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Smart and Customized Electrical Conductivity Sensor for Measurements of the Response Time from Sprayers Based on Direct Injection

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Abstract: In the application of herbicides on the basis of direct injection systems, spraying response time plays an important role for the quality of spraying, particularly when operating in real time. The response time is defined as the time elapsed from the time of injection until the concentration of the mixture (water mixed with herbicide) reaches 95 % of its regime value in the sprayer nozzles. In the response time, the transport delay and the rise time for achieving the desired concentration are considered. This paper describes an intelligent sensor mounted near the sprayer nozzles to measure the concentration response time in an herbicide direct injection system, which uses a highly stable sinusoidal excitation signal. The sensor calibration was performed with NaCl solutions at concentrations similar to those found in actual application conditions. Using an integrated system based on the Arduino platform, an algorithm was developed to relate the measurements to the response time. The integrated system comprises the sensor with its own sensing hardware, A/D converter, processing and storage capabilities, software drivers, self-assessment algorithms and communication protocols. The immediate application of the integrated system is in the monitoring of the response time of a precision herbicide application. The results point to the next generation of smart devices that have embedded intelligence to support decision making in precision agriculture. *Copyright © 2015 IFSA Publishing, S. L.*

Keywords: Intelligent sensor, Electrical conductivity, Direct injection, Response time.

1. Introduction

Brazil has experienced in the last two decades a significant increase in the use of pesticides for agricultural production. Despite the significant growth of the area cultivated with transgenic seeds, a technology that promises to reduce chemical use in agricultural production, sales of these products increased by over 72 % between 2006 and 2012 and is still rising up according to data from the Brazilian National Union of the Industry of Agricultural Defense Products [1], association which represents the pesticide manufacturers in the country.

In In the same period, the cultivated area with grains, fiber, coffee and sugar cane grew by less than 19 %, from 68.8 million to 81.7 million hectares, according to the Brazilian National Company for Supply [2]. This means that the average consumption of pesticides, which was just over 7 kilograms per hectare in 2005, rose to 10.1 kilograms in 2011, an increase of 43.2 %. Although this amount indicates more protection for products and higher incomes, the uniform rate of application leads to soil and water contamination. A key approach to reduce environmental pollution is to use variable-rate application.

An approach to develop variable-rate sprayer technologies is to install automation and control procedures in conventional sprayers. In order to adjust the sprayer operation, reference for variables such as working pressures, travelling speeds, and spraying concentration rates can be selected to achieve uniform drop size distribution.

The agricultural machinery and technologies available today allow chemical application variable rate based on prescription maps or sensors [3]. Variable-rate application can be performed by varying the concentration of the chemical on-the-go using a direct injection system [4]. The direct injection system is an electronically controlled system in which the chemical is injected into the carrier stream. The direct injection system has separated chemical and carrier reservoirs and the chemical can be injected into the carrier stream in different positions.

In the literature, reports of systems to inject concentrated pesticides into the carrier stream began to appear in the 70th decade [5]. In [6], Vidrine and collaborators tested the feasibility of injecting concentrated pesticides. In [7], Reichard and Ladd developed a field sprayer which included injection of pesticides at specific rates accounting for variations in travel speed. In [8], Chi and collaborators developed a flow rate control system which allowed the measurements of concentrated pesticides. In [9], Ghate and Perry developed a field sprayer based on the use of a compressed air to inject chemical into the carrier stream. In [10], Miller and Smith reported the development of a direct injection system. In general, during the spraying process errors can be observed. Research works on the evaluation of the application rate errors have shown that errors are not only due to the deviations from the target flow rates but also due to interaction between the dynamics of the systems and sprayer response time. By now, is quite well known that the direct injection system sprayer response time depends on the sprayer dynamics and on the transport delay [11].

The transport delay is due to flow rates and distance of the nozzle from the injection point. The farther from the injection point the nozzle is, the larger the uniformity of the mixture, but the higher the transport delay of the sprayer. Several studies on the performance of direct injection sprayers and the response time have appeared [12-20]. Therefore, the conventional implements can be reorganized to operate in variable-rate using control systems [21].

An advantage of the injection rate application over pressure-based variable rate application is the ability to change the herbicide type as well as to perform on-line changes in the concentration [22]. The direct injection systems advantage is in the mixing of the required amount of chemicals with water, saving the excess amount for later use [23]. A key indicator to determine the precision of a direct injection sprayer is the control system response time. For sprayers, how much shorter the response time, much higher will be its field precision.

This paper presents the complete version of a smart and customized conductivity sensor (SCCS) for the evaluation of the response time of direct injection sprayers based on the electrical conductivity measurements. Previous discussions related to its development were presented in [24], and [25]. With the response time measurements in variable rate sprayers, a looking-ahead approach, which is useful to increase competitiveness and support sustainability in agriculture can be performed.

After this introduction, this paper is organized as follows. Section 2 presents the theoretical background on electrical conductivity; Section 3 presents the materials and methods for the development of the SCCS and the procedures for its validation. Finally, the results and discussions are presented in Section 4, followed by the conclusion in Section 5.

2. Theoretical Background

The electrical conductivity, also called specific conductance, is the ability of a solution to conduct an electric current. The mechanism for the electrical current conduction in electrolyte solutions is not the same as for metals. In liquids, this process is based on the movement of solvated ions, which are attracted by an electrical field. Therefore, the physical-chemical process is related to the occurrence of combination between the molecules of a solvent with molecules or ions of the dissolved substance. As electrolyte solutions obey Ohm's law in the same way as the metallic conductors, when powered by direct current passing through the body of the solution, the conductance denoted G is defined as the inverse of the resistance expressed in Ω^{-1} or Siemens (S). The conductance G of a homogeneous body having uniform section is proportional to the cross-sectional area of the conductor A and inversely proportional to the length of the conductor denoted by ℓ, that is:

$$G = \frac{\sigma A}{\ell}, \quad (1)$$

where the proportionality constant σ is the electrical conductivity given in S/m. The ratio ℓ/A is called the conductivity cell constant and depends on the instrumentation used. The conductivity increases with increasing temperature. Furthermore, the conductivity of a solution depends on the number of ions present and for this reason the most common is the use of the molar conductivity defined as:

$$\Lambda_m = \frac{\sigma}{M}, \tag{2}$$

where Λ_m is the equivalent conductivity or the molar conductivity in Sm^2/mol and M is the molarity or molar concentration in mol/L. The molar conductivity varies with the concentration of the electrolytes. The main reason for this effect is the change in the number or mobility of the ions present. The first case occurs in weak electrolytes, where the dissociation of ions in a solution is not complete. The second case occurs on strong electrolytes, where in the solution the dissociation of the molecule into ions is total, resulting in a very strong interaction between the oppositely charged ions, and can reduce its mobility.

The measurements of electrical conduction in ionic solutions are useful for a quick and routine analysis of solutions, since it is a simple measure related to the properties of the solution. In this context, the conductivity of a solution in a cell having an arbitrary dimension can be obtained by measuring the resistance of a solution of known concentration to determine the cell constant. After the cell constant is determined, the values of conductivities of different solutions can be obtained from experimental measurements data. For devices without automatic temperature compensation, the conductivity must be determined at the reference temperature.

The measurement of absolute values of conductivity requires the use of linear temperature compensation. Therefore, an electrical conductivity measured at room temperature can be corrected to one reference temperature, such per example, 25°C as follows:

$$G_{25} = \frac{G_\theta}{1+(\alpha/100)(\theta-25)}, \tag{3}$$

where θ is the room temperature, G_θ is the conductivity measured at room temperature and α is the temperature coefficient of variation in %/°C. Typical values for temperature coefficients are given in Table 1 [26].

Table 1. Typical temperature coefficients of substances.

Substance	α (%/°C)
Acids	1.0 to 1.6
Bases	1.8 to 2.2
Salts	2.2 to 3.0
Potable water	around 2.0

In solutions, yet it is necessary to correct the conductivity observed by subtracting the conductivity of the solvent, to get the value of $\sigma_{corrected}$. Therefore, the molar conductivity Λ_m shall be written as:

$$\Lambda_m = \frac{\sigma_{corrected}}{M} \tag{4}$$

Thus, turning the unit concentration mol/L to mol/cm^3, the equivalent conductivity Λ_m between two electrodes spaced 1 cm away due to 1 mol of substance may be given as:

$$\Lambda_m = \frac{1000\sigma_{corrected}}{M} \tag{5}$$

Then, for a parallel plate sensor, the conductance G can be determined based on the molar conductivity Λ_m. The corrected specific conductivity of the electrolyte is then given in terms of the total ionic concentration M (mol/cm^3) of the substance in the electrolyte solution and the equivalent conductivity. Therefore, by using the Equation (1), the conductance G can be found as:

$$G(A,\ell,\Lambda_m,M) = \left(\frac{\Lambda_m M}{1000}\right)\times\left(\frac{\ell}{A}\right) \tag{6}$$

Peck and Roth defined response time (t_T) as the period from the instant the injection begins until the chemical concentration rate reaches 95 % of the equilibrium rate [27]. The rise time (t_r) and transport delay (t_d) characteristics of a sprayer proposed by these authors are shown in Fig. 1. A 95 % concentration rate corresponds to the chemical concentration of the spraying, which is necessary for satisfactory weed control [28].

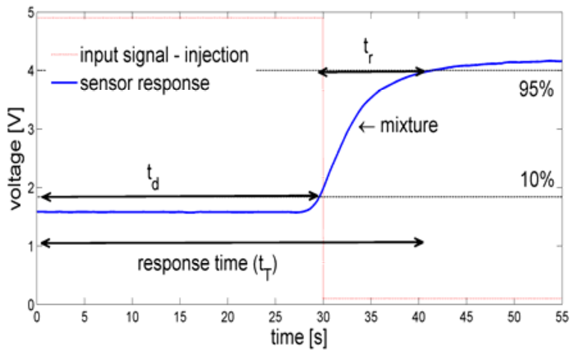

Fig. 1. Delay time (t_d), rise time (t_r), and response time (t_T) of a typical injection system as described in [27]. The dotted line indicates the time behavior of the concentrated mixture (water-NaCl) as a response to an injection input.

The response illustrated in Fig. 1 can be identified as a first order system plus delay time. The time response is given by:

$$T_r = T_d + 3T_c, \tag{7}$$

where $3T_c$ is the requested time to reach 95 % in concentration in relation of the steady state value, i.e., after T_d seconds [29].

3. Material and Methods

The injection sprayer systems can reduce applicator exposure to chemicals during the mixing and loading process. A direct injection sprayer has a typical control loop as shown in Fig. 2. In this figure, the upper blocks indicate the direct injection components and corresponding variables q_{href}, V_h, and q_h, which represent the set point for the chemical flow, controlled, and measured variables respectively. In the lower blocks, at the some figure, is possible to observe the sprayer components, which are described as q_{fref}, V_f, and q_m, which represent the set point for the mixture flow, controlled, and measured variables respectively. In this type of direct injection sprayer, the injection point is located upstream from the sprayer pump as presented in [30], and [31]. The water flow q_W is dependent of both the flow mixture q_m and the injection flow q_h. The customized smart sensor is assembled at the nozzle in the end of the boom to measure the flow mixture concentration, which is proportional to its output denoted v_{SCCS}.

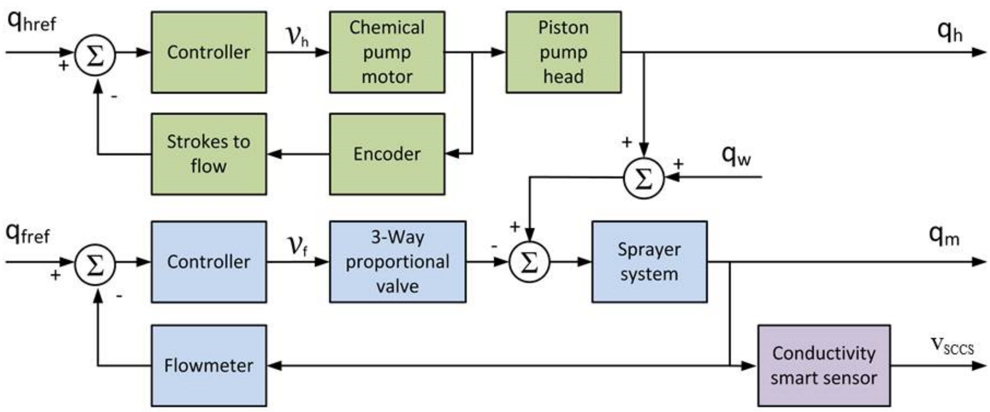

Fig. 2. Block diagram of herbicide and mixture control.

The components of the customized smart sensor designed to measure the response time in spraying systems using direct injection of pesticides are shown in Fig. 3. For the implementation of the smart sensor, voltage regulators, opto-isolators and filters, as well as an integrated circuit for signal generator having the capability of frequencies adjustment were used. Active analogue filters, non-inverting amplifier drives and isolators circuits were implemented with operational amplifiers.

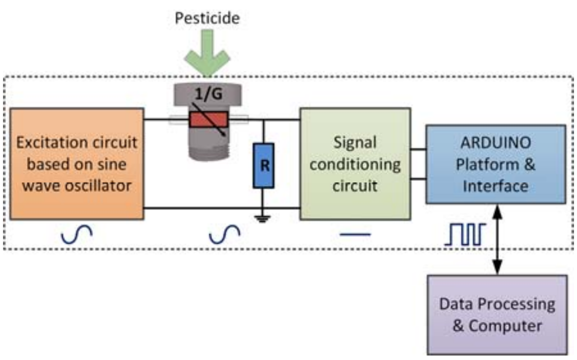

Fig. 3. Block diagram of the SCCS for response time measurements in spraying systems based on direct injection of pesticides.

3.1. Excitation Circuits

An excitation circuitry (Fig. 4) for the SCCS was implementing to provide a sinusoidal signal with appropriate frequency and magnitude. Such module was designed to produce signals with high stability and accuracy in an operating frequency range of 0.01 Hz to 1 MHz (Fig. 5).

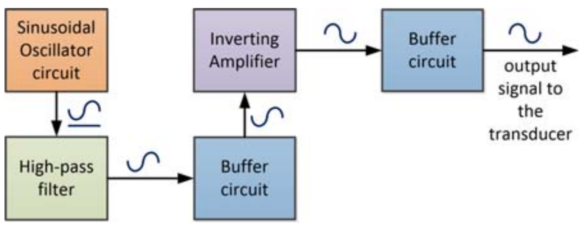

Fig. 4. Block diagram for the excitation circuitry.

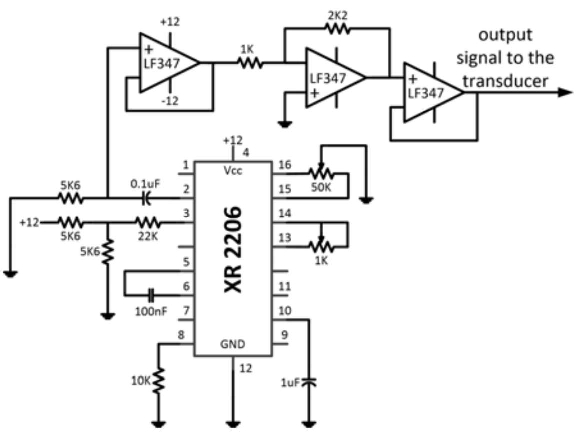

Fig. 5. The circuit of the excitation signal generator.

For the generation of the sinusoidal signal, an XR2206 integrated circuit, which produces sinusoidal signals with considerably low harmonic distortion, was used [32]. The oscillator frequency was set to 1.0684 kHz, which is suitable for the application and reducing the electrolysis and the polarization of the solution. In order to tailor the sinusoidal signal for the sensor application considered, a high-pass filtering and a signal amplification module were also used. After conditioning, the signal was appropriate for use presenting voltage limits as V_{max} = 4.96 V and V_{min} = -4.92 V.

The output signals of each of the stages of the excitation circuitry were analyzed using an oscilloscope (model TDS2012B, Tektronix®) and graphics were later built in Matlab® software.

3.2. Signal Conditioning

A signal conditioning circuitry was implemented to obtain a precise continuous voltage level with appropriate magnitude to be connected to an Arduino Uno platform. The Arduino Uno is an electronic prototyping platform, hardware open and single board, designed with an Atmel AVR microcontroller with built-in input-output support and a standard programming language with origin in Wiring projects, essentially based on C/C ++ [33]. The circuitry comprises a precision rectifier, a second order low-pass filter and an isolator buffer circuit (Fig. 6).

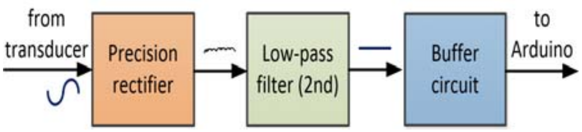

Fig. 6. Block diagram of the signal conditioning circuitry.

For signal conditioning (Fig. 7), the operational amplifier integrated circuit (model LF347), which presents broad bandwidth range (4 MHz), high Slew-Rate (13 V/s), high impedance input (10^{12} Ω), and fast settling time (2 μs) was used [34]. A buffer circuit was implemented with a low voltage operational amplifier (model OPA344) with an output type Rail to Rail [35] to isolate and protect the Arduino Uno platform against voltage surges or malfunctioning of the designed circuits.

The output of the buffer circuit is limited to voltages from 0 V to 5 V, safe input voltage range for the analogue/digital converter (ADC) of the Arduino Uno platform. This ADC has 6 channel 10-bit resolution with absolute accuracy of ±2 LSB (≈15 mV), and maximum sample rate of 15 kS/s.

The frequency response and impedance characteristics of the buffer circuit were analyzed through computer simulations performed in LTspice® software.

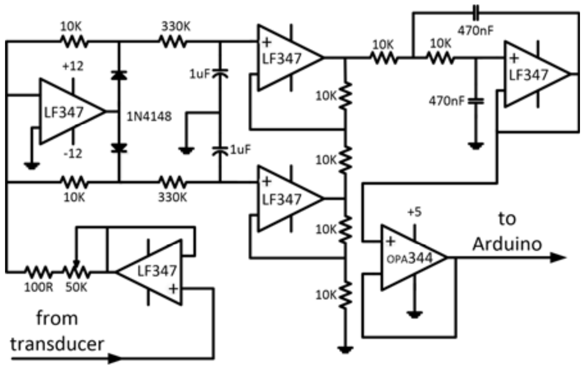

Fig. 7. The circuit for signal conditioning.

3.3. Sensor Mounting and Calibration

Based on the theoretical backgrounds previously presented, a set of parallel plates conductivity type transducers was built and analyzed for measuring the response time based on the electrical conductivity of the mixed flow in an agricultural direct injection spraying system. Two stainless steel electrodes with a diameter of 5 mm were used. The transducer was constructed with a polyacetal base and assembled direct into the nozzle body equipped with a diaphragm check valves. Fig. 8 illustrates the positioning and location of the SCCS for response time measurements.

To analyze the sensor with a static fluid, the electrodes were coupled to the base and spaced at three different distances chosen as 0.5 mm, 1.5 mm and 1 mm, resulting in constant cells equal to 0.255 cm^{-1}, 0.500 cm^{-1} and 0.764 cm^{-1}, respectively. The calibration was performed using a commercial conductivity meter (model mCA150, Tecnopon), with an operating range of 0 to 200 µS/cm, resolution of 0.1 µS/cm, 2 % of full scale accuracy and 1 % of full scale precision [37]. The measurements performed with the commercial conductivity meter were checked with a standard KCl solution (0.02000 mol/L). Static tests were carried out for the analysis of solutions consisting of water and NaCl. The procedures were conducted for three different cell constants at 25 ºC.

3.4. Response Time Measurements

In order to validate the developed sensor, a real experiment to measure the response time of a sprayer system based on direct injection was performed. The experiment was set for a cell constant of 0.500 cm^{-1}.

For real time analysis, the conductivity was measured and the results were processed via LabVIEW® software, i.e., using the Arduino Uno platform, which allows the computational processing and intelligence aggregation [36].

The initial concentration of the injected NaCl solution was 50 g of salt for 16 L of potable water. This NaCl solution was injected upstream from the sprayer pump at 2.3 L/min during 30 seconds. The mainstream flow was regulated at 16 L/min and 23 L/min with pressure at 200 kPa and 400 kPa, respectively. For each regulated flow, 3 repetitions of the response time measurements were conducted.

To obtain a time constant T_c in a range of variation lower than 5 %, the liquid temperature could not vary more than ±2.5°C during the conductivity acquisitions. This threshold was determined based on simulation using the Equations (3) and (7), as well as calibration curves. For validation, and in order to consider a general scenario, it was used a temperature coefficient of variation (α) equal to 3.0 %/°C.

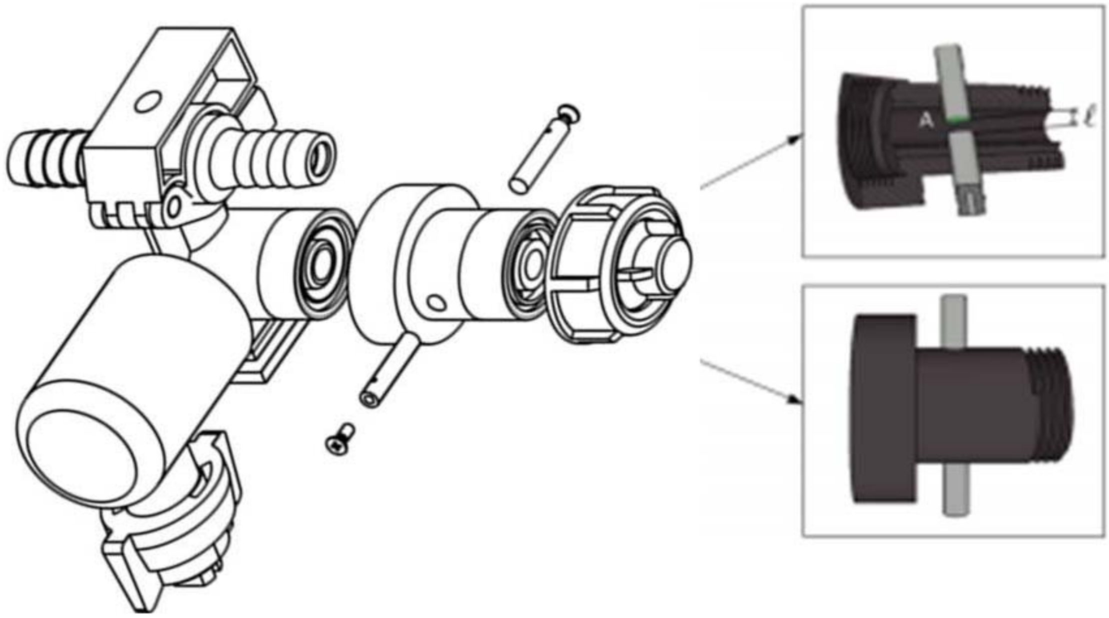

Fig. 8. Details of the customized smart sensor (SCCS) to measure the response time of direct injection sprayers.

The individual time responses and the transport delay time for each repetition were analyzed in an actual spraying system. Fig. 9 illustrates the sensor location in the actual sprayer system.

Fig. 9. Instrumental arrangement for validation of the intelligent sensor to measure response time of a direct injection sprayer with TeeJet® QJS Multiple Nozzle Bodies e-ChemSaver.

4. Results and Discussion

The computational processing of data and analysis with the developed conductivity sensor was performed using the LabVIEW® software, after signal conditioning and the analogue/digital conversion with the Arduino Uno platform. The use of the electronic Arduino Uno platform and the LabVIEW® interface allowed the aggregation of intelligence for self-diagnostic of the SCCS, as well as its self-assessment based on the use of a specific algorithm (Fig. 10). The data valid flag was determined experimentally based on the dynamic range of the SCCS defined by 0.50 V ±2LSB < v_{SCCS} ≤ 4.90 V ±2LSB, which is related with the accuracy allowed by the internal ADC of the Arduino Uno platform.

The calibration results identified the electrodes faces distance for a better accuracy of the conductivity sensor which is dependent on the conductivity cell constant of the transducer. The shorter the distance between the faces of the electrodes for the same cross-sectional area, the greater will be the accuracy of the measurements. The calibration curves are shown in Fig. 11, Fig. 12 and Fig. 13 for constant cells given respectively by 0.255 cm^{-1}, 0.500 cm^{-1} and 0.764 cm^{-1}. Table 2 shows the experimental values obtained for determining the response time t_T.

A first set of experiments were conducted and the results are shown in Fig. 14. In this case, a water-NaCl solution flow of 16 L/min and pressure of 200 kPa were used. The dynamic responses obtained for the three repetitions demonstrated the sensor accuracy and reliability.

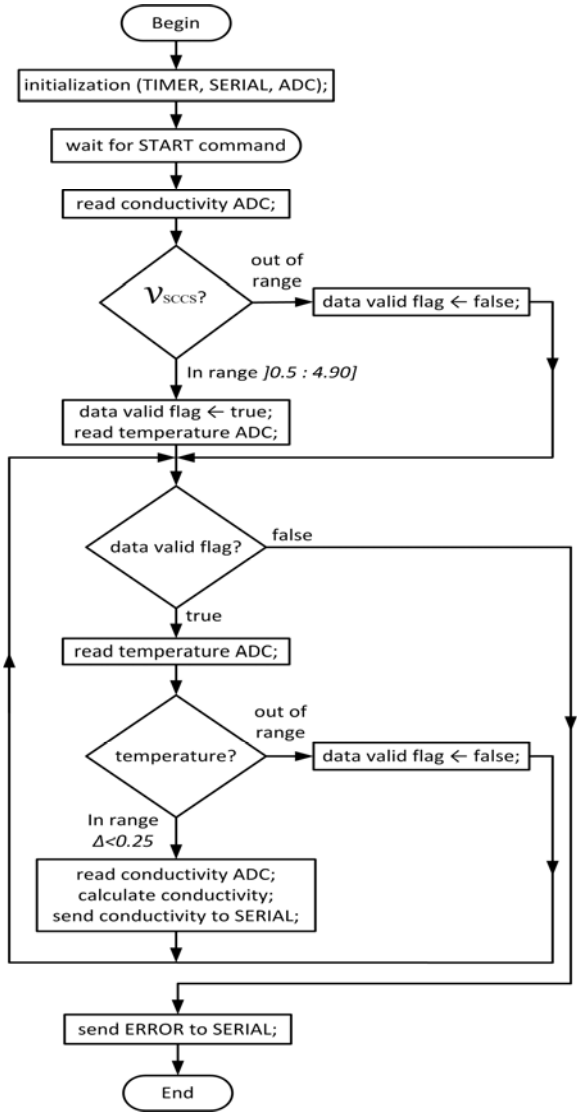

Fig. 10. The flow-diagram of the algorithm for self-assessment and self-diagnostic.

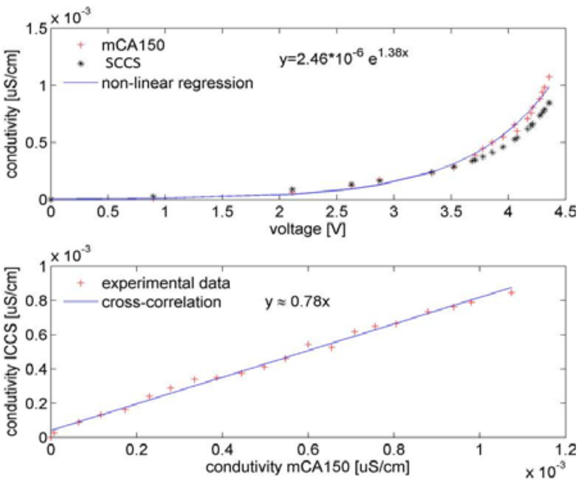

Fig. 11. Calibration curves and comparison of measurements of the electrical conductivity from experimental solutions obtained with the SCCS with constant cell of 0.255 cm^{-1}.

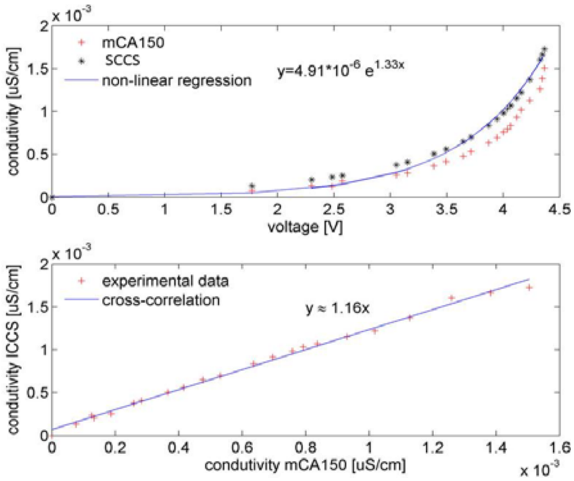

Fig. 12. Calibration curves and comparison of measurements of the electrical conductivity from experimental solutions obtained with the SCCS with cell constant of 0.500 cm^{-1}.

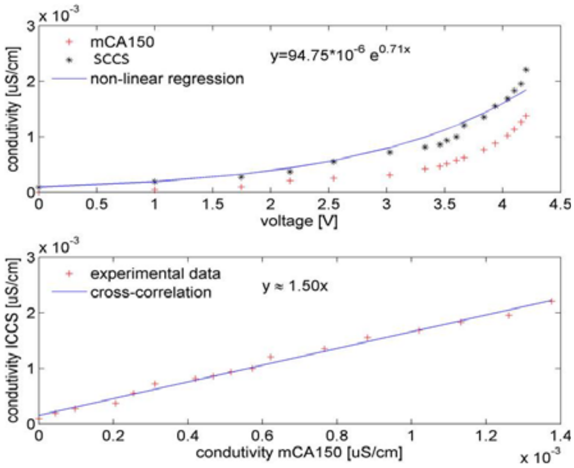

Fig. 13. Calibration curves and comparison of measurements of the electrical conductivity from experimental solutions obtained with the SCCS with cell constant of 0.764 cm^{-1}.

Table 2. Experimental values of delay and response times (Mean is Average Values, Std is the Standard Deviation, and CV is the Coefficient of Variation).

Flow (L/min)	Repetitions and statistical analysis	V_{min} (0%)	V_{max} (100%)	t_d (s)	t_T (s)
16	1st	1.58	4.16	29.56	42.48
	2nd	1.57	4.17	28.80	41.55
	3rd	1.57	4.15	28.36	41.40
	Mean	1.58	4.16	28.91	41.81
	Std	0.008	0.010	0.607	0.585
	CV	0.005	0.002	0.021	0.014
23	1st	1.56	3.99	22.53	32.81
	2nd	1.53	3.96	22.52	33.01
	3rd	1.55	3.97	23.09	33.77
	Mean	1.55	3.97	22.71	33.20
	Std	0.012	0.013	0.326	0.506
	CV	0.008	0.003	0.014	0,015

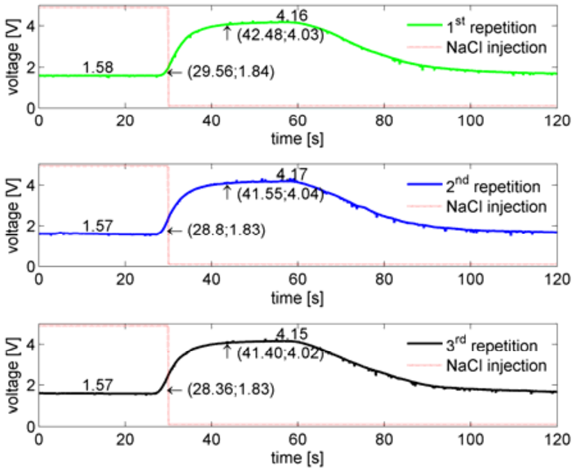

Fig. 14. Transients and transport delay times of the sprayer with the SCCS assembled in an actual spraying system with water-NaCl solution flow of 16 L/min and pressure equals to 200 kPa.

For this experimental arrangement, the average delay time was 28.91 s and the average response time 41.81 s.

A second set of experiments were conducted and the results are shown in Fig. 15. In this case, a water-NaCl solution flow of 23 L/min and pressure of 400 kPa were used. The results obtained for the sprayer system having a flow rate equal to 23 L/min and pressure of 400 kPa, as occurred previously, have shown again, accuracy and reliability in the measurements obtained with the developed sensor. The average delay time was of 22.71 s and the average response time 33.20 s.

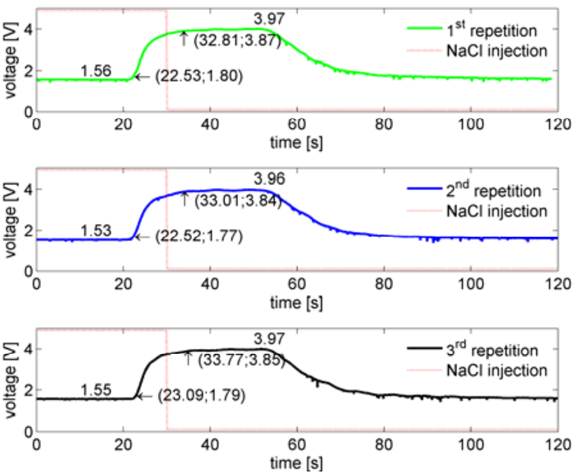

Fig. 15. Transients and the transport delay times obtained with the SCCS assembled in an actual spraying system with water-NaCl solution flow of 23 L/min and pressure equal to 400 kPa.

Also, it is important to notice that the use of faster circuits implies higher current densities, lower voltage tolerances and higher electric fields, which make integrated circuits more vulnerable to electrical failure.

The integrated circuits used in the intelligent sensor are new generations of electronic devices and they provided good performance.

Furthermore, the use of the polyacetal base was adequate and results have shown a robust mechanical design.

The reliability assessments are crucial for the end user as adjustments to electrical conditions and thermal management, since the electrical conductivity is dependent on the temperature of the flows related to the mixture of water plus pesticide.

5. Conclusions

A smart and customized sensor to measure the response time of spray systems based on direct injection was presented. The results have shown its usability in real time applications. The decision to embed the smart sensor directly in the sprayer nozzle provides a scenario where the input data from the physical sensor could be analyzed by various knowledge-based routines. The sensor output could be raw data or preprocessed information. This information could be in the form of a flag, which shows a confidence level of the response time for pesticide applications.

The results based on the calibration curves for the sensor in three different assemblies showed that the accuracy of measurements depends directly on the conductivity cell constant. However, to determine the response time of a direct injection system of pesticides, a customized sensor with shorter spacing between its electrodes can provide an adequate sensitivity for sensing the level of the concentration in the mixture involving pesticide plus water.

The results of the sprayer system response time with direct injection obtained in this research work have shown that the smart sensor developed has good repeatability, reliability and practicality. Furthermore, the results show the decreasing of the response time with the increasing of the flows in consequence of the increased speed in which the mixture of water and pesticide travels through the system.

The use of an intelligent sensor provides more additional information than that of traditional sensors. The information provided by an intelligent sensor can include actual data, corrected data, validity of the data, and reliability of the sensor.

Furthermore, such SCCS development meets future prospects in practical applications, bringing potential benefits for sustainability, as well as precision agriculture processes.

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References

[1]. SINDAG. SINDAG and Embrapa study agchem aerial application in Brazil, Accessed at March 5, 2015. [Online]. Available: http://news.agropages.com/News/NewsDetail—13170.htm (2014).

[2]. CONAB, Monitoring of the Brazilian grain crops - season 2013/14 (original in Portuguese), Brazilian National Company for Supply, *Tech. Rep*., 2014.

[3]. M. Sökefeld, Variable rate technology for herbicide application, in Precision Crop Protection - the Challenge and Use of Heterogeneity. *Springer Verlag*, 2010, pp. 335-347.

[4]. J. Vondrica, Study on the process of direct nozzle injection for realtime site-specific pesticide application, Ph.D. dissertation, *Institut für Landtechnik der Rheinschen Friedrich-Wilhelms-Universität,* 2008.

[5]. K. L. Hughes, A. R. Frost, A review of agricultural spray metering, *Journal of Agricultural Engineering Research,* Vol. 32, Issue 3, 1985, pp. 197-207.

[6]. C. G. Vidrine, C. E. Goering, C. L. Day, M. R. Gebhardt, D. B. Smith, A constant pesticide application rate sprayer model, *Transaction of the ASAE,* Vol. 18, Issue 3, 1975, pp. 439-443.

[7]. D. L. Reichard, T. L. Ladd, Pesticide injection and transfer system for field sprayers, *Transactions of the ASAE*, Vol. 26, Issue 3, 1983, pp. 683-686.

[8]. L. Chi, R. L. Kushawara, F. W. Gigsby, Chemical flow rate control in injection-type sprayers, *Canadian Agricultural Engineering*, Vol. 30, Issue 1, 1988, pp. 19-26.

[9]. S. R. Ghate, C. D. Perry, Ground speed control of pesticide application rates in a compressed air direct injection sprayers, *Transaction of the ASAE*, Vol. 37, Issue 1, 1994, pp. 33-38.

[10]. M. S. Miller, D. B. Smith, A review of application error for sprayers, *Transactions of the ASAE*, Vol. 35, Issue 3, 1992, pp. 787-791.

[11]. P. S. Lammers, J. Vondricka, Direct injection sprayer, in Precision Crop Protection - the Challenge and Use of Heterogeneity, *Springer Verlag*, 2010, pp. 295-310.

[12]. R. S. Budwig, J. M. McDonald, T. J. Karsky, Evaluation of chemical injection system for mobile agricultural spray equipment, *Transaction of the ASAE*, 1988, Paper No. 88-1592.

[13]. F. D. Tompkins, K. D. Howard, C. R. Mote, R. S. Freeland, Boom flow characteristics with direct chemical injection, *Transaction of the ASAE*, Vol. 33, Issue 3, 1990, pp. 737-743.

[14]. K. A. Sudduth, S. C. Borgelt, J. Hou, Performance of chemical injection sprayer system, *Applied Engineering in Agriculture*, Vol. 11, Issue 3, 1995, pp. 343-348.

[15]. Y. M. Koo, H. R. Sumner, Total flow control for a direct injection sprayer, *Applied Engineering in Agriculture*, Vol. 14, Issue 4, 1998, pp. 363-367.

[16]. H. Zhu, R. D. Fox, H. E. Ozkan, R. D. Brazee, R. C. Derksen, A system to determine lag time and mixture uniformity for inline injection sprayers, *Applied Engineering in Agriculture*, Vol. 14, Issue 2, 1998, pp. 103-110.

[17]. E. A. Anglund and P. D. Ayers, Field evaluation of response times for a variable rate (pressured-based and injection) liquid chemical applicator*, Applied Engineering in Agriculture*, Vol. 19, Issue 3, 2003, pp. 273-282.

[18]. P. Hloben, Study on the response time of direct injection systems for variable rate application of herbicides. PhD dissertation, *Universitäts und Landesbibliothek Bonn*, 2007.

[19]. A. EL Aissaoui, F. Lebeau, M.-F. Destain, K. Houmy, Applying control volume finite element for modeling direct injection boom spraying, in *Proceedings of the Congress 7th World Congress of Computer in Agriculture*, Reno, USA, 22-24 June 2009, pp. 190-198.

[20]. N. S. Hassen, C. S. Nor Azwadi, J. M. Sheriff, Advanced techniques for reducing spray losses in agrochemical application system, *Life Science Journal*, Vol. 11, Issue 3, 2014, pp. 56-66.

[21]. M. Jafari, A. Hemmat, M. Sadeghi, Development and performance assessment of a DC electric variable-rate controller for use on grain drills, *Computers and Electronics in Agriculture*, Vol. 73, Issue 1, 2010, pp. 56-65.

[22]. M. L. Stone, D. K. Giles, K. J. Dieball, Distributed network system for control of spray droplet size and application rate for precision chemical application, *Transaction of the ASAE*, Canada, 1999, Paper no. 99-3112.

[23]. A. Landers, The theory and constituent parts of a direct injection sprayer, Accessed at January 27, 2015. [Online]. Available: http://vivo.cornell.edu/individual/AI-24241250305 (1998).

[24]. H. V. Mercaldi, C. H. Fujiwara, E. A. G. Peñaloza, V. A. Oliveira, P. E. Cruvinel, An intelligent and customized electrical conductivity sensor to evaluate the response time of a direct injection system, in *Proceedings of the 6th International Conference on Sensor Device Technologies and Applications* (*SENSORDEVICES'15*), Venice, Italy, 23-28 August 2015, pp. 19-24.

[25]. C. H. Fujiwara, H. V. Mercaldi, E. A. G. Peñaloza, P. E. Cruvinel, V. A. Oliveira, Direct injection system response time determination using a conductivity smart sensor directly coupled into herbicide sprayer nozzle, *Abstracts Proceedings of the XLIV Brazilian Congress of Agricultural Engineering (CONBEA'15)*, Sao Pedro-SP, Brazil, 13-17 September 2015, pp. 171.

[26]. A guide to conductivity measurement: Theory and practice of conductivity applications (MELTER/TOLEDO), Accessed at September 27, 2015. [Online]. Available: http://www.tau.ac.il/~chemlaba/Files/conductivity_guide_EN%20(2).pdf (2013)

[27]. D. R. Peck, L. O. Roth, Field sprayer induction system development and evaluation, *Transaction of the ASAE*, 1975, Paper No. 75-1541.

[28]. K. A. Bennet, R. B. Brown, Direct nozzle injection and precise metering for variable rate herbicide application, *Transaction of the ASAE*, 1997, Paper No. 97-1046.

[29]. K. Ogata, Modern Control Engineering, 4th ed., *Prentice Hall PTR*, 2001.

[30]. U. R. Antuniassi, P. Miller, M. Paice, Performance evaluation of injection metering systems, *Revista*

Brasileira de Engenharia Agricola e Ambiental, Vol. 6, Issue 1, 2002, pp. 159-165.

[31]. K. P. Gillis, D. K. Giles, D. C. Slaughter, D. Downey, Injection mixing system for boomles, target-activated herbicide spraying, *Transaction of the ASAE*, Vol. 46, Issue 4, 2003, pp. 997-1008.

[32]. Exar Corporation, Datasheet XR2206, Accessed at February 24, 2015. [Online]. Available: https://www.sparkfun.com/datasheets/Kits/XR2206 104 020808.pdf (2008)

[33]. Arduino, Arduino Uno, Accessed at March 16, 2015. [Online]. Available: http://arduino.cc/en/Main/ArduinoBoardUno (2015)

[34]. Texas Instruments, Datasheet LF147, LF347-N. Accessed at February 24, 2015. [Online]. Available: http://www.ti.com/lit/ds/symlink/lf147.pdf (2013)

[35]. Texas Instruments, Datasheet OPA344. Accessed at March 04, 2015. [Online]. Available: www.ti.com/lit/ds/symlink/opa344.pdf (2008)

[36]. R. Taymanov, K. Sapozhnikova, Metrological self-check and evolution of metrology, *Measurement*, Vol. 43, Issue 7, 2010, pp. 869-877.

[37]. Tecnopon, Instructions manual mCA150. Accessed at February 24, 2015. [Online]. Available: http://www.tecnopon.com.br (2014).

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