Real-time Detection and Reconfiguration of Sensors in Agricultural Sprayers Subject to Failures

Deniver R. Schutz*,†, Vilma A. Oliveira†, Paulo E. Cruvinel*

*Embrapa Instrumentation
Brazilian Agricultural Research Corporation, São Carlos, SP, Brazil
† Department of Electrical and Computer Engineering
São Carlos School of Engineering
University of São Paulo, São Carlos, SP, Brazil
Email: deniver@usp.br, voliveira@usp.br, paulo.cruvinel@embrapa.br

***Abstract*—The application of pesticides in agriculture is crucial to increase food production and pest control. However, improper application results in high costs and environmental and human health risks. Currently, the importance of innovations in technologies to improve reliability in agricultural spraying systems is recognized. This paper presents a real-time strategy for faults analyzing, when using a flow sensor during the operation of an agricultural sprayer. Additionally, a method sensor-based for reconfiguring the control loop using the fluidic resistance and pressure data is proposed. Results demonstrate the effectiveness of this arraignment considering an additional pressure sensor in the sprayer system to ensure reliability, i.e., even when the flowmeter fail. Besides, based on such strategy the agricultural spraying process is not interrupted.**

***Keywords*-Sensors in agriculture; reability; real-time processing; agricultural sprayers; support decision-making.**

I. INTRODUCTION

In general, pesticide spray application by agricultural sprayers is realized at a constant rate (l/ha), regardless of the density of pests and diseases, compromising application efficiency [1]. On the other hand, the application of pesticides using Variable Rate Application (VRA) takes into account the spatial variation of pests and its on the crop. With the assistance of data from prescription maps, sensors, and actuators, the VRA system adjusts the quantity of pesticides in liters per hectare in real time, controlling the flow rate and pressure [2].

Controlling the flow and the pressure in an agricultural sprayer system is important for several reason. A precise flow application allows to reduce the production costs, as it ensure that the correct amount in applied in the crop, while efficient pressure control aids in the quality of application. In other words, the correct flow and pressure control and the accuracy in the spray rate help to minimize loss and optimize the use of resources [3]. Therefore, it is essential to ensure proper functioning of the instrument responsible for monitoring the flow and the pressurre of the syrup (mixture of the quimical active component plus water). Any failure in these components can result in the improper application of pesticides, increasing the risk of contamination in neighboring areas and loss of product due to over-application or under-application [4]. In fact, it is crucial to prevent faults during the timing window in agricultural processes.

A fault is defined as a departure from an acceptable range of an observed variable or a calculated parameter associated with a process. Additionally, a fault can be considered as an abnormality process or symptom, such as deviations like too high pressure or even a high flow into a hydraulic system [5] [6].

Currently, the detection of abnormal events or malfunctions in agricultural machinery relies mainly on the presence of the operator. However, due to increased workload and the growing complexity in machinery, supervising these failures have become to be challenges. This can lead to operations with uncertain data, resulting in inadequate control and operations far from ideal. Therefore, an evolution in techniques and technologies for automatic fault detection and diagnosis have been required [5].

Modern agriculture sprayers use flow and pressure sensors to monitor the spray bar, allowing precision application of pesticides and other chemicals. However, there are challenges in finding note only a flow sensor but also a pressure sensor that can withstand high vibration,useful life wear, disturbance in weather and harsh chemicals, without breaking the bank to address the needs of agriculture applications. In such a context an alternative should be considered either a flow or pressure sensor fail during agricultural operation. In fact, both sensors may fail to meet required levels of flow and pressure ratings or do not have whetted materials and electrical connection options needed for agricultural applications. Of coarse, helpfully there still have some options in the market, like for instance the use of the pressure sensors E2G™ and KM15™ from Ashcroft® and the VKP-063 from Velki® and the use of flow sensors FM600-250 from BELIMO® and DN50 IP from Impac® company.

Besides, recent works have been developed to create fault-tolerant systems in hydraulic componets. In [7], is presented method for analyzing the reliability and failure of agricultural sprayers using smart sensors, a microcontroller, and a controller area network protocol. This system helps in ensuring the correct rate of pesticide application for pest control, reducing measurement errors, and minimizing the impact on the environment. Likewise, Bayesian convolutional neural networks are employed in [8] to predict the lifespan of solenoid valves,

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enhancing system reliability. In [9], an active Sensor-Fault-Tolerant Controller (SFTC) is proposed for an independent metering control system, capable of tolerating faults in input, output, and feed pressure sensors using analytic redundancy. A real-time fault diagnostic method for hydraulic systems is proposed by [10] using data from multiple sensors. It introduces a Multi-Sensor Convolutional Neural Network (MS-CNN) that incorporates feature extraction, sensor selection, and fault diagnosis into an end-to-end model.

This research work aims to develop a real-time strategy for detecting faults in the flow sensor and reconfiguring the closed-loop control system using a pressure sensor to ensure sprayer operation continuity in case of eventual failures.

In this document, after this introduction, Section II shows constituent components of the spraying module of the Agricultural Sprayer Development System (SPDA), a method for the identification of the fluidic resistance K_t, and the method for fault evaluation. Sections III and IV present discussions of the results based on both with simulation by MatLab® and real data with the SPDA, respectively. Finally, the conclusion is presented in Section V.

II. DETECTION AND RECONFIGURATION STRATEGY

The block diagram of the spraying system is presented in Figure 1, with the Fuzzy Generalized Predictive Controller (Fuzzy GPC), developed by [11] [12], used to regulate the system flow rate.

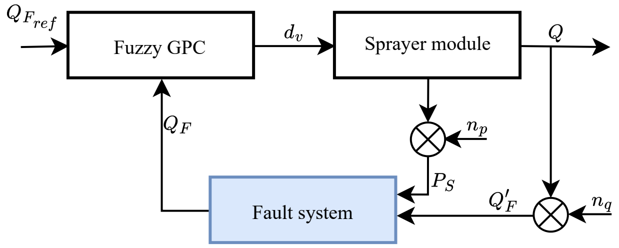

Figure 1. Block diagram of the arraignment for fault evaluation and reconfiguration system.

In Figure 1, n_p and n_q represent noises inserted in the same sequence as the signals P_S and Q'_F, with the objective of simulating reading signals closer to reality and are determined by:

$$\begin{aligned} n_q &= Q'_F \cdot 0.05 \cdot rand \\ n_p &= P_S \cdot 0.05 \cdot rand \end{aligned} \tag{1}$$

with *rand* used to generate random numbers from a continuous uniform distribution in the range [0, 1].

A. Failure assessment

The assessment of possible failure occurs by comparing the Root Mean Square Error (RMSE) index with a threshold l_f defined by the designer through a priori knowledge. If the RMSE deviation exceeds this threshold, the system identifies the occurrence of a failure. RMSE is the standard deviation of the residuals. It is a measure of the magnitude of the distance between two points. The calculation of RMSE is given by:

$$RMSE = \sqrt{(Q_{PS} - Q'_F)^2} \tag{2}$$

where Q'_F is the reading value of the flowmeter and Q_{PS} is the estimated flow valuated considering the pressure P_S and the fluidic resistance K_t:

$$Q_{PS} = \sqrt{\frac{P_S}{K_t}}. \tag{3}$$

Algorithm 1 evaluates the flow signal Q'_F from the flowmeter and adjusts the closed-loop if a fail is detected. In this case, the control variable becomes to be estimated by the flow Q_{PS}, derived from the pressure sensor signal P_S.

Algorithm 1 Evaluation of failure

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Input: Reading from the pressure sensor ($P_S$), reading from the flowmeter ($Q'_F$), fault threshold defined by the designer ($l_f$).
Output: Flow ($Q_F$)
Initialize
$Q_{PS} \leftarrow \sqrt{\frac{P_S}{K_t}}$   (3)
$RMSE \leftarrow \sqrt{(Q_{PS} - Q'_F)^2}$   (2)
$Q_F \leftarrow Q'_F$
if $RMSE > l_f$ then
    Failure alarm for the operator.
    $Q_F \leftarrow Q_{PS}$;
end if
Return:$Q_F$
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B. K_t identification

The hydraulic relationship for the spraying system operating under turbulent flow regime is given by:

$$\Delta P_S = Q^2 \ K_t \tag{4}$$

where K_t, P_S, and Q are, respectively, the fluid resistance, the pressure, and the flow of the spraying system. Therefore, by understanding the fluid resistance, it has become feasible to estimate the flow of the system through pressure readings, also in both directions [13].

To find the fluid resistance, an open-loop experiment was conducted on the SPDA using 2 bars with 7 MagnoJet® M063/1 CH06 nozzles on each bar. Starting from an initial condition, with the valve V_{P1} fully open ($\theta_{vp} = 0$) and with a PWM signal duty cycle $d_v = 0$ for 2 seconds, $d_v = 70$ is applied for 7 seconds, closing the return of Valve V_{P1}. Then, $d_v = 0$ is applied for 7 seconds, keeping it stationary. Finally, $d_v = -100$ is applied for 7 seconds, opening the return of V_{P1}. The results are presented in Figure 2. K_t was obtained using (4).

Based on Figure 2, one can observe that at average operating point of the proportional valve $\theta_{vp} = 80$ rad [14], the fluid resistance behaves linearly, thus it can be approximated to an average value of $K_t = 0.41$. In the highlighted segments from

0 to 6.3 s and from 21 to 22 s, since the flow was null the fluid resistances were indeterminate.

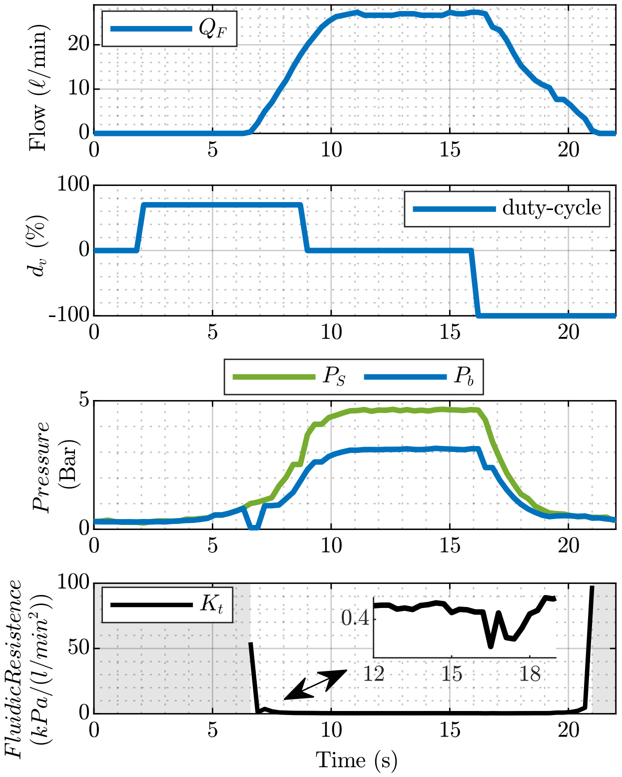

Figure 2. Open-loop experiment for obtaining the fluid resistance K_t.

III. Simulation results

The results were obtained with the sprayer module described in Figure 3 which, together with the actuator, was responsible for regulating the syrup application rate via liquid flow control [12] [11].

A three-phase motor, driven by a three-phase inverter, maintained a constant flow rate of the piston-type spraying pump model MB-42 Jacto®. Its purpose was to draw water from a 300 l reservoir to act as a diluent, sending it to a hydraulic system, which pumping the syrup to the nozzles bar.

A three-way proportional valve denoted as V_{P1} of the needle type, model 463022S from ARAG®, was the main actuator of the system to regulate the syrup flow. It had the capacity to control flow rates of up to 150 l/min with a maximum pressure of 2000 kPa and a response time of 7 s. Its piston is actuated by a direct current motor, coupled to an H-bridge used to control the piston position ($0 \leq \theta_{vp} \leq 94.2\,\text{rad}$) and the rotation direction (valve opening or closing) through PWM signals. Automatic return solenoid valves, denoted as V_{S1} and V_{S2} are used to direct the flow to the nozzles bars [14].

The flow rate of the solution was measured by an electromagnetic flowmeter (model 4621AA30000, ORION® company), with a measurement range between 5 to 100 l/min, capable of withstanding pressures of up to 40 bar. Two piezoelectric pressure sensors, model A-10 from WICA®, was coupled to the system; one monitors the pressure of the distribution bar and the other monitors the pressure at the end of nozzles bar. At the end of the section bars, five-way nozzle holders (model QJS, Teejet®) were attached, responsible for forming the spray droplets [15].

For simulation it has been used the MatLab® software to control a proportional valve V_{P1} in a spraying module. The procedure follows the same operating condition as the open-loop experiment presented in Section II-B. The model parameters of the spraying plant and the tuning gains of the Fuzzy GPC are defined in [11], as presented in Table I.

TABLE I
PARAMETERS OF SPRAYER MODULE [11], [14].

Parameter	Value
a_1 (V_{P1} resistance curve parameter)	2.8110^{-6}
β (V_{P1} resistance curve parameter)	6.53
K_M (Motor gain)	1.10 rad/V
T_M (Motor time constant)	5.0010^{-2}
K_{pH} (H-Bridge gain)	0.12
τ_F (pesticide transportation delay)	0.6 s
Q_B (Sprayer pump flow)	40 l/min
K_T (Fluidic resistence with CH06)	0.41 kPa/(l/min)^2
m (Number of spray bars with nozzles)	2
n (Number of nozzles per bar.)	7
λ_0 (Fuzzy GPC control gain)	1
δ_0 (Fuzzy GPC reference gain)	5
l_f (Fuzzy GPC reference gain)	1

For the simulation procedure, it is considered the following conditions:

1) The pressure sensor is operational and it is not subject to failures.
2) The sensor fail occurs at the intermediate operating point of the system, when its fluid resistance can be represented by an average value.

In the first simulation test, a total loss fault of the flowmeter signal was introduced, while in the second simulation test, random gain faults were added using the $rand$ function of MatLab®. Both faults were implemented between the intervals of 105 and 183 s. The results are observed in Figures 4 and 5, respectively.

Analyzing the results, it was observed that despite the flowmeter failures, the system successfully detected them and reconfigured itself in a closed-loop fashion using the pressure sensor. The change between sensors during the operation, after the observed fail, occurred without significative signal losses, leading to a robust operation.

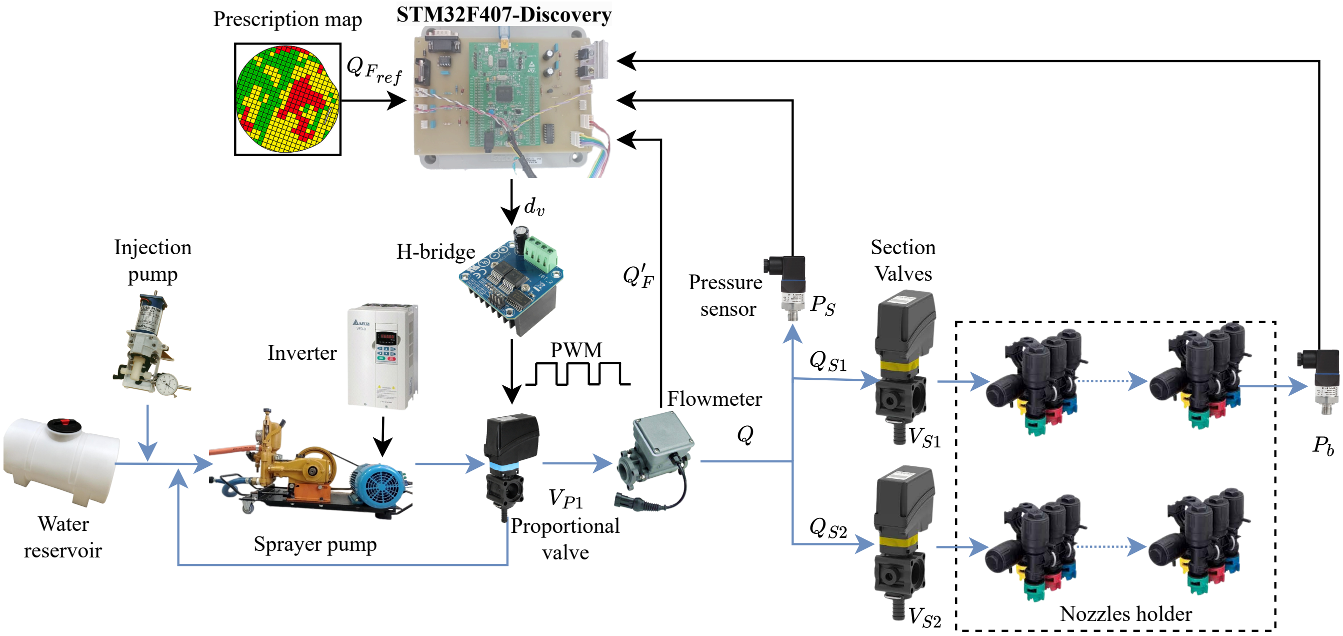

Figure 3. Sprayer module diagram of SPDA.

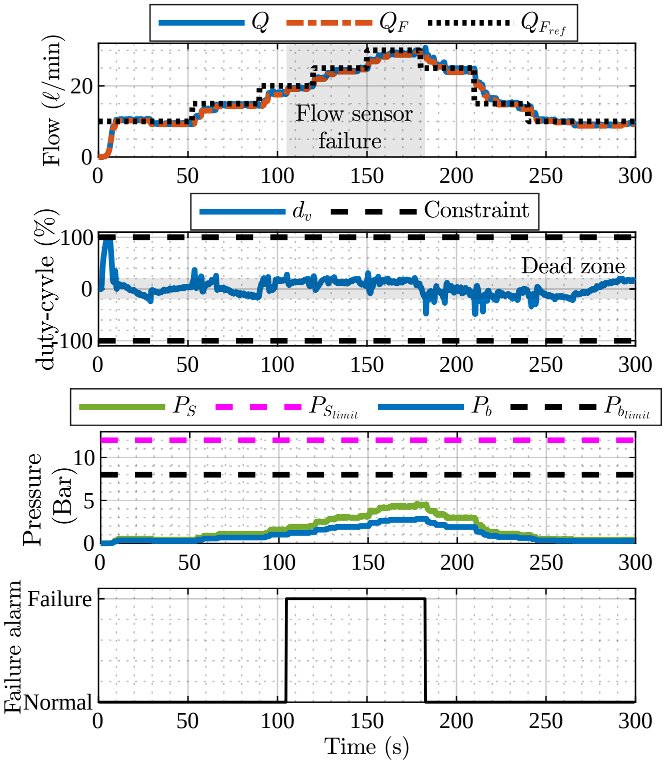

Figure 4. Simulation for total loss of flowmeter signal.

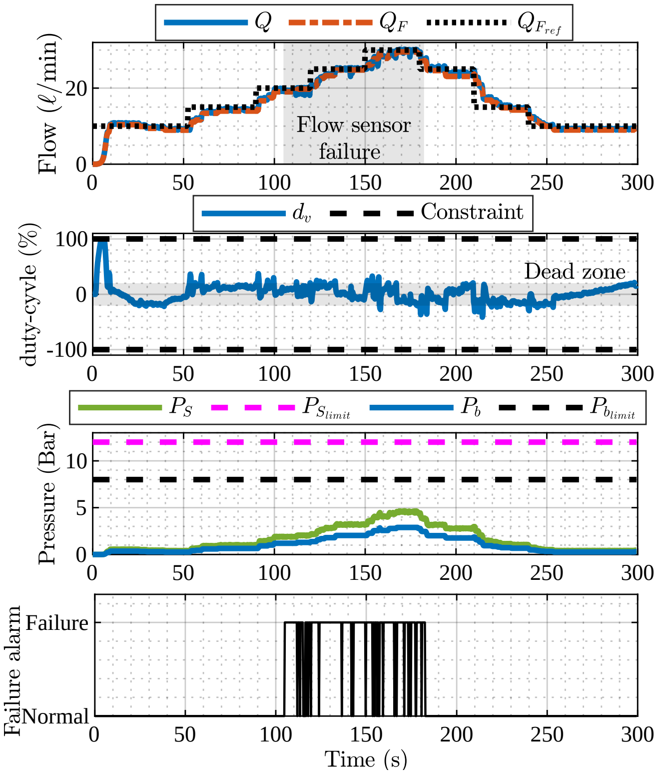

Figure 5. Simulation for gain failure in the flowmeter signal.

IV. EXPERIMENTAL RESULTS

The fuzzy GPC described in [11] and the fault analysis and reconfiguration system were embedded using a STM32F407-Discovery and the C# language.

To maintain plant safety, reference values were used to avoid pressure spikes above 8 and 12 bar, respectively int the spray tip bar and the spray bar (P_b and P_s). Two spray bars were used, each of then having 7 M063/1 CH06 nozzles spaced at a distance of 50 cm. Besides, it was used a working speed equal to 10 km/h and a constant spray pump flow rate equal to 40 l/min. Figure 6 presents the result of the control system when a total failure occurred in the flowmeter signal between 99s and 163s.

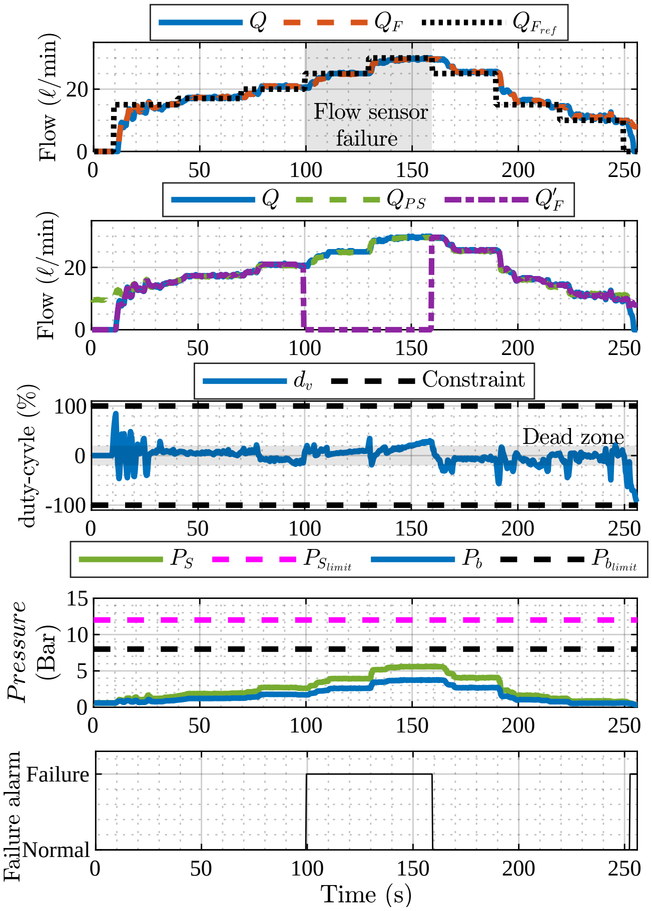

Figure 6. Flow responses of the sprayer operating with M063/1 CH06 nozzle for a stair reference.

The results confirm the opportunity to exchange the sensors during the operation, which improved reliability, as well as the practical and experimental effectiveness of using fuzzy GPC control in conjunction with the analysis and reconfiguration system for flow control. By understanding the fluid resistance at the average operating point of the proportional valve V_{P1}, it is feasible to identify the fault, communicate it to the operator and reconfigure the control loop using the pressure sensor.

It is noticeable in Figure 6 that at points where the flow reaches zero, corresponding to when the return of proportional valve is fully open, the estimated flow Q_{Ps} was great than zero, indicating a false positive fault. This occurs due to the fact that the pressure sensor model A-10 from Wika® presents a deviation in its signal when occurred absence of flow.

V. CONCLUSION

In this work, a sensors based-method was shown to aggregate value and robustness to agriculture sprayers. The opportunity to exchange sensors in agriculture sprayer during the operation showed reliability improvement. Results obtained by simulations were confirm using real data considering variations in flow and pressure in a sprayer bar.

The use of fluidic resistance has proven promising in the control loop reconfiguration strategy through pressure sensor, preventing interruptions in the spraying process caused by flowmeter failures. Additionally, the utilization of the STM32F407 Discovery has been found to be ideal for embedded implementation.

As a perspective for future work, it is being consider methods for obtaining fluidic resistance in real time, as well as the development a new sensor to evaluate the impact of residual error on the estimation of average fluidic resistance.

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