Real-time Evaluation of Failure and Reliability in Agricultural Sprayers Using Embedded Sensors and Controller Area Bus Protocol

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***Abstract*—This paper presents a method for the operational analysis of agricultural sprayers based on their smart sensor devices. It is becoming increasingly necessary to study a sprayer's reliability, which is one of the major concerns in real-world agricultural machinery during field operation. A method is thus presented in this study for the verification of the reliability and indication of the failure of an agricultural spraying system using smart sensors, a microcontroller, and a controller area network protocol for communication and data analysis. Smart sensors were used for sensing the pressure, flow of pesticides, and temperature for the spray quality control evaluation. These smart sensors play an important role in supporting variable control, and they should not only be operating correctly but should also ensure the verification of application quality, which depends on the correct rate of pesticide application for pest control. Furthermore, these smart sensors were embedded in the main parts of the sprayer machine. Such a system facilitates the real-time and low-cost periodic verification of the sensors' calibration as well as the evaluation of the entire operation, in addition to indicating necessary corrections and sensor replacements. Such an innovative system would play a strategic role in allowing users to appropriate such knowledge and decrease the measurement errors in variables that are directly related to pest-control efficiency as well as reduce the resulting impact on the environment.**

Keywords*—Real-time processing; Failure and reliability; Calibration of sensors; Agricultural sprayers; Decision-making support; CAN bus; Precision farming.

I. INTRODUCTION

Embedded sensor systems are computer-based systems that can be part of larger systems. The former perform some of the requirements of these larger systems. The majority of such embedded systems are also characterized as real-time systems. These systems, especially in agriculture, are required to meet stringent specifications for safety, reliability, availability, and other attributes of dependability [1]-[3].

The high complexity of embedded real-time systems results in increasing demands with respect to engineering requirements, high-level design, early error detection, productivity, integration, verification, and maintenance, which increases the importance of the efficient management of its life-cycle properties, such as maintainability, portability, and adaptability [4].

The constructive design of dependable distributed real-time systems using pre-validated components requires precise interface specifications of the components in the temporal and value domains [5]. The digital transformation and its impacts on agricultural automation have been providing, from the technological point of view, tools for risk-management development based on the use of the agriculture 4.0 concepts [6]–[9]. Such an approach facilitates the rational use of agricultural inputs and the promotion of paths for realizing improved productivity and sustainability gains.

Today, not only in scientific research areas but also in the agricultural industry, it has become possible to use scalable computational architectures, mainly those based on embedded and smart ones [10]. Such architectures have the potential to comprise multiple processor nodes with the use of language to allow the implementation of new integrated risk models. Without agricultural mechanization and its advanced automation, it will be practically impossible to meet such needs and provide solutions for realizing food and nutrition safety [11]-[15].

The automation of agricultural machinery is an intensive area of research and development with an emphasis on the enhancement of food quality, preservation of operator comfort and safety, precision application of agrochemicals, energy conservation, and environmental control. Current automation applications are oriented towards and assist in the attainment of environment friendly and more sustainable systems of agricultural and food production [16][17]. The global mechanization of farming practices has revolutionized food production, thus enabling it to keep pace with the global population growth [18][19].

In terms of the current technology development for agriculture, there is a need for more investments, system innovation, and a better understanding of how people and machines can interact to each other. In addition, almost every piece of agricultural equipment comprises sensors and controls these days, and a number of sensing technologies are used in agriculture for providing data that help farmers monitor and optimize crop cultivation. In such a context, the assessment of sensor failure and reliability is important for machinery design engineers and researchers.

The methodology for assessing sensor reliability has adaptive aspects and should be customized as a function of the sensor application. In agriculture, for instance, the design of embedded electronic-sensor-based systems in machinery for field operation has been shown to require the inclusion of failure and reliability evaluations. Thus, three general approaches for designing such sensor-based systems can be considered: system failure owing to uncalibrated sensors, system-failure rate prediction, and physics-of-failure reliability assessment [20]-[23].

In general, the sensors in an agricultural sprayer are organized in sensor networks. If using the concept of redundancy, the failure of a single device may not be critical to the pesticides application. However, when failures occur in sensors, the consequences are likely to be disastrous, particularly in the case of 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 related economic aspects and the plant's health, but also its effect on the environment. The cause of such a failure must be determined as soon as possible; otherwise, the negative consequences could become more widespread [24].

The droplets sprayed during a pest control process are of different sized, and a percentage of the liquid volume is sprayed as fine droplets, regardless of the nozzle model used. However, the droplets should be of uniform size in order to realize the necessary efficiency for pest control. Similarly, some parameters are used to analyze the spectrum of the droplet size of sprays, such as the Volume Median Diameter (VMD) and the Coefficient of Variation (CV). The analysis of the spectrum uniformity comprise the use of the values of terms presented in $DV_{0.1}$, $DV_{0.5}$, and $DV_{0.9}$, which represent the droplet diameters such as the percentage of cumulative spray volume, which means, equal to 10%, 50% and 90% respectively. The diameter of 50% of the cumulative volume ($DV_{0.5}$) represents the VMD of a pesticide spray's application.

The uniformity of the droplet distribution is not only dependent on internal machinery parameters but also on external factors. The internal parameters are related to the sprayer machinery, i.e., the temperature and pressure of the syrup in the sprayer's boom, as well its flow in the nozzles [25]. The external factors are mainly related to the strength of the wind and its direction as well as the ambient humidity and temperature [26]. Although the internal factors can be controlled, the external ones cannot be controlled, and the latter contribute to the drift effect, which is undesirable. Nevertheless, such an effect can be minimized by selecting the type of nozzle based on the type of application required for the pest control management of an agricultural crop [27].

However, it should be noted that the internal sprayer's variables play an important role for the efficiency of the pest control process and should be correctly adjusted and controlled. Two terms that serve to express uniformity are the Extension (E_x) and Relative Amplitude (RA), which quantifies the range that covers 80% of the spray volume, and a comparative index respectively. The higher the value of the RA, the more heterogeneous is the spray spectrum, which implies a lower distribution uniformity.

Figure 1 presents three different results of pesticide applications for pest control that have the same VMD but different uniformities and RA values [28][29]. It can be observed in Figure 1(a) that the application has good homogeneity as the sizes of the drops applied are very similar, thus indicating a low variation in the size of the drops. This indicates that this pesticide's application process is more effective in contrast to that presented in Figure 1(c), which shows very small drops and very large drops, which can affect the quality of the pesticide's application process. In Figure 1(b), an intermediate result is presented, which can also occur during the pesticide's application on a real agricultural field.

According to the records, isolated component evaluations of sprayers have been performed since the 1940s, but only in the 1970s did technical inspection programs emerge [30]. Around 1960, the implementation of the first Sprayer Inspection Project began in Germany. In 1969, other countries, such as Italy, began to perform inspections and, since then, the improvement of quality and the reduction of the negative impacts of these applications were observed [31]. There exist reports that state that agricultural sprayers have been inspected since 1991 in Norway [32]. The periodic inspection of sprayers implemented in Europe, in addition to the verification of reliability demonstrate the importance of the educational process [33]. In Belgium, obligatory inspections have been performed on agricultural sprayers in use since 1995, with the main objectives set as the maintenance of the equipment and the education of applicators [34][35]. In a project executed in Spain's Valencia region, the inspected sprayers were divided into operative or non-operative as a function of their condition of use [36]. In Argentina, a survey conducted in the 1990s indicated the need for the technical maintenance of spraying machines because the majority of them were malfunctioning [37].

In Brazil, the first sprayer inspection was performed in 1998, where an evaluation was performed in the State of Paraná, and inadequate working conditions of the pressure gauges of some of the sprayers were observed [38]. Today, in several countries, periodic sprayer inspections are performed, and various groups of researchers have reported that the best conditions for the use of sprayers are closely related to their constant maintenance. In such a context, the uniformity of the spray distribution realized by the sprayer boom, working pressure, temperature of the mixture, and volume of the pesticide, which should be adjusted for effective pest control [39]-[43], play important roles in realizing the best conditions for the use of sprayers.

Currently, agricultural spraying is used with a focus on precision agriculture, wherein 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 work focused on the quantification of the economics of the localized application (variable rate), it is common to observe improvements in the cost/benefit relation [44][45].

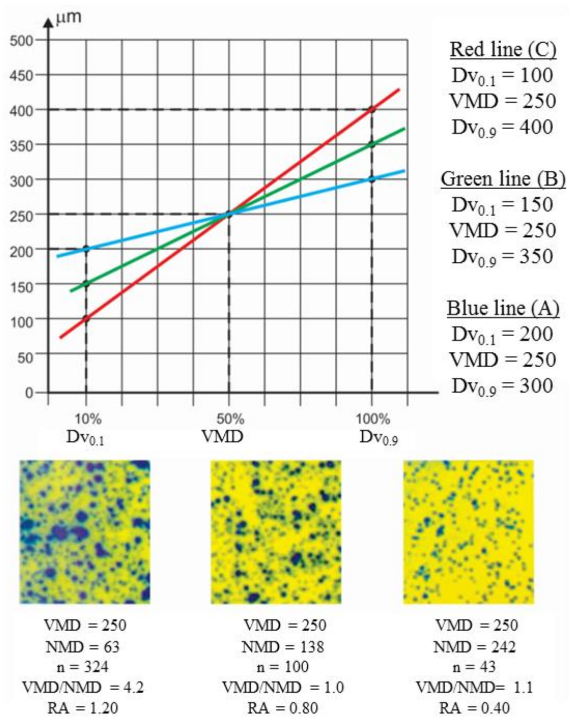

Figure 1. Examples of different uniformities observed for the pesticide's applications, with them all having the same VMD but with differences in the distribution and RA values. The values of $DV_{0.1}$, VMD, and $DV_{0.9}$ should be observed (adapted from [28] and [29]).

Variables, such as the temperature, flow, and pressure of the pesticide in a sprayer, have a direct influence on these results, thus affecting the volume and distribution of the drops in the plantation, which directly influence the efficiency of the application. If there is no control over volume and distribution of the pesticide drops, wastage of the pesticide can occur. Extremely fine drops can be carried by the wind, thus spreading and contaminating the environment, which characterizes the drift phenomenon. Extremely large droplets—although they reduce the occurrence of drift—provide less coverage of the application target because the pesticide volume that the leaves of crops can hold is limited by their size [46][47]. Therefore, it is important to know the precise values of the variables of temperature, pressure, and flow to have greater control over the application of these agricultural products. For the automation of those sprayers processes, embedded computer systems are currently being used.

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

When performed properly, a periodic evaluation of the sensors' calibration or even a verification of the electronics used for signal processing can rectify mistakes, and network robustness can be established. In addition, the 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 of agricultural sprayer devices during their operation are presented herein. The presented concept and the obtained results can be used in various sprayers' modalities and can make improving their reliability possible in relation to the sensor calibration, which defines the quality of the application of pesticides. As the control circuits rely on the feedback from voltage/current sensors, the performance of the whole system used for the pesticide application is likely to be affected by the sensors' failure rates, dynamic characteristics, and signal-processing circuits. This approach proactively incorporates reliability into the process by establishing a method of verifying the calibration of the sensors, i.e., including verification modules for important variables of the spraying process in an unsupervised and automated interface.

This work has been focused on the temporal specification of interfaces in composable distributed real-time systems, and four principles of composability have been established, which include the independent development of nodes, stability of prior services, performability of the communication system, and reduplication of the determinism.

This system presents the temporal firewall interface that forms a fully specified operational interface for failure and reliability evaluation in agricultural sprayers. This paper explains how the temporal firewall interface supports the four principles of composability. The interfaces are then classified from the point of view of composability, and how these interfaces correspond to the time-triggered and event-triggered communication paradigms is demonstrated.

After this introduction, there is Section II, which describes the materials and methods used in this study. In Section III, the results obtained are discussed, and the conclusions are presented in Section IV.

II. MATERIALS AND METHODS

To design the module to be developed 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 the validation of the developed module, 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 [48]. This platform is used for sprayer development and performs analyses 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, a modular input/output system and a complete software tool chain for programming applications. This ASDS is 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 comprises hydraulic devices used to develop 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 2).

Figure 2. ASDS dedicated to the application of liquid agricultural inputs.

The ASDS platform comprises 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 via a graphical user interface (GUI), where the user can interact with the digital devices via graphical elements with icons and visual indicators, thereby allowing them to select and manipulate symbols to obtain a practical result.

For the organization of a reference database comprising accurate reference values for flow, pressure, and temperature, calibrated and high-precision sensors were used. The sensors were subjected to known temperature, pressure, and flow conditions to obtain voltage values related to these conditions. In such a context, it was important to observe the droplet size (Table I), which influences the effectiveness of the spraying in covering the target and penetrating the leaves into a plant. Smaller droplets have a better coverage capacity, i.e., they offer a greater drops/cm^2 value). Furthermore, smaller droplets provide greater penetration capability and are recommended when good coverage and penetration are required. However, smaller droplets can be more sensitive to evaporation and drift processes. In productive agricultural systems, in general, large drops are preferred for the application of herbicides, such as glyphosate, while fine droplets are preferred in the case of insecticides, fungicides, and other products of less systemicity.

The extant technical literature comprises broad-nozzle descriptions, their recommended use, the selection of the proper nozzle type, and calibration method. However, any modification in the values of the temperature and pressure on the boom will change the drop characteristics, i.e., the sprayer´s operation.

Although the appropriate selection of the nozzle type is relevant, is also very important to take into consideration the technology for pesticides application. Therefore, the whole sprayer system is involved in the application process, not only in determining the amount of spray applied to an area, the uniformity, and the coverage, but also the target and the potential amount of drift. Furthermore, during operation, the nozzles facilitate the breaking of the mixture into droplets and also propel the droplets in the appropriate direction. Drift can be minimized by selecting the response time of the sprayers, the best time for applications with respect to climatic conditions, the controllers, which are used to obtain the optimal pressure or even the optimal volume, as well as the nozzle that produces the required droplet size while providing adequate coverage at the intended application rate.

TABLE I. SPRAY TIP CLASSIFICATION BY DROPLET SIZE (BASED ON THE STANDARD ASAE S-572)

Classification category	Symbol	Color code	Approximate VMD (μm)
Very Fine	VF	Red	<100
Fine	F	Orange	100-175
Medium	M	Yellow	175-250
Coarse	C	Blue	250-375
Very Coarse	VC	Green	375-450
Extremely Coarse	XC	White	>450

It is still important to observe and take into consideration that even when a tip predominantly produces large drops, there exists a small portion of fine droplets in the applied volume.

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 in order to realize the synchronization. The CAN bus was developed by Bosch [49] as a multimaster, message broadcast system that specifies a maximum signaling rate of 1 Mbps and wherein the modules can act as masters and slaves depending on their use [50]. This protocol works with multicast messages, wherein all the modules connected to a network receive all the sent messages. The connected modules check the status of the bus and determine whether another module of a higher priority is not sending messages; if this is observed, the module whose message has the lowest priority interrupts the transmission and allows the highest-priority message to be sent.

Communication in a CAN network, in version 2.0A, occurs through messages or frames, which can be of the following types: data frame, remote frame, error frame, or overload frame. Each type of frame has specific internal fields, which are relevant to the information to be sent. The data frame in a CAN 2.0A network (Figure 3), which is of interest in this work, consists of five main fields:

(1) The arbitration field includes the identifier (ID; 11 bits) used to identify the message and solve problems related to message collisions; in such a context the remote transmission request (RTR; 1 bit) indicates whether it is a data or remote frame.

(2) The control field includes the extended ID (IDE; 1 bit), which indicates whether the frame has an ID of 11 bits (standard) or and 29 bits (extended). Furthermore, it comprises the r0 (1 bit), which is reserved for future modifications, and the data length code (DLC; 4 bits), which is used to convey the number of bytes of the data frame.

(3) The data field is named Data (0–8 bytes) for the transmitted message.

(4) The cyclic redundancy check (CRC; 15 bits) field is used to detect transmission errors.

(5) The fields acknowledge slot (ACK; 1 bit) has the function of indicating the time for which the transmitter waits for the indication that some node in the network has received the frame successfully.

It should be noted that the message or frame also has signals for start of frame (SOF; 1 bit), which indicates the beginning of a transmission, and end of frame (EOF; 7 bits), which is used to convey the end of a transmission. In addition, two more delimiters are also available: one for the CRC and the other for the ACK, both having 1 bit each.

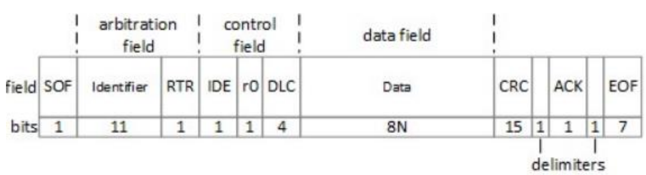

Figure 3. CAN 2.0A data frame for standard message identifier (11 bits). Both the ID and IDE bits are always 0.

The anti-collision mechanism based on the arbitration field, which allows the efficient exchange of messages in the CAN, implies additional attention for the network design. Such a requirement is to allow all “nodes” to transmit their messages at the desired time. Therefore, during the network design, it is necessary to consider the time for which each frame uses the CAN bus as well as the priority of each message or frame in order to avoid overloading the bus. In addition, with the increase in the network complexity and data traffic, it is necessary to analyze the Worst Case related to the Transmission Time (WCTT), which is the longest time gap between the queuing of a message and the arrival at the destination [51][52].

One of the main contributions of this work is a methodology for guaranteeing the validity of the variables measured using a calibration module. For such a purpose, a CAN network was implemented at a laboratory scale, wherein the traffic time in the network can be neglected in relation to the sample rates of the variables, thus ensuring the exchange of messages in real time. For this, the network bit rate was adjusted to 500 kbps and both the bus load and traffic time variation of each message in the bus were analyzed using the NI-CAN USB 8473 from National Instruments.

In networks of greater complexity, it is necessary to use other methodologies such as intelligent scheduling or dynamic ID allocation, and in the case of a control system, it may be necessary to compensate for the delay times [53].

The method used 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 value of another variable (x). This type of regression is used in 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 [54]. This technique follows the same steps as those of linear regression but comprises the use of a concept based on Eq. (1).

$$y = a_0 + a_1 x + a_2 x^2 + \cdots + a_m x^m + e \qquad (1)$$

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 that used in the least-squares method, but the error is now represented by a function of degree greater than 1, as shown in Eq. (2).

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

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

Subsequent to the construction of a database comprising precalibrated values along with a mathematical model obtained, as mentioned earlier, an intelligent calibration and correction system can be applied 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 using the results obtained from the use of the models. Thus, using this comparison method, the system can determine whether a sensor is calibrated, i.e., the same concept can be replicated for each monitored variable. Furthermore, either a real-time recalibration can be performed or the sensor can be replaced, if necessary.

The methods of comparison comprise the use of the relative change, Euclidean distance (ED), Root Mean Square Error (RMSE), and percent error [55]. The ED and RMSE methods were used in the developed solution. For the comparison of the measured values of the variables, the ED takes into consideration the distance between two points that can be calculated via 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 shown in Eq. (3).

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

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). The residuals are a measure of how far the data points are from the regression line, and based on such a concept the RMSE represents the standard deviation of the residuals (prediction errors). Thus, it indicates how concentrated the data are around the line of best fit and is given by Eq. (4).

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

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

In addition, an accurate power supply is used because such a system will be used not only for the verification of the sensors' calibration, but also their possible failure and reliability. For the 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.

The majority of 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 [56]. At this point, the accuracy and stability of the reference directly influences the conversion performance.

In agricultural spraying systems, the most commonly used sensors are as follows: (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 in which 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 these values back to the spray quality control system.

The CAN controller comprises a hardware implementation of the CAN's protocol, and it is responsible for all the access control to the bus and for controlling not only the message arbitration but also the transmission rate. In this manner, the users are required to define the types of messages that will be sent and program the recorders.

The transceiver used was manufactured by NXP-Philips Semiconductors. It was used because it is fully ISO11898 compatible and supports high-speed CAN. It can also act as the entire interface between the network and the physical bus [57]. 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 power supply is applied at pin 2, and the ground potential (GND) is connected to pin 3. Pin 8 of the transceiver is called the "silent mode," and, if a 5-V voltage is applied at this pin, the mode is activated, thus preventing the component from sending CAN messages to the bus.

If no voltage is applied at this pin, the transceiver operates normally. Pin 5, named Voltage-Reference (VREF), provides the average CAN bus voltage, and pins 1 and 4, named TXD and RXD, respectively, are responsible for receiving or sending the serial signal that is used by the CAN controller to decode the CAN messages. 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 manner, 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 4 presents both the CAN arrangement and 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. However, it is able to transmit messages in the CAN2.0A and B standards, that is, 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 the necessary instructions for writing and reading the registers. Each register has a byte for address that is used via 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 address

Figure 5 presents the integration of the Arduino-based architecture and a CAN with the sensors (temperature, pressure, and flow) in the sprayer system. The module that comprises the Arduino platform is a low-cost, functional, and easily programmable device. 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 universal serial bus cable and is programmed using free software called Arduino IDE (integrated development environment) and a language based on C/C++. The Analog-to-Digital (A/D) converter inputs, having a 10-bit resolution for a considered voltage range from 0–5 V, were used to read the signals related to the pressure and temperature sensors, which were obtained after the signals were correctly conditioned. The flow sensor used already has a digital output and its reading was obtained via timer 1 of the Arduino, which has a resolution of 16 bits.

Furthermore, it was configured as a counter, and in this manner, a reading was obtained at intervals of 50 ms.

Figure 6 depicts the software structure for the sensors' monitoring as well as the spraying process for the failure and reliability analysis. First, all sensors are tested in relation to failure. The process of monitoring the operation of the agricultural sprayer in real time is then started and is periodically repeated.

The flags are used to alert the operator of the operational status. Either the group of sensors or 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.

As a function of the measured values of the variables, such as the flow, pressure, and temperature, a verification is performed periodically to determine whether the sprayer is operating adequately or if there is need for the adjustments of these variables. Such a 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 via the software. To obtain information regarding the operational conditions, a set of flags is used for signaling by the GUI. In addition, if a sensor is required 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, the CAN protocol has been used because its advantages involve data communication and the use of only two wires, which reduces its cost and facilitates its 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 CAN controller (MCP2515) dedicated to translating the signals made available serially by the transceiver were used [58].

III. RESULTS AND DISCUSSION

The sensors that generate analog signals were connected directly to the calibration module, which analyzed and corrected the data obtained through the algorithms. The data were then 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 of the intelligent calibration and correction was performed using the Arduino-based architecture and the algorithms with the use of mathematical models. When the algorithm was 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 those of the reference model 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 outside the typical range of the sensors, there was an indication for sensor replacement, and the user was informed via a flag. There was a specific flag for each type of sensor, i.e., FLAG#1, FLAG#2, and FLAG#3, respectively, for the sensors used for the flow, pressure, and temperature measurements.

Reliability is an important performance index of agricultural sprayers. A paradigm shift in the reliability research of agricultural sprayers has resulted in the publication of 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 7.

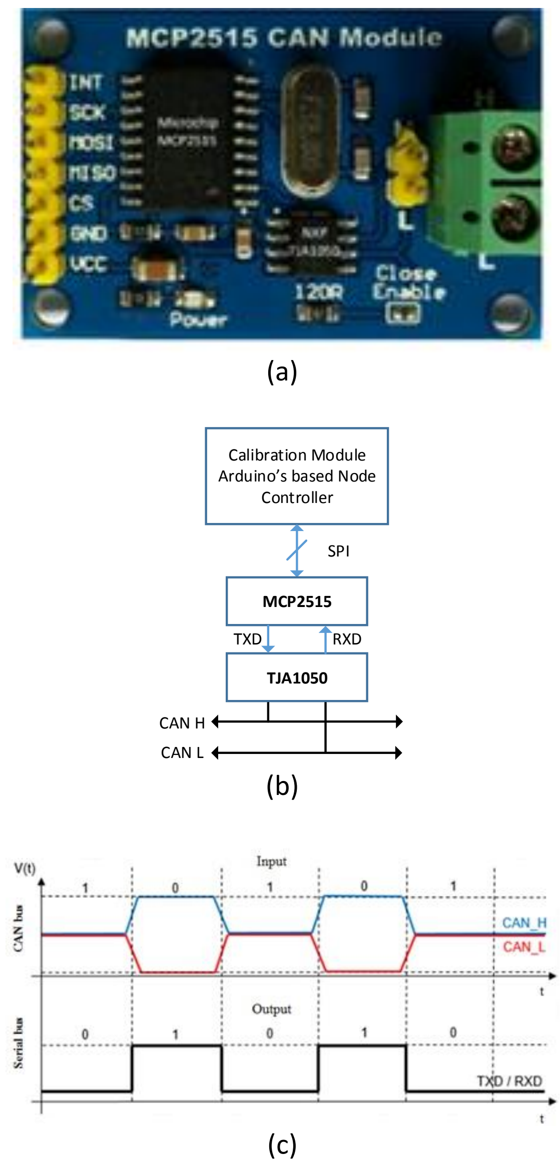

Figure 4. (a) Arduino CAN bus shield (MCP 2515); (b) block diagram of the structural architecture for the operation; and (c) input and output diagram of the TJA1050 transceiver.

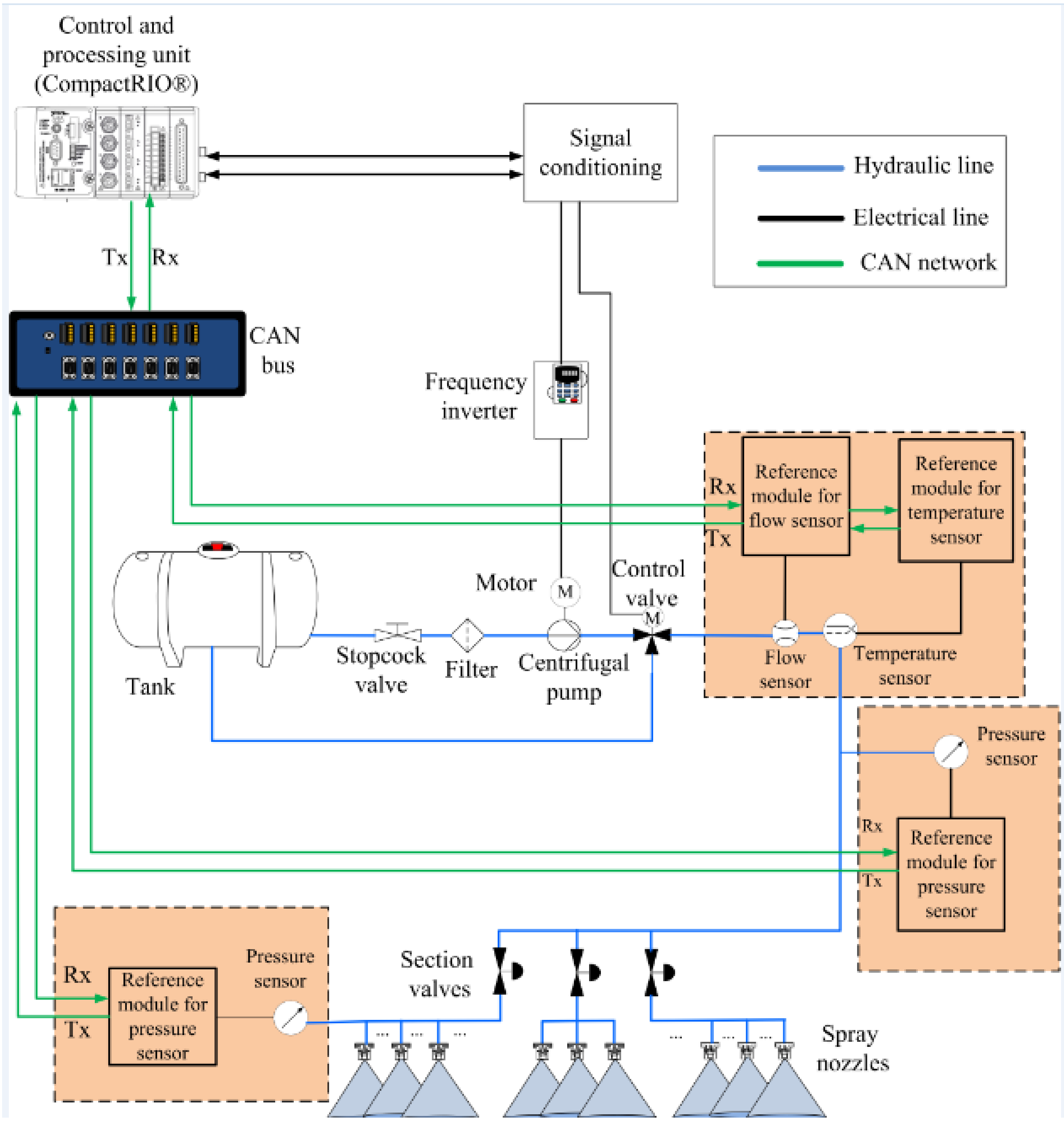

Figure 5. Block diagram of the sprayer system, in which the electrohydraulic configuration and the CAN network can be seen: in the red blocks are the modules based on the Arduino architecture, one for each sensor's modalities, for measurements of flow, pressure, and temperature.

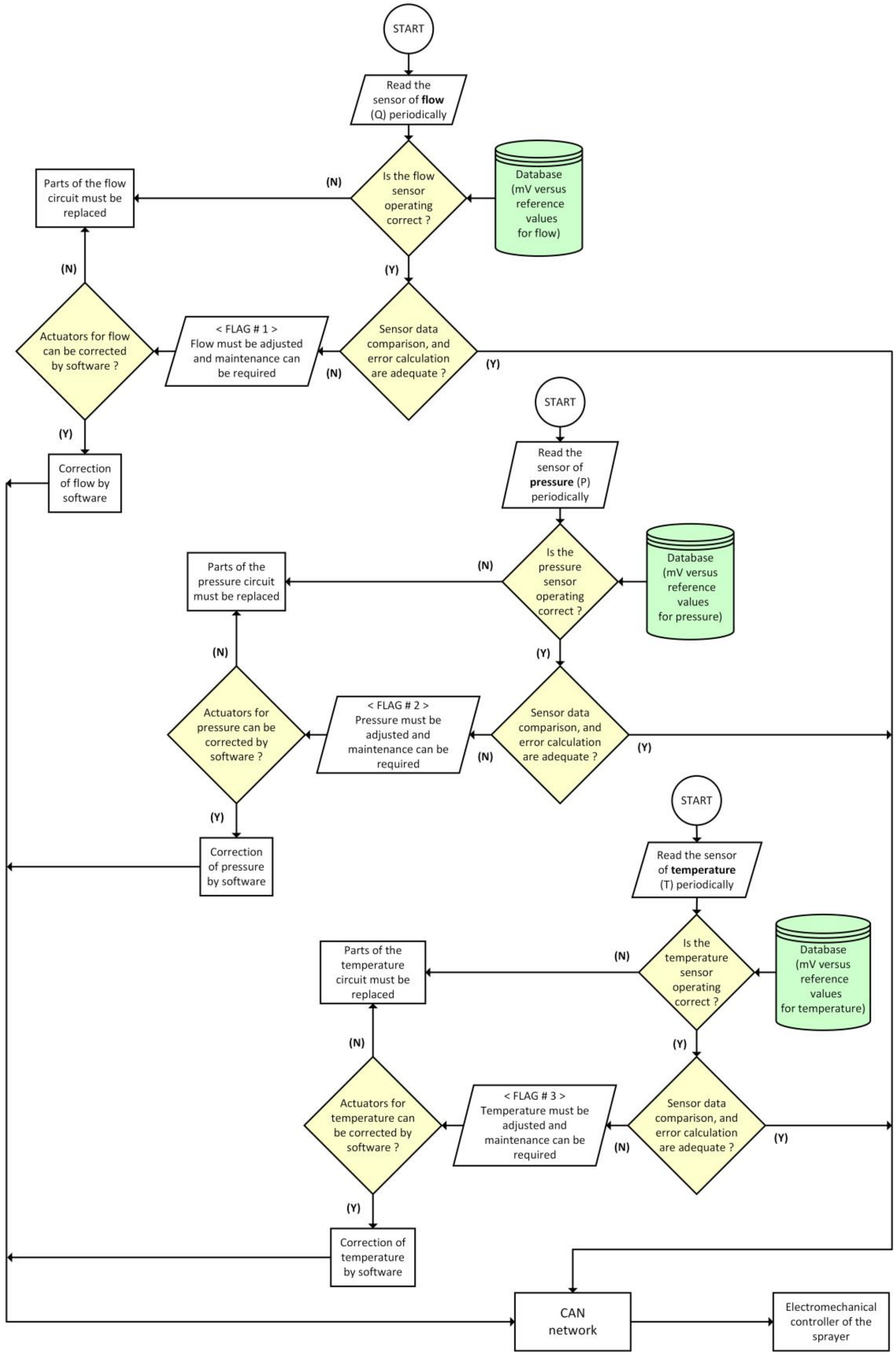

Figure 6. Software structure for monitoring the sensors used for measurements as well as the process used for spraying for the failure and reliability analyses.

For the flag structure, the context of sensitivity and specificity was used to summarize the performance of a diagnostic test with outcomes that determined the level of a standard for operation. When the test was quantitative, the receiver operating characteristic curves were used to display the performance of all the possible cut points of the quantitative diagnostic marker. Attention was focused on 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 in advance.

Table II lists the results as evidence of the successful 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 used to find and guarantee that an approved safety element of an agricultural sprayer reliably or consistently functions in accordance with the manufacturer specifications. Furthermore, the robustness margin is based on the formulation of the robustness requirements in the agricultural industry. These tests do not require specific, detailed uncertainty models, and, hence, these margins can be evaluated based on the interpretation of the analyzed 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 the loss of its hydraulic characteristics and purpose. Similarly, the design specifications and performance tests are typically related to the performance specifications. Besides, the specifications are written in projects and should be observed when implemented. The design specifications for a piece of machinery are straightforward in relation to its purpose and application.

Destruction level	**Design Specification (Performance tests)**	**Robustness margin**	**Safety (Approval tests)**	**Optimal operating point**

Figure 7. Structure of the flags, in which the operational conditions of the sprayers based on the flow, pressure, and temperature as well as the constraints can be observed.

TABLE II. 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 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 the decision making for realizing an accurate and adequate operation. In the same manner, the concept of the destruction level is related to the region wherein one can identify risks to the machinery's lifetime 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 [59]. The electromagnetic flowmeter had a measuring range of 5–100 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 a reading at a related frequency in Hertz. With the aid of the Arduino and the developed 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 8).

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 the Arduino and the developed software, considering intervals of 0.15 bar for a useful operating range of 0.5 to 3.0 bar, reference pressure values were sent to the pressure sensor, and the values obtained were recorded (Figure 9). In addition, to obtain a reference database with accurate temperature values, a calibrated sensor, type PT 100 of the Mit-Exact brand, was used, which was initially dipped in a beaker of 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 manner, it was possible to measure the unknown resistance of the sensor. The values were recorded at intervals of 5 °C, i.e., while taking into consideration an experimental range for the evaluation of different levels of the sprayer operation (Figure 10).

According to the flag structure for each variable, it is possible to perform, 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 provide a recommendation for a sensor's replacement.

The prognostics and fault-tolerant strategies for reliable field operation can thus be obtained.

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

To illustrate the flexibility of the network used, Table III shows how the CAN messages were assembled.

TABLE III. CAN MESSAGES STRUCTURE AND TRANSMISSION INTERVAL

Sensor	CAN ID	DLC	Data (number of bits)			Transmission interval
Flow	100	3	LOW (8)	HI (8)	FLAG (2)	50ms
Pressure near flowmeter	101	3	LOW (8)	HI (2)	FLAG (2)	10ms
Pressure at boom	102	3	LOW (8)	HI (2)	FLAG (2)	10ms
Temperature	103	3	LOW (8)	HI (2)	FLAG (2)	10ms

As observed in Table III, the number of messages on the organized network is reduced. However, it is necessary to define a set of unique identifiers for each node. According to the resolution required for each variable, a number of bytes is allocated in the data frame, that is, as identified in the DLC field.

For example, the temperature and pressure variables are obtained via a 10-bit A/D converter, and, to maintain such a resolution, the data can be divided into two parts, LOW and HI, comprising 8 and 2 bits, respectively. However, the CAN controller does not transmit only the 2 bits that refer to the HI part of the data of interest. It transmits the total bytes, and this form of operation is indicated in the DLC field.

The transmissions of the flags along with the data facilitate the identification of the status of each sensor. In this context, it is important to note that, for each new node inserted, which implies a higher load on the bus, attention will be required to be focused to avoid instability in the CAN network, i.e., such a situation could result in a variable transmission time. Therefore, the WCTT must be kept in mind during the design of the control loop strategy in order to avoid destabilizing the control loop of a larger distributed architecture.

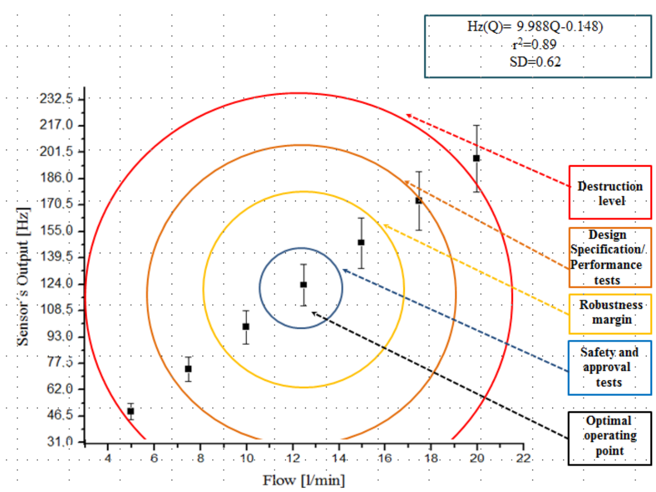

Figure 8. Reference curve for the flow sensor (electromagnetic flowmeter, model Orion 4621A300000) installed at the outlet of the water pump, and the experimental range results obtained for an agricultural sprayer's operation.

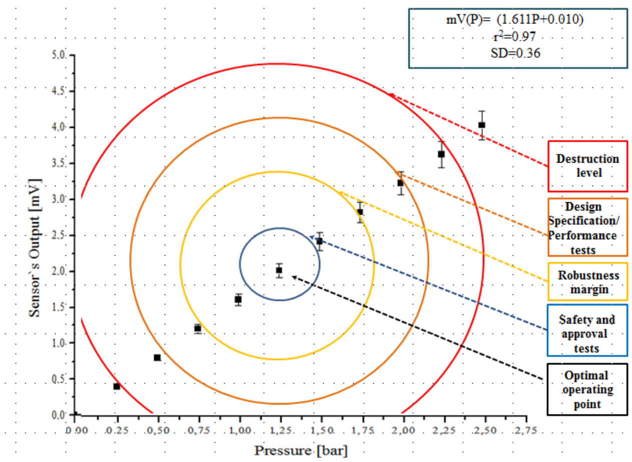

Figure 9. Reference curve for the pressure sensor (WIKA model A-10) installed at the boom, and the experimental range results obtained for an agricultural sprayer's operation.

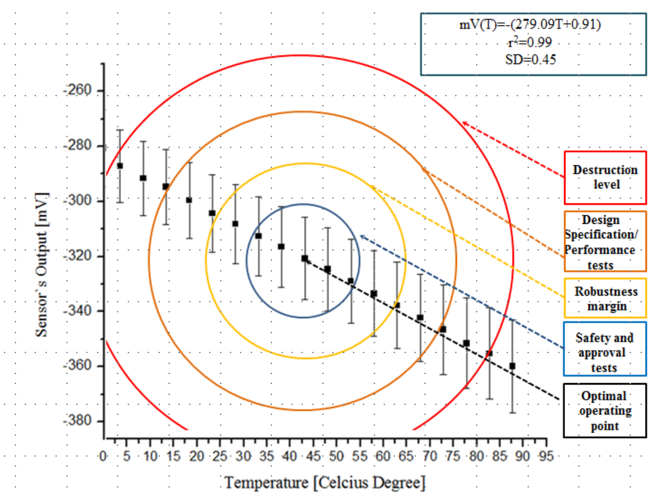

Figure 10. Reference curve for the temperature sensor (PT 100 of Mit-Exact) used to measure the temperature of the syrup, which is formed by adding the pesticides to water, and the experimental range results obtained for an agricultural sprayer's operation.

It is worth noting that, with the increase in the network complexity, it may be interesting to migrate to the latest version of CAN, known as CAN-FD (flexible data-rate), which allows a greater amount of data traffic than CAN 2.0, thus significantly reducing the load on the bus in terms of the utilization rate [60].

IV. CONCLUSIONS

An intelligent system for the evaluation of the failure and reliability of agricultural sprayers based on the sensors' information and a smart support decision-making architecture was presented. The obtained results showed that it is possible to observe real-time prognostics as well as to 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 while 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. The proposed topology demonstrated feasibility for the implementation of the calibration modules, i.e., it benefited from the CAN networks, which are becoming widely used in agricultural machinery, based on the SAE J1939 standards collection. Furthermore, there are opportunities for the realization of real-time monitoring and fault-tolerant design hat can facilitate an extended lifetime and reduced failure rate as well as a better understanding of the failure mechanisms because more failure-mechanism-specific accelerated testing can be designed, which can result in improved reliability predictions for sensor-based agricultural machinery and its applications.

ACKNOWLEDGMENT

This research was supported by the Brazilian Corporation for Agricultural Research (Embrapa), Process No. 11.14.09.001.05.06, and the São Paulo Research Foundation (Fapesp), Process No. 17/19350-21.

REFERENCES

[1] P. E. Cruvinel, E. A. G. Penãloza, P. B. Andrade1, and H. V. Mercaldi, "Real-Time Failure and Reliability Analysis of Agricultural Sprayers Based on Sensors, Arduino Architecture, and Controller Area Bus Protocol", Proceedings of the IARIA, SENSORDEVICES 2019: The Tenth International Conference on Sensor Device Technologies and Applications, Nice, France, 2019, pp. 38-48.

[2] N. Wang, N. Zhang, and M. Wang "Wireless sensors in agriculture and food industry-recent development and future perspective", Science directs, Computers and Electronics in Agriculture, vol. 50, pp. 1-14, 2006..

[3] O. Elijah, T. A. Rahman, I. Orikumhi, C. Y. Leow and M. N. Hindia, "An Overview of Internet of Things (IoT) and Data Analytics in Agriculture: Benefits and Challenges", IEEE Internet of Things Journal, vol. 5, no. 5, pp. 3758-3773, 2018.

[4] Q. Li and C. Yao, Real-Time Concepts for Embedded Systems, CRC Press, pp. 287, 2017.

[5] J. Lin *et al.*, "A Survey on Internet of Things: Architecture, Enabling Technologies, Security and Privacy, and Applications", IEEE Internet of Things Journal, vol. 4, no. 5, pp. 1125-1142, 2017.

[6] J. M. Antle, J. W. Jones, and C. E. Rosenzweig, "Next generation agricultural system data, models and knowledge products: introduction", Agricultural Systems, vol. 155, pp. 186-190, 2017.

[7] VDMA Verlag, Guideline Industrie 4.0, 2016. [retrieved: June, 2020]. Available from: https://www.vdma-verlag.com/home/artikel_72.html.

[8] L. Klerkx, E. Jakku, and P. Labarthe, “A review of social science on digital agriculture, smart farming and agriculture 4.0: New contributions and a future research agenda”, NJAS - Wageningen Journal of Life Sciences, vol. 90–91, pp. 16, 2019. [retrieved: June, 2020]. Available from: https://doi.org/10.1016/j.njas.2019.100315.

[9] D. C. Rose and J. Chilvers, “Agriculture 4.0: Broadenings Responsible Innovation in an era of smart”, Farming Frontiers in Sustainable Food Systems, vol. 2, Issue 87, pp. 23, 2018. [retrieved: June, 2020]. Available from: https://doi.org/10.3389/fsufs.2018.00087.

[10] K. Pohl *et al*., Model-Based Engineering of Embedded Systems: The SPES 2020 Methodology, Springer Verlag, pp. 300, 2012.

[11] Food Security Information Network (FSIN): *Global Report on Food Crises (GRFC 2019)*, pp. 202, 2019. [retrieved: June, 2020]. Available from: http://www.fsinplatform.org/sites/default/files/resources/files/GRFC2019FullReport.pdf.

[12] Food and Agriculture Organization of the United Nations: “Global agriculture towards 2050”, FAO, Rome, 2009.

[13] J. K. Schueller, “Automation and control”. In: CIGR Handbook of Agricultural Engineering, Information Technology, vol. VI, ed. by A. Munack (CIGR, Tzukuba) pp. 184–195, Chap. 4, 2006.

[14] T. Stombaugh, E. Benson, and J. W. Hummel, “Automatic guidance of agricultural vehicles at high field speeds”, ASAE Paper No. 983110 (ASAE, St. Joseph), 1998.

[15] M. Yitayew, K. Didan, and C. Reynolds, “Microcomputer based low-head gravity-flow bubbler irrigation system design”, Computer and. Electronics in Agriculture, vol. 22, pp. 29–39, 1999.

[16] F. R. Miranda, R. E. Yoder, J. B. Wilkerson, and L. O. Odhiambo, “An autonomous controller for site-specific management of fixed irrigation systems, Computer and Electronics in Agriculture, vol. 468, pp. 183–197, 2005.

[17] S. Fountas *et al*., *“*Farm management information systems: current situation and future perspectives”, Computer and. Electronics in Agriculture, vol. 115, pp. 40-50, 2015.

[18] C. G. Sørensen *et al*., *“*Conceptual model of a future farm management information system”, Computer and Electronics in Agriculture, vol. 72, Issue 1, pp. 37-47, 2010.

[19] A. Kaloxylos *et al*., “Farm management systems and the future internet era”, Computer and Electronics in Agriculture, vol. 89, pp. 130-144, 2012.

[20] M. Pecht and V. Ramappan, “Are components still the major problem: a review of electronic system and device field failure returns”, IEEE Transaction on Components, Hybrids, Manufacturing Technology, vol, 15, pp. 1160-1164, 1992.

[21] C. T. Leonard, “Mechanical engineering issues and electronic equipment reliability: Incurred costs without compensating benefits”, Journal of Electronic Packaging, vol. 113, pp. 1-7, 1991.

[22] A. Bar-Cohen, “Reliability physics vs reliability prediction”, IEEE Transaction on Reliability, vol. 37, pp. 452, 1988.

[23] P. D. T. O’Connor, “Reliability prediction: Help or hoax?”, Solid State Technology, vol. 33, pp. 59-61, 1990.

[24] H. V. Mercaldi, E. A. G. Peñaloza, R. A. Mariano, V. A. Oliveira, and P. E. Cruvinel, “Flow and Pressure Regulation for Agricultural Sprayers Using Solenoid Valves”, In: International Federation of Automatic Control (IFAC), Elsevier, vol. 50, Issue 1, 2017, pp. 6607-6612, doi.org/10.1016/j.ifacol.2017.08.693.

[25] A. Marangoni Junior and M. C. Ferreira, “Influence of working pressure and spray nozzle on the distribution of spray liquid in manual backpack sprayers”, Arquivos do Instituto Biológico, vol.86, 2019. [retrieved: June, 2020]. Available from: https://doi.org/10.1590/1808-1657000442018.

[26] T. Arvidsson, L. Bergström, and J. Kreuger, “Spray drift as influenced by meteorological and technical factors”, Pest Management Science, vol. 67, Issue 5, pp. 586-598, 2011.

[27] ASAE S572. Spray nozzle classification by droplet spectra. In: ASAE Standards, St. Joseph, pp. 389-391, 2000.

[28] J. C. Christofoletti, Shell manual of machinery and techniques for the application of pesticides, (original in Portuguese Language: Manual Shell de máquinas e técnicas de aplicação de defensivos agrícolas), São Paulo, Shell, pp.124, 1992.

[29] D. L. Reichard, H. E. Ozkan, and R.D. Fox, “Nozzle wear rates and test procedure”, Transaction of the ASAE, vol. 34, no. 6, pp. 2309-2316, 1991.

[30] ISO 16122-2, Agricultural and forestry machinery – Inspection of sprayers in use – Part 2: Horizontal boom sprayers, ISO Publication, pp. 18, 2015.

[31] H. Ganzelmeier and S. Rietz, “Inspection of plant protection in Europe”. In: International Conference on Agricultural Engineering. Part II, Oslo. Proceedings, Eurageng, pp. 597-598, 1998.

[32] N. Bjugstad, Controlo of crop sprayers in Norway, Oslo: Ageng, Eurageng, 1998.

[33] M. A. Gandolfo, “Periodic inspection of agricultural sprayers” (original title: Inspeção periódica de pulverizados agrícolas). Doctoral Thesis, Faculty of Agronomic Sciences, São Paulo State University (UNESP), SP, Brazil, pp. 92, 2002.

[34] B. Huyghebaert *et al*., “Compulsory inspection of crop sprayers already in use Belgium”, Selection of control method, Madrid: Ageng, CD-ROM, 1996.

[35] P. Braekman *et al*., “Organisation and results of the mandatory inspection of crop sprayers in Belgium”, Belgium: Ministry of Small Enterprises, Traders and Agriculture, pp. 9, 2005.

[36] L. M. Val, “Programs for the formation of the applicators and equipment’s maintenance” (original title: Programas de formación de aplicadores y programa de revisión de equipos. In: Jornada Internacional en Tecnologia de Aplicacion, 2007, Proceedings, Montevidéo: Republic University, CD-ROM, 2007.

[37] J. C. Magdalena and A. P. Di Prinzio, “Calibration service for fruit growing sprayers in Black River and Neuquén” (original title: Servicio de calibración de pulverizadoras frutícolas en Río Negro y Neuquén), In: Congreso Argentino de Ingenieria Rural, Córdoba. Proceedings.... Argentina: National Cordoba University, vol. 2, pp. 137-148, 1992.

[38] E. Fey, “State of the art in relation to the spray process of the associates from the COOPERVALE” (original title: Estado de arte do processo de pulverização junto a associados da COOPERVALE), Supervised Internship Report Ponta Grossa State University, Maripá – PR, Brazil, pp. 26, 1998.

[39] J. Langenakens and M. Pieters, “The organization and first results of the mandatory inspection of crop sprayers in Belgium”, In: Aspects of applied Biology - Optimizing pesticide application, Agricultural Research Centre Ghent, pp. 233-240, 1997.

[40] S. Sartori, “Sprayers for tractor ground application” (original title: Pulverizadores para aplicação terrestre tratorizada), In: Simpósio Brasileiro sobre Tecnologia de

Aplicação de Defensivos Agrícolas, Jaboticabal, SP, Brazil, Proceedings... FUNEP, vol. 1, pp. 46-79, 1985.

[41] G. F. Dedordi *et al.*, "Technical-operational evaluation of bar sprayers in Pato Branco region" (original title: Avaliação técnica-operacional de pulverizadores de barras na região de Pato Branco), Acta Iguazu, Cascavel, PR, Brazil, vol. 3, no. 1, pp. 144-155, 2014.

[42] J. F. Schlosser, "Application technology and machine use: use of agrochemicals" (original title: Tecnologia de aplicação e uso de máquinas: uso de agroquímicos), Federal University of Santa Maria, Textbook - Technical Series, Module 5, 2002.

[43] F. Olivi and A. Simão, "In order to speed up the maintenance of sprayers, the diagnostic case provides technical support and spare parts" (original title: Com o objetivo de agilizar a manutenção dos pulverizadores, a maleta de diagnóstico dá suporte técnico e na reposição de peças). Agricultural News. [retrieved: February, 2020]. Available from: https://noticiasagricolas.com.br/videos/maquinas-e-tecnologias/.

[44] K. R. Felizardo, H. V. Mercaldi, P. E. Cruvinel, V. A. Oliveira, and B. L. Steward, "Modeling and model validation of a chemical injection sprayer system", Applied Engineering in Agriculture, vol. 32, Issue 3, pp. 285-297, 2016.

[45] X. Wei, S. Jian, and H. Sun, "Design and Test of Variable Rate Application Controller of Intermittent Spray Based on PWM", Journal of agricultural machinery vol. 43, Issue 12, pp. 87-129, 2012.

[46] H Liu, H Zhu, and Y Shen, "Development of digital flow control system for copy multi-channel variable-rate sprayers", Journal Transactions of the ASAE, vol. 57, Issue 1, pp. 273-281, 2014.

[47] American Society of Agricultural and Biological Engineers (ASAE) Standards: S572 - Spray nozzle classification by droplet spectra, no. 99, St. Joseph USA, pp. 389-391, 2000.

[48] P. E. Cruvinel *et al*., "An advanced sensors-based platform for the development of agricultural sprayers," In: Sergey Y. Yurish (Ed.). Sensors and Applications in Measuring and Automation Control Systems. [S. l.]: IFSA, pp. 181-204. (Advances in Sensors: Reviews; vol. 4), 2016.

[49] K. Etschberger, "Controller Area Network. Basics, Protocols, Chips and Applications", IXXAT, ISBN 3-00-007376-0, 2001.

[50] R. B. Gmb "CAN Specification, Version 2.0", Postfach 50, D-7000 Stuuugart 1, 1991. Imported into Framemaker 4 by Chuck Powers, BOSCH, Motorola MCTG Multiplex Applications, April 3, 1995.

[51] E. Godoy *et al*., "Design of CAN-based distributed control systems with optimized configuration", Journal of the Brazilian Society of Mechanical Sciences and Engineering, vol. 32, no. 4, pp. 420-426, 2010.

[52] B. Woonhyuk, J. Seyong, S. Hoin, K. Soontae, S. Bongsob, C. Dongkyoung, "A CAN-based Distributed Control System for Autonomous All-Terrain Vehicle (ATV)", 17th World Congress of The International Federation of Automatic Control, IFAC Proceedings, Seoul, Korea, vol. 41, Issue 2, pp. 9505-9510, 2008.

[53] J. R. Edwards, "Polynomial regression and response surface methodology," In: C. Ostroff & T. A. Judge (Eds.), Perspectives on organizational fit, pp. 361–372. San Francisco: Jossey-Bass, 2007.

[54] L. Tornqvist, P. Vartia, and Y. Vartia, "How should relative changes be measured?" The American Statistician, vol. 39, Issue 1, pp. 43–46, 1985.

[55] P. E. Danielsson, "Euclidean distance mapping," Computer Graphics Image Processing, vol. 14, pp. 227-248, 1980.

[56] T. Chai and R. R. Draxler, "Root mean square error (RMSE) or mean absolute error (MAE)? - arguments against avoiding RMSE in the literature," Geoscience Model Development, vol. 7, pp. 1247–1250, 2014.

[57] R. H. Walden, "Analog-to-digital converter survey and analysis", IEEE Journal on Selected Areas in Communication, vol. 17, no. 4, pp. 539–550, 1999.

[58] TJA 1050 Data Sheet – High speed CAN transceiver. Product specification, Integrated Circuits, Philips Semiconductors, pp. 18, 2003.

[59] ORION Electro-Magnetic Flow Meter. [retrieved: June, 2020]. Available from: mcpheeenterprises .com/orion-electromagnetic-flowmeter/.

[60] R. de Andrade *et al*., "Analytical and Experimental Performance Evaluations of CAN-FD Bus", IEEE Access. 10pp., 2017. [retrieved: June, 2020]. Available from: file:///C:/Users/HP/Downloads/v38-CAN-FD-Performance-10APR2018-Max2_Publicada.pdf.