Flow and Pressure Regulation for Agricultural Sprayers Using Solenoid Valves ⋆

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Abstract: This work deals with the problem of controlling the application rate from prescribed maps and regulating the pressure on the sprayer booms in precision agriculture. In spraying, the droplet size is related to the application quality which is affected by the type of nozzle and the operating pressure on the sprayer boom. However, as the pressure is dependent on the flow, using conventional nozzles the flow can not be controlled without changing the pressure. It is proposed to control a set of solenoid valves according to an established sequence which yields the desired flow. The control is based on the calculation of the fluidic resistance of solenoid valves to provide the desired flow rate while maintaining the pressure on the booms within acceptable limits to keep the drop size. A sprayer is simulated with commercial nozzles and also preliminary experimental control results of a set of solenoid valves via an industrial network are presented to validate the proposed approach.

Keywords: Application errors, CAN bus, curved paths, precision agriculture, variable rate application.

1. INTRODUCTION

Weed control is usually performed with the application of agro-chemicals, which directly reflects in the cost of the agricultural production and in the environment. A commonly form of application of agrochemicals is using sprayers. The tractor-implement or self-propelled boom sprayers allow applications in large areas (Sharda et al., 2011). These sprayers are equipped with pumps, valves and spray nozzles, which produce drops by fission of the beam of water. The agrochemical is forced by hydraulic energy through a small hole, forming a blade, which disintegrates into drops.

The agrochemical is commonly applied at constant rates in a particular area, even though parts of that area might be affected in different ways by pests. Due to the spatial variability, which is related to the degree of infestation of invasive plants, fungus or animal species, a variable rate application is sought (Sökefeld, 2010; Felizardo et al., 2013).

In a variable rate application the flow of the agrochemical is changed according to the degree of infestation. The reference values of application rates are known in advance and stored in a prescription map (Reyes et al., 2015). The controller uses the application rate references, sprayer displacement speed, the number of nozzles and their spacing on the boom to regulate the application flow.

In ground spraying systems with fixed ends (single nozzles), the operating range is limited by the ratio of flow and pressure, called fluidic resistance. In this regard, an important aspect in agrochemical application is related to the drop size. This is characterized by its shape and size which can vary, according to ASAE S-572 norm of the American Society of Agricultural and Biological Engineers (ASABE) among very thin, thin, medium, thick and very thick, depending on the type of tips and the operating pressure on the sprayer booms (ASABE, 2009). Very fine drops can be carried by the wind, spreading and contaminating the environment, characterizing the drift phenomenon (Cruvinel et al., 1999). Very thick droplets, although reduce the drift, provide less coverage of the application target because the volume of water that the leaves can hold is limited due to their size.

One of the challenges of modern agriculture is the application in curved paths since there will be different speeds along the sprayer booms, leading to application errors (sub-application or over-application) on the crop. To reduce the errors, it is necessary to control the flow in each spray nozzle, which is not possible in sprayers with fixed nozzles. For this, solenoid valves with high switching frequency (typically greater than 10 Hz) driven by pulse-width modulation (PWM) were developed and registered as a US Patent Giles and Comino (1992). Acting on the duty cycle of the PWM signal it is possible to control the flow and pressure independently, because of the possibility of varying the fluidic resistance of the valves.

In this work, an alternative to the use of PWM valves to solve the problem of controlling the flow and regulating the pressure is proposed. For that, it is used an assembly with three low speed solenoid valves (typically 2Hz) and an appropriate switching sequence for regulating the flow, which is obtained by calculating the difference between the fluid resistance required for the desired flow and the fluid resistance equivalent of combinations of different nozzles in each set of valves.

2. MODELING AND FLOW CONTROL OF AGRICULTURAL SPRAYERS

The solenoid valves used are composed of a body and a sliding plunger with two positions which is attached to a spring as shown in Fig 1. Coupled to the valve there is a coil which when electrified generates a force that attracts the plunger. When the valve coil feed is disconnected, the spring again takes the piston to the rest position. In this case, it features two flows related to the open and closed states of the valve, which will depend on the pressure and flow rate.
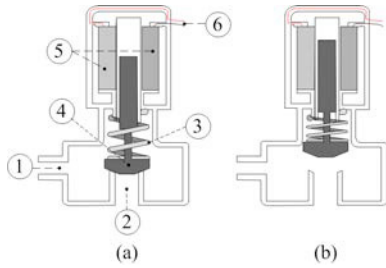

Fig. 1. Solenoid valve. (a) Closed: the plunger (4) does not allow fluid to pass from the inlet (1) to the outlet (2) when solenoid coil (5) is energized by connectors (6). (b) Open: the return spring (3) moves the plunger until the equilibrium position allowing fluid to pass from the inlet to the outlet.

2.1 Curved Path Application Error

In agricultural sprayers, the reference flow for a spray nozzle denoted $Q_{n_{ref}}(i)$ can be calculated by:

$$Q_{n_{ref}}(i) = \frac{D_n v_n(i)E}{60000} \qquad (1)$$

where D_n is the application rate [l/ha] from the prescription map, $v_n(i)$ is the sprayer nozzle speed [km/h] with i the nozzle location, E is the distance between the nozzles location in the boom [cm], 60000 is a unit correction constant and $Q_{n_{ref}}(i)$ is the flow rate at the spray nozzle [l/min] needed to maintain the desired application rate. The total flow of the sprayer is given by $Q_p = \sum_1^i Q_n(i)$, $i = 1, \cdots, 14$, where $Q_n(i)$ is the flow rate delivered in each nozzle location i.

In Fig. 2, the sprayer used in agricultural applications is shown in two typical situations. In a straight trajectory, most used path by agricultural machinery, there is no problem in using conventional sprayers. However, in a curved path, which occurs in the field, application errors due to the curve radii become a concern (Peñaloza et al., 2014).

The linear speed of each sprayer nozzle v_n in [m/s] for a curved path is given by $v_n(i) = \dot{\theta} * R_n(i)$, where $\dot{\theta}$ is the angular speed of the sprayer in [rad/s], and $R_n(i)$ is the nozzle position relative to the center of the curved path.

2.2 Pressure Model

For turbulent flow, the relationship between pressure and flow of the main components of the hydraulic circuit such as valves, pipes, spray nozzles and hoses is given by (Steward and Humburg, 2000; Felizardo et al., 2016):

$$\Delta P = K_q Q^2 \qquad (2)$$
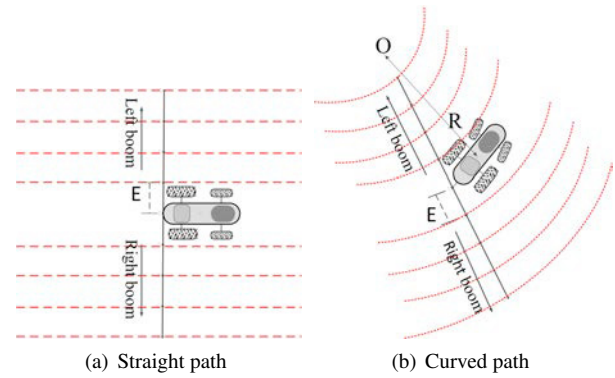

(a) Straight path   (b) Curved path

Fig. 2. Maneuvers of a tractor-sprayer. (a) In the straight trajectory the speed of each of the spray nozzle is equal to the sprayer speed. (b) In the curved path each nozzle has a relative speed which varies according to its position and the curve radius.

where ΔP is the pressure drop [kPa] across the hydraulic element, Q is the flow [l/min] and K_q is the fluidic resistance [kPa/$(l/min)^2$].

2.3 Driving Strategy for the Solenoid Valves

The main idea of the control strategy is to maintain the flow in a reference value defined by (1). For this, it is necessary to reduce the error between the flow provided by the sprayer system (2) and the flow references. The flow error is given by:

$$e_n(i) = Q_n(i) - Q_{n_{ref}}(i) \qquad (3)$$

where $e_n(i)$ is the error of the nozzle sprayer i. Replacing (1) and (2) in (3) we obtain:

$$e_n(i) = \sqrt{\frac{\Delta P}{K_q}} - \frac{D_n v_n(i)E}{60000}. \qquad (4)$$

Therefore, the flow error not only depends on the hydraulic sprayer system parameters, but it is also affected by the sprayer speed variation.

Assuming that the pressure drop ΔP is constant and that the sprayer is following a curved path, that is, the speed of i points varies according on the curved path radius. In this situation, to reduce the error, the nozzle fluidic resistance must change. The main objective is to ensure that the error tends to zero. Assuming the best condition when $e_n(i) = 0$ in (4), we obtain:

$$K_{q_{ref}}(i) = \frac{\Delta P}{Q_{n_{ref}}^2(i)} \qquad (5)$$

where $K_{q_{ref}}(i)$ is the fluidic resistance needed to make the error close to zero. Therefore, to reduce the error, the fluidic resistance of each set of nozzles must be made close to this reference value.

Considering sets of three solenoid valves attached to nozzles, which provide three different fluidic resistances and their respective combinations, a valve driving strategy for each set to respond to the speed variation in curvilinear paths was sought. The set of nozzles equivalent fluidic resistance denoted $K_{qe}(j)$, $j = 0, \cdots, 7$, is thus obtained by Felizardo et al. (2016):

$$\frac{1}{K_{qe}(j)} = \frac{1}{K_{q1}(j)} + \frac{1}{K_{q2}(j)} + \frac{1}{K_{q3}(j)} \qquad (6)$$

where $K_{qe}(j)$ is the fluidic resistance of each set of valves and $K_{q1}(j), K_{q2}(j), K_{q3}(j)$, are the corresponding fluidic resistance of nozzles 422WRC11003 / 02 / 015, respectively (Table 1).

The driving strategy uses the vector of fluidic resistance $K_{q_{ref}}(i)$ at each nozzle position i in the sprayer boom as input (left and rigth boom) and the *SEL* vector as output containing the correct nozzle selection to reduce the error. The driving strategy described in Algorithm 1 searches the combination of nozzles which yields $K_{qe}(j), j = 0, \cdots, 7$, for a lower application error.

Algorithm 1 Selection of spray nozzles

Require: $K_{qref}[i]$ vector containing the desired fluidic resistances;

$\quad\quad K_{qe}[j]$ vector containing the fluidic resistances given by the possible combinations of nozzles;

$\quad\quad Err[i,j]$ Storage array of error values;

$\quad$ **for** $i = 1$ to 14 **do**

$\quad\quad$ **for** $j = 1$ to 7 **do**

$\quad\quad\quad Err[i,j] \leftarrow K_{q_{ref}}[i] - K_{qe}[j]$

$\quad\quad$ **end for**

$\quad\quad SEL[i] \leftarrow min(Err[i, 1:j])$

$\quad$ **end for**

$\quad$ **return** $SEL[i]$ vector containing the selected sequence of nozzles for each set of solenoid valves;

2.4 Driving Module Using CAN

An agricultural sprayer may have several booms which implies a large number of solenoid valves. The use of a Controller Area Network protocol (CAN) to control solenoid valves is attractive since only a compound of two-wire bus is used to transmit information. The viability and implementation of a CAN network to control different types of actuators have been demonstrated (Godoy et al., 2009).

To control each valve, the use of an Electronic Control Unit (ECU) which is responsible for interpreting incoming messages and sending new ones is required. Therefore, the ECU does not need to be connected in standard TTL which would require a lot of wiring, making it cumbersome to implement a switching strategy for each set of valves of the sprayer boom (Darr et al., 2004).

The ECU minimum configuration contains a microcontroller, a CAN controller and a CAN transceiver. The microcontroller is responsible for hosting the decision-making algorithms. The CAN controller is responsible for assembling the message packets which will be sent according to the CAN protocol specifications and operates in conjunction with the microcontroller. The CAN transceiver converts the signals coming from the CAN controller to the bus standard differential voltage levels.

3. FLOW AND PRESSURE SIMULATIONS

Considering the modeling of the agricultural sprayer development plant (ASDP) described next, the outputs flow and pressure were simulated. The simulations were carried out in MATLAB® and Simulink®. The nozzles were chosen according to the ASDP operation range. The fluidic resistance of the nozzles denoted K_q were calculated by (2) with ΔP and Q taking from the nozzle manufacturer's catalog. The minimum and maximum flow at 200 kPa and 400 kPa for each nozzle,

respectively, and the $K_{qe}(j), j = 0, \cdots, 7$, calculated by (6) for each of the possible combinations of nozzles are displayed in Table 1.

Table 1. Set of nozzles combinations and the respective fluidic resistances

	Nozzle model 422WRC			
	11003	11002	11015	
$Q_{min}[l/ha]$	0.98	0.65	0.49	
$Q_{max}[l/ha]$	1.39	0.92	0.69	
j	Active nozzles			$K_{qe}(j)$
0	0	0	0	∞
1	0	0	1	836.6
2	0	1	0	473.0
3	0	1	1	154.1
4	1	0	0	207.6
5	1	0	1	92.5
6	1	1	0	75.1
7	1	1	1	44.5

3.1 Agricultural Sprayer Development Plant

The agricultural sprayer development plant used is composed of the chemical and carrier-chemical subsystems. A detailed description and modeling of this plant was presented in Cruvinel et al. (2011) and Felizardo et al. (2016). The ASDP basic configuration consists of two booms each with 7 nozzles spaced 50 cm, totalizing 7 m of boom.

This hydraulic plant is located at the Laboratory of Agricultural Precision Spraying of the Embrapa Instrumentation and was built as a collaboration between Embrapa Instrumentation and the Control Laboratory of the Department of Electrical Engineering of the University of São Paulo at São Carlos.

The ASDP automation was performed with a CompactRIO embedded controller (model cRIO-9073, National Instruments) containing a reconfigurable field programmable gate array (FPGA), a 266 MHz real time processor and I/O modules (NI, 2010).

From a prescription map and calculated speeds it is possible to obtain the flow rate required at each nozzle. Algorithm 1 uses the actual and desired flow to select the combination which leads to the better approximation of the desired flow rate. For this, the difference between the desired fluidic resistances and all possible fluidic resistances (Table 1) for each set connected to the booms is obtained.

3.2 Simulation Results and Discussion

To evaluate the nozzles switching strategy using Algorithm 1, two scenarios were simulated (Table 2). In the scenario called A, it was used an application rate D_n of 163 and 231 l/ha as reference and a conventional single nozzle model 422WRC11005. In the scenario called B, it was used an application rate D_n of 196 and 280 l/ha and a conventional single nozzle model 422WRC11006. The application rates were chosen to constrain the pressure to the range [200 400] kPa. Outside this range of pressure, the size of the droplets generated affects the application efficiency on the target be that weeds, insects, fungi or other pests. In both scenarios, the simulation results for a conventional single nozzles sprayer and the proposed control strategy with 14 sets of solenoid valves switched according to Algorithm 1 and Table 1 was compared.
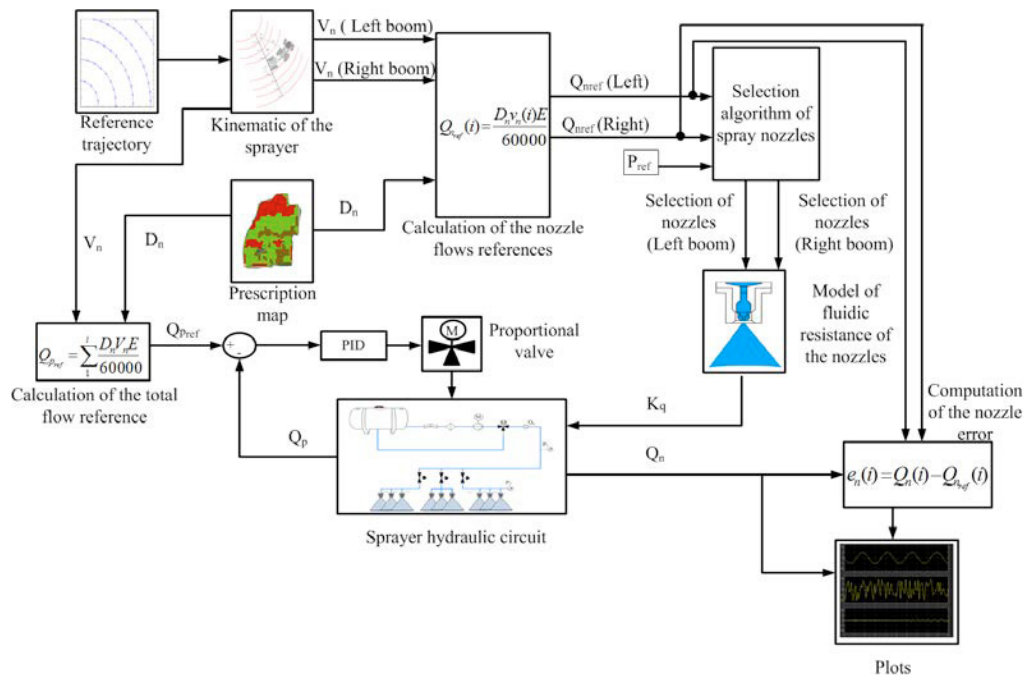
Fig. 3. Block diagram of the spraying system indicating as inputs the reference trajectory and the prescription map. From the curved path and reference trajectory, the speed of the nozzles in the booms with respect to the direction of rotation are calculated.

Table 2. Sprayers evaluation scenarios

Scenario	D_p [l/ha]	v_p [km/h]	Nozzle 422WRC	Radius [m]
A	163-231	12	11005	20-100
B	196-280	12	11006	20-100

In the simulations, 14 sets of solenoid valves (model QJS, Teejet) and nozzles (model ASJ® WRC, Arag) were used. Figure 3 shows the block diagram of the hydraulic plant used in the simulation processes.

The obtained results for the two scenarios A and B considered are presented in Figs. 4, 5 and 6. For each scenario, the application rate was varied from minimum to maximum of the range shown in Table 2 at instant 250 s.

In both scenarios, the system pressure with solenoid valves presented a variation smaller that with single nozzles. This means that with the use of solenoid valves one obtains an independent pressure regulating and flow control, resulting in less variation of the droplet size. Moreover, there was no saturation of the control signal which was limited to 12V.

The reduced flow error and the regulation of the pressure show the potential of the use of sets of solenoid valves. However, it appears that the use of a valve assembly do not fully eliminate the error under curved path application, which is limited to the combinations of the fluidic resistance (Table 1).

4. EXPERIMENTAL RESULTS USING THE SPRAYER DEVELOPMENT PLANT AND A CAN DEVICE

We present now experimental results for the pressure and flow regulation. We considered a simplified operation of the sprayer plant for the case of only one set of solenoid valves. The solenoid valves were activated according to the fluidic resistances given in Table 1.

The control of the solenoid valves was performed with a CAN device. Two tests were carried out, one to check for errors and delays in the transmission of messages under bus loading and the other to verify the range of flow rates attainable with the combination of nozzles at a fixed pressure.

To evaluate the transmission, we considered two transmission speed rates (125 e 250 Kbits/s) and the dispatch of messages with 8 bytes by the CAN bus. In the first test, we used an interval of 10 ms between each dispatch, in the second and third test, intervals of 100 and 1000 ms, respectively were used. Using the *NI-CAN Bus Monitor* tool, available in the *DAQ Manager of the National Instruments*, it was possible to analyze the loading and delays in the transmission of messages. The results are shown in Table 3. The bus loading for the dispatch intervals 100 and 1000 ms was zero and can be considered negligible. The amount of registered messages dispatched per second was 99, 9.99 and 1 for retransmission rates of 10, 100 and 1000 ms, respectively, for both speeds. No errors were recorded when sending messages under the conditions of the tests carried out.

Table 3. Delays between messages transmission under bus loading

Time (ms)	Delay (ms)		Bus loading (%)	
	125 kbit/s	250 kbit/s	125 kbit/s	250 kbit/s
10	0.009	0.005	10	5
100	0.009	0.005	-	-
1000	0.009	0.004	-	-

For testing the flow rates which can be attained, we used a pre-established driving strategy showed in Table 4. Thus, for each test condition and a sampling period of 50 ms, the solenoid valve was kept activated for 10 seconds and the results for two pressures, 100 and 200 kPa were recorded. In the first case (100 kPa), we started controlling the solenoid valves in the range of 0 and 500 samples, whereas in the second case (200 kPa), the control was initiated in the range of 500 and 1000 samples. The results are displayed in Fig. 7.

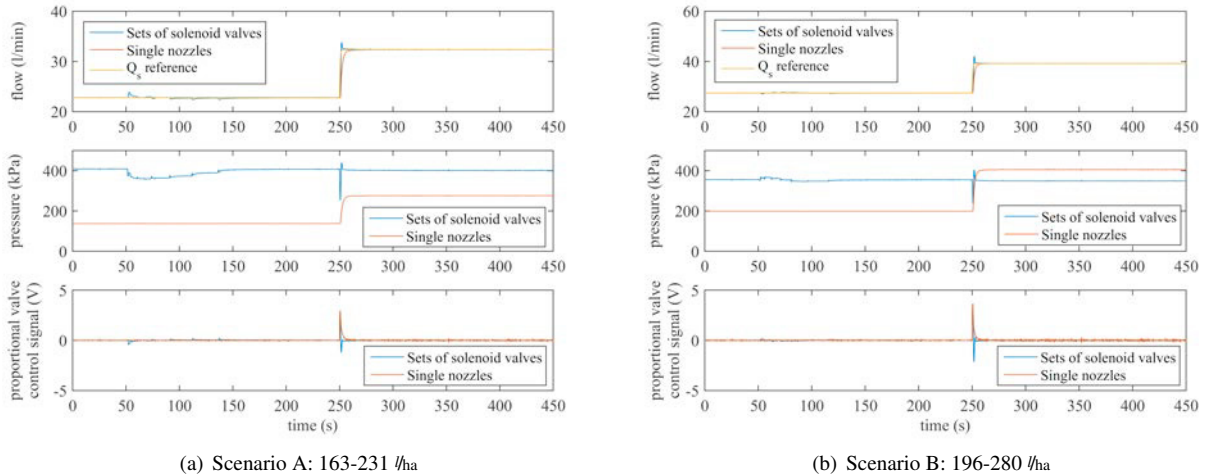(a) Scenario A: 163-231 l/ha

(b) Scenario B: 196-280 l/ha

Fig. 4. Behavior of the flow, pressure and proportional valve control signal for both scenarios. There is a small overshoot in the system flow with solenoid valves but the pressure for the sprayer with solenoid valves were almost constant with a fast variation near the instant 250 s.

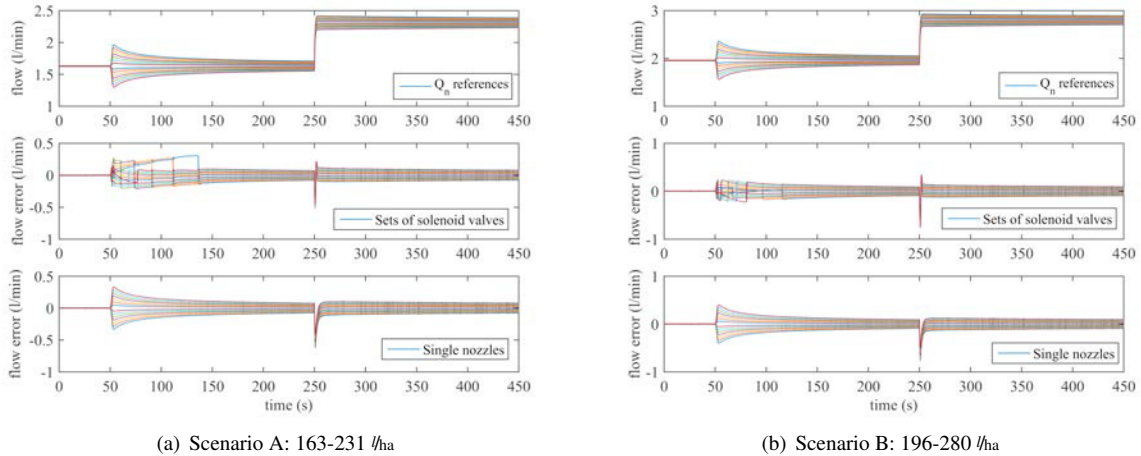(a) Scenario A: 163-231 l/ha

(b) Scenario B: 196-280 l/ha

Fig. 5. Flow references and error resulting from the selection performed by Algorithm 1 with valves solenoids and also with single nozzles. Note the decrease in the flow amplitude error for the instants between 50 and 250 s and the response time, found near the instant 250 s.

(a) Scenario A: 163-231 l/ha
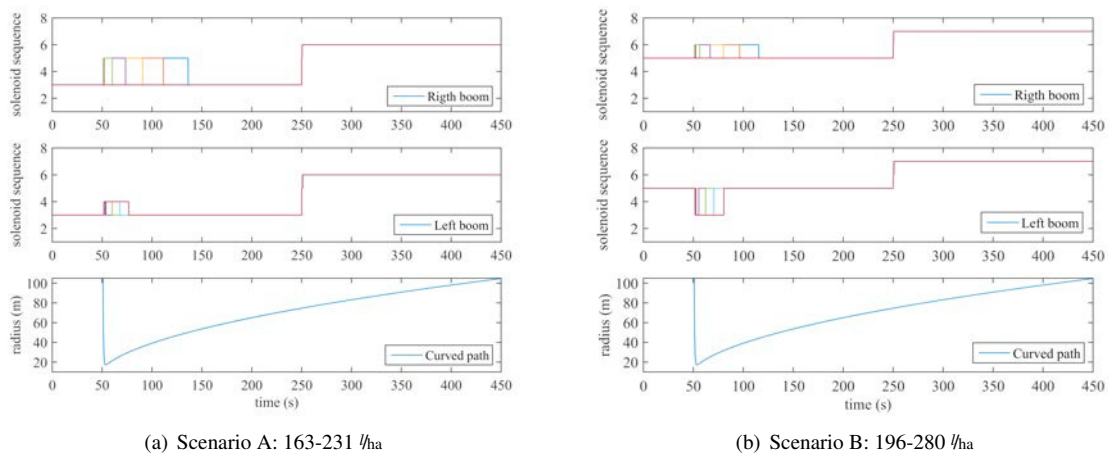
(b) Scenario B: 196-280 l/ha

Fig. 6. Selection of nozzles for each set on the left and right boom, and trajectory radii. Note that for a radius greater than about 60 m, all sets converge to the same value of the selection which indicates an approximate behavior to that of a straight path.

For each fixed pressure, it was possible to obtain four different values of flow rates, totalizing 8 possible states (Fig. 7(b)).

The state transition 1 to 2 of the switching sequence for the pressure of 200 kPa took approximately 50 samples, totalizing

Table 4. Sequence of tests used for activating the spray solenoid valves denoted $V_k, k = 1, 2, 3, 4$

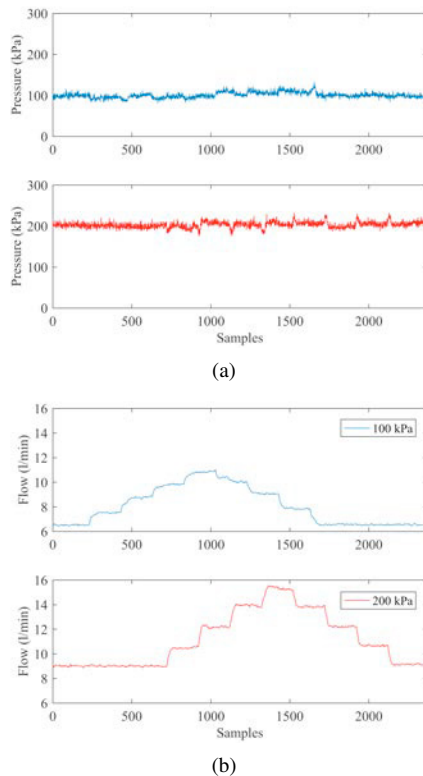| State	Active valves	Time (s)
1	None	10
2	V_1	10
3	V_1 and V_2	10
4	V_1, V_2 and V_3	10
5	V_1, V_2, V_3 and V_4	10
6	V_2, V_3 and V_4	10
7	V_3 and V_4	10
8	V_4	10
9	None	10

Fig. 7. Pressure and flow rates obtained with the valve sequence according to Table 4. In the first test we maintained the pressure at 100 kPa and start to control the valves in the range between 0 and 500 samples, whereas in the second test we maintained the pressure at 200 kPa and start to control the valves in the range between 500 and 1000 samples.

250 ms, greater than was required for the CAN network to send information to control the valves, such that the sprayer control was not affected by the use of a CAN communication protocol.

5. CONCLUDING REMARKS

The results presented showed that the use of a new control strategy in a variable rate application sprayer leads to more accurate solutions. In the case of a particular sprayer with solenoid valves, we have showed that the range of attainable flow was increased and the pressure was kept around an operational point to ensure the quality of the application in terms of the properties of the droplets.

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