Real-Time Failure and Reliability Analysis of Agricultural Sprayers Based on Sensors, Arduino Architecture, and Controller Area Bus Protocol

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Abstract—**In this study, a solution for the operational analysis of agricultural sprayers based on their sensor devices for measurements, surveillance, signal conditioning, and interfacing circuits is proposed. The agricultural electronics-based machinery industry has significantly expanded during the past 10 years, and performance and cost advances have enabled the feasibility of operations for decision-making capabilities for food production. However, it is becoming increasingly necessary to study the system reliability, which is one of the major concerns in real agricultural machinery during field operation. A method is presented for the verification of the failure and reliability of an agricultural spraying system using a microcontroller, operating in an Arduino-based architecture, a controller area network protocol for communication and data analysis, and sensors for pressure, flow, and temperature, which are frequently used in such agricultural machinery for the spray quality control. All these sensors play an important role to support the variables control, and they must not only be operating correctly but must also ensure the verification of the application quality, which depends on the correct rate of pesticide application for pest control. Such a system allows to verify, in real time and at a low cost, the sensors' calibration in addition to the evaluation of the whole operation, including the indication for corrections and sensor replacement, if necessary. In other words, it is possible to periodically check the sensor and sprayer reliability. Thus, the knowledge of sensors has become imperative for such applications in agriculture. Furthermore, the establishment of computational procedures for the evaluation of correct operation is equally important, which plays a strategic role, so that users can appropriate such knowledge and decrease measurement errors in variables that are directly related to the efficiency of pest control, as well as reduce the impact on the environment.**

Keywords—failure and reliability of sensors; calibration of sensors; agricultural application quality; decision-making support; CAN bus; precision farming.

I. INTRODUCTION

Agriculture is essential for the production of food, and this production has become even more necessary because of the continuous growth of the world population [1]. Because of the resource constraints and the need to feed 9 billion people globally by 2050, it has been argued that more food should be produced but that, at the same time, production should become more sustainable regarding people, planet, and profit [2]. Today, the whole world is seeking food security, and agricultural machinery plays in this context a very important role.

Without agricultural mechanization and its advanced automation, it will be practically impossible to meet such needs and provide solutions to achieve food and nutrition safety [3]-[5]. Automation of agricultural mechanization is an intensive area of research and development, with emphasis on enhancement of food quality, preservation of operator comfort and safety, precision application of agrochemicals, energy conservation, and environmental control, among others. Automation applications are today oriented toward and assist in the attainment of environmentally friendly and more-sustainable systems of agricultural and food production [6][7]. The mechanization of farming practices throughout the world has revolutionized food production, enabling it to keep pace with population growth [8][9].

In terms of technology development for agriculture today, there are requests for more investments, system innovation, and a better understanding of how people and machines must interact. In addition, almost every piece of agricultural equipment has sensors and controls these days, and a number of sensing technologies are used in agriculture, providing data that help farmers monitor and optimize crops. In such a context, the assessment of sensor failure and reliability is important for the machinery designers' engineers and researchers.

The methodology for assessing sensor reliability has adaptive aspects and should be customized as a function of their application. In agriculture, for instance, the design of embedded electronic-sensor-based systems in machinery for the field has been shown to require the inclusion of failure and reliability. In such a way, three general approaches can be considered: system failure because of uncalibrated sensors, system failure-rate prediction, and physics-of-failure reliability assessment [10]-[13].

In general, the sensors in an agricultural sprayer are organized in sensor networks. If using redundancy, the failure of a single device may not be critical to the applications. However, when failures occur in sensors, the consequences are likely to be disastrous, particularly for critical applications, such as the application of pesticides for pest control. The impact of an incorrect application of pesticides is well known, not only in terms of the economic aspects and on the plant's health, but also on the environment. The cause of such a failure must be determined as soon as possible; otherwise, the negative consequences could become more widespread [14].

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According to records, isolated component evaluations of sprayers have been carried out since the 1940s, but only in the 1970s did technical inspection programs emerge [15]. Around 1960, the implementation of the first Sprayer Inspection Project in Germany began. In 1969, other countries, such as Italy, began to carry out inspections and, from there, the quality improvement and the reduction of the negative impacts obtained through the applications [16] were noticed. There are reports that, in Norway, agricultural sprayers have been inspected since 1991 [17]. The periodic inspection projects of sprayers implemented in Europe, besides verifying the working condition and adequacy of the equipment, show the importance of the educational process [18]. Belgium has performed obligatory inspections on agricultural sprayers in use since 1995, setting as main objectives the maintenance of equipment and the education of applicators [19][20]. In a project carried out in Spain's Valencia region, the inspected sprayers were divided into operative or not operative as a function of their condition of use [21]. In Argentina, a survey conducted in the 1990s showed the need for technical maintenance of spraying machines, because the majority of them were in trouble [22]. In Brazil, the first sprayer inspection was performed in 1998, where an evaluation was done in the State of Paraná, finding inadequate working conditions of the pressure gauges of some sprayers [23]. Today, several countries are performing periodic sprayer inspections, and various groups of researchers have reported in the literature that the best conditions of the use of sprayers are closely related to their constant maintenance. In such a context, the uniformity of the spray distribution applied by the sprayer boom, the working pressure, the temperature of the mixture, and the volume of the pesticide, which must be adjusted for effective pest control [24]-[27], play important roles.

Currently, through technical-support programs, machinery companies have been providing such periodic maintenance service; however, it is still based on an external diagnostic toolkit [28].

Today, agricultural spraying is used with a focus on precision agriculture, where control, supervision, and the highest quality of the application process are sought, to increase the safety and efficiency of the application processes. These aspects are also related to the minimization of the environmental impacts resulting from these agrochemical application processes. In such work, which quantifies the economics of the localized application (variable rate), it is quite common to observe improvements in the cost/benefit relation [29][30]. Variables, such as temperature, flow, and pressure, have a direct influence on these results, affecting the volume and distribution of the drops in the plantation, which directly influence the efficiency of the application. If there is no control of the pesticide drops, waste can occur. Extremely fine drops can be carried by the wind, spreading and contaminating the environment, which characterizes the drift phenomenon. Extremely thick droplets, although reducing the drift, provide less coverage of the application target, because the pesticide volume that leaves can hold is limited by their size [31][32]. Therefore, it is important to know precisely the values of the variables of temperature, pressure, and flow to have a greater control of the application of these agricultural products. For the automation of these sprayers' processes, embedded computer systems are currently being used.

The innovation presented in this report is based on the inclusion of the concept of on-the-go periodic measurements for operational surveillance based on the monitoring of flow, pressure, and temperature of the mixture to obtain in real time not only the information regarding the operational failure, but also the sprayer reliability analysis.

When done properly, a periodic evaluation of the sensors' calibration, or even a verification of the electronics used for signal processing, can correct mistakes, and network robustness can be established. In addition, selection of a reliability assessment approach is of fundamental importance, because it is related to the effective design of strategies for the operation of reliable sensors.

Furthermore, research on sensors and their effects on the reliability and response characteristics when operating in agricultural sprayer devices is presented. The presented concept and the results can be used in various sprayers' modalities and make increasing reliability possible in relation to the sensor calibration, which defines the quality of the application of pesticides. Because the control circuits rely on the feedback from voltage/current sensors, the whole system for pesticide application has performance that is likely to be affected by the sensors' failure rates, their dynamic characteristics, and the signal-processing circuits. This approach proactively incorporates reliability into the process by establishing a way to verify the calibration of the sensors, i.e., including verification modules for important variables of the spraying process in an unsupervised and automated interface.

In the rest of this work, in Section 2, the materials and methods used are described. In Section 3, the results obtained are discussed, and the conclusions are presented in Section 4.

II. MATERIALS AND METHODS

To design the development of the module for the virtual verification of the calibration of the sensors in a spraying system, the use of a low-cost Arduino architecture was considered. For validation, the platform developed at the Brazilian Agricultural Research Corporation (Embrapa Instrumentation) in partnership with the School of Engineering of São Carlos University of São Paulo (EESC-USP) was used [33]. This platform is used for sprayer development and analyzes and operates as an Agricultural Sprayer Development System (ASDS). It uses a National Instruments embedded controller, NI-cRIO, which works on the platform LabVIEW. The NI-cRIO architecture integrates four components: a real-time processor, a user-programmable field-programmable gate array, modular I/O, and a complete software tool chain for programming applications. This ASDS has an advanced development system that makes possible the design of architectures involving the connections of hydraulic components and devices, mechanical pumps, and electronic and computer algorithms. Such a system also has hydraulic devices used to make any configuration of commercial agricultural sprays and new prototypes of sprayers, a user interface for system monitoring and control, and an electromechanical structure that emulates the movement of the agricultural sprayer in the field (Figure 1).

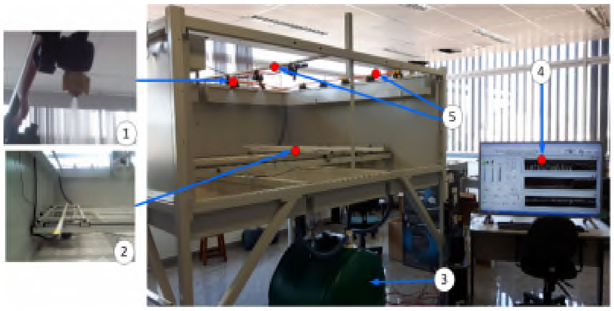


Figure 1. Agricultural Sprayer Development System (ASDS) dedicated to the application of liquid agricultural inputs.

The ASDS platform has the following components: (1) spray nozzle, (2) system that emulates the movement of the sprayer, (3) pesticide disposal tank, (4) user interface for the development system, and (5) spray booms. In such a platform, the data are presented by a graphical user interface (GUI), where the user can interact with the digital devices by graphical elements with icons and visual indicators, thereby being able to select and manipulate symbols to obtain the practical result.

The Controller Area Network (CAN) bus was also used. It is a synchronous serial communication protocol. Modules connected to a network send messages to the bus at known time intervals, so synchronization is done. The CAN bus was developed by Bosch [34] as a multimaster, message broadcast system that specifies a maximum signaling rate of 1 Mbps, where the modules can act as masters and slaves, depending on the use [35]. This protocol works with multicast messages, where all modules connected to a network receive all messages sent. The connected modules check the status of the bus and analyze whether another module with a higher priority is not sending messages; if this is noticed, the module whose message has the lowest priority interrupts the transmission and allows the highest-priority message to be sent.

For the organization of a reference database with correct values, calibrated and high-precision sensors were used. They were subjected to known temperature, pressure, and flow conditions to obtain voltage values related to these conditions.

The method to obtain and approximate the model was based on the use of polynomial regression. In addition, such a concept can be used to estimate the expected value of a variable (y), given the values of another variable (x). This type of regression is used for models that obey polynomial and nonlinear behavior, as in the previous case. For these types of model, it is necessary to adjust for a higher-degree polynomial function [36]. This technique follows the same steps of linear regression, but using a concept based on Eq. (1).

$$y = a_0 + a_1 x + a_2 x^2 + \cdots + a_m x^m + e, \tag{1}$$

where (y) is a polynomial function in which *a* represents real numbers (sometimes called the coefficients of the polynomial), *m* is the degree, and (*e*) represents an error. In this case, the mathematical procedure is the same as in the least-squares method, but the error is now represented by a function of degree greater than 1, such as in Eq. (2).

$$\sum_{i=1}^{n} e_i^2 = \\ = \sum_{i=1}^{n} \left(y_i - a_0 - a_1 x_i - a_2 x_i^2 + \cdots + a_m x_i^m \right)^2 \tag{2}$$

Thus, Eq. (2) must be derived in parts from the terms that accompany x_i and be equated to zero to find a system of equations, which makes it possible to calculate its values.

In addition, after the construction of a database with precalibrated values together with a mathematical model obtained as mentioned earlier, an intelligent calibration and correction system can be applied by using such a dataset as a reference to compare the results obtained from the sensors operating in real time. Such sensors have their calibrations checked periodically with the results obtained from the use of the models. Thus, using this comparison method, the system can identify whether a sensor is calibrated, i.e., the same concept can be replicated for each monitored variable. Additionally, either a real-time recalibration can be performed or the sensor can be replaced, if necessary.

The methods of comparison are relative change, Euclidean Distance (ED), Root-Mean-Square-Error (RMSE), and percent error, as among others [37]-[39]. The ED and the RMSE methods were used in the developed solution. The ED for comparison of the measured values of the variables takes into account the distance between two points that can be calculated by the application of the Pythagorean Theorem. In the algorithm, the ED is primarily calculated as the square root of the sum of the squares of the arithmetic difference between the corresponding coordinates of two points, as in Eq. (3).

$$d(x, y) = \sqrt{(x - x_{ref})^2 + (y - y_{ref})^2}, \tag{3}$$

where, $d(x, y)$ is the ED, (x) is the measured point, (x_{ref}) is the measured variable at the reference point, (y) is the variable at the measured point, and (y_{ref}) is the variable obtained at the reference point. In addition, as a second verification, the RMSE is used. It represents the standard deviation of the residuals (prediction errors). Residuals are a measure of how far the data points are from the regression line, and RMSE is a measure of how spread out are these residuals values. In other words, it indicates how concentrated the data are around the line of best fit, as in Eq. (4).

$$RMSE = \sqrt{(x_{ref} - x)^2}, \tag{4}$$

where (x_{ref}) is the reference variable, and (x) is the measure variable.

In addition, an accurate power supply is used, because such a system is going to be used not only for the verification of the sensors' calibration, but also their possible failure and reliability. For calibration, it is necessary to consider one power supply that generates a precise and high-stability reference voltage. Such a voltage serves as a parameter for the intelligent calibration and correction system, and it is also responsible for feeding each of the electronic devices used.

Most analog-to-digital and digital-to-analog converters internally have voltage references that are used in the process of converting the signal, either to quantize its analog signal or to convert its digital signal to analog [40]. At this point, the accuracy and stability of the reference directly influence the conversion performance.

In agricultural spraying systems, the most commonly used sensors are: (1) temperature sensors, used to measure the temperature of the syrup, which is formed by the addition of the pesticides to water, as well as the temperature of the environment where the spraying occurs; (2) pressure sensors, used to measure the pressure in the spray bar near the spray nozzles; and (3) flow sensors, which measure the flow in the tubes and spray bar, and are used to measure and feed back these values to the spray quality control system.

Figure 2 shows the integration of the Arduino-based architecture and a CAN with the sensors (temperature, pressure, and flow) in the sprayer system. The module that has the Arduino platform is a low-cost device, functional, and easily programmable. The Arduino Uno is a board consisting of an ATMEL ATMEG328 microcontroller and input and output circuits, and it can be easily connected to a computer via a USB cable and is programmed through free software called Arduino IDE (integrated development environment) using a language based on C/C++.

Figure 3 depicts the software structure for the sensors' monitoring, as well as the spraying process for failure and reliability analysis. First, all sensors are tested in relation to failure. Then, the process to monitor the operation of the agricultural sprayer in real time starts and is repeated periodically. The flags are used to alert the operator of the operational status. Either the group of sensors or any single one of them can fail during an operation. For this reason and because of the probability of its occurrence, a previous routine is used to verify the operation based on the use of previously calibrated values and references of electrical voltage. The reference modules receive an electrical signal from the Arduino architectures using the controller area bus protocol and determine whether they are calibrated or must be replaced. Additionally, as a function of the measured values of the variables, such as flow, pressure, and temperature, verification is performed periodically to determine whether the sprayer is operating adequately or if there is need for adjustments of these variables. Such verification can also indicate whether parts of the circuits related to each variable must be replaced when the correction of a failure cannot be made by software. To obtain information regarding the operational conditions, a set of flags is used for the signaling by the GUI. In addition, if a sensor needs to be recalibrated, the system performs the necessary correction to deliver the appropriate information to a CAN bus, where the control and processing unit collects the sensors' information of all the modules.

Furthermore, CAN has been used because its advantages involve data communication and the use of only two wires, which reduces the cost and facilitates the physical implementation.

To communicate between the Arduino and the CAN bus, two important elements that are not directly found in the standard Arduino Uno were used. For this, a CAN transceiver (TJA1050) and a CAN microcontroller module (MCP2515) dedicated to translating the signal made available serially by the transceiver were used (Figure 4).

The transceiver used was manufactured by NXP-Philips Semiconductors. It was used because it is fully ISO11898 compatible and supports high-speed CAN. It also can act as the entire interface between the network and the physical bus [41]. The inputs/outputs (pins 6 and 7) for the transceiver can be directly connected to the CAN L and CAN H lines of the CAN bus used. A 5-V voltage from a power supply is used, pin 2, and pin 3 for the ground potential (GND). Pin 8 of the transceiver is called “silent mode,” where, if a 5-V voltage is applied, the mode is activated, preventing the component from sending CAN messages to the bus. If no voltage is applied to this pin, the transceiver operates normally. Pin 5, Reference Voltage (VREF), provides the average CAN bus voltage, and pins 1 and 4, named Transmit Data (TXD) and Receive Data (RXD), respectively, are responsible for receiving or sending the serial signal that is used to decode CAN messages by the CAN controller.

At each decoded dominant bit, the transceiver sends a 1-bit serial via the TXD pin, and, at each recessive bit, the transceiver sends a 0 bit. In this way, the messages are transferred bit by bit from the transceiver to the MCP2515 CAN controller, which decodes the sequence according to the CAN protocol. Figure 5 shows how the communication between the transceiver and the microcontroller is performed. The transceiver RXD pin receives the CAN message sent by the microcontroller. In addition, when a full message is received, it is passed to the CAN bus via the CAN H and CAN L pins.

The MCP2515, manufactured by Microchip, is a stand-alone CAN controller that implements the CAN specification, Version 2.0B. It can transmit and receive standard and extended data frames, with 11 or 29 bits as message identifiers (frame IDs), respectively. The MCP 2515 was used, because it makes the serial peripheral interface bus communication with another microcontroller possible, and its manufacturer, Microchip, provides necessary instructions for writing and reading the registers. Each register has a byte for address that is used by some instructions to make the necessary settings. The addressing of each register is different from its content, that is, the initial setting of the bits for a register is not equal to the numerical value of its addressing.

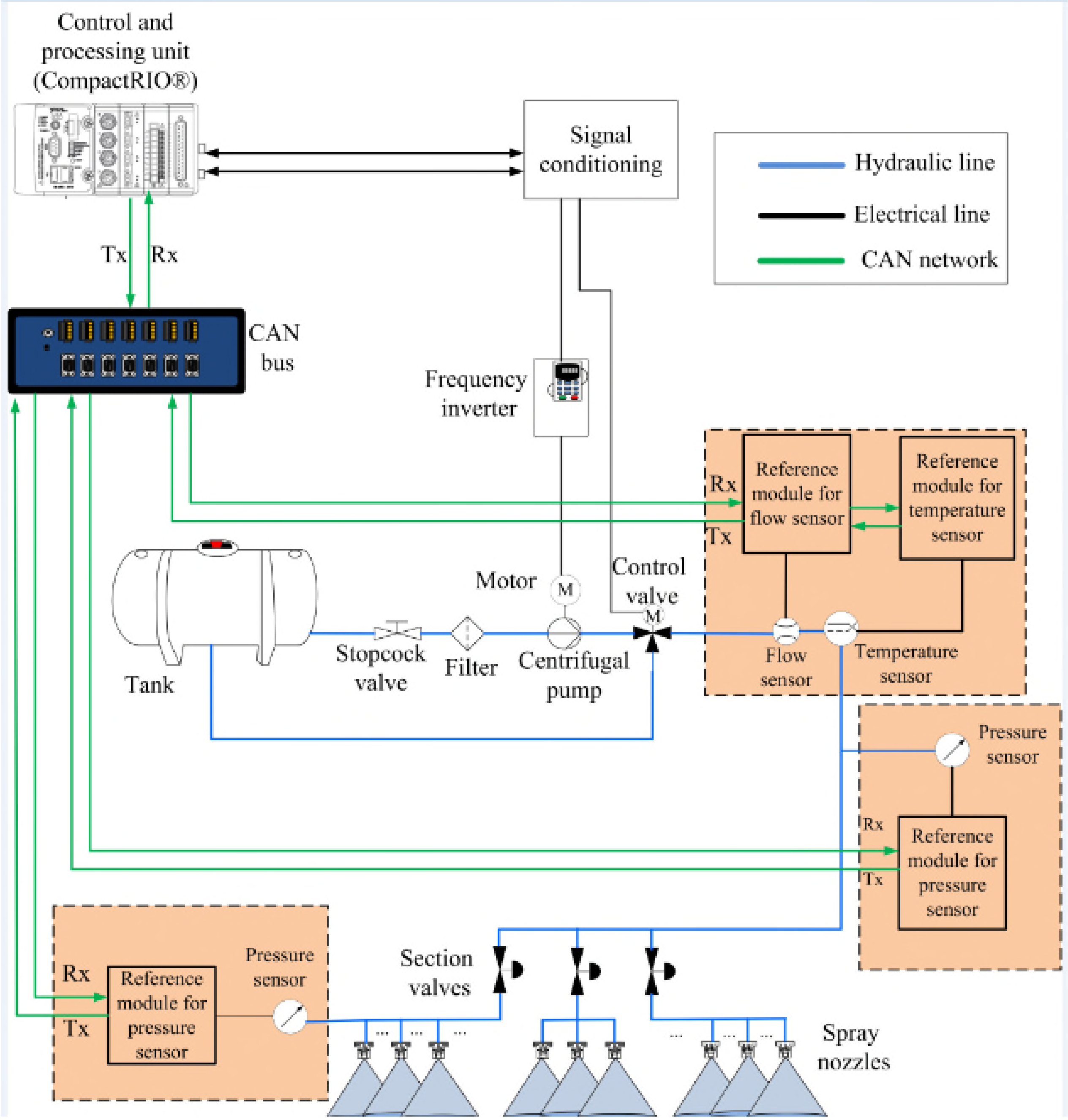


Figure 2. Block diagram of the sprayer system, in which the electrohydraulic configuration and the CAN network can be seen: in the red blocks are the modules based on the Arduino architecture, one for each sensor's modalities, for measurements of flow, pressure, and temperature.

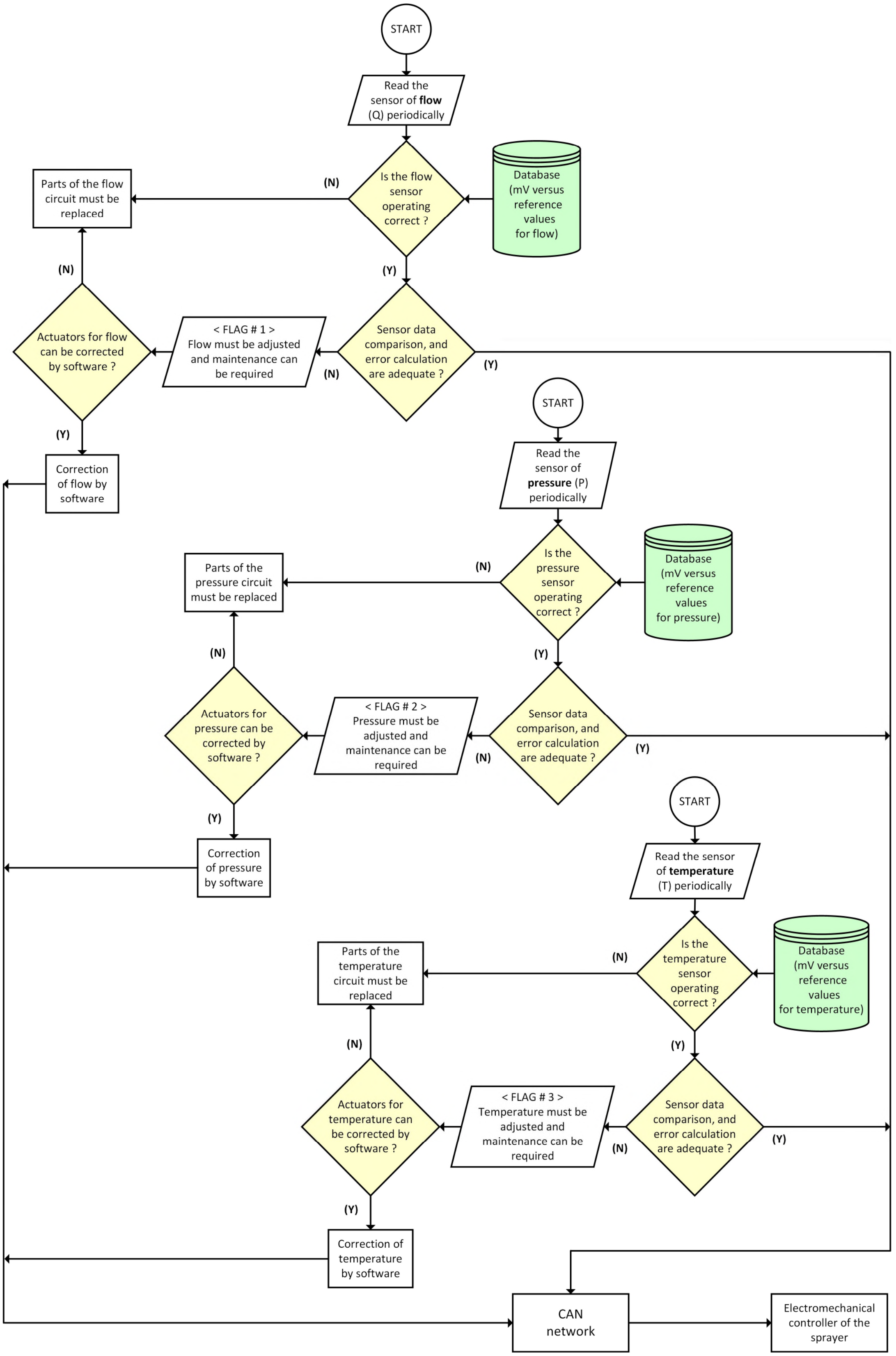
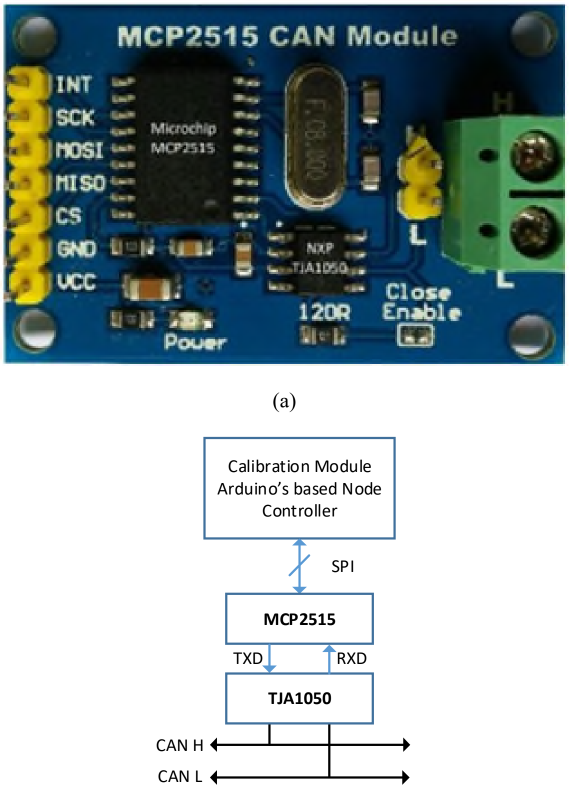


Figure 3. Software structure to monitor the sensors used for measurements, as well as the process for spraying for failure and reliability analyses.



(a)

(b)

Figure 4. (a) Arduino CAN bus shield (MCP 2515) and (b) the structural architecture for operation in block diagram.

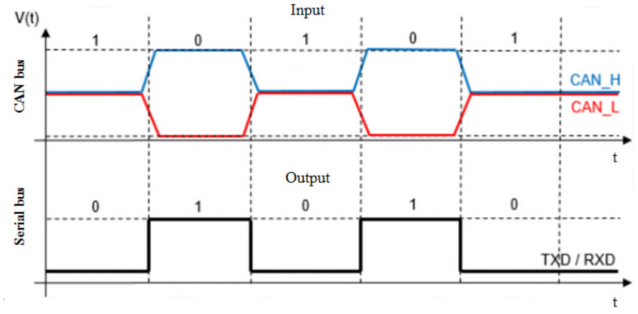


Figure 5. Input and output diagram of the TJA1050 transceiver

III. RESULTS AND DISCUSSION

The sensors, which generate analog signals, were connected directly to the calibration module, which analyzed and corrected the data obtained through the algorithms. Then, the data were sent to the CAN network, which used the control and processing unit for presenting the information with the values calibrated by the supervision software. The implementation for the intelligent calibration and correction was carried out by means of the Arduino-based architecture and the algorithms, which used the mathematical models. When the algorithm started, it received the values of the sensor with the parameter to be analyzed, or temperature, pressure, or flow, and then this value was compared with the reference model, which was constructed using the database. If the result of the comparison was satisfactory, this value was sent to the CAN bus; otherwise, this value was corrected by the software through emulation, and only then was the value sent to the bus. When the read values were out of the typical range of the sensors, there was an indication for sensor replacement, and the user was informed by means of a flag. There was a specific flag for each kind of sensor, i.e., FLAG#1, FLAG#2, and FLAG#3, respectively, for the sensors being used for flow, pressure, and temperature measurements.

Reliability is an important performance index of agricultural sprayers. A paradigm shift in reliability research on agricultural sprayers has left a simple handbook based on a constant failure rate for the smart-system sensor-based and the support real-time decision-making approaches. Based on this, for each flag, the structure was considered to be that presented in Figure 6.

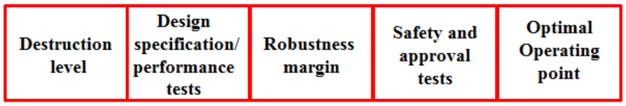


Figure 6. Structure of the flags, in which the operational conditions of the sprayers based on flow, pressure, and temperature, as well as constraints, can be observed.

For the flag structure, the context of sensitivity and specificity summarized the performance of a diagnostic test with outcomes that determined the level of a standard for operation. When the test was quantitative, receiver operating characteristic curves were used to display the performance of all possible cut points of the quantitative diagnostic marker. Here, it was being used for both the reference curve of the sensors and the polynomial regression method. Attention was given to determining an optimal decision rule, which is also called the optimal operating point. Such a point provides a graphical interpretation for decision making. The construction of the databases for the three different sensors, which were related to the calibration and correct operation of the agricultural sprayer in a specific range of use, was organized previously.

Table I shows results as evidence of the operation of the algorithms applied for a commercially available sprayer´s inspection based on the system for real-time failure and reliability analysis.

Safety and approval tests are related to finding and guaranteeing that an approved safety element of an agricultural sprayer reliably or consistently functions in accordance with manufacturer specifications. Furthermore, the robustness margin is related to the formulation for robustness requirements in the agricultural industry. They do not require specific, detailed uncertainty models, and, hence, these margins can be evaluated based on the experience and interpretation of the analysis results. They are, in general, evaluated in the frequency domain, or even by using the information related to the safety margin of a machine's operation, without loss of its hydraulic characteristics and purpose. Likewise, the design specification and performance tests are typically related to performance specifications. They are written in projects and should be observed when implemented. The design's specifications for a piece of machinery are straightforward related to its purpose and application.

TABLE I. RESULTS FOR A REAL-TIME FAILURE AND RELIABILITY ANALYSIS.

FLAG # 1	**Destruction level (Q_6 and Q_7)**	**Design Specification/ Performance tests (Q_4 and Q_5)**	**Robustness margin (Q_2 and Q_3)**	**Safety and approval tests (Q_1)**	**Optimal operating point (Q_0)**
[l/m]	$3.00 \leq F_6 < 6.00$ $19.00 < F_7 \leq 21.50$	$6.00 \leq F_4 < 8.25$ $16.90 < F_5 \leq 19.00$	$8.25 \leq F_2 < 10.25$ $14.00 < F_3 \leq 16.90$	$10.25 \leq F_1 \leq 14.00$	12.25

FLAG #2	**Destruction level (P_6 and P_7)**	**Design Specification/ Performance tests (P_4 and P_5)**	**Robustness margin (P_2 and P_3)**	**Safety and approval tests (P_1)**	**Optimal operating point (P_0)**
[bar]	$0.00 \leq P_6 < 0.38$ $2.12 < P_7 \leq 2.49$	$0.38 \leq P_4 < 0.63$ $1.81 < P_5 \leq 2.12$	$0.63 \leq P_2 < 1.00$ $1.50 < P_3 \leq 1.81$	$1.00 \leq P_1 \leq 1.50$	1.25

FLAG #3	**Destruction level (T_6 and T_7)**	**Design Specification/ Performance tests (T_4 and T_5)**	**Robustness margin (T_2 and T_3)**	**Safety and approval tests (T_1)**	**Optimal operating point (T_0)**
[°C]	$0.00 \leq P_2 < 10.00$ $75.00 < P_3 \leq 87.50$	$10.00 \leq T_4 < 22.50$ $65.00 < T_5 \leq 75.00$	$22.50 \leq T_2 < 31.25$ $55.00 < T_3 \leq 65.00$	$31.25 \leq T_1 \leq 55{,}00$	42.50

Therefore, information's contained in the structures of the flags are used to evaluate the range of the feedback variables used in the control of the agricultural machines to support decision making for a correct and adequate operation. In the same way, the concept behind the destruction level is related to the region where one can find risks for the machinery lifetime and that must be avoided.

For the acquisition of a reference curve for the flow sensor, an ORION electromagnetic flowmeter, model Orion 4621A300000, installed at the outlet of the water pump of the ASDS was used [42]. The electromagnetic flowmeter had a measuring range from 5 to 100 l/min for pressures up to 4000 kPa. The calibration constant of this flowmeter, according to the manufacturer, was 600 pulses per liter, and the flow rate in liters per minute was obtained from reading a related frequency in Hertz. With the aid of LabVIEW software, a group of reference flows in liters per minute was sent to the sensor, and a set of values was obtained from the sensor flow (Figure 7).

Also, for the acquisition of a reference database with pressure values, a WIKA model A-10 pressure sensor was used. The voltage signals of the A-10 sensor varied from 0 to 10 V, proportional to their pressure measurement ranges from 0 to 16 bar, and this sensor had a reading error and a maximum linearity of 0.016 bar. With the aid of LabVIEW software, reference pressure values considering intervals of 0.15 bar for a useful operating range from 0.5 to 3.0 bar were sent to the pressure sensor, and the values obtained were recorded (Figure 8). In addition, to obtain a reference database with correct temperature values, a calibrated sensor, type PT 100 of the Mit-Exact brand, was used, which was initially dipped in a beaker with water and ice. This water was heated, with the aid of a mixer, to 95°C. As the temperature values increased, the internal resistance of the sensor also increased. For a better perception of the variation of the values of the sensor's resistance, a Wheatstone bridge was used. In this way, it was possible to measure the unknown resistance of the sensor. The values were recorded considering intervals of 5°C, i.e., taking into account an experimental range for evaluation of different levels of the sprayer operation (Figure 9).

According to the flag structure for each variable, it is possible to carry out, in real time, the agricultural sprayer's diagnosis, as well as, if actions are required, to find its prognostic and corrections based on the actuation by its control circuit, or even recommendation for any sensor's replacement.

Then, based on such a context, the prognostics and fault-tolerant strategies for reliable field operation can be obtained.

However, joint efforts from engineers and researchers in a transdisciplinary way are still required to fulfill the needs in such a field of knowledge and promote completely the new paradigm shift in reliability of agricultural machinery.

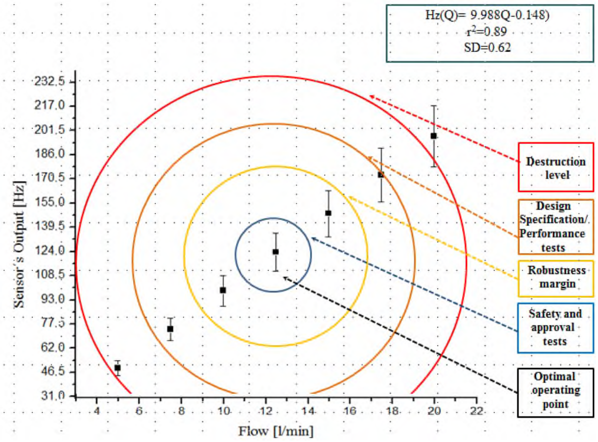


Figure 7. Reference curve for the flow sensor (Electromagnetic flowmeter, model Orion 4621A300000) installed at the outlet of the water pump, and the experimental range results obtained for an agricultural sprayer's operation.

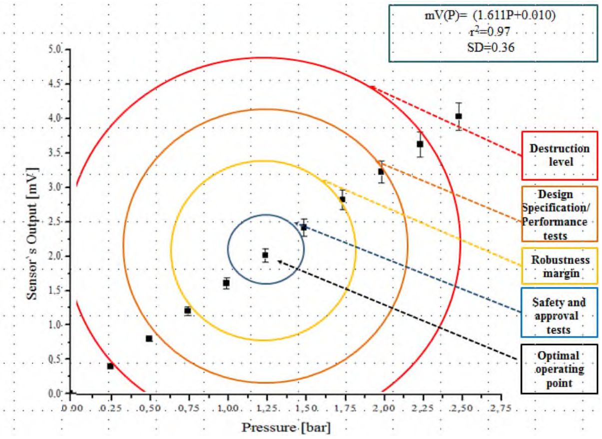


Figure 8. Reference curve for the pressure sensor (WIKA model A-10) installed at the boom, and the experimental range results obtained for an agricultural sprayer's operation.

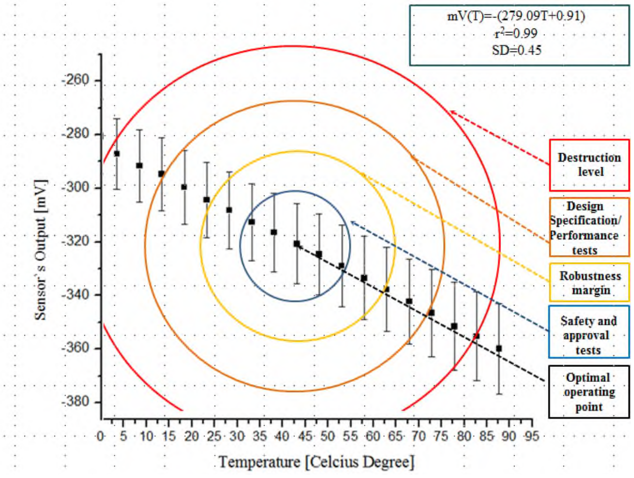


Figure 9. Reference curve for the temperature sensor (PT 100 of Mit-Exact) used to measure the temperature of the syrup, which is formed by the pesticides added to water, and the experimental range results obtained for an agricultural sprayer's operation.

IV. CONCLUSIONS

An intelligent system for evaluation of the failure and reliability of agricultural sprayers, based on the sensors' information and a smart support decision-making architecture, was presented.

Results showed that it is possible to observe real-time prognostics, as well as help with robustness, to ensure quality aggregation in pest control processes based on agricultural spraying systems. In addition, such a system enabled the configuration of a sensor's recalibration using an unsupervised algorithm considering the use of a CAN bus protocol operating with the measurements of the flow rate, pressure, and temperature in the controlled circuit process of an agricultural sprayer.

Furthermore, there are opportunities for a condition of real-time monitoring and fault-tolerant design that can enable an extended lifetime and reduced failure rate, as well as a better understanding of failure mechanisms, because more failure-mechanism-specific accelerated testing can be designed, which can lead to improved reliability predictions for sensor-based agricultural machinery and its applications.

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