data collection at a speed at which spraying operations are typically carried out along a row in an orchard.

With the work developed, it was possible to detect the beginning and the end of the trees' canopy and calculate their volume.

With these parameters, the theoretical savings obtained in the spraying process were calculated, firstly assuming that the sprayer would only be turned on when trees were being detected and lastly taking into account the volume of the trees calculated.

Each data collection creates a map with the trajectory of the sprayer and where the trees are represented according to their canopy volume.

Although this algorithm is not applied in real-time in a spraying process, the results indicate a very acceptable savings rate.

In the first iteration of saving the product by switching off the sprayer when no trees were detected, the results showed a 28% reduction in the required volume. Finally, considering the volume of trees canopy obtained in the row, the saving obtained had an average value for the right and left rows of 78%.

In the future, the presented algorithm will be validated in real spraying applications over several months. In this way, the work will be evaluated not only from a technological point of view but also from an agronomic one.

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