Preprints of the 21st IFAC World Congress (Virtual)
Berlin, Germany, July 12-17, 2020

A Low-Cost Prototype to Automate Agricultural Sprayers ⋆

Fabio P. Terra [*,**] **Gabrielle R. A. da Rosa** [**]
Jardel J. P. Prado [**] **Paulo L. J. Drews-Jr.** [**]

[*] *Federal Institute of Education, Science and Technology (IFSul), Brazil (e-mail: fabioterra@gmail.com)*
[**] *Automation and Intelligent Robotics Group (NAUTEC), Center of Computational Science (C3), Federal University of Rio Grande (FURG), Brazil (e-mail: gabriellerar@gmail.com, jardelprado.tec@gmail.com, paulodrews@furg.br)*

Abstract: The world's population growth in the last decades demanded a great increase in agricultural production, especially in food. Therefore, in order to reduce possible losses and guarantee productivity, farmers depend more and more on the application of agrochemicals in their crops. This massive use of pesticides represents not only a high cost to the farmers but also a risk to their health, to the environment and even to the safety of the food consumed by the population. In this context, new technologies have been developed to make agricultural spraying more effective, reducing the amount of pesticide applied and dosing its use according to the need of the crop. The recognition of its spatial and temporal variability is treated by Precision Agriculture. In the case of pest management it can be done using variable-rate sprayers or using on/off application with individual nozzle control. Thus, this paper proposes a low-cost prototype in a modular solution to automate existent agricultural sprayers. The solution allows individual nozzle opening, with on/off control, using solenoid valves, pressure and flow sensors, Arduino boards, and smartphone. Additionally, the prototype has a data logger function to store nozzle status and sensor values, allowing future analysis and application reports.

Keywords: Precision agriculture, Ag 4.0, boom sprayer, automation, individual nozzle control, on/off application, Arduino.

1. INTRODUCTION

In the second half of the twentieth century, the agricultural revolution provided high motorization-mechanization of the farm equipments, selection of varieties of plants and animal breeds with high yield potential. At this time, it also began the widespread use of fertilizers and concentrated feed for livestock, as well as plant and animal care products, enabling vigorous progress in developed countries. Then, from the green revolution, new pest management techniques have brought major changes in agriculture, with the increasing application of pesticides (Evenson and Gollin, 2003; Wheeler, 2002).

Advances in food production helped with longevity rates and, consequently, demographic increase. According to the latest United Nations report, the world population in 2019 was 7.7 billion persons, forecast to reach 9.7 billion by 2050.

This rapid population growth has brought new challenges to agriculture and especially to produce food. So, in recent years, major investments have been made in the modernization of agriculture. However, these advances have had little diffusion in developing countries, where most family farmers are poor and can not acquire high-tech heavy machinery and large amounts of agricultural inputs.

On the other hand, the high use of pesticides may also cause environmental pollution and imbalance of the agrosystem. 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 was not intended (Dexter, 1993). According to Gil and Sinfort (2005), the complete elimination of drift is utopian, but the resulting problems can be reduced when the application is carried out under suitable climatic conditions, with well-regulated equipment and correct agronomic prescription.

Another relevant aspect is the increased resistance of some weed species (Owen and Zelaya, 2005). According to Machado et al. (2005), the widespread use of herbicides and other chemicals favors the emergence of increasingly resistant species, which demands the use of pesticides with ever higher toxicity rates, in addition to a greater number of applications. This represents more costs for producers, in addition to the environmental and health aspects already discussed.

Fortunately, there has also been significant evolution in agricultural machinery. We are in the era of so-called Precision Agriculture. Nowadays, the machines have high-end embedded technology, ranging from geolocation systems,

⋆ This work was supported by Research Support Foundation of Rio Grande do Sul State (FAPERGS), Brazil, project 17/2551-0000896-0

through autopilot, telemetry and productivity monitoring systems, to the conceptual fully autonomous moving and operating machines (Case, 2020; John Deere, 2020).

Technological advancement has also come for agricultural sprayers. The most sophisticated sprayers are capable of automatically opening and closing spray nozzles, for example, avoiding product overlap, doing spot spraying, or adjusting the flow rate of the pesticide in curvilinear trajectories, among many other functions. Some of these automation solutions are supplied by companies like Raven, Weed-it, and Blueriver.

However these cutting-edge technologies are still very expensive and inaccessible to smallholders and family farming, which represent the majority of agricultural establishments, at least in Brazil (IBGE, 2018).

Thus, the purpose of this paper is to discuss and validate, in practical terms, the possibility of prototyping an embedded solution to automate agricultural sprayers, allowing on/off application with individual nozzle control.

It is also evaluated the hydraulic pressure in the spray boom, from various scenarios of opening and closing the nozzles. Thus, checking whether the automation system may impact the droplet size, and so if it will demand additional regulatory control for the boom pressure.

The problem statement is the need to reduce the use of pesticides in crops. It is proposed to add some intelligence to the boom sprayer, using low-cost technology equipment, such as sensors, valves, and Arduino platform, allowing more effectiveness in pest control and less amount of agrochemicals applied. So, reducing costs to the farmer and also the impacts to environment and human health.

2. LITERATURE REVIEW

2.1 Agricultural Sprayers

Agricultural sprayer is an equipment that is used to apply pesticides or fertilizers, also called agrochemicals, in order to promote crop protection and nutrient availability. Pesticides include herbicides, insecticides, fungicides, among others.

There are several types and models of sprayers, all of which aim to allow the product to be distributed in the correct quantity and in the desired locations. The most common types are manual backpack, air-blast, tractor-mounted boom sprayer, self-propelled, and airplane sprayer.

The focus of this paper is the tractor-mounted boom sprayer, as it is the most used equipment in small and medium size farms. Fig. 1 shows the conventional application method using a tractor-mounted boom sprayer. It works coupled to a tractor and is equipped with: a reservoir for the spray mix, which is the pesticide diluted in water; a pressurization pump, which receives kinetic energy from the tractor's Power Take-off (PTO) shaft; and two booms, left and right. Fixed to the booms are a set of spray tips (nozzles) attached to a hose, or rigid tube, that carries the pressurized spray mix. It is also common to have an anti-drip device at the top of each nozzle, composed of spring-diaphragm assembly, and allowing liquid escape through the tip only when the system is pressurized.

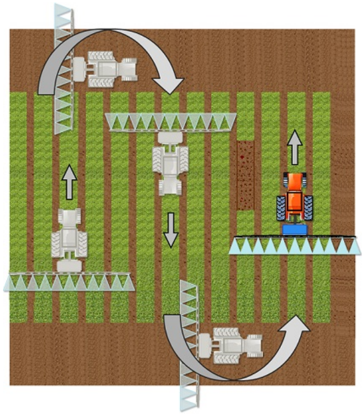

Fig. 1. Conventional boom spraying.

2.2 Precision Agriculture

According to Zhang and Pierce (2016), precision agriculture (PA) is a new farming practice that has been developing since the late 1980s. PA is a concept based on sensing/observing and responding with management actions to spatial and temporal variability in crops. Its central point is to identify within-field variability and manage it. Once we recognize that the cultivation land is not uniform, we need to act in each portion according to its specific need, and that is called Site-Specific input Application (SSA) (Lind and Pedersen, 2017; Bernardi et al., 2014).

According to Molin et al. (2015); Heege (2013), the identification and mapping of weeds can be done either with an offline or real-time approach. The offline approach is based on infestation maps, which must be prepared prior to application. The real-time detection is guided by sensors.

The site-specific application of pesticides, both offline or real-time detection, can be implemented via a variable rate system (VRA) or by on/off application.

The method proposed in this work is based on real-time detection and uses on/off application, in order to allow individual nozzle control, as shown in Fig. 2.

2.3 Related Work

Gil et al. (2013) present a prototype for variable rate pesticides application in a vineyard, using an air-blast sprayer. The plants are detected laterally, by ultrasonic sensors and their volume are calculated to set the opening of the valve that releases the pesticide. They use NI Compact Field Point Controller, I/O modules, and LabView running on a laptop in the tractor cabin. The authors establish several premises and admit that there may be errors in the execution. Even so, it is a very interesting solution. They conclude that there is an urgent need for a low-cost and easy-to-use solution that could be adopted by farmers.

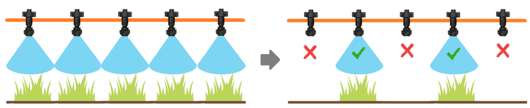

Fig. 2. Conventional system *vs* individual nozzle control.

Felizardo et al. (2016) present a mathematical model for a spray bench and perform lab experiments to validate it. They conclude that the performance of the system can be properly estimated from the model; and that it is useful for designing appropriate controllers, capable, for example, of varying the application rate from a previous map.

Mercaldi et al. (2017) present a model correlating pressure and flow in a spraying system. They analyze the variation of the linear speed of each nozzle for curvilinear trajectories of the tractor and use a proportional valve in each section to vary its fluidic resistance, indirectly controlling the flow through the nozzles. They perform the experiments in a lab bench with one electronic control unit for each valve, all interconnected via CAN bus.

Ferreira et al. (2018) propose varying the spray rate by controlling the rotation speed of the spray pump, which is quite interesting academically, especially from the point of view of energy efficiency, but impractical for implementation in the field, since traditional spraying systems are coupled to tractors and driven by the mechanical energy they receive from the tractor's PTO.

Terra et al. (2019) also present a lab bench developed for carrying out tests with spray nozzles. They use various equipment, discuss some existing technologies to automate the opening and closing of the nozzles, and propose the use of low-cost solenoid valves. They present the mathematical model of the fluidic resistances of the test bench, evaluate the relative pressure and flow behavior, and finally propose a control strategy to keep the boom pressure stable.

According to the papers studied, there is little specific documentation on low-cost modular solutions, adaptable to existing small agricultural sprayers, in the context of family farming, which seems to be a good research opportunity. In addition, it is believed that a modular and generic solution can open new opportunities for scientific and technological development in this area.

3. MATERIAL AND METHODS

The methodology to develop the proposed solution embraces electromechanical modifications, instruments (sensors and valves), electronics (microcontrollers, circuits and interconnections), software, and also the procedures to perform the practical experiments.

The hypothesis investigated intends to verify the viability of an automation system for remotely open and close the spray nozzles, and also to check whether nozzle closure causes significant variation in the boom pressure.

The investigation takes place from: understand the operation of the existing boom sprayer; design, development, construction and installation of the automation solution covering hardware and software; conducting operational tests; and analysis of collected results.

The prototype uses a boom sprayer consisting of: 10 m boom length; 320 L spray mix reservoir; positive displacement pump (diaphragm) of 43 L/min at 540 rpm; 20 fan-tipped nozzles with anti-drip; 1/2" hose; particulate filters; and an adjustable relief valve mounted in a block with pressure gauge and three manual shut-off valves, first for

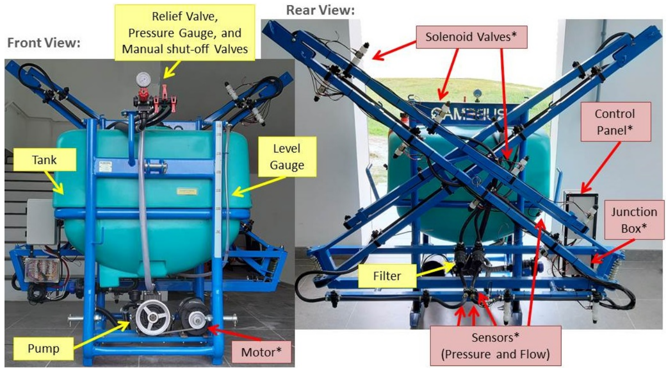

Fig. 3. Prototype: spray boom modified.

upper reservoir agitator, second for the left side boom, and third for the right side boom.

The spray nozzles and tips are Magno MF 015 110°, fan type, green, fine class, with volume median diameter (VMD) in the range of 150 to 250 μm. They give an average flow rate of 0.50 L/min for pressure at 2 bar, 0.61 L/min for 3.1 bar, and 0.70 L/min for 4.1 bar.

Fig. 3 shows the modified sprayer. Items installed by the project are marked in red with an asterisk.

The right side boom was fully instrumented, with an on/off valve for each spray nozzle, and pressure and flow sensors. In the left bar, it was only installed a flow sensor, in order to allow future comparison between the total volume applied by right (automated) and left (original) booms.

The on/off valves installed are normally open (NO) solenoid type, with 12 V_{DC} coil, 1/2" NPT male connection, and working pressure up to 8 bar. They are installed individually in each nozzle, between the anti-drip system and the spray tip. For that, it was necessary to manufacture specific Tecnil connections, as shown in Fig. 4.

To evaluate the spray mix consumption, two volumetric flow meters are used, one for each sidebar of the sprayer. This sensor, model YSF-S201, 5 V_{DC}, has $G1/2$" threaded connections and works based on counting pulses, such that every 7.5 pulses corresponds to 1 L/min.

Opening and closing nozzles cause variation in instant spray mix consumption, which may cause pressure variations. These variations may impact spray droplet size, which might compromise application effectiveness and increase drift. Therefore, it is measured the pressure in the boom. Two hydraulic pressure sensors are installed: one near the pump discharge; and another at the opposite end

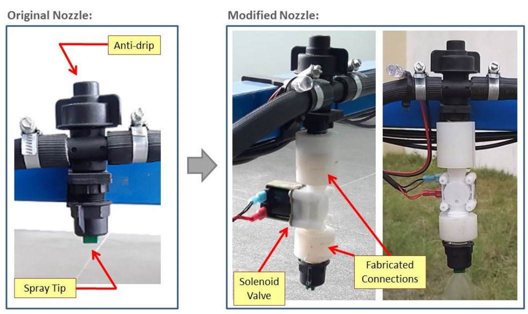

Fig. 4. Solenoid on/Off valve installation.

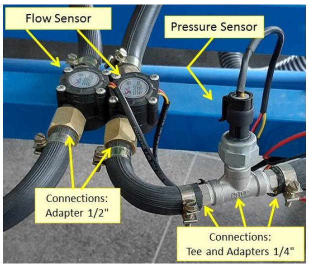

Fig. 5. Pressure and flow sensors installation.

of the boom. Pressure sensors are piezo-resistive, model HK1100C, 5 V_{DC}, with $G1/4$" threaded connections and their measuring range are from 0 to 12 *bar*. Fig. 5 shows the sensors installation in the boom sprayer, highlighting the connections and adapters.

Fig. 6 shows a summary of the automation architecture. The main control is done by ATmega2560 (Arduino MEGA). This controller reads the signals from pressure sensors via analog inputs. Requests the flow readings via I2C communication to the slave controller ATmega328P (Arduino UNO). Sends opening and closing commands to the valves via digital outputs through a power module.

Main controller also keeps up-to-date clock information through I2C communication with a Real-Time Clock module; and writes the perceived events to a non-volatile memory SD card. It also communicates Bluetooth with the Android application via module HC-05, to get commands from tractor drivers' smartphone.

A dedicated secondary controller (UNO) is used to read the pulses from the flow sensors, calculate the corresponding flow rate, and send the result via I2C bus whenever requested by the communication master (MEGA). This segregation is necessary because the pulse counting is done via interruption over an one second interval, which impair the rest of processing, causing great slowness and even failures in the Bluetooth communication.

The power module shown in Fig. 6 contains the galvanic isolation circuits with optocouplers. It receives 5 V_{DC} signals from the Arduino and converts it to 12 V_{DC} via a set of relays. The 12 V_{DC} level is necessary to drive the solenoid valve coils, in which was installed

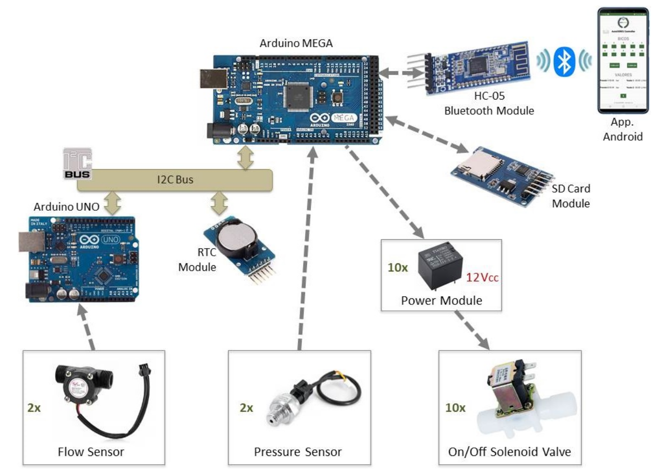

Fig. 6. Automation architecture.

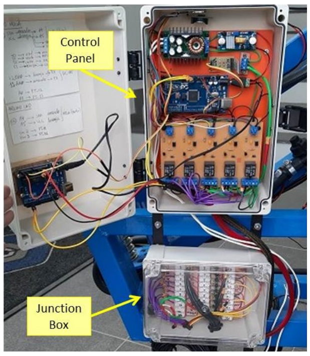

Fig. 7. Control panel and junction box.

anti-parallel flyback diodes to mitigate the appearance of reverse voltage spike in their de-energizing. Also, it is used two voltage regulators (DC-DC buck-boost converters) to supply the different voltage levels needed by the circuits.

The controllers and all auxiliary modules are assembled within a control panel, an acrylic enclosure, waterproof IP-65 (IEC 60529 standard). The interconnections of instrument cables are made through a set of terminal blocks installed in a junction box, another IP-65 acrylic box. These boxes are shown in Fig. 7.

Fig. 8 shows a diagram with all instruments used in the boom sprayer and tagged based on ISA 5.1 standard. Hence each PT symbol represents a pressure transmitter; FT, a flow transmitter; XV, an on/off solenoid valve; LG, a level gauge; PG, a pressure gauge; and PCV, a self-operated pressure regulator valve. This scheme is referred to as a Process/Piping and Instrumentation Diagram (P&ID). In yellow with red asterisk are the sensors and valves installed by this work.

Note that LG-00, PG-00 and PCV-00 are part of the original boom sprayer. They are necessary for the farmer to verify the amount of spray mix still available in the reservoir (LG); and also to adjust (PCV) and check (PG) the working pressure. PCV acts as a relief valve, protecting the system against overpressure, and recirculating the excess pumped flow back to the reservoir.

At first, during the experiments, since no tractor was available, an electric motor was used to torque the pump via a belt pulley mechanism. The motor, 1 *hp*, three phase, was driven by a Variable-Frequency Drive (VFD), set to 37 Hz such that the pump speed was 540 *rpm*, which is the nominal speed provided by the tractor PTO.

4. RESULTS AND DISCUSSION

Several experiments were carried out at the Center of Computational Sciences of the Federal University of Rio Grande. Initially, to validate the functioning of the prototype and then to evaluate the behavior of pressure in the boom from different nozzle opening and closing scenarios, in different closing sequences. Fig. 9 shows pictures of some of the experiments.

Table 1 shows a set of data collected, with pressure adjusted at 4.1 *bar*, and nozzles closed in increasing order, from first to tenth. From the data, it is possible to plot curves correlating the state of the nozzles to

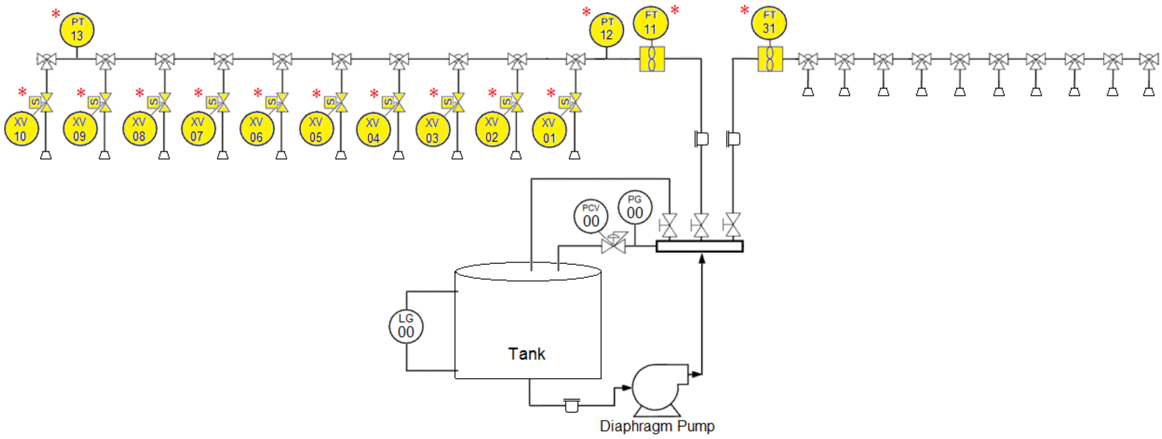

Fig. 8. P&ID: Process/Piping and Instrumentation Diagram of the boom sprayer.

Fig. 9. Experiments with the prototype.

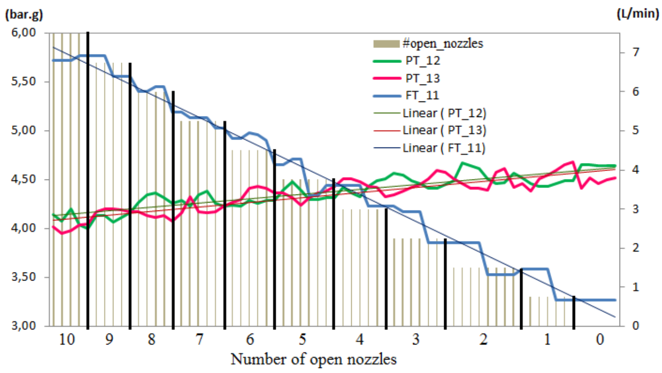

Fig. 10. Curves for 4.1 *bar* and closing nozzles sequence.

the values of pressure and flow in the boom, which is shown in Fig. 10. Note that sensor curves are plotted using linear interpolation, by interconnecting points for all measurements.

Table 1. Experimentally collected data.

DATE	TIME	PT-12	PT-13	FT-11	TIP-01	TIP-02	TIP-03	TIP-04	TIP-05	TIP-06	TIP-07	TIP-08	TIP-09	TIP-10
23/09/2019	14:16:09	4,08	4,07	6,80	1	1	1	1	1	1	1	1	1	1
23/09/2019	14:16:19	4,11	4,16	6,27	0	1	1	1	1	1	1	1	1	1
23/09/2019	14:16:23	4,14	4,17	5,73	0	0	1	1	1	1	1	1	1	1
23/09/2019	14:16:29	4,26	4,30	4,93	0	0	0	1	1	1	1	1	1	1
23/09/2019	14:16:35	4,29	4,32	4,13	0	0	0	0	1	1	1	1	1	1
23/09/2019	14:16:40	4,39	4,29	3,73	0	0	0	0	0	1	1	1	1	1
23/09/2019	14:16:46	4,45	4,43	2,93	0	0	0	0	0	0	1	1	1	1
23/09/2019	14:16:50	4,55	4,38	2,27	0	0	0	0	0	0	0	1	1	1
23/09/2019	14:16:57	4,60	4,54	1,47	0	0	0	0	0	0	0	0	1	1
23/09/2019	14:17:03	4,67	4,49	0,67	0	0	0	0	0	0	0	0	0	1
23/09/2019	14:17:10	4,71	4,54	0,13	0	0	0	0	0	0	0	0	0	0

Although the measurements present some noise, it is observed that flow is reduced as the nozzles are closed, while the pressure increases. Every nozzles closure causes a mass accumulation in the boom, which, by the principle of mass conservation, will cause a slight variation in the fluid density, according to its Bulk Modulus, and, as a result, in a fixed volume, it will cause a pressure increase. This behavior is shown in Figure 10. Similarly, sequential opening of the nozzles causes pressure reduction.

The pressure on the boom, however, remains close to the adjusted setpoint, varying only 0.5 *bar* approximately. This is due to the performance of the relief valve (PCV-00). Fig. 11 shows the behavior of this valve, correlating the boom pressure with the recycle flow. In the graph, it is possible to observe that the recycle flow increases as the boom pressure increases.

With the automation solution proposed in this paper, it is assumed that it will be rare the need to close many nozzles simultaneously during pesticide application. The most common will be the closure of only a few nozzles, either to minimize overlap, compensate planting failures, or even to avoid pesticide losses at the end of the crop.

Thus, the experimental data are analyzed for the scenarios where only three nozzles are closed; and then five of the total. It was considered the pressure ranges informed by the manufacturer of the tips, that are 2.0; 3.1; and 4.1 *bar*. The results are shown in Table 2. Note that pressure values are obtained from the arithmetic mean ($\overline{P}$) of all

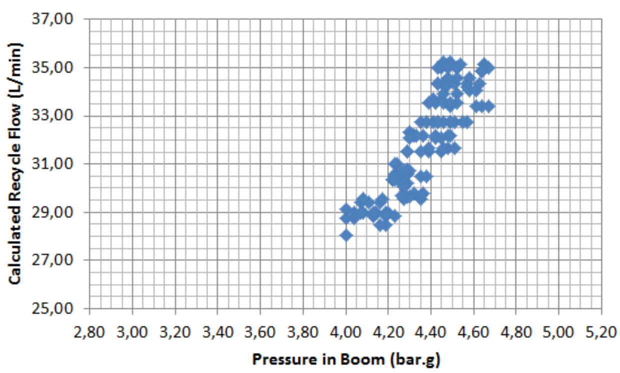

Fig. 11. Flow vs Pressure in PCV for 4.1 *bar*.

Table 2. Boom pressure for typical scenarios.

P_{set} [bar.g]	# Open Nozzles	$\overline{P} \pm s$ [bar.g]	Pressure Variation [bar.g]	[%]
2.0	10	2.01 ± 0.02	-	-
	7	2.08 ± 0.02	0.07	3.5%
	5	2.14 ± 0.02	0.13	6.5%
3.1	10	3.11 ± 0.02	-	-
	7	3.25 ± 0.04	0.14	4.5%
	5	3.32 ± 0.04	0.21	6.8%
4.1	10	4.07 ± 0.05	-	-
	7	4.25 ± 0.04	0.18	4.4%
	5	4.37 ± 0.04	0.30	7.4%

values measured by the sensors for each scenario, with their respective sample standard deviation (s).

The pressure variation in the boom ranges from 3.5% for seven open nozzles, with pressure set at 2.0 *bar*; up to 7.4% for five open nozzles, with pressure set at 4.1 *bar*. Thus it is assumed that the original relief valve (PCV-00) presents satisfactory performance for the most probable operational cases and so that the projected automation solution will not affect the droplet size.

5. CONCLUSION

This paper presented a modular automation solution for individual spray nozzle control, in the context of precision agriculture with site-specific application (SSA). The solution can be adapted, with as little intervention as possible, to the tractor-mounted boom sprayers, widely used in family farming around the world.

The main contribution of this work is the study of the SSA problem in spraying, and the proposal of a low-cost technological solution, developed and validated with a prototype.

As future work, it is proposed to quantify the real gains of the solution, in field, measuring the volume of spray mix applied to the crop, comparing to historical data, and calculating the savings.

Integration with other parts of the project will also continue, especially the computer vision, discussed in Weber et al. (2018) and do Nascimento et al. (2019). So, the opening and closing of the nozzles will no longer depend on the intervention of the tractor driver. It will be done automatically by the perception of the crop.

Finally, it is still necessary to calculate and implement electronic filters to attenuate the noise in sensor signals.

REFERENCES

Bernardi, A.C.d.C., Naime, J.d.M., Resende, A.V.d., Bassoi, L.H., and Inamasu, R.Y. (eds.) (2014). *Agricultura de precisão: resultados de um novo olhar*. Embrapa.

Case (2020). Autonomous concept vehicle. www.caseih.com/northamerica/en-us/innovations.

Dexter, A.G. (1993). Herbicide spray drift. *NDSU*.

do Nascimento, G., Weber, F., Rosa, G., Terra, F., and Drews-Jr, P. (2019). A perception system for an autonomous pesticide boom sprayer. In *Latin American Robotics Symposium (LARS)*. IEEE.

Evenson, R.E. and Gollin, D. (2003). Assessing the impact of the green revolution, 1960 to 2000. *Science*, 300(5620), 758–762.

Felizardo, K.R., Mercaldi, H.V., Cruvinel, P.E., Oliveira, V.A., and Steward, B.L. (2016). Modeling and model validation of a chemical injection sprayer system. *Applied Engineering in Agriculture*, 32(3), 285.

Ferreira, C.A.J.G., Cruvinel, P.E., Peñaloza, E.A.G., Oliveira, V.A., Mercaldi, H.V., et al. (2018). A hydraulic-pump speed controller in agricultural sprayers based on the automation and use of the control area network bus. In *2018 IEEE 12th International Conference on Semantic Computing (ICSC)*, 358–362. IEEE, USA.

Gil, E., Llorens, J., Llop, J., Fàbregas, X., Escolà, A., and Rosell-Polo, J. (2013). Variable rate sprayer. part 2–vineyard prototype: Design, implementation, and validation. *Computers and Electronics in Agricul.*, 136–150.

Gil, Y. and Sinfort, C. (2005). Emission of pesticides to the air during sprayer application: A bibliographic review. *Atmospheric Environment*, 39, 5183–5193.

Heege, H.J. (2013). *Precision in crop farming: site specific concepts and sensing methods: applications and results.* Springer Science & Business Media, Dordrecht.

IBGE (2018). Censo Agropecuário. censos.ibge.gov.br/agro/2017.

John Deere (2020). New 'driverless' tractor concept. www.farm-equipment.com/articles/17489-john-deere-reveals-new-driverless-tractor-concept.

Lind, K.M. and Pedersen, S.M. (2017). Perspectives of precision agriculture in a broader policy context. In *Precision Agriculture: Technology and Economic Perspectives*, 251–266. Springer, Switzerland.

Machado, A.L.T., Reis, A.d., Moraes, M.d., and Alonço, A.d.S. (2005). *Máquinas para preparo do solo, semeadura, adubação e tratamentos culturais.* UFPel.

Mercaldi, H.V., Peñaloza, E.A.G., Mariano, R.A., Oliveira, V.A., and Cruvinel, P.E. (2017). Flow and pressure regulation for agricultural sprayers using solenoid valves. *Internacional Federation of Automatic Control - IFAC*, 50(1), 6607–6612.

Molin, J.P., do Amaral, L.R., and Colaço, A. (2015). *Agricultura de precisão.* Oficina de Textos, São Paulo.

Owen, M.D. and Zelaya, I.A. (2005). Herbicide-resistant crops and weed resistance to herbicides. *Pest Management Science: formerly Pesticide Science*, 61, 301–311.

Terra, F.P., da Rosa, G.R.A., and Drews-Jr, P.L.J. (2019). Evaluation of the pressure-flow relationship in a boom of an autonomous robotic agricultural sprayer. In *Latin American Robotics Symposium (LARS)*. IEEE.

Weber, F., Rosa, G., Terra, F., Oldoni, A., and Drews, P. (2018). A low cost system to optimize pesticide application based on mobile technologies and computer vision. In *Latin American Robotic Symposium.* IEEE.

Wheeler, W.B. (2002). Role of research and regulation in 50 years of pest management in agriculture. *Journal of Agricultural and Food Chemistry*, 50(15), 4151–4155.

Zhang, Q. and Pierce, F.J. (2016). *Agricultural automation: fundamentals and practices.* CRC Press, USA.