A Model Based Intelligent Sensor to Control Sprinklers in Spray Actions

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***Abstract*—Application of pesticides in crops is used to achieve food production. The use of technologies has become possible to decrease not only the biological risk but also the ecological and human ones that may occur during the application of pesticides. When using large sprayer machines, risks increase considerably due to the complexity of the trajectories required to cover the entire crop area. In this context, it is required a better analysis of the effects of different maneuvers on the quality and efficiency of the spray. This paper presents an intelligent control system based on models and smart sensors for automatic spray tip operation that enables error corrections as a function of the boom trajectory. As a new technology, such intelligent control and topology allow to increase quality and efficiency of the application of pesticides by agricultural sprayers.**

***Keywords*—*Intelligent sensor*; *electronic control*; *GPC*; *spray quality*.**

I. INTRODUCTION

In the last years, the concepts of precision agriculture and agriculture 4.0 has been the basis for novel methodologies for the application of technologies in most agricultural processes. Advanced automatic control units and the use of adequate instruments (sensors and actuators) increase production efficiency. In [1] an intelligent sensor is proposed to detect the concentration of agrochemicals at the exit of the spray nozzles for a sprayer with a direct agrochemical injection system. The intelligent sensor is mounted near the spray nozzles to measure the concentration response time, which uses a highly stable sinusoidal excitation signal. The results showed that the use of the intelligent sensor reduces the delay time errors produced by injecting agrochemicals near the output of the sprayer pump. With the assistance of the mounted sensor and an adequate control strategy, the appropriate concentration value for the application can be achieved.

Monitoring, failure detection, and automatic calibration of sensors and actuators have also been proposed. Systems with the ability to detect failures and make calibration settings are important, since working with agricultural machinery in the field is subject to great vibrations and critical climatic conditions. In this sense, the methodology presented in [2] supports the construction of a sensor virtual calibration module for agricultural sprayers. Such module for virtual calibration makes possible to validate the calibration of sensors operational conditions in real time of commercial sprayers, for instance, pressure, flow, temperature. Therefore, allowing to checkup if the sensor's operational procedures are or not correct.

On the other hand, advanced automatic control strategies allow to achieve a high degree of precision in the appropriate application of agrochemicals. In the work developed in [3] an intelligent fuzzy-Generalized Predictive Control (GPC) for Agricultural Sprayers is used. Thus, the authors use a predictive controller to advance control actions based on the delay dynamics of the hydraulic circuit of the agricultural sprayers. Among the results obtained in [3] it can be highlighted that the use of controllers based on predictive approaches increase the robustness in the presence of variations in the parameters of the sprayer.

This work proposes an intelligent automatic control strategy to improve production efficiency and quality. In this context, in Section II the key concepts of quality and efficiency of variable rate application are presented. Additionally, application examples are presented for each of these basic concepts. In the sequence, in Section III, the results and analysis about the use of new methodologies and technologies relevant in the area, are presented. Finally, in Section IV the conclusions of the work are reported.

II. APPLICATION OF ADVANCED MODEL CONTROL, ACTUATORS AND SENSORS

In agricultural sprayers, there are two main concerns, the first is related to the quality of the application to maintain uniformity in the size of drops that are sprayed and the second is efficiency to eliminate errors related to volume and application rate.

A. Quality of the Application

There are climatic and geographical factors that can drastically affect the quality of an application. Factors such as wind speed, terrain slopes, and temperature differences can cause

ISBN: 978-1-68558-083-4

errors in the spectrum of drops in the powder applications. On the other hand, the operating conditions of agricultural machinery for each application affect quality. Factors such as the application speed V_p in $[km/h]$, pressure Δ_p in $[bar]$ and flow of the hydraulic circuit of the sprayer Q_p in $[\ell/min]$, the geometry of the spray nozzle and exit velocity in nozzle V_l in $[m/s]$ have direct effect on the spectrum of drops delivered.

The quality of the drops spectrum is measured from median diameters that define each of the characteristics of the spectrum (statistical moments of a probabilistic distribution). External factors such as climatic conditions and the topographic slop of the terrain impact the spectrum of drops [4] [5] [6]. Data obtained in laboratory allowed the development of models and definition of a quality description vector [7] [8]. Among the most used quality description are the Volumetric Mean Diameter (VMD), Sauter Mean Diameter (SMD), Relative Amplitude (RA) and diameter of droplets D_{01} and D_{09} that represents 10% and 90% of the total volume of liquid is in drops of smaller diameter, respectively. All these descriptors are organized in a quality vector where each one is characterized in $[\mu\text{m}]$ [8]. From advanced analytical models, valuable information on the effect of the operating conditions on the drops spectrum can be obtained. In this sense, in Figure 1 is observed the influence of the diameter of the output hole, for different orifice values d_0 of the full cone nozzles models CH0.5, CH1, CH3 and CH6, produced by MAGNOJET,$^{®}$ on the spray cone angles for pressure and flow established conditions [9] [10]. Thus, the strong effect on the spray cone angle can be observed from the variation of the hole diameter over a defined pressure.

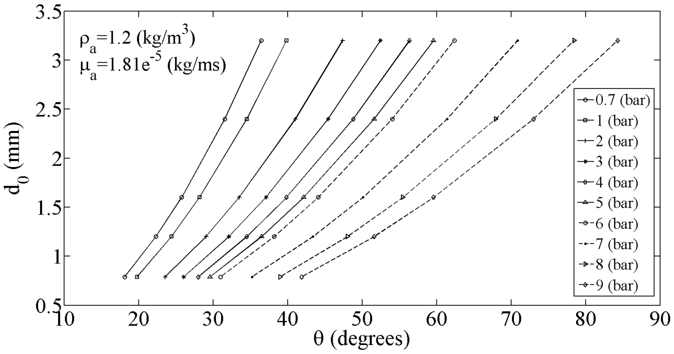


Figure 1. Relationship between the diameter of the nozzle orifice d_o and the cone angle θ for a full cone spray nozzle, simulated for different values of pressure Δ_p, for full cone nozzle.

Based on correlation analysis, each operation condition and quality parameters were compared as shown in Table I. It is observed that the pressure in the nozzle has a negative correlation with most of the proposed quality descriptors. Thus, the pressure is quite negatively correlated with the VMD (-0.61), with the $D_{0.1}$ (-0.54), SMD (-0.50), $D_{0.9}$ (-0.49) and Application Rate AR (-0.46). Besides, the pressure has a small correlation with the Covered Area CA (-0.26) and it is not correlated with the Relative Amplitude RA (-0.00). It is also important to highlight the strong negative correlation of the pressure with the other two operating conditions d_0 (-0.71) and V_p (-0.62) and this is a good indicator that the data obtained represent in a good way the hydraulic process for the production of droplets for full cone nozzles.

On the other hand, the velocity of application V_p has a high positive correlation with the VMD (0.80), the diameter $D_{0.9}$ (0.75), the application rate AR (0.71), Covered Area CA (0.66), the diameter $D_{0.1}$ (0.60) and SMD (0.53). Accordingly, just like the pressure of the nozzles, the speed of application has a fundamental effect on the quality descriptors. Therefore, the correlation analysis determines the relationship between the operating conditions and the statistical moments that determine the quality of the application. This analysis serves as a decision-making basis for intelligent control strategies, once it characterizes the positive or negative effect of the operating conditions on the quality vector.

B. Application Efficiency

The efficiency is determined by biological factors related to pests, harmful plants and the type of culture that attacks. Frequently the prescription of agrochemical type and concentration as well the nozzle type is carried out by a specialist, is given by the Application Rate (AR) in $[\ell/ha]$ [11]. Thus, efficiency is related to obtaining the appropriate AR value for each treatment. In this sense, external and internal factors can affect efficiency, leading to an AR error. As main internal factors that can lead to an erroneous AR are capacity of the sprayer to flow and pressure regulation and as a external factor, the curvilinear maneuvers that the agricultural machinery executes can lead to a relevant increase in AR errors. The study of the effect of curved maneuvers on agricultural production processes has been widely studied [12]. The kinematics on a curved path, Figure 2, show that are different speeds for each position of the nozzles on the sprayer boom, that is, velocity reduction for nozzles that are in the inner side of the curve (Left boom) .

Simulation environments, based on sprayer kinematic movement models, allow determinining the effect of curvilinear maneuvers present in real fields as well serving as a basis for decision-making in the agricultural spraying process. In Figure 3 the effect of curved trajectories on the pulverization error calculated from the Application Rate (AR) was observed. The results obtained through simulations showed the need for individual regulation of the flow in the spray nozzles, in order to compensate for the effects of the curvilinear path.

A feasible solution is the use of solenoid valves commanded by a voltage in the coil that mechanically opens and closes the valve. In Figure 4 a diagram inside a solenoid valve and a set of solenoid valves used for agricultural spray are shown. The internal operation of the solenoid valve (see Figure 4a) is as follows: in the closed step, 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 and in the open step, the return spring (3) moves the plunger until the equilibrium position, allowing fluid to pass from the inlet to the outlet.

TABLE I
CORRELATION COEFFICIENTS BETWEEN THE QUALITY DESCRIPTORS AND OPERATING CONDITIONS OF THE AGRICULTURAL SPRAYING PROCESS.

Correlation analysis for quality descriptors and operating conditions ($n = 280$)										
	Δ_p	V_p	d_0	CA	AR	RA	VMD	$D_{0.1}$	$D_{0.9}$	SMD
Δ_p	1.00									
V_p	-0.62	1.00								
d_0	-0.71	0.99	1.00							
CA	-0.26	0.66	0.63	1.00						
AR	-0.46	0.71	0.72	0.89	1.00					
RA	-0.00	0.32	0.28	0.40	0.24	1.00				
VMD	-0.61	0.80	0.81	0.70	0.88	0.25	1.00			
$D_{0.1}$	-0.54	0.60	0.63	0.53	0.83	-0.05	0.84	1.00		
$D_{0.9}$	-0.49	0.75	0.75	0.62	0.77	0.45	0.84	0.70	1.00	
SMD	-0.50	0.53	0.55	0.48	0.64	-0.16	0.76	0.65	0.29	1.00

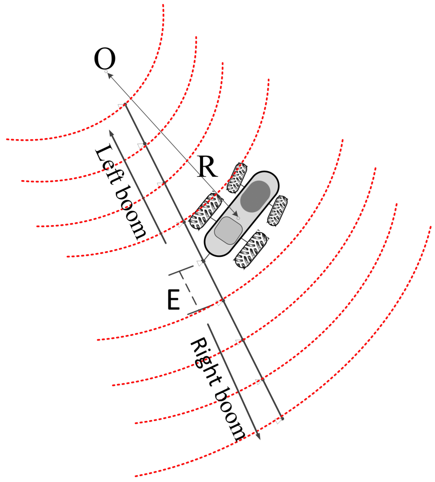
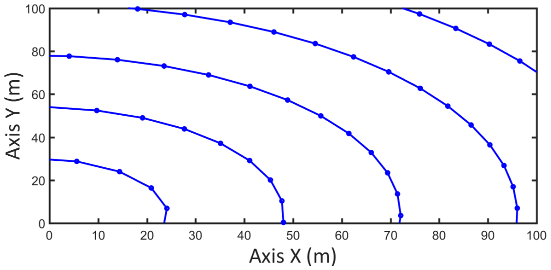
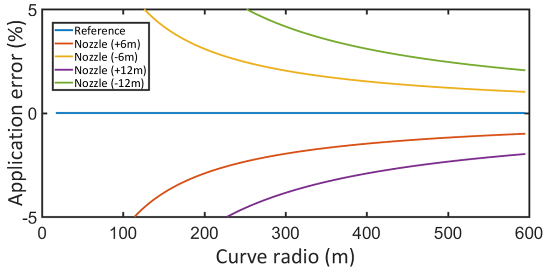


Figure 2. Curved path in which each nozzle has a relative speed which varies according to its position and the curve radius R in relation to the reference point O (figure extracted from [9])

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 the relation $\Delta P = K_q Q_p^2$, where K_q is the fluidic resistance. This information is important, since changing the spray tips varies the hydraulic resistance of the system. Therefore, the change of spray nozzles can be used to control or regulate the pressure or flow of the system. The fluidic resistance ratio for three different types of standard flat fan nozzles, used for herbicides application,(models 11003, 11002, and 11015 of the brand Arag®) is shown in Table II [12]. It is important to note that the results shown in this section are carried out with different nozzle models in relation to those used in subsection II-A. Which does not invalidate the control topology purposed in this work, but requires additional experimentation to adjust the models and algorithms in order to achieve high levels of application quality and efficiency. To observe the effect that the switching (variation of fluidic resistance in Table II) of the tips in the pressure and flow, two lateral spray booms were equipped with 14 tips each, nozzle model 422WRC11002, and the set of solenoid valves with 4 tips (V1 to V4), nozzle model 422WRC11005, was mounted on the central spray boom.

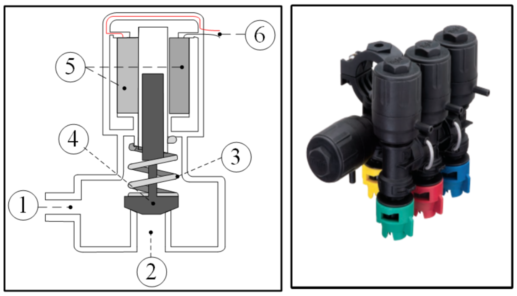


(a) Curved path



(b) Application error

Figure 3. Kinematics simulation environment for the agricultural sprayer. (a) Path designed to evaluate the performance of the agricultural sprayer in curvilinear trajectories. (b) Application error in relation to the radius of the curvilinea trajectory.



(a) (b)

Figure 4. Individual control system for each spray nozzle. (a) Electromechanical system of the solenoid valve (b) Solenoid valves set (model QJS, Teejet®) and nozzles (model ASJ WRC, Arag®) (Figures adapted from [12])

From this information, intelligent nozzle selection strategies can be implemented for opening and closing solenoid valves

TABLE II
SET OF NOZZLES COMBINATIONS AND THE RESPECTIVE FLUIDIC RESISTANCES

	Nozzle model 422WRC			
	11003	11002	11015	
Q_{min}[l/min]	0.98	0.65	0.49	
Q_{max}[l/min]	1.39	0.92	0.69	
j	Active nozzles			$K_q(j)$
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

in a set. Thus, consider the following test configuration: a sampling period of 50 ms, the solenoid valve is kept activated for 10 seconds and the data for two pressures, 100 and 200 kPa are colect. After the implementation of an intelligent algorithm, which properly choose the solenoid valves that must be activated, an appropriate nozzle switching sequence is obtained as shown in the Table III [12].

TABLE III
SEQUENCE OF TESTS USED FOR ACTIVATING THE 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

The results of this smart switching strategy, based on independent actuators for each nozzle, can be observed in Figure 5. For each fixed pressure, it was possible to obtain four different values of flow rates, totalizing 8 possible states. In addition, it is observed that in the experiment performed when there is no switching of any spray nozzle (all closed), the hydraulic pressure of the system did not increased exponentially. This fact is because in the experiment, there are two other open spray booms that perform this hydraulic compensation. It is important to emphasize that when using actuators distributed to the sprayer bar, it allows to control the flow values (maintaining the desired AR) and additionally, it allows to regulate the pressure in adequate values (maintaining uniformity in the size of drops). Thus, it is observed that intelligent control strategies and high precision actuators, allow automatic control with great accuracy and therefore, increases the AR range without any human intervention.

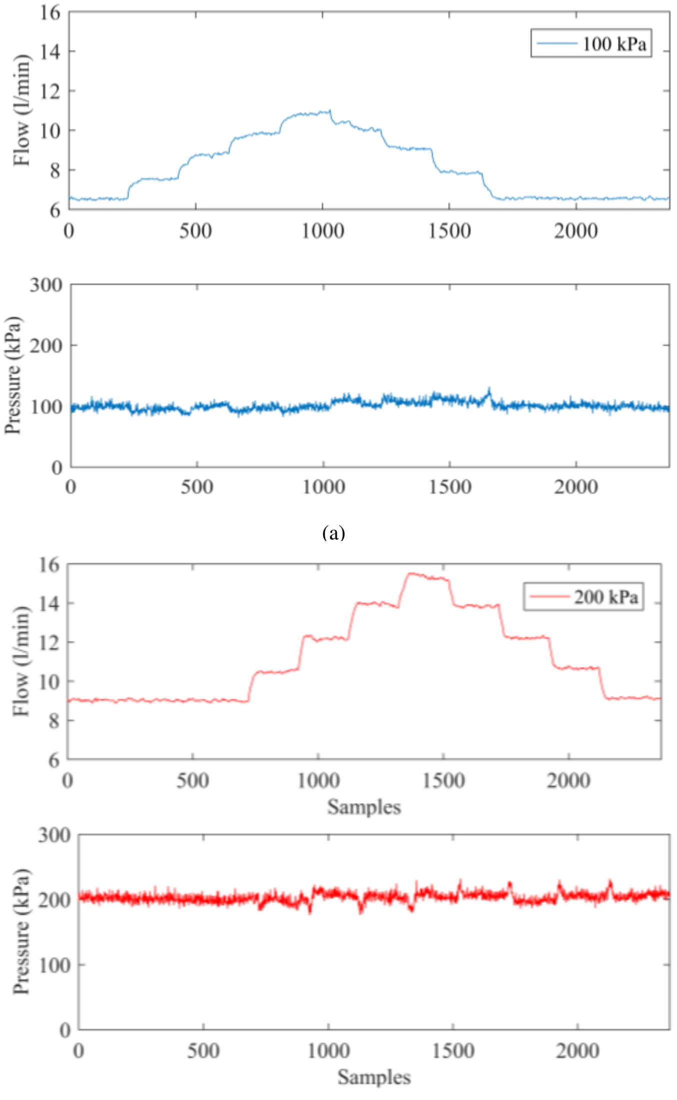


Figure 5. Pressure and flow rates obtained with the valve sequence according to Table III. (a) In the first test the pressure is maintained at 100 kPa. (b) In the second test the pressure is maintained at 200 kPa.

III. RESULTS AND DISCUSSIONS

Based on the new concepts, methods and technological devices, presented in this work, the need to create intelligent systems that can execute actions precise and efficiently in agricultural sprayers is observed. In this context, intelligent automatic control strategies must be implemented, which are based on the two approaches studied: the quality and efficiency of the application, in order to obtain a new hybrid implementation methodology.

The use of predictive control techniques (intelligent controller) together with information on application quality, obtained through an expert system, allows the design of new controllers topology for use in agricultural sprayers in the form presented in Figure6. This topology is divided into two main layers, one related to the intelligent controller and another related to a specialist system. The control layer is based on predictive control techniques (C) and the plant model (G) which must consider the delay time of the dynamics of the process. In this context, the use of a conductivity sensor allows to evaluate the delay time in direct agrochemical injection systems for various operating conditions of an agricultural sprayer. Information on the delay time is generally not used in real time control due to its intrinsic relationship with past events, but its modeling based on the variables measured in the sprayer allows its incorporation into an algorithm of anticipation of references increasing the accuracy of the application [13].

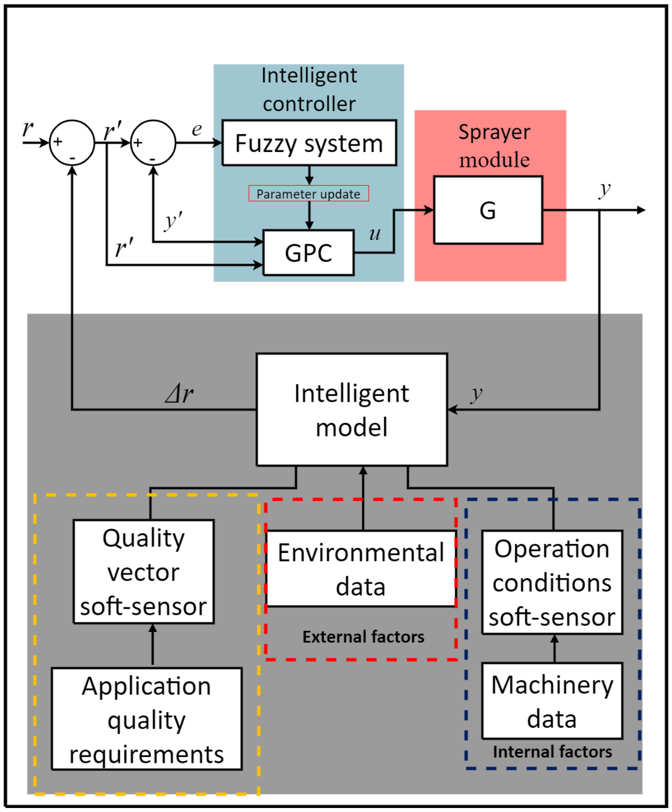


Figure 6. New intelligent control topology for increased quality and efficiency of variable rate application.

On the other hand, in the proposed topology, there is a layer based on a specialist system. At this stage of execution, intelligent models, based on the historical data, are developed to deliver additional information (Δr) to adjust the reference (r) for the control loop [8]. These reference values are delivered as output and are calculated from data from the machine (internal factors) and data from the environment where the application (external factors) is performed. In the topology, this data base is related to the requirements (quality vector values) of application quality. Thus, from this type of architectures, a balance between the efficiency and the quality of the variable rate application for agricultural sprayers is obtained.

IV. CONCLUSIONS

The use of new technologies based on advanced models, intelligent sensors and actuators, as well as adequate automatic control strategies, allow to achieve quality and efficiency in the application of agrochemicals. With the use of these technologies, a reduction in human and ecological risks related to this type of agribusiness processing can be achieved.

It is important to highlight that the integration of movement dynamics of agricultural machinery into intelligent control systems allows the evaluation of complex field situations and offers knowledge bases to execute actions to mitigate their effects.

The use of intelligent topologies for control allowed to perform efficient actions for pesticide variable rate application. Additionally, the intelligent system can offer adequate conceptual bases to perform decision-making processes to aggregate quality during spraying, which may bring improvements to pest control into a crop region.

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