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REGULAR PAPER

Autonomous Agricultural Sprayer using Machine Vision and Nozzle Control

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Abstract

This paper proposes a modular system of precision agriculture to automate sprayers, optimizing the application of pesticides through a robotic system based on computer vision and individual nozzle on/off control. The system uses low-cost equipment such as Arduino boards, solenoid valves, pressure and flow sensors, smartphone, webcam, and Raspberry Pi. The motivation is to reduce the amount of pesticides applied in crops, not just for potential savings for the farmers, but also for environment protection issues, as well as for food safety. The system can be used in any crop planted in rows such as onion, soybean, corn, beans, and rice. The results show that our system can detect lines in plantations and can be used to retrofit conventional boom sprayers, so it is an important step to develop a kit capable of upgrade a conventional sprayer to a fully autonomous robotic sprayer even at affordable cost in the context of small and medium size farms.

Keywords Precision agriculture · Site-specific spraying · Machine vision · Boom sprayer automation

1 Introduction

The agricultural revolution in the 1950s brought high mechanization to agricultural equipment. Soon after that, it also began the widespread use of fertilizers and new pest management techniques with pesticides, which play an important role in agricultural production [1, 2].

Pesticides are used to prevent disease and infestation of crops, but their application can be a problem by entering the soil, as well as surface and groundwaters via leaching and run-off. They can also affect habitats and contribute to biodiversity loss, deteriorating ecosystem services, such as insect-mediated pollination, soil composition, and the provision of clean drinking water [3–5].

So the objective of this research is to propose a low-cost robotic system capable of updating any conventional agricultural sprayer, using machine vision and individual nozzle on/off control. Our system aims to reduce the use of pesticides in crops, giving the boom sprayer some intelligence, by installing valves, sensors, controllers, and cameras. The system also allows remote activation and monitoring via smartphone. The idea is to bring more effectiveness to agricultural spraying, using less agrochemicals. Less product applied means cost savings for the farmer, as well as safer production with less pesticides in the environment.

Actually the development of autonomous vehicles for agriculture and autonomous tractors are already well covered in literature [6–13]. The challenge now is to robotize the sprayer in such a way it could save pesticides promoting a more efficient application.

Pesticides –or Agrochemicals– are the various chemical products used in agriculture. Typically, they are toxic and, in most cases, the term refers to the broad range of insecticides, herbicides, fungicides, and nematicides. They may also include synthetic fertilizers, hormones and other growth

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agents [14]. Pesticide residues in food may pose a risk to human health [15], while residues in animal feed pose risks to animal health and can enter the food chain [3].

According to latest US EPA (Environmental Protection Agency) report, over 2.7 million tonnes of pesticides are used worldwide each year, which represent expenditures of almost $ 56 billion at the producer level [16]. The main consumer market is China, with 1.7 million tonnes of pesticides annually, followed by the United States, with 407 thousand tonnes, and Brazil, with 377 thousand tonnes [17].

The massive use of plant protection products has favored the emergence of herbicide-resistant weed species [18], which demands the application of more and more pesticides, or even the use of different active ingredients. Also, in some extreme situations, more than 90% of the pesticide applied may move to unwanted places and even reach groundwater [19]. This is largely due to the spray drift, which is the undesired movement of pesticide spray droplets or vapors from the target area to areas where application is not intended.

On the other hand, the population growth has brought new challenges to agriculture, especially to produce food, and major investments have been made to modernize agriculture. We are in the era of Precision Agriculture. There are already machines with high-end embedded technology, geolocation systems, autopilot, telemetry, productivity monitoring systems, and even fully autonomous moving and operating machines [20, 21].

Agricultural sprayers are not left behind. Modern sprayers can open and close nozzles or sections automatically based on maps. So they can reduce off-target application that could be double coverage into a previously treated area that might occur when spraying into an angled headland or when overlapping adjacent swaths. It could also be application outside the field boundary [22]. These new spraying equipment allow to improve efficiency, providing input savings, and reducing environmental impacts [23–25].

Nevertheless, this cutting-edge technology is still very expensive, which leads to low adoption in developing countries, like Brazil, where most agricultural establishments are smallholders and family farmers [26]. That's exactly the motivation of this work: make robotic technology available not only to the big agribusiness companies but also to the small and medium size farms.

This work is an extended version of a previous one by Terra et al. (2019) [27], a paper titled "Evaluation of the pressure-flow relationship in a boom of an autonomous robotic agricultural sprayer", presented in the 2019 IEEE Latin American Robotics Symposium. The main contribution of the original article is the mathematical modeling of an agricultural boom sprayer and the evaluation of the combined behavior of pressure and flow, thus allowing the study of control strategies so that the pressure in the boom could remain stable, regardless of the nozzle opening scenarios.

Now, this paper goes beyond and contributes proposing an intelligent robotic system to the problem of pesticides spraying. The system has a modular design and allows the retrofit of conventional boom sprayers. This paper covers all the implementation steps, starting with a new physical model proposition, going through the construction of a sprayer lab test bench, and ending with a field-tested intelligent system. In this paper we also describe the instrumentation and controllers used, and the image processing pipeline developed.

2 Background Theory

In this section, we describe a conventional boom sprayer and also some important concepts about precision agriculture in the context of a site-specific application of pesticides.

2.1 Boom Sprayer

The boom sprayer is a hydraulic sprayer used in agriculture to apply pesticides and promote crop protection. It consists of a tank, a pump, a boom, and multiple nozzles. A sprayer converts the pesticide formulation into droplets. This conversion is accomplished by forcing the spray mixture through a spray nozzle under pressure. The size of droplets depends on both, nozzle type and system pressure.

It is called boom sprayer when it has a boom, transverse to the movement of the tractor and parallel to the soil, to cover bigger areas. Boom sprayers can be trailer-mounted or mounted on the 3-point hitch of a tractor, called tractor-mounted.

This paper focuses on the tractor-mounted boom sprayer, as shown in Fig. 1, which is the most used type in small and medium size farms. The equipment has a set of spray tips (nozzles) fixed to the boom. At the top of each nozzle it usually has an anti-drip device that prevents leakage when the system is off and depressurized.

The conventional method of applying pesticides using tractor-mounted boom sprayer is shown in Fig. 2. It is possible to notice some problems that may occur in spraying such as the double coverage caused by the overlap of adjacent lanes, the application outside the field boundary during return maneuvers and on the last pass, and the application in areas with plantation gaps. These are the sort of problems that our robotic system helps to solve.

2.2 Precision Agriculture

According to the International Society of Precision Agriculture (ISPA), precision agriculture (PA) is a management

Fig. 1 Example of a tractor-mounted boom sprayer

strategy that gathers, processes and analyzes temporal, spatial and individual data and combines it with other information to support management decisions according to estimated variability for improved resource use efficiency, productivity, quality, profitability and sustainability of agricultural production [28]. The central point of PA is to recognize that the cultivation land is not uniform, and by that act in each portion according to its specific need. This is called Site-Specific input Application (SSA) [29, 30].

According to Heege [31], the identification and mapping of weeds can be done either with offline or real-time approach. The offline approach is based on prior infestation maps, while the real-time detection is based on a set of sensors. Furthermore, according to Molin and Colaço [32], the site-specific application of pesticides, both offline or real-time detection, can be implemented either using variable rate systems (VRA) or using on/off application. These concepts are shown in Fig. 3, highlighting in blue the methods proposed in this paper that uses real-time detection and on/off application.

In this work, we implement the site-specific application of pesticides using individual nozzle on/off control. In this type of control, it is possible to open or close each nozzle according to the need of each part of crop. And even better, the system can close the nozzle whenever it detects there is no crop at all under the nozzle. Figure 4 shows how works a system with individual nozzle on/off control in comparison to a conventional one without any sort of control.

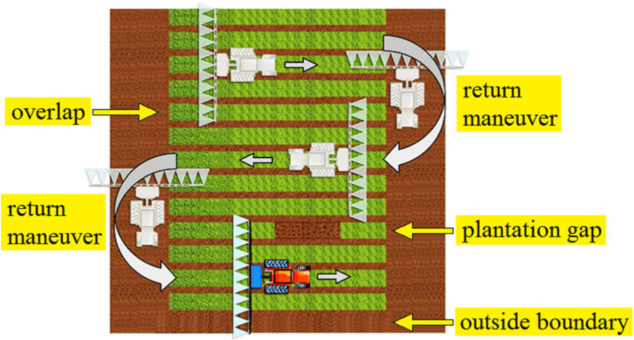


Fig. 2 Conventional boom spraying

3 Related Works

Extensive research has been done on technology development for agriculture. Contributions to the mathematical modeling of a boom sprayer have been presented in the work of Felizardo et al. [33]. They developed a model for chemical direct injection system to assist prediction of variable rate application errors. They also validated the model by using a laboratory-scale sprayer test bench.

Mercaldi et al. [34] proposed to regulate pressure in agricultural sprayers using proportional valves. The control strategy was based on the fluidic resistance calculation of each valve and it works keeping the boom pressure stable while providing the desired flow rate. Authors also presented a pressure and flow model to estimate the application error in curved path.

Another site-specific application system was proposed by Terra et al. (2019) [27]. This work evaluated the pressure-flow relationship in a lab bench boom sprayer. They presented the mathematical model of the fluidic resistances of the boom and evaluate the dependent behavior between pressure and flow. Finally, they installed a needle-type valve and demonstrated that it is possible to regulate pressure by recirculating part of flow back to the tank.

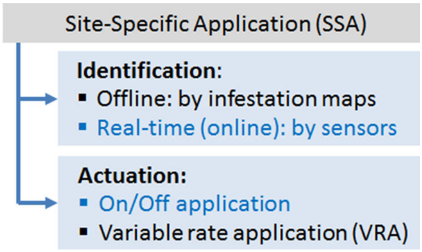


Fig. 3 Precision Agriculture Methods. In blue, the ones used in this work

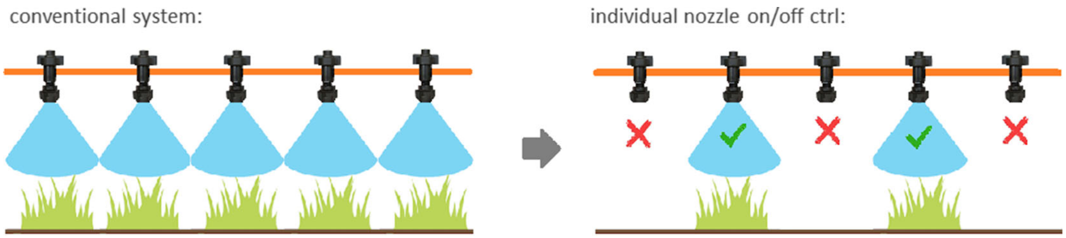


Fig. 4 Difference between conventional system and individual nozzle on/off control

A system-approach solution for variable rate sprayer was presented by Escolà et al. [35] and by Gil et al. [36]. They presented the design, implementation, and validation of prototypes capable of adapting the volume application rate according to the canopy volume. They used light detection and ranging (LiDAR) sensors and compact field point controllers (cFP-2120). Although the proposed system is not really low-cost, it makes significant contributions.

In the same way, Zhang et al. [37] demonstrated that it is possible to apply adjusted volume rate of pesticides based on canopy size. Real-time technology was integrated with different sensors such as infrared, ultrasonic, LiDAR, and stereo vision cameras. They presented a comparison of their performance to detect the targets.

Esau et al. [38] proposed a smart sprayer for spot-application of agrochemical in wild blueberry using machine vision. Authors used nine digital color cameras connected to a computer running Windows 7. Each camera was associated with the on/off control of three nozzles. They concluded that the smart sprayer allows image capture and processing to send triggering signals fast enough to open the nozzles and spray at the proper location required, and doing so the system should have potential to reduce the farmer's input costs and increase farm profitability. Basso and Pignaton de Freitas [39] also used perception techniques not for spraying but for guidance. They proposed a crop row detection and line follower algorithm for an unmanned aerial vehicles (UAV) using Raspberry Pi 3 and Raspberry Pi Camera.

Other relevant system-approaches using machine vision were presented by Weber et al. [40] and do Nascimento et al. [41]. The first one presented a low cost system, using mobile technologies and computer vision to detect the plantation lines and optimize pesticides application. The second proposed a perception system that detects the rows and the existence of plants in each row. In second paper, authors used more robust algorithms which required more processing power. So it was not real-time performance.

Contrasting to the papers studied, this work brings a robotic system approach to the problem of pesticide spraying. We propose a whole new intelligent automation system, adaptable to any existing boom sprayer. In addition, we focus on a low-cost system, aiming to make it available even in the context of family farming.

4 Material and Methods

In order to develop the proposed system, it is necessary to define a methodology that embraces mechanical modifications, sensors and valves installation, electronic components and microcontrollers specification, circuit boards designing, software development and testing, image acquisition requirements, and also the procedures to perform validation experiments.

The investigation takes place from:

(i) understand how a boom sprayer operates, according to its mathematical model;
(ii) design and build a lab bench to validate a low-cost automation concept;
(iii) design, make, and install the automation system in a conventional boom sprayer;
(iv) design, code, and install the perception system to detect the plantation rows; and
(v) perform individual and integrated experiments.

4.1 Mathematical Model

In this work, we model a spraying system based on the evaluation that the boom is composed of hydraulic constraints (pressure losses) that cause a reduction in flow and, consequently, in fluid pressure [42]. As discussed by Terra et al. (2019) [27], the elements that oppose the fluid flow result from the viscous friction with the internal walls of the piping, curves, connections, valves and, mainly, the spray tips. All of these elements have fluidic resistance.

4.1.1 Reynolds Number

According to Hughes [43], the fluid flow profile affects the relationship between pressure and flow. So, it is

Table 1 Reynolds number and flow profile for 4.1 *bar* pressure

Nr. open nozz.	$Q\ (L/min)$	Re	Flow Profile
1	0.7	1,170	Laminar
2	1.4	2,339	Transient
3	2.1	3,509	Turbulent
4	2.8	4,679	Turbulent

used the Reynolds Number (1) to determine the flow regime:

$$Re = \frac{\rho \cdot d_i \cdot v}{\mu}\ , \tag{1}$$

where ρ is the density of the fluid $[kg/m^3]$; d_i is the internal pipe diameter $[m]$; v is the average fluid velocity $[m/s]$; and μ is the dynamic viscosity $[Pa \cdot s]$.

According to Garcia [42], the flow regime is laminar when Reynolds number is less than 1100, and turbulent when it is greater than 3500. Between these two limits, it is called transient flow. Note that these ranges are approximate and vary from author to author.

In a typical spraying system, the pipe is a 1/2” diameter hose, and in this work, we consider nozzles with flat fan spray tip, green color and fine drop size class, model MAGNO MF 015 110°. These nozzles gives 0.5 L/min flow at 2 *bar* pressure; 0.61 L/min at 3.1 *bar*; and 0.7 L/min at 4.1 *bar*.

After converting units and doing some calculations, the Eq. 1 can be used to identify the flow profile. Results are presented in Table 1 in which we observe that from only three open nozzles, the profile is already turbulent.

4.1.2 Flow through the boom

Once identified the predominant flow regime, the system can be correctly modeled in order to write the relationship between the pressure in the boom and the flow through the spray tips.

According to von Linsingen [44], and based on the conservation of mass principle in and out of a control volume (CV), it is known that the mass flow through the control surface (CS) is equal to the change in mass inside the control volume (CV) considered.

In the studied system, the fluid flows through a hose and exits through ten branches, each one with a spray nozzle, as show in Fig. 5.

A fixed control volume can be modeled in a steady state regime by assuming that the hose is rigid, the spray tips are identical, the flow is unidirectional, and the fluid is incompressible so not modified within the CV. Doing some math it is possible to prove that the sum of flows that exits through all nozzles is the same flow that enters the boom:

$$Q_e = Q_1 + Q_2 + Q_3 + \ldots + Q_{10}\ . \tag{2}$$

Assuming constant density (ρ) and constant acceleration of gravity (g) in the analyzed region, one can integrate the Euler equation of the permanent regime between any two chosen points (1 and 2) of the same current line. The result will be Bernoulli’s equation for a one-dimensional, incompressible flow of an ideal fluid in steady state, given by:

$$\frac{1}{\rho}\, p_1 + \frac{1}{2}\,({v_1}^2) + g\, z_1 = \frac{1}{\rho}\, p_2 + \frac{1}{2}\,({v_2}^2) + g\, z_2\ , \tag{3}$$

where p_1 and p_2 are the pressures at point one and point two of the current line; v_1 and v_2 are the flow speed; and z_1 and z_2 are the elevation at the same two chosen points.

In each spray nozzle, the fluid flows through a small orifice (spray tip), which is a sharp reduction in the flow area. Assuming that this hole is a sharp edged orifice, fluid flow can be represented by Fig. 6.

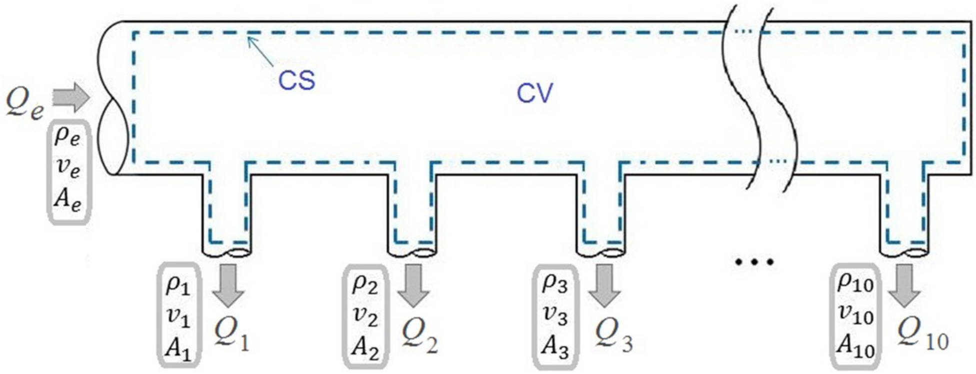


Fig. 5 Fixed control volume in a hose with ten branches

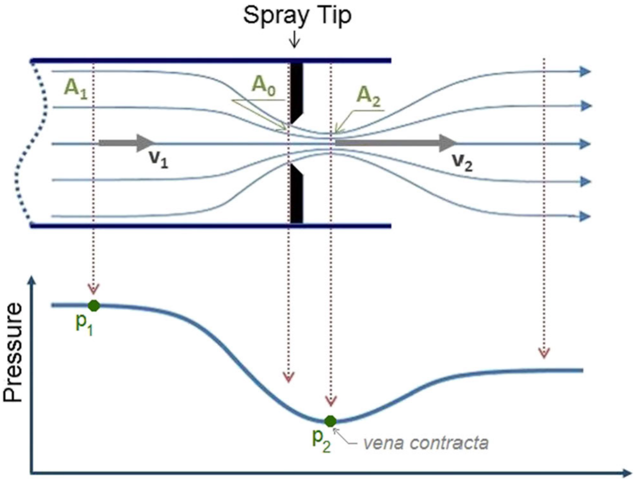


Fig. 6 Fluid flow through one spray tip

Assuming the height variation negligible, applying the Bernoulli's equation and making some simplifications, it is obtained:

$$Q_b = K_b \sqrt{\Delta p}\ , \tag{4}$$

where $\Delta p = p_1 - p_2$ is the differential pressure between the points upstream and downstream of the orifice (Fig. 6); and K_b is a constant value, function of discharge coefficient (C_d), orifice area (A_0), and density, according to:

$$K_b = C_d\ A_0 \sqrt{\frac{2}{\rho}}\ . \tag{5}$$

For the spray tips used, the K_b calculated is $18.22 \times 10^{-9}\ Pa^{-1/2}\ m^3/s$.

4.2 Laboratory Bench

From the mathematical modeling and from the understanding of the system's behavior, a laboratory test bench is built in the Center of Computational Sciences (C3) of the Federal University of Rio Grande (FURG), Brazil, as presented by Terra et al. (2019) [27]. The bench consists of a 100 liter reservoir, a spray pump, a hose, and a five meter spray boom with seven nozzles in series. The test bench is quite similar to a conventional spraying system. The main difference is that some sensors and valves are installed. Figure 7 shows the bench developed, highlighting the equipment used.

Figure 8 shows the process/piping and instrumentation diagram (P&ID) of the laboratory sprayer bench. Symbols tagged as PT and FT represent pressure and flow sensors respectively. XV tag is used for the on/off solenoid valves, PG for manometers, and PCV for the pressure regulator valve.

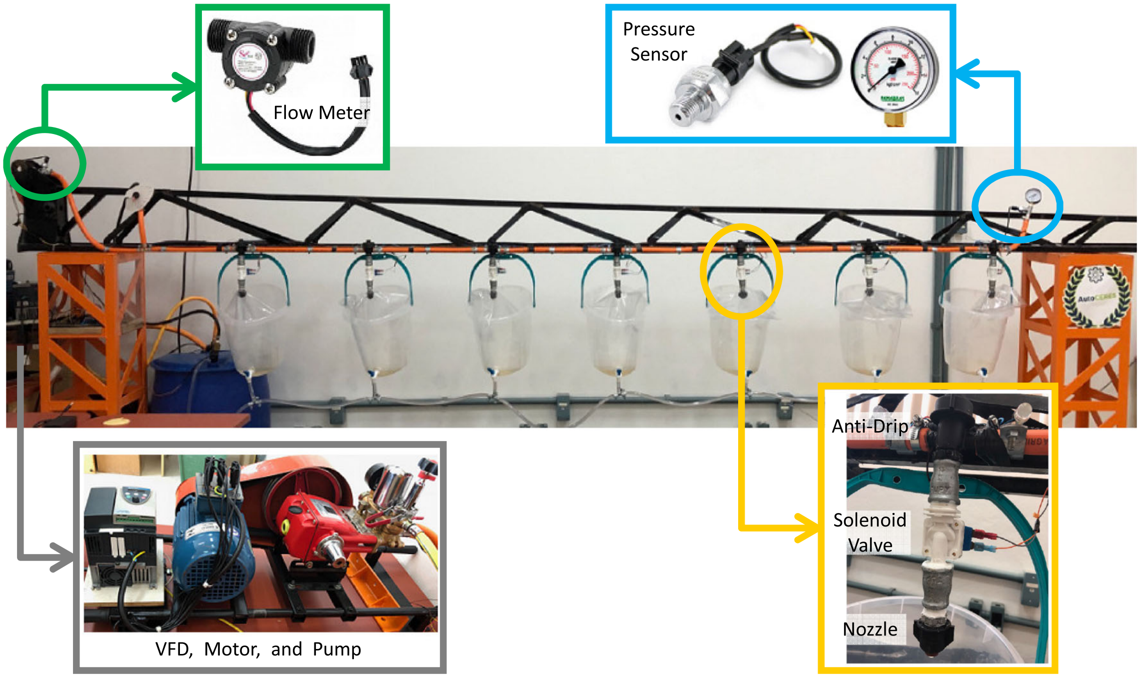


Fig. 7 Spray Test Bench: Overview of the boom sprayer built in laboratory

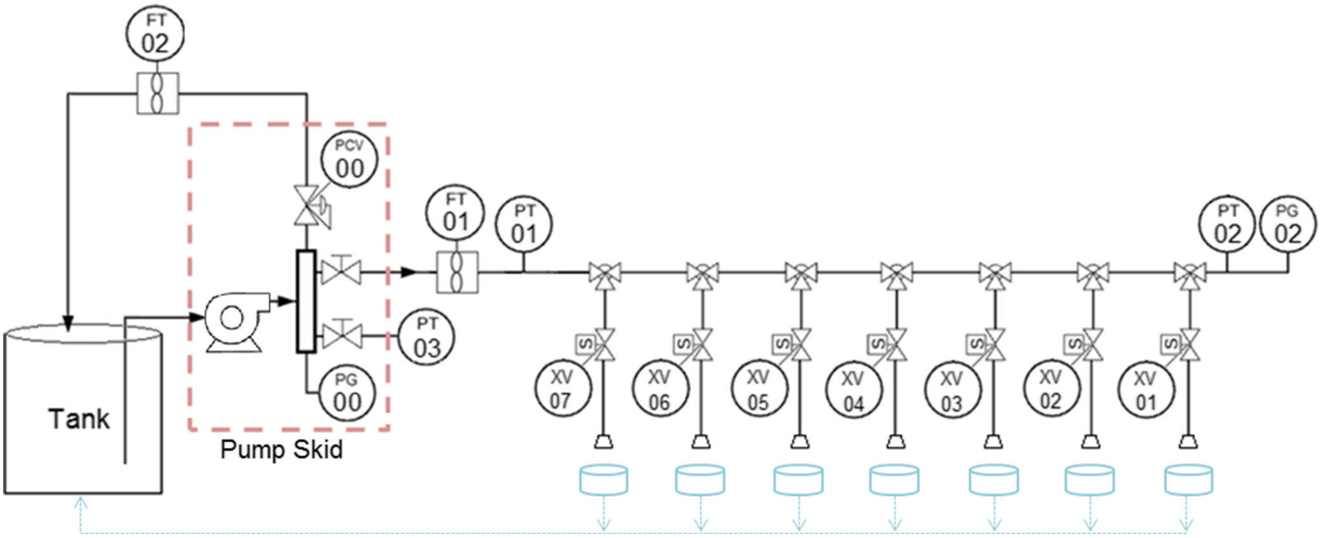


Fig. 8 P&ID of the laboratory test bench boom sprayer

With this bench it is possible to perform several experiments in order to validate the automation concept as also discussed by Terra et al. (2019) [27]. The next step then is to prove the system in a field trial, using a tractor-mounted boom sprayer.

4.3 Field Solution

In order to perform field tests, the automation system is installed in a conventional 10 m boom sprayer with 320 L spray mix reservoir, diaphragm pump of 43 L/min at 540 rpm, 20 fan-tipped nozzles with anti-drip, relief bypass valve, and pressure gauge. The spray tips used are Magno MF 015 110°, fan type, fine class, green, with volume median diameter (VMD) of 150 to 250 μm. They perform 0.50 L/min at 2 bar, 0.61 L/min at 3.1 bar, and 0.70 L/min at 4.1 bar.

Figure 9 shows the Process/Piping and Instrumentation Diagram (P&ID) of the boom sprayer. PE symbol represents a pressure sensor; FE, a flow sensor; XV, an on/off solenoid valve; LG, a level gauge; PG, a pressure gauge; and PCV, a self-operated pressure regulator valve. Observe that LG-00, PG-00, and PCV-00 already belonged to the original boom sprayer. They are typically used by the machine operator to adjust (PCV) and check (PG) the working pressure before start the application; and also to verify the amount of spray mix available in the reservoir (LG). Note that in spraying systems, PCV valve acts as a relief bypass, keeping pressure stable, recirculating part of the pumped flow back to the reservoir, and protecting system against overpressure.

As discussed by Terra et al. (2020) [45], the control logic is implemented using an Arduino MEGA ATmega2560. This main controller communicates Bluetooth with the Android application via module HC-05. The smartphone

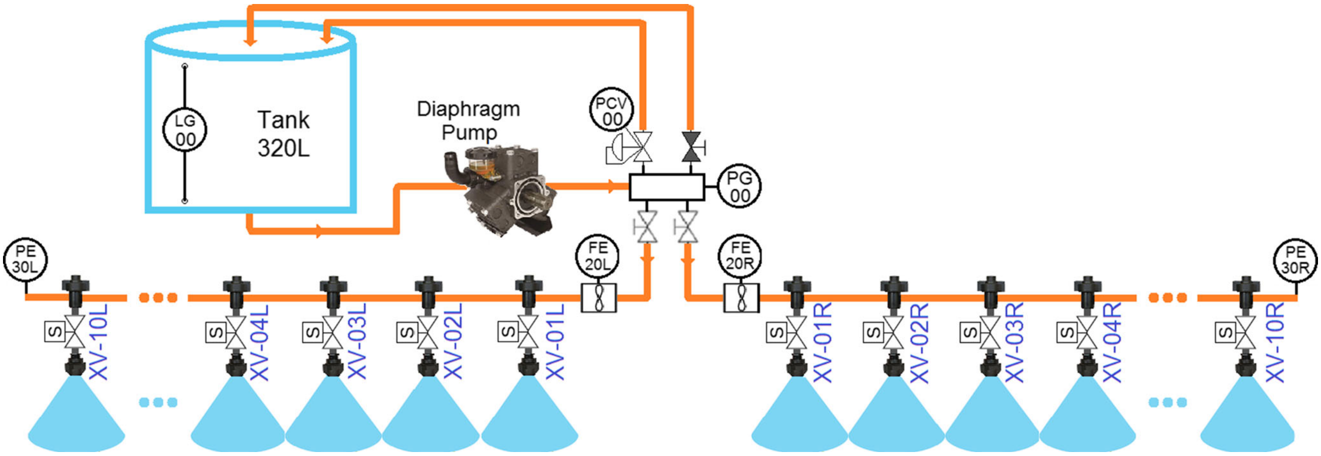


Fig. 9 P&ID of the automated boom sprayer

application allows tractor driver (machine operator) to send commands to open or close nozzles individually and also shows instantaneous pressure and flow measured values.

For that, Arduino MEGA write open/close commands to solenoid valves via digital outputs; reads pressure sensors via analog inputs; and gets flow values from the slave controller Arduino UNO ATmega328P via I2C communication.

It is also used a real-time clock (RTC) module in the main controller to keep up-to-date clock information and register events with timestamp in a SD memory card.

An overview of the code that runs in the main controller is shown in Algorithm 1 as a pseudocode.

Algorithm 1: Main Controller: Arduino MEGA.

```
initialize global constants and variables;
define inputs/outputs;
initialize modules for Bluetooth, RTC, and SD Card;
initialize I2C communication as master;
while system is on do
    read bluetooth;
    if command received then
        open/close respective nozzle;
    end
    read pressure sensors;
    ask for flow values via I2C;
    update actual_status variable;
    if actual_status <> last_status then
        send actual values to Android App via
          bluetooth;
        store data in the SD Card;
        last_status ← actual_status;
    end
end
```

The secondary controller, Arduino UNO, is dedicated to read flow sensor pulses. It calculates the corresponding flow rate and makes it available on the I2C bus. This controller counts pulses via interruptions during an interval of one second. Thus, it has to stop the rest of processing not to losing any sensor pulse.

All electronic circuits, controllers, and auxiliary modules are assembled within an acrylic enclosure waterproof IP-65 (IEC 60529 standard), called control panel in this work. The instrument cables are connected through a set of terminal blocks installed in another IP-65 acrylic box, called junction box. Figure 10 shows the boom sprayer with the equipment, sensors, and valves used.

Figure 11 shows the automation system installed in a boom sprayer mounted on a tractor.

4.4 Perception System

The perception system works in two ways: data acquisition and image processing. The data acquisition is the part responsible to capture the image and send it to the processing unit. The images are acquired by the camera fixed along the boom sprayer. After an image is captured, it is processed by the system's algorithm and results on the crop row detection.

The whole perception system is built with cameras and processing units. The cameras take images in real time and the processing units run the algorithms. The camera used is a Logitech C920 HD 1080p with 70.42^o horizontal field of view (FOV), and the image processing unit is a Raspberry Pi 3B, as shown in Fig. 12.

As the project is aimed at smallholders and family farmers, the components used to build the perception system are chosen considering the criteria of lowest-price with technically acceptable performance. Therefore, users can have access to good technology without having to spend a lot of money.

In the proposed approach, each camera is fixed to the boom sprayer with a support. So, the camera is pointed to the field covering an area equivalent to four nozzles. After the image acquisition, the processing starts indeed.

The processing system is implemented using C++ and OpenCV library. The structure of the processing system is represented in the Fig. 13. There are three main parts of the process: (1) Segmentation and Noise Removal, (2) Lines estimation, and (3) Lines Verification.

4.4.1 Part 1: Segmentation and Noise Removal

Segmentation After a frame acquisition, the concept of Region of Interest (ROI) is used. The image is cut to have a faster processing speed, thus the system uses only a 25% of the original image. The segmentation process is done firstly because it separates the plant from the background. It works by analysing each pixel and verifying if it is the green sought according to some parameters. The method used is similar to the one presented by Underwood et al. [46], where the parameters k and t are used to define the intensity of the green to be segmented.

Noise Removal The Noise Removal is nothing more than the application of some image processing techniques through the image already segmented. After the segmentation, it is normal to have some pixels that are out of interest or some noise at the image. We use two kernels doing morphological operation to remove them. First, one erosion, and then another one to amplify the result. So we have the necessary information to begin the lines estimation.

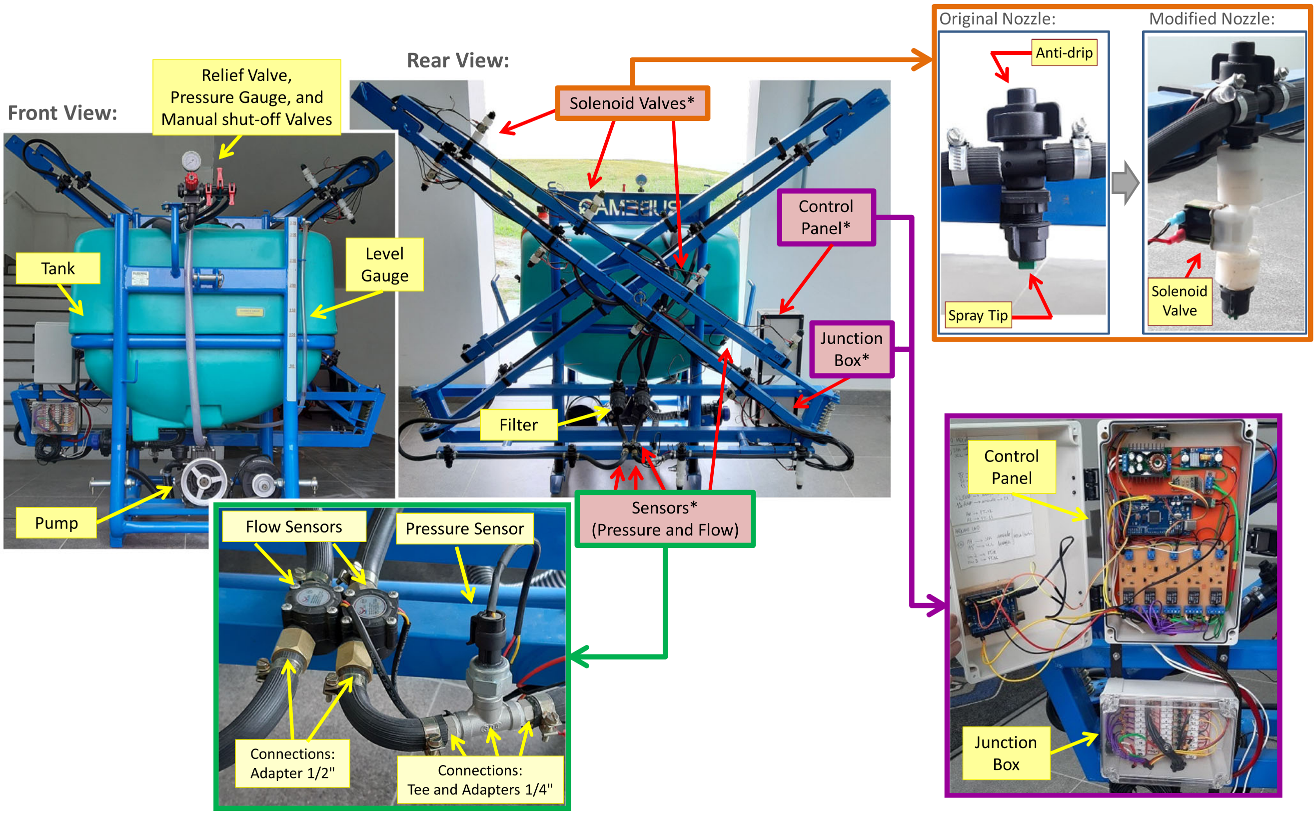
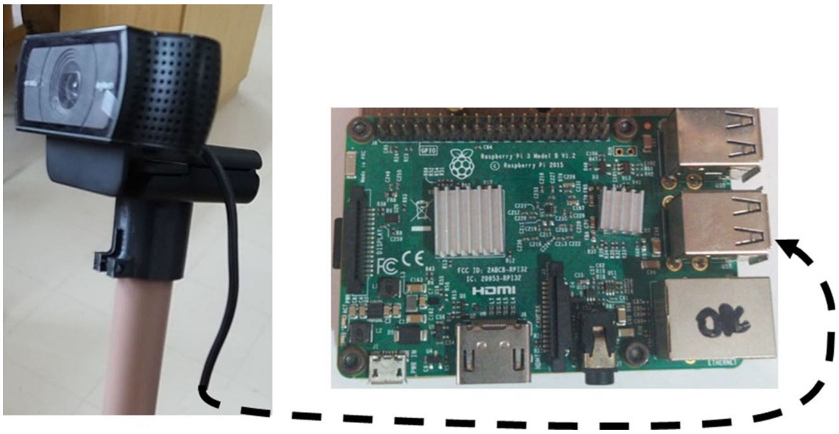


Fig. 10 Field Solution: Overview of the boom sprayer with instruments and controller

Fig. 11 Automated Sprayer mounted on a tractor

Fig. 12 Camera Logitech C920 and Raspberry Pi 3B



4.4.2 Part 2: Lines Estimation

Estimating the lines are an essential step to the crop row detection. If the output of previous part is good, it will become easier to work with. To get more accuracy, the data is organized in groups by proximity. Each group represents one line. To estimate the line, the covariance matrix is calculated and then we use the concept of eigenvector and eigenvalues, as proposed by do Nascimento et al. [41].

4.4.3 Part 3: Lines Verification

Subsequently the Lines Estimation and before considering the found lines, some metrics are considered to have a better result. Even though the methods for the lines estimation have some precision, often there are some lines that are out of the range or even crossing over the others. To improve that, it is implemented some metrics that prevents those "bad" lines. So we check the line angle and the point of intersection.

Firstly, the lines go through a function that verifies if their slopes are between the internal of 30^o and 135^o. Any line out of this range will be rejected. Afterwards, the accepted lines go to another function in the algorithm that verifies if there is some intersection between them occurring inside the ROI. If the function finds any intersection, both lines are rejected. Finally, all other lines that have passed the test are considered crop rows.

4.5 System Integration

After the crop rows detection, the perception system has to inform the automation system which nozzle to open or close. According to the position of the camera on the boom and considering the nozzles position and the crop rows detected, it is possible to define the group of nozzles that should be open or close. To integrate both perception and automation systems, we adopt an I2C communication between Raspberry Pi and Arduino.

5 Results and Discussion

In this section, we present the results of nozzle control obtained from the experiments carried out with the laboratory bench and with the field solution, respectively. Finally, we present the results of the perception system.

5.1 Laboratory Bench

The main result obtained with the built-in lab bench is the proof of concept that the proposed automation system is feasible, even using low cost sensors and valves.

Several experiments are performed with the bench. At first, focused on the system validation and then aiming to check how the sprayer responds in terms of pressure and

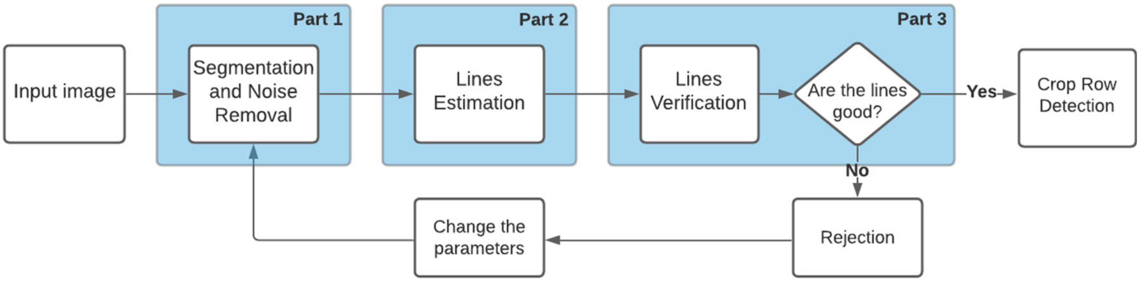


Fig. 13 Flowchart of Perception System

Table 2 Data collected during experiments with lab bench sprayer

Press. (bar)	Flow (L/min)	TIP_01	TIP_02	TIP_03	TIP_04	TIP_05	TIP_06	TIP_07
3.57	5.60	ON	ON	ON	ON	ON	ON	ON
3.88	5.07	OFF	ON	ON	ON	ON	ON	ON
4.24	4.40	OFF	OFF	ON	ON	ON	ON	ON
4.64	3.60	OFF	OFF	OFF	ON	ON	ON	ON
4.96	2.80	OFF	OFF	OFF	OFF	ON	ON	ON
5.27	1.70	OFF	OFF	OFF	OFF	OFF	ON	ON
5.58	1.00	OFF	OFF	OFF	OFF	OFF	OFF	ON

flow for various scenarios of opening and closing nozzles. Table 2 shows a set of data observed in an experiment. The pressure is set at 3.5 *bar* initially with all nozzles open.

Figure 14 shows the behavior of pressure and flow as the nozzles are closed sequentially from one to six. By closing three nozzles, we observe that the pressure rises 30%. Then, with five nozzles closed, the pressure rises to 5.27 *bar*, which represents an increase of 48% to the pressure adjusted initially. High pressure variations affect droplet size and so the effectiveness of spraying. In this case, this is happening because the pump used is oversized for this application with a lab boom having only seven nozzles. So, to keep pressure stable, it would be necessary to use a smaller pump or replace the PCV with another with a higher flow capacity. A third possible solution is the one discussed by Terra et al. (2019) [27] by designing some pressure control strategy and using a modulating vale by-passing the PCV.

5.2 Field Solution

To perform the field experiments, the sprayer is mounted to a tractor and the system is powered by the tractor's 24 V_{dc} battery. The experiments are performed using no pesticides and the spray mix reservoir is full-filled with tap-water. The pressure is set to 2.4 *bar* with all nozzles open. During the tests a lot of data is collected and stored on SD card. Table 3 shows a set of data observed during one of these experiments. This Table correlates the values measured by the pressure and flow sensors, with the nozzle status at each time.

The collected pressure and flow data can be plotted according to each nozzle closing scenario. In Fig. 15, we observe that the system has a certain hysteresis so measured values present some small difference between closing and opening sequences.

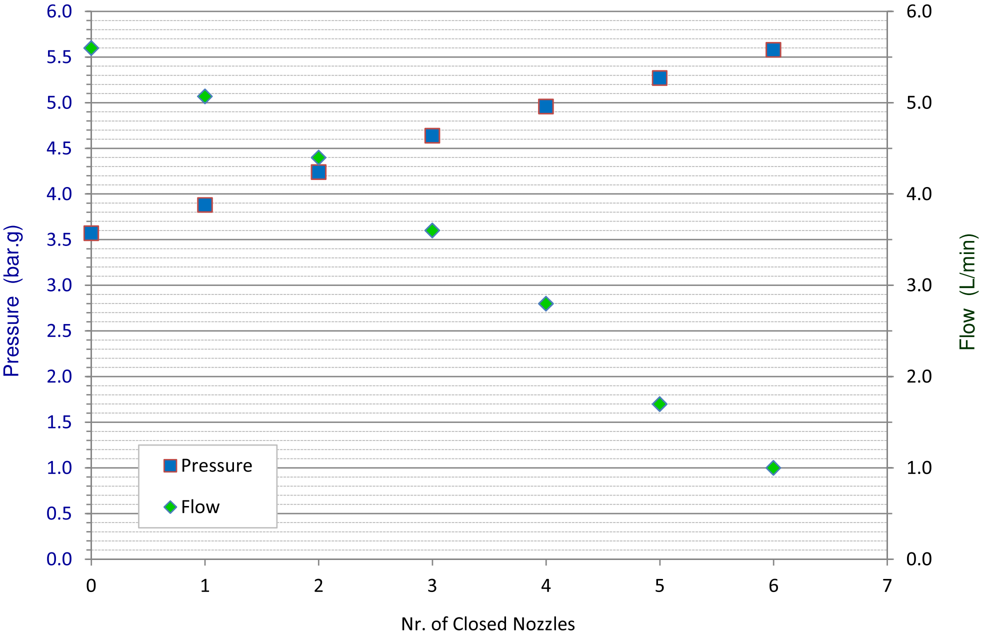


Fig. 14 Pressure and flow measured during experiments with laboratory bench

Table 3 Data collected during experiments with tractor-mounted boom sprayer

DATE	TIME	PE-30R (bar)	FE-20R (L/min)	TIP_01	TIP_02	TIP_03	TIP_04	TIP_05	TIP_06	TIP_07	TIP_08	TIP_09	TIP_10
18/02/2020	15:20:50	2.41	4.45	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON
18/02/2020	15:20:52	2.44	4.07	OFF	ON	ON	ON	ON	ON	ON	ON	ON	ON
18/02/2020	15:20:56	2.46	3.84	OFF	OFF	ON	ON	ON	ON	ON	ON	ON	ON
18/02/2020	15:21:00	2.47	3.47	OFF	OFF	OFF	ON	ON	ON	ON	ON	ON	ON
18/02/2020	15:21:05	2.48	2.72	OFF	OFF	OFF	OFF	ON	ON	ON	ON	ON	ON
18/02/2020	15:21:10	2.50	2.29	OFF	OFF	OFF	OFF	OFF	ON	ON	ON	ON	ON
18/02/2020	15:21:15	2.54	2.00	OFF	OFF	OFF	OFF	OFF	OFF	ON	ON	ON	ON
18/02/2020	15:21:19	2.60	1.36	OFF	OFF	OFF	OFF	OFF	OFF	OFF	ON	ON	ON
18/02/2020	15:21:23	2.64	0.93	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	ON	ON
18/02/2020	15:21:28	2.69	0.77	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	ON
18/02/2020	15:21:32	2.73	0.58	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF
18/02/2020	15:21:35	2.72	0.51	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF
18/02/2020	15:21:38	2.71	0.93	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	ON
18/02/2020	15:21:41	2.70	1.07	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	ON	ON
18/02/2020	15:21:44	2.70	1.47	OFF	OFF	OFF	OFF	OFF	OFF	OFF	ON	ON	ON
18/02/2020	15:21:48	2.68	2.21	OFF	OFF	OFF	OFF	OFF	OFF	ON	ON	ON	ON
18/02/2020	15:21:52	2.67	2.58	OFF	OFF	OFF	OFF	OFF	ON	ON	ON	ON	ON
18/02/2020	15:21:56	2.64	3.11	OFF	OFF	OFF	OFF	ON	ON	ON	ON	ON	ON
18/02/2020	15:21:59	2.60	3.73	OFF	OFF	OFF	ON	ON	ON	ON	ON	ON	ON
18/02/2020	15:22:04	2.55	3.92	OFF	OFF	ON	ON	ON	ON	ON	ON	ON	ON
18/02/2020	15:22:08	2.43	4.09	OFF	ON	ON	ON	ON	ON	ON	ON	ON	ON
18/02/2020	15:22:14	2.37	4.50	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON

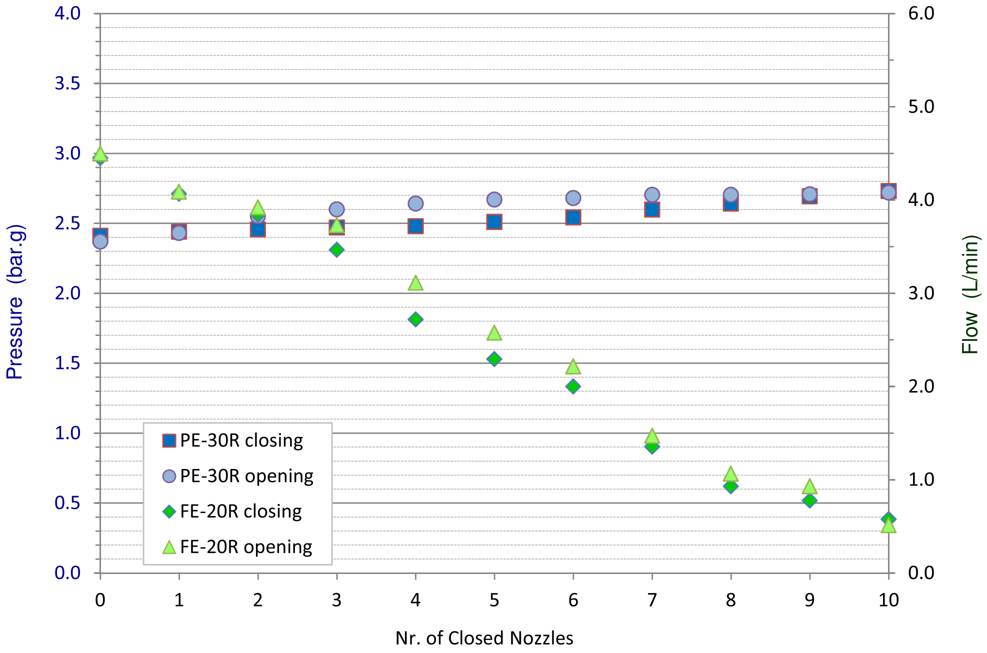


Fig. 15 Pressure and flow measured during field experiments

By analysing data we noticed that the pressure increases as the nozzles are closed. However, different from the lab results, now the pressure increases only 9.5% for a scenario of five nozzles closed. Table 4 shows the calculation of the pressure variation for a scenario of three and five nozzles closed. The pressure values informed are obtained by calculating the arithmetic mean ($\overline{P}$) of all sensor measurements. The standard deviation ($\pm\, s$) is also calculated.

5.3 Perception System

The image processing pipeline proposed achieved satisfactory results as we discuss below. Figure 16 shows an image captured in a soybean plantation.

As it is demonstrated by the perception system flowchart (Fig. 13), the first part of processing covers segmentation and noise removal. So the algorithm gets the region of interest and does the image segmentation, whose results are shown in Figs. 17 and 18 respectively.

Then, we execute the morphological operations, erosion and dilation, to remove noise. The outputs are shown in Figs. 19 and 20.

Once we have a good enough image, the algorithm perform all the calculations to estimate where the rows are. After that, it checks whether the corresponding lines are within the expected parameters. If so, it is in the last processing part, called Crop Row Detection, and we get the final output result as shown in Fig. 21.

The perception system is also tested with Onion plantation images, as shown in Fig. 22. The image is processed doing all the same steps discussed before. The intermediate outputs are presented hereafter. Figure 23 shows the region of interest. Figure 24 shows the segmentation. Figures 25 and 26 show the morphological operations, erosion and dilation. And finally, Fig. 27 shows the output result of the crop row detection.

Table 4 Boom pressure for typical scenarios

P_{set}	# Closed	$\overline{P} \pm s$	Pressure Variation	
[bar.g]	Nozzles	[bar.g]	[bar.g]	[%]
2.4	0	2.42 ± 0.15	–	–
	3	2.58 ± 0.09	0.16	6.6%
	5	2.65 ± 0.10	0.23	9.5%

Fig. 16 Soybean - Input image

Fig. 17 Soybean - Region of Interest

Fig. 18 Soybean - Segmentation

Fig. 19 Soybean - Erosion

Fig. 20 Soybean - Dilate

Fig. 21 Soybean - Result: Crop Row Detection

Fig. 22 Onion - Input image

Fig. 23 Onion - Region of Interest

Fig. 24 Onion - Segmentation

Fig. 25 Onion - Erosion

Fig. 26 Onion - Dilate

Fig. 27 Onion - Result: Crop Row Detection

6 Conclusion

In this paper we proposed a low-cost robotic system to automate agricultural sprayers using machine vision and individual nozzle control. The proposed solution set up a site-specific application with real-time detection using cameras and on/off application using solenoid valves. The automation control was implemented in an Arduino platform and the images were processed in a Raspberry Pi unit. The image processing system was coded in C++ and uses OpenCV library.

This paper also introduced the mathematical model of a boom sprayer in terms of pressure and flow. We presented not only the design and construction of a laboratory sprayer test bench, but also its adaptation to a field system, including the image processing pipeline used to detect the crop rows. Then we discussed the experiments carried out and the results observed.

The main contribution of this work was the proposal of a robotic system to the problem of pesticide spraying. It uses modular automation approach and allows the retrofit and the technological update of any conventional boom sprayer used in undergrowth crops.

As future work, we propose to evaluate the performance of the machine vision system using other food crops typical in southern Brazil, such as corn, beans, and rice. In the same way, we suggest to make some improvements in the Part 1 of the processing chain to automate the ROI definition and the adjustment of parameters. The idea is to tune parameters automatically whenever the number of found lines is unsatisfactory.

Additionally, we propose to improve the integration of the whole system, for example, allowing the Android Application to display the results of the crop rows identification, in real-time, on the smartphone screen.

Finally, we propose the improvement of our system so that it could be installed in any conventional sprayer in order to convert it into a fully autonomous robotic sprayer.

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Declarations

Competing interests The authors have no conflicts of interest to declare that are relevant to the content of this article.

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