Developing Affordable Sensors in Agriculture Based on Results Obtained at Embrapa Instrumentation

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***Abstract*— Agricultural sensors are crucial in improving crop yields and reducing resource waste. It has led researchers to develop affordable sensors that can be easily integrated into existing farming systems. Developing inexpensive sensors involves using low-cost materials and simple manufacturing methods, ensuring reliable and accurate measurements. One of Embrapa Instrumentation's objectives is the research and development of sensors applied to agriculture. This article briefly discusses a sensor for soil moisture measurement using the microwave technique; a system for measuring the apparent electrical conductivity of soils; a Sensor for measuring water and plant relationships; and the Sensor for evaluating spray solution concentration to control weeds to improve crop yield and reduce water. Using affordable sensors in agriculture can provide an effective and sustainable solution to enhance the productivity of small and medium farms, thus increasing food security and supporting sustainable agriculture.**

Keywords - Affordable sensors; Agriculture; soil moisture; soil resistance; water-plant measuring; spray quality; pest control.

I. INTRODUCTION

The applications of sensors in general, and more specifically, affordable sensors, are the basis for developing devices for instrumentation, automation, precision agriculture, and digital agriculture.

The global agricultural sensors market size was valued at USD 4.74 billion in 2021. It is expected to reach USD 16.83 billion by 2030, growing at a Compound annual growth rate (CAGR) of 15.12% during the forecast period (2022–2030) [1].

The low-cost sensor is a technology initially developed for consumer and research applications. Competitive and low-cost due to economies of scale, these sensor technologies allow new applications or more economical use of sensors in production and environments [2].

Despite being used in research, most field sensors are still in their infancy in their commercial relationship. Soil moisture sensors can be mentioned, sensors that can correlate fertility, scales that could indicate performance, sensors, and indicators of pests and diseases, among others, and if they were present in the field, they could be connected to IoT (Internet of things) [3]–[5].

Below is a brief discussion of affordable sensors for agriculture, which were developed at Embrapa Instrumentation. In the next sections there are the descriptions of the recent development of affordable sensors, which are: a sensor for measuring soil moisture using microwaves with two techniques (waveguide and free space); a system for measuring the apparent electrical conductivity of ECa soils; a sensor for measuring the water and plant relationship; and a sensor to evaluate spray solution concentration to control weeds to improve crop yield and reduce water.

The sensors listed have something in common: they are affordable and designed to be used in agricultural environments. They are capable of measuring different aspects of the environment, such as soil, water, plants, and weed control. Additionally, they can be integrated into IoT technologies.

II. SENSOR FOR SOIL MOISTURE MEASUREMENT, USING MICROWAVE TECHNIQUES

The content and availability of water in the soil are parameters of fundamental importance in the various fields of basic and applied science, as well as in technologies for agriculture, geology, meteorology, hydrology, and various areas of engineering.

The most used techniques for measuring soil water are gravimetric, neutron moderation and gamma-ray attenuation, Time Domain Reflectometry (TDR), and remote sensing.

Through the interaction of electromagnetic waves, at microwave frequency, with the water-soil system, greater or lesser attenuation of the signal is obtained depending on the volumetric moisture content present. Figure 1 presents a system for measuring soil moisture content that uses microwave signal transmission and reception through the waveguide technique, in the X band, with an operating frequency of 10 GHz and a power of 25 mW. In tests carried out at the laboratory level, we proved the correlation of the attenuation in dB with the volumetric humidity in clayey, sandy, and glass microsphere soils [6].

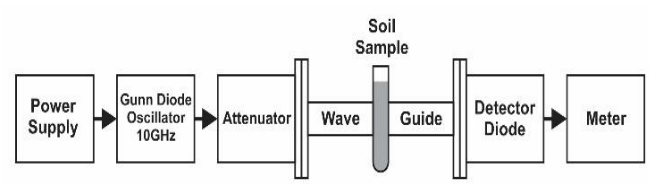

Figure 1. Presents a system for measuring soil moisture content that uses microwave signal transmission and reception through the waveguide technique.

Figure 2 presents the results that show the influence of water in the water-soil system, in the attenuation of microwaves, through the relation of the attenuation of the signal in dB by the volumetric soil moisture in sandy soil (1.20 < soil density (g/cm^3) < 1.26), clayey (0.83 < soil density (g/cm^3) < 0.92)) and glass microsphere (1.13 < soil density (g/cm3) < 1.19)). The error in sample preparation was 4.7%. All measurements were conducted under laboratory conditions (room temperature ~23.0 ± 0.5 0C and relative humidity 36%).

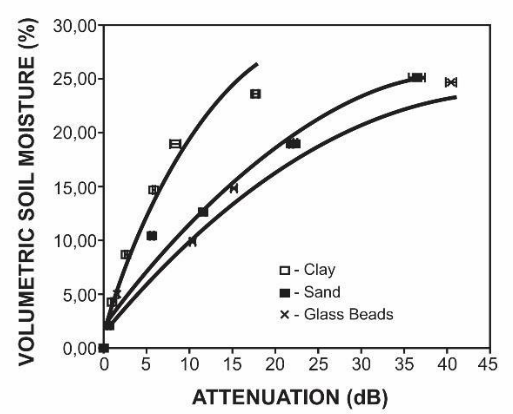

Figure 2. The attenuation calibration curve in dB, as a function of the volumetric soil moisture of the samples

A network analyzer, model 8510 from Hewlett-Packard, was used, evaluating the parameter insertion loss S_{21} (dB) to compare with the results obtained in the attenuation system in dB. Figure 3 presents the results for all samples with a linear regression where their r^2 was 0.976.

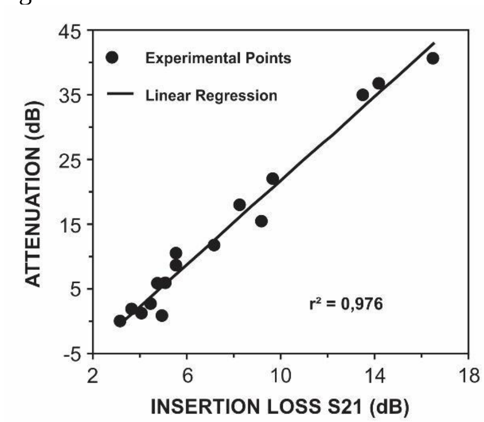

Figure 3. Comparison between the results obtained with the proposed system and those obtained the insertion loss S_{21} (dB), using the 8510 HP network analyzer.

Investigating the behavior of plant root system growth as a function of soil water is essential for studying root physiology. Figure 4 shows a non-invasive tool based on the transmittance of electromagnetic waves in the microwave frequency range, operating close to 4.8 GHz, which was developed using microstrip patch antennas to determine volumetric soil moisture in rhizoboxes. Antennas were placed on both sides of the rhizobox, and the S parameters were measured using a vector network analyzer.

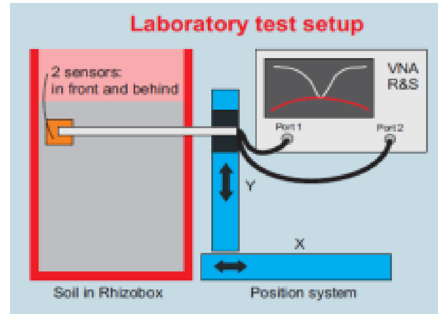

Figure 4. Block diagram of the system developed to measure S21 (dB) of soil moisture in the rhizobox, using the Vector Network Analyzer, in the microwave frequency range (4.6–5.0 GHz).

The dispersion parameter S_{21}(dB) was also used to show the effect of different soil types and temperatures on the measurement. In addition, the sensitivity, reproducibility, and repeatability of the system were evaluated (Figure 5). The measurement was carried out three times to each dot (n = 3). The red dots represent the reproducibility (98.9%) averages, and the black dots represent the repeatability (93.0%) averages. The quantitative results of soil moisture, measured in rhizoboxes, presented in this work, demonstrate that the microwave technique using microstrip patch antennas is a reliable non-invasive, and accurate system, and has shown potentially promising applications for measurement of roots based on rhizobox phenotyping [7].

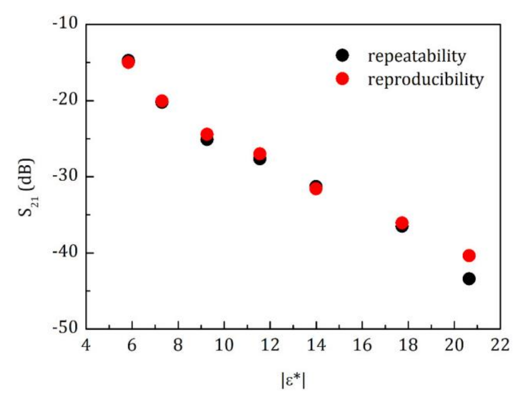

Figure 5. The relation between $|\varepsilon^*|$ versus the average of S_{21} (dB) shows the repeatability and reproducibility of the system developed were calculated.

Figure 6 shows the relationship between the S_{21} measured with the developed system and the volumetric soil moisture θ_V (%) determined and calculated by the second and third-order polynomial equation. The calibration was obtained using four (04) samples, which are: Cerrado Soil (squares), Kaktus Soil (open circles), and Glass Beads (triangles). The experiment was carried out at the standard laboratory ambient conditions (Temperature (T(°C)) = 25.0 ± 0.5 °C and Relative Humidity (RH(%)) 30%).

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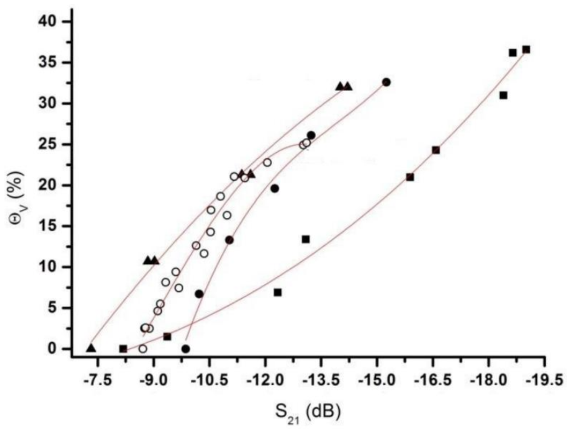

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III. SYSTEM FOR MEASURING THE APPARENT ELECTRICAL CONDUCTIVITY OF SOILS ECa

Soil apparent electrical conductivity (ECa) originated from measuring soil salinity, a pertinent problem in arid zones associated with irrigated crops and areas with shallow water tables. Soil ECa is greatly influenced by a vast combination of physical and chemical properties of the soil, such as soluble salts; mineralogy and clay content; the amount of water present in the soil; volumetric density; organic matter, and soil temperature.

The most effective application of apparent soil electrical conductivity is at field scale in mapping the spatial variability of many edaphic properties, e.g., organic matter, moisture, and in the determination of a wide variety of anthropogenic properties, such as: leaching fraction; irrigation and drainage patterns; compaction patterns due to machinery [8].

Soil ECa is a quick, more reliable, and easy tool than other techniques, but it only sometimes correlates with crop yield. Therefore, the ECa measurement is among the most frequent tools used in research in precision agriculture for the space-time characterization of edaphic and anthropogenic properties that influence crop productivity.

The measurement of electrical conductivity (σ) originates from the measurement of electrical resistivity (ρ), which consists of using a sample of known shapes and dimensions (square, cylindrical, and others).

The electrical resistance is then calculated by the following equation:

$$R = \rho\left(\frac{L}{A}\right) \qquad (1)$$

Where:

R = electrical resistance [Ohms, Ω];
ρ = electrical resistivity [Ohms x centimeters, Ω.cm];
L = sample length [cm, cm].

For samples of undefined shapes and dimensions, the method known as the four-point system [9] [10] is used, Figure 7, which consists of using four metal electrodes sequentially aligned with known distances.

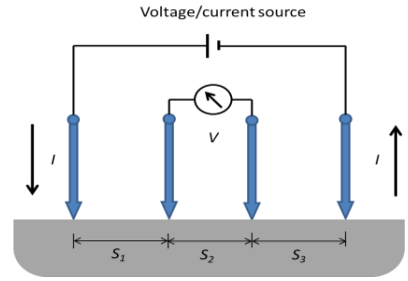

Figure 7. Four-point system.

Applying electrical current I (Ampere) to the outer electrodes and with a voltage V (Volts) reading from the two center electrodes. The resistivity is then calculated with the following equation:

$$\rho = \frac{2.\pi\left(\frac{V}{I}\right)}{\frac{1}{S_1} + \frac{1}{S_2} - \frac{1}{S_1 + S_2} - \frac{1}{S_2 + S_3}} \qquad (2)$$

Electrical conductivity, σ, is defined as the inverse of electrical resistivity, so we have:

$$\sigma = \frac{1}{\rho} \qquad (3)$$

Figure 8 illustrates the block diagram of the developed system, which uses the PIC18F258 manufactured by Microchip Technology [20] as its central processor. The system was designed for reading two four-point measurement systems, consisting of two voltmeters, one of unitary gain and the other of gain three for deeper measurements, an alternating voltage source of 159 Hz for measuring electric current, three signal filters for reading channels, three alternating to continuous signal converters, 1024 bits; 1 bit resolution; 4.88×10^{-3} Volts dc; 32-character LCD (Liquid Crystal Display) for viewing electrical conductivity measurements and control information, four-function keyboard for user-machine communication; standard RS232 serial port for communication and transfer of stored data and NMEA (National Marine Electronics Association) sentences for GNSS (Global Navigation Satellite System) system and flash memory for storage of collected data, the capacity of 64 KBytes, in Figure 9 the system is illustrated.

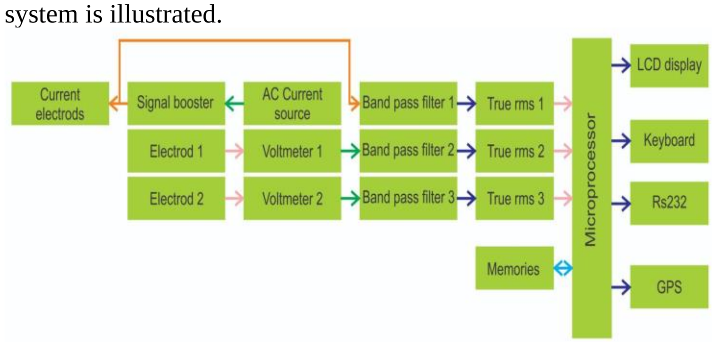

Figure 8. Apparent electrical conductivity system block diagram.

Figure 9. Electrical conductivity measurement system.

Figure 10 illustrates measurements taken using the system in an area where vines are planted in the study and definition of homogeneous areas for this crop.

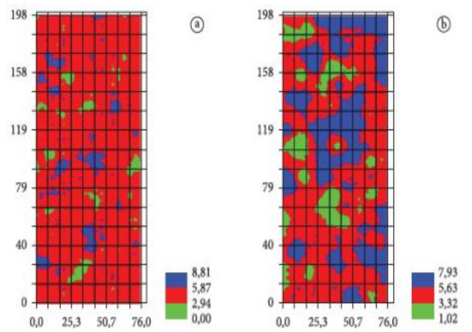

Figure 10. Maps of homogeneous zones of apparent soil electrical conductivity, a - ECa at a depth of 0.3 m; b - ECa at depth 0.9 m, grapevine crop, semi-arid region, Brazil

Continuing the work with a conductivity measurement system, we evaluated the possibilities of implementing direct reading of soil electrical conductivity data and making them available in the cloud for analysis in artificial intelligence, making these data available to interested parties, direct integration with productivity maps, soil attributes, soil fertility for decision-making in crop management possibly in real time, configurations for variable rate application systems, updating of the technology used due to the constant modernization of these technologies, making it possible to expand the system for the use of IoT and use of programming for cell phones .

IV. SENSOR FOR MEASURING WATER AND PLANT RELATIONSHIPS

Studies in water relations of higher plants often present many ongoing debates about the mechanisms responsible for the ascent of water in plants. In the 70's, one of the most useful techniques to aid in direct measurements of plant cells, called the pressure probe [11], was developed. It consisted of a glass capillary connected to a chamber filled with oil that punctured the cell wall, thus establishing a hydraulic connection between the cell sap and oil content.

Using an optical microscope, it was possible to measure the movement of the oil/cell sap boundary, the meniscus, and then by raising or lowering the oil pressure inside the chamber mechanically until the meniscus returned to its original position, one could measure the pressure with a sensor in the oil chamber. Through this technique, as well as a series of improvements (such as system automation), it was possible to more accurately determine how plant cell pressure varies under different physical conditions, thus enabling an understanding of the hydraulic conductivity of cell membranes and the volumetric modulus of the cell's elasticity [12].

Unfortunately, there had not been a detailed physical model describing how to calculate measurement errors, time constants, dynamical behavior, and temperature correlation. Bertucci Neto [13] developed a physical model of the pressure probe and proposed an automated pressure probe based on thermal, instead of mechanical, compensation [13].

The meniscus movement could be parameterized and correlated with the pressure applied to the capillary tip. One of the detection techniques developed was based on video image digitization. A single video line related to the meniscus position was striped and digitized. In this manner, the meniscus position is correlated to the time base. In Figure 11 the whole video image is shown, while Figure 12 shows the information of a video frame and a striped video line related to the meniscus position.

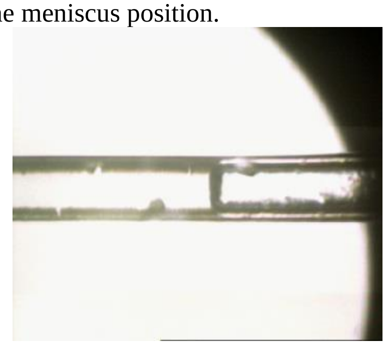

Figure 11. Video image of the meniscus in the capillary.

The information obtained on the single video line is shown in Figure 13 as well as the digitized signal. The other technique was based on image treatment (through LabView). The meniscus positional datum was used to control the system and return the meniscus to its original position through a feedback loop. Through the camera signal, it was, therefore, possible to select a region in the image in which a single video line carried the entirety of the data on the meniscus' position. As predicted in the modeling study, the relationship between electric heating voltage and the meniscus position in pixels is quadratic, as shown in Figure 14. The quadratic approximation presents a standard deviation of less than 10 pixels. By using a feedback loop and including a PID controller, it was possible to keep the meniscus in its original position after a pressure step input.

This is shown in Figure 14, where the measured and modeling responses are compared. Although dynamical measurements can present large errors, primarily during short meniscus movements, the techniques can be appropriated to measure long-term pressure variations in plant cells.

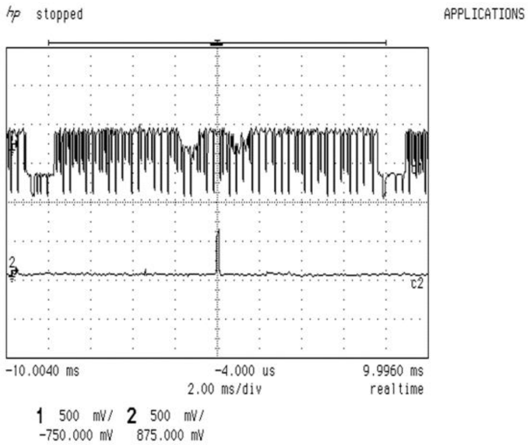

Figure 12. Oscilloscope signal. Above: Video signal of 262.5 lines of a frame. Down: Single video line stripped from the frame in the region of the meniscus image.

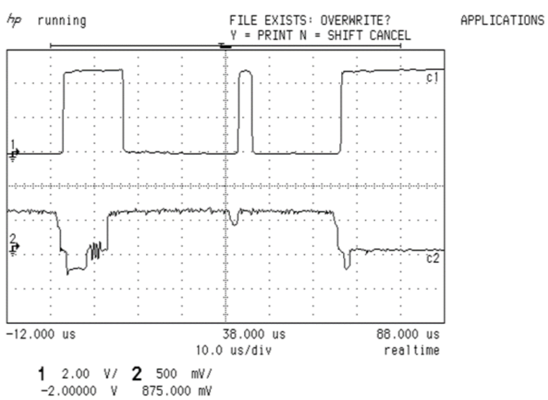

Figure 13. Oscilloscope signal. Above: digitized signal after the voltage comparator. Down: voltage information of the single video line.

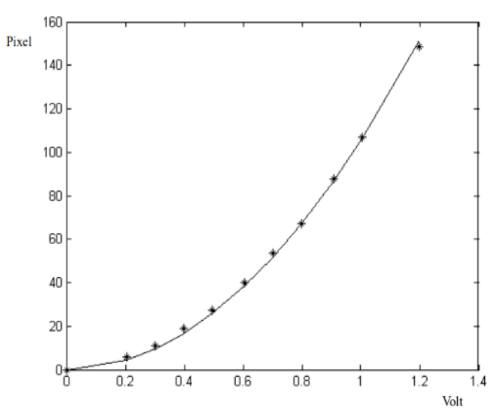

Figure 14. Quadratic behavior between electric power in volt and meniscus' displacement.

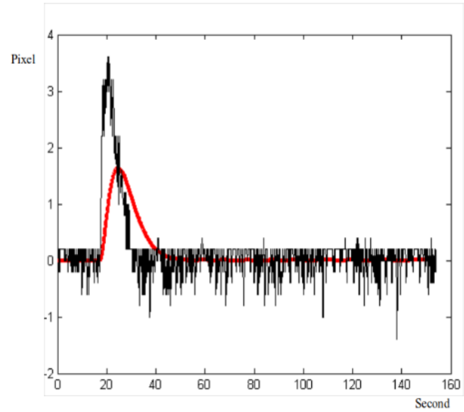

Figure 15. Meniscus returning to the origin position after a pressure step at the tip of the capillary due to the PID control action. Red line: simulated response; black line: measured response.

V. SENSOR FOR THE PH REAL TIME MEASUREMENTS IN AGRICULTURAL SPRAY SOLUTION

The pH is a scale from 0 to 14 used to determine the degree of acidity of a solution, being possible to classify it as acidic (pH < 7), basic (pH > 7), or neutral (pH = 7). It is based on the degree of acidity of an aqueous solution based on the concentration of hydronium ions (H3O+).

Acidic solutions have excess hydronium ions and a pH lower than 7. On the other hand, basic solutions have an excess of hydroxyl ions (OH-) and pH values greater than 7. In addition, solutions considered neutral have the same concentration of H_3O+ ions and OH- ions, and their pH measurement is 7.

The negative logarithm of the molar concentration of H3O+ ions in the form can obtain the pH measurement:

$$pH= -\log[H_3O^+] \quad (4)$$

Naturally when one is considering water the process of auto-ionization has the same amount of H_3O+ and OH- ions. Therefore, aqueous solutions of any substance have these two types of ions, and the condition of acidity or basicity of the medium is defined by the ratio between the amounts of H_3O+ and OH-, so as follows (Table I).

TABLE I. MEDIUM AND STATUS IN TERMS OF THE PH OCCURRENCE.

medium	status
Acid	excess H_3O^+ ions
Basic	excess OH^- ions
Neutral	equal amounts of H_3O^+ and OH^- ions

Hydronium ions are formally represented as H_3O+. However, it is common to find the notation H+ for hydronium ions or to refer to the acidity of a medium.

Pesticides, insecticides, and herbicides have their effectiveness modified by the pH of the solution resulting from the preparation of syrup that involves the active agent of these products and water.

Generally, for weed control, herbicides are used, which work better in slightly acidic pH, around pH 4 to 6, and in some exceptions may act better in slightly alkaline. Glyphosate, for example, acts preferentially between pH 3.5 to 5.0, being a weak acid [14] [15].

At this pH of the spray solution, the ions are dissociated, favoring the foliar absorption of glyphosate due to the greater ease of crossing cell membranes, increasing the effectiveness of the product [16]. Besides, the effectiveness of glyphosate is affected both by the pH of the medium and by the presence of cations in the spray water [17].

The above or below ideal range can initiate degradation of the molecule, or hydrolysis. For example, when a weak acidic herbicide is mixed in a solution with an acidic pH, it tends to remain intact, however if it is mixed in a solution with an alkaline pH, it can result in the breakdown of molecules. In fact, despite many pesticides having a buffering effect in their formulations, special attention should be considered in pH value monitoring. Therefore, regardless of the pH of the pre-existing spray solution, one may adjust to the pH close to the ideal of each formulation.

This is a fact that the producer must be aware of, especially in mixtures with fungicides and insecticides, which may have negative effects on the effectiveness of other pesticides.

A pH sensor has been developed to operate in real time directly embedded into a spray nozzle, which is located on the spray boom (Figure 16).

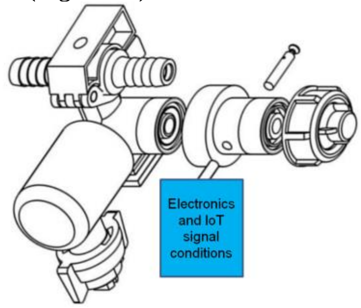

Figure 16. Technical draw of the intelligent pH sensor assembled on the nozzle for direct injection sprayer.

It has been used as a Raspberry Pi (RPi) due to its powerful processor, rich I/O interface and Internet of Things (IoT) capability, which allowed the remote control across existing spray boom infrastructure and reduced human intervention [18]. Besides, the developed IoT pH system can gather measurements data for intelligent evaluation by resident software.

The RPi is a mini-embedded computer developed in the United Kingdom by the Raspberry Pi Foundation in association with Broadcom. The model used was the RPi 3 B+, where its specifications can be seen in Table II.

TABLE II. RASPBERRY PI 3 MODEL B+ CHARACTERISTICS

Processor	BCM2837B0 Cortex-A53 (ARMv8) 64-bit		
Clock	1.4 GHz	GPIO	40 pins
Memory	1 GB SDRAM	Gigabit Ethernet	1 connector
USB Port	4 USB 2.0	HDMI	1 connector
Camera serial interface (CSI)		Display serial interface (DSI)	
Wireless (dual band)		Bluetooth 4.2/BLE	
3,5mm 4 Jack output		Micro SD card slot	
Support Power-over-Ethernet		Input DC 5V/2.5A	

The internal memory is defined using a micro SD card, where the kernel of the operating system is also present, being recommended the use of at least 8 GB of memory. In addition, the RPi 3 B+, unlike previous family models, enables BCM43438 wireless LAN and Bluetooth Low Energy (BLE) communication, allowing wireless data exchange.

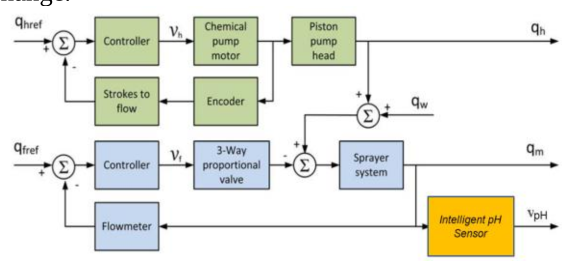

Figure 17. Block diagram for the fungicides, herbicides or insecticides, mixture control, and the intelligent pH sensor.

When it is being applied to a direct injection sprayer it has a typical control loop as shown in Figure 17. 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 same figure, is possible to observe the sprayer components, which are described as qfref, Vf, and qm, 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 [18], and [19]. The water flow qw is dependent on both the flow mixture qm and the injection flow qh. The intelligent sensor is assembled to measure the pH of the spray solution, which is proportional to its output denoted VpH.

Figure 18 shows the flow-diagram of the algorithm for real time self-diagnostics.

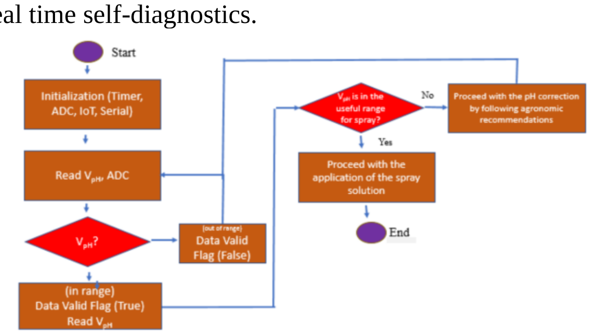

Figure 18. Computational Flow diagram for the real time measurements and flag related to the spray solution pH evaluation.

The calibration curve for the intelligent sensor for pH measurements is presented in Figure 19

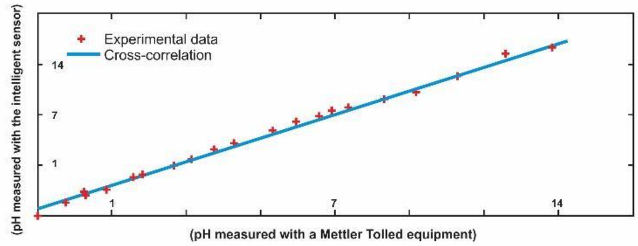

Figure 19. Calibration Curve and comparison with values obtained with prepared solutions with well-known pH values.

Using the microwave techniques since the temperature affects the error of volumetric soil moisture measurements; a calibration curve requires information on soil temperature and soil water content. The distinct effect of porous media on the calibration curve (S_{21} (dB) vs θ_V (%)) was also observed, giving the opportunity to use such an approach to investigate plant root growth in different soil types and moisture.

Techniques that allow deepening the study of water relations in plants are impacting areas of Agronomic Engineering in addition to cutting-edge areas such as Plant Phenotyping.

The information provided by the intelligent pH sensor could be in the form of a flag, which shows a confidence level of the spray solution quality during its applications. Furthermore, the results show additional information than traditional sensors and meet prospects in practical applications, bringing potential benefits for sustainability, precision agriculture processes, and the potential to be used in IoT systems. His configurations will depend on demand and large-scale applications.

VI. CONCLUSIONS

Using the sensor developed with microwave technique (waveguide and microstrip antenna) in the GHz frequency, is possible to see that the main benefits with the instrument proposed here, that are: the use of a non-destructive methodology, easy measurement of soil water, portability, the use of non-ionizing radiation, speed in the measurement and low cost.

The use of the apparent electrical conductivity of the soil has demonstrated as an important tool for precision agricultural work, its ease, simplicity and practicality lead to time and cost savings in carrying out decision-making in the areas of management and spatial variability of study areas. But ECa alone does not answer all questions needed after the data mosaic she provides, mine that data and make it more user friendly.

The physical model of the pressure probe was improved, and an automated pressure gauge was developed to investigate the displacement of the meniscus in the observation of the water-plant ratio.

An intelligent sensor to measure the pH of spray systems based on direct injection was presented. The results have shown its usability in real time applications. The decision to embed such an intelligent sensor directly in the sprayer nozzle provides a scenario that can be useful to avoid losses in agricultural production.

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