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Affordable Sensors for Agricultural Applications

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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. The developing of low-cost sensors involves adequate materials and simple manufacturing methods, ensuring reliable and accurate measurements. Embrapa Instrumentation's has been putting efforts for the low-cost agricultural sensor's development. This article discusses a sensor for soil moisture measurement using the microwave technique; a sensor for measuring the apparent electrical conductivity of soils; a sensor for measuring water and plant relationships; and a sensor for evaluating spray solution concentration to weeds control to improve crop yield and reduce the use of water. Such affordable sensors in agriculture can provide an effective and sustainable solution to enhance productivity into small and medium farms, as well as increasing in food security and supporting sustainable agriculture.**

Keywords - affordable sensors; soil moisture; soil electrical conductivity; water-plant measuring; spray quality; pest control.

I. INTRODUCTION

This paper presents an extended version of a previous study presented at the Eighth International Conference on Advances in Sensors, Actuators, Metering and Sensing (ALLSENSORS 2023), organized by the International Academy, Research and Industry Association (IARIA), and held in Venice in April 2023 [1].

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 Tate (CAGR) of 15.12% during the forecast period (2022–2030) [2].

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 [3][4].

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) [5].

The review by Kayad and their colleagues highlights the numerous advantages of using sensor applications to enhance the quality of life for humans. The comprehensive paper covers various topics, such as soil and plant sensing, farm management, and post-harvest applications. The examples illustrate how sensors can measure soil moisture content, keep tabs on drain pipes, monitor topsoil displacement during harrowing, prevent spray drift in vineyards, evaluate winter wheat and tree health with thermography, and remotely oversee the various agricultural processes. Furthermore, the review delves into the digitalization of food systems and the utilization of archived data from plowing operations. Lastly, the paper explores the potential of post-harvest sensor applications for sunflower seeds [6].

Below, one may find a brief discussion of affordable sensors for agriculture that 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 to provide support for weed control. Additionally, they can also 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.

The choice of microwave frequency, 10 GHz, was based on two main reasons: first, because this is an intermediate frequency, between maximum absorption by water and maximum penetration of the electromagnetic wave in the water-soil system; second, because oscillators are commercially found. tuned to that frequency. Under normal temperature conditions, in the frequency range of 1.0 GHz to 30 GHz, the water power constant is in the range of 40 to 80 and the loss tangent varies from 0.15 to 1.20. Most dry matter, in particular dry soil, has a dielectric constant of the order of 1 to 5 and losses. Between 0.001 and 0.050, i.e., differences in this order of magnitude.

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 [7].

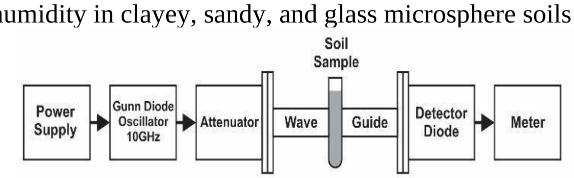

Figure 1. A system for measuring soil moisture content that uses microwave signal transmission and reception through the waveguide technique.

The electrical specifications, provided by the manufacturer, of the gunn system used are listed in Table I.

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/cm3) < 1.26), clayey (0.83 < soil density (g/cm^3) < 0.92)) and glass microsphere (1.13 < soil density (g/cm^3) < 1.19)). The error in sample preparation was 4.7%. All measurements were conducted under laboratory conditions (room temperature ~23.0 ± 0.5 °C and Relative Humidity (RH%) equal to 36%).

The combination of sand, lime, and clay mixed with water can affect the microwave signal and the detection of soil through microwaves. A study conducted by Schmugge [8] delved into the influence of soil texture on soil detection through microwaves. By analyzing the behavior of water molecules when introduced to soil, researchers could understand the effect of soil removal better.

When water molecules align with an applied field, they exhibit a high dielectric constant. However, factors such as freezing, high frequencies, or a solid connection to soil particles can restrict water's free molecular rotation, decreasing its dielectric constant. When first added to dry soil, the initial water molecules attach to the particle surface due to physical-chemical interactions, leading to a slight increase in the dielectric constant. As more water is added and surpasses a transitional level, these molecules move away from the particle surface and contribute to a more significant increase in the power constant. The water retention of soil depends on particle size or texture distribution, with clay soils possessing a larger water surface and retaining more water. Consequently, they bind more firmly to water compared to sandy soil. The transition point occurs in clay soil at higher moisture levels than in sandy soil.

TABLE I. OPERATING CHARACTERISTICS OF THE GUNN SYSTEM

RF central frequency	10,250MHz-4V varactor bias
RF output power	25 mW
Tuning: mechanical Electronics	±100MHz 60 MHz Minimum
Stability in frequency	350 kHz/°C
RF power vs temperature and tuning voltage	6 dB max
Noise figure	12 dB max
Entry requirements: Gunn Voltage Gunn Current Tuning Voltage	 + 10 Vdc 500 mA maximum +1 a+20 volts
Temperature of operation	30 °C to +70 °C

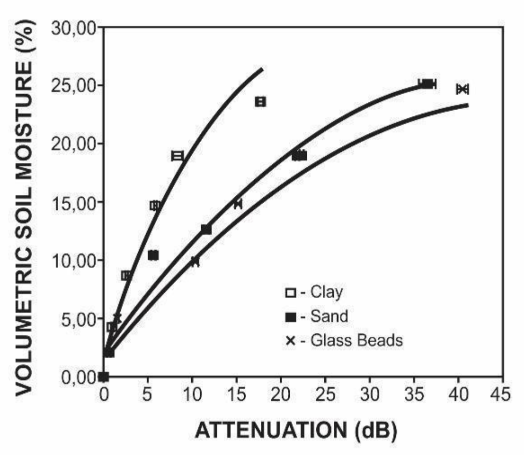

Figure 2. The attenuation calibration curve in dB, as a function of the volumetric soil moisture of the samples.

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.

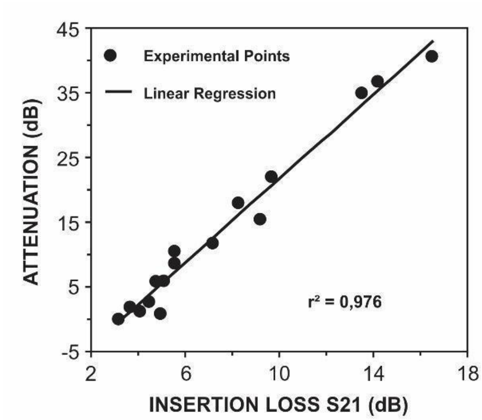

Figure 3. Comparison between the results obtained with the proposed system and those obtained the insertion loss S_{21} (dB), using the 8510 HP network analyzer.

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.

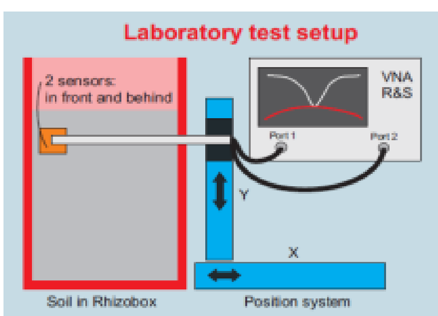

Figure 4. Block diagram of the system developed to measure S21 (dB) of soil moisture in the rhizobox, using the Vector Network Analyzer, in the microwave frequency range (4.6–5.0 GHz).

The dispersion parameter S21 (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 (Fig. 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 [9].

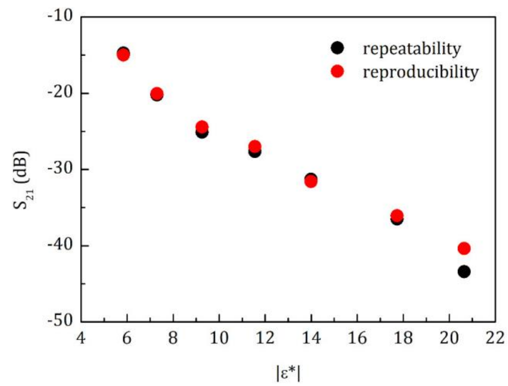

Figure 5. Relation between $|\varepsilon^*|$ versus the average of S_{21} (dB) shows the repeatability and reproducibility of the system developed were calculated.

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 RH (%) equal to 30%.

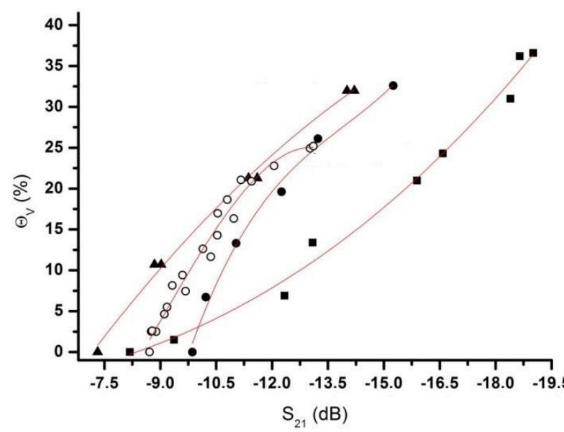

Figure 6. Relationship between the S_{21} measured with the developed system and the volumetric soil moisture θ_V (%). The four (04) samples used are Cerrado Soil (squares), Kaktus Soil (open circles) and Glass Beads (triangles).

Besides, by 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 (%)) has also been 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.

III. SYSTEM FOR MEASURING THE APPARENT ELECTRICAL CONDUCTIVITY OF SOILS

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 [10].

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 frequently used tools in precision agriculture research 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 following equation then calculates the electrical resistance:

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

where R is the electrical resistance [Ohms, Ω], ρ is the electrical resistivity [Ohms x centimeters, Ω.cm], and L is the sample length [centimeters, cm].

For samples of undefined shapes and dimensions, the method known as the four-point system [11] is used (Figure7), which consists of using four metal electrodes sequentially, aligned, i.e., taking into account the predefined distances S_1, S_2, and S_3.

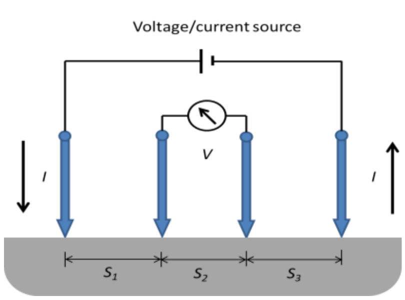

Figure 7. Four-point system.

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:

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

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

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

Figure 8 illustrates the block diagram of the developed system, which uses the PIC18F258 manufactured by Microchip Technology [12] 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; $4.88\text{x}10^{-3}$ Volts dc; 32-character Liquid Crystal Display (LCD) 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 the National Marine Electronics Association (NMEA) sentences for Global Navigation Satellite System (GNSS) system and flash memory for storage of collected data, as well as memory capacity equal to 64 Kbytes (Figure 9).

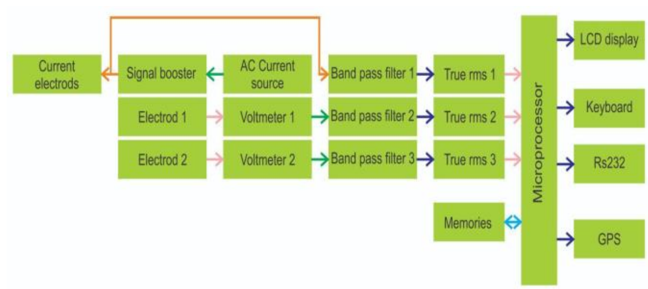

Figure 8. Apparent electrical conductivity system block diagram.

Figure 9. Electrical soil conductivity measurements system.

A. Applications of soil apparent electrical conductivity.

Scudiero et al. [13] developed a mobile platform and data post-processing algorithm to facilitate geospatial measurements of CEa along or near driplines. Gamma-ray (γ-ray) spectrometry is commonly used for clay content and type mapping. The development of this platform allows for better characterization of soil properties in micro-irrigated orchard systems using motion detection technology.

Luchiari Junior et al. worked to define management zones using electrical conductivity through electromagnetic induction to define management zones according to other parameters used in the work [14] where it specifies that the electrical conductivity map revealed similar patterns to the reflectance and management zone maps (Figure 10).

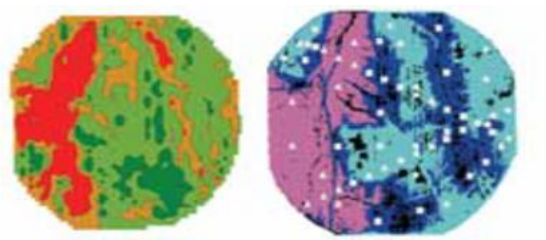

Figure 10. a) Map of apparent electrical conductivity of the soil; and b) Map of homogeneous management zones.

Vilela et al. [15] and Resende and Vilela [16] conducted a thorough assessment of the application of precision agriculture in annual crops. They particularly focused on the tools utilized to characterize the variability of the areas under study, such as soil electrical conductivity sensors, digital terrain elevation models, and aerial images. These tools facilitated the identification of factors that affect productivity variations in the study plots.

Moreover, Oliveira, Franchini, and Debiasi [17] conducted a study on the spatial variability of soybean, corn-soybean productivity, and soil electrical conductivity in a specific type of soil, namely, a Latossolo Bruno. According to the authors, ECa and soybean productivity are determined by the space where they were mapped. Soybean productivity was significantly and inversely correlated with ECa, which makes ECa a valuable parameter in defining different management zones within a crop. (For more information, please refer to Figure 11).

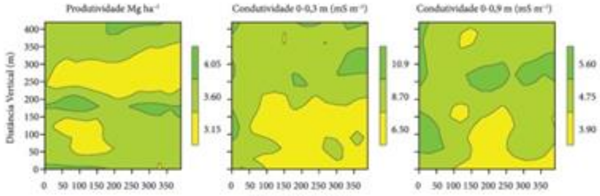

Figure 11. Apparent electrical conductivity and soybean productivity maps.

Brandão et al. [18] conducted a study in the Cerrado region of Goiás, Brazil, to investigate the correlation between soil electrical conductivity (ECa) and pH. The study generated ECa maps to evaluate spatial variability and found a substantial similarity between ECa and pH values. The authors concluded that ECa can be used to characterize variability and estimate soil acidity in the Cerrado Biome.

Oliveira and Benites [19] conducted a study on soil variability to indicate the opportunity for precision agriculture in a direct planting system. The study used quantitative techniques to evaluate the potential of information in supporting a decision-making process for the production system. The authors emphasized soil electrical conductivity's importance in interpreting spatial variation and supporting optimized soil sampling schemes.

Greco et al. [20] conducted a geostatistical study of the electrical conductivity and altitude of soil cultivated with sugar cane. The study aimed to verify the spatial variability of the soil's electrical conductivity and the soil's slope under a direct planting system. The authors concluded that the spatial variability in the electrical conductivity results correspond to differences in altitude, which can help diagnose soil and plant characteristics that vary according to the terrain's topography (Figure 12).

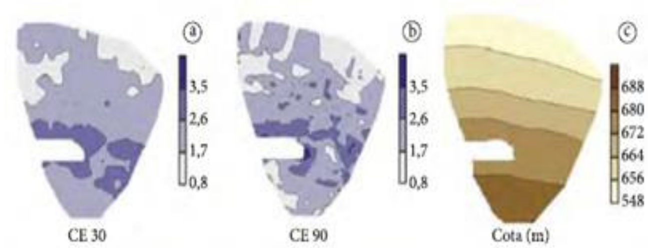

Figure 12. Isoline maps a) apparent electrical conductivity 0-30 cm; b) conductivity 0-90 cm and c) altitude elevation.

Perez et al. carried out a study on spatial variability in crop-livestock integration systems [21], where it has been correlating a given pest with electrical conductivity. Such authors concluded that a pattern of reinfestation is associated with areas of greater electrical conductivity.

Salton et al. studied electrical conductivity to correlate with some physical and chemical attributes of an oxisol with a 15-year management history [22], where they found that electrical conductivity can help delimit management zones and homogeneous areas when subjected to the same management system.

Tutmez [23], in this study were used advanced regression algorithms for the interpretation capacity of functional precision models against the lower-level mechanistic models. To explore the relationships between electrical conductivity (EC), which is the most critical indicator for salinity and irrigation, and soil parameters (texture, chemical concentrations), a comparative assessment based on supervised learning algorithms was conducted and the results were interpreted. by statistical learning. A comparative evaluation of the results revealed that unlike conventional mechanistic models, machine learning interpretation provides additional interpretations, meta-data and transparency for sustainable soil and environmental management.

To improve management techniques in grape cultivation, Miele, Flores, and Filippini Alba study the use of various precision agriculture techniques [24], including soil electrical conductivity, to assist in making the best decisions ways of management. Also, Nascimento et al. conducted a study in the grapevine to determine homogeneous areas with electrical soil conductivity in semi-arid soil [25]. Figure 13 illustrates measurements taken using the system in the study's area where vines are planted and the definition of homogeneous areas for this crop.

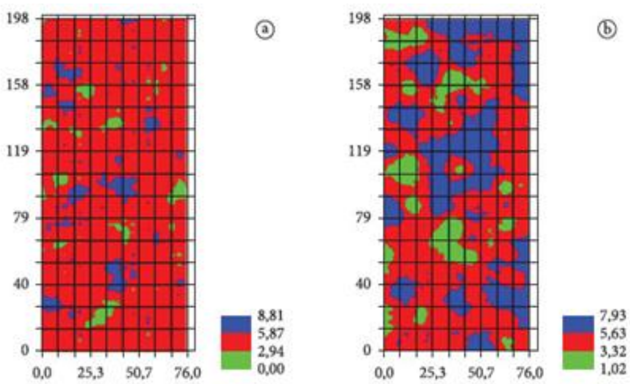

Figure 13. Maps of homogeneous zones of apparent electrical conductivity of the soil, grapevine culture, semiarid region, in Brazil.

Rabello and their team have comprehensively explained their research on electrical conductivity methods, equipment development, and adaptations of imported systems for use in agricultural implements such as subsoilers and seeders [26]. Furthermore, they have detailed the creation of a tropical system suitable for general electrical conductivity measurements [27] [28].

The developed system, as described above, is based on the 4-point electrical conductivity measurement methodology that consists of 4 metallic rods, where 2 rods are injected with a known electric current and two are used to measure the potential difference. Similar equipment uses the same methodology, but with rods with already defined distances between them. Unlike the equipment developed, the rod distances are adjustable (within their limitations), thus enabling the measurement of electrical conductivity at different depths and measurements at different agricultural crops

The authors are currently continuing their research on conductivity measurement systems. They have produced reports assessing the feasibility of directly reading soil electrical conductivity data and making it available on the cloud for analysis using artificial intelligence. This will enable interested parties to access the data, integrate it with productivity maps, soil attributes, and soil fertility, and make real-time decisions regarding crop management. The system can also be configured for variable rate application systems, updated with modern technologies, expanded for use with the IoT, and programmed for use on 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 [29], 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 [30].

So far, in that time, there had not been a detailed physical model describing how to calculate measurement errors, time constants, dynamical behavior, and temperature correlation. Bertucci Neto developed a physical model of the pressure probe and proposed an automated pressure probe based on thermal, instead of mechanical, compensation [31].

Figure 14. Video image of the meniscus in the capillary.

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 14 the whole video image is shown, while Figure 15 shows the information of a video frame and a striped video line related to the meniscus position.

The information obtained on the single video line is shown in Figure 16 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.

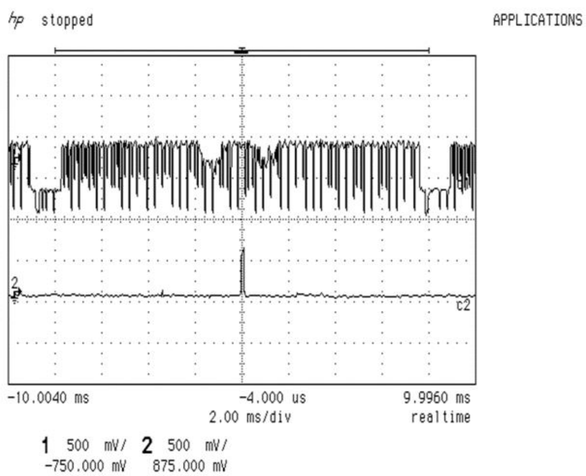

Figure 15. Oscilloscope signal. Above: Video signal of 262.5 lines of a frame. Below: Single video line stripped from the frame in the region of the meniscus image.

As predicted in the modeling study, the relationship between electric heating voltage and the meniscus position in pixels is quadratic. The quadratic approximation presents a standard deviation of less than 10 pixels. After applying an external pressure, the meniscus' position returns to its origin with the help of a Proportional -Integral – Derivative (PID) controller action. The Control System Principle (CSP) was based on a regulation method in which the electrical power signal, generated as a counterbalance, is correlated with the measure, in order to maintain the output signal (in this case the meniscus' position) constant despite pressure variations applied on the capillary's tip'. Figure 17 shows the quadratic behavior between the voltage signal applied to the heater versus the meniscus displacement in pixel. Using this data, a linear expression relating electric power supply in watt and displacement in pixel can be obtained. This calculation is useful to the linearization of the mathematical model set up. Based on experimental data, it is possible to calculate the dynamical response of the power generated by the heater to keep the meniscus on its original position. This is shown in Figure 18 where the experimental signal in watt (in black) represents the effort made by the electric heater to keep the meniscus on its original position. In the same figure, for comparison purposes, a theoretical simulated outcome based on actual parameters is shown in red.

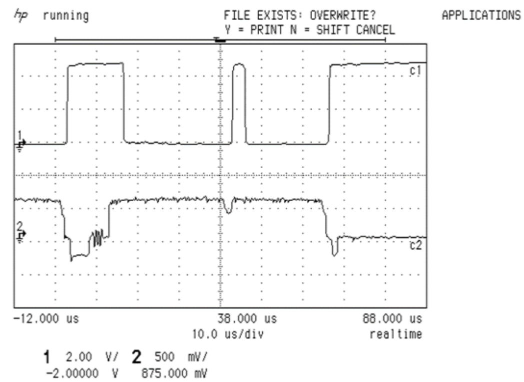

Figure 16. Oscilloscope signal. Above: digitized signal after the voltage comparator. Down: voltage information of the single video line.

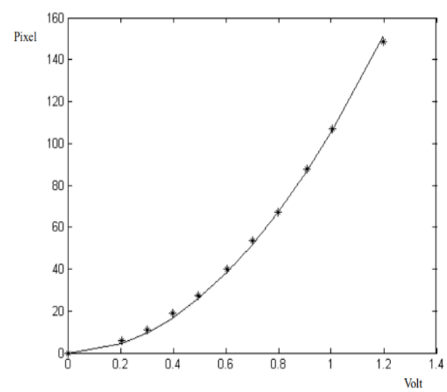

Figure 17. Quadratic behavior between electric power in volt and meniscus' displacement.

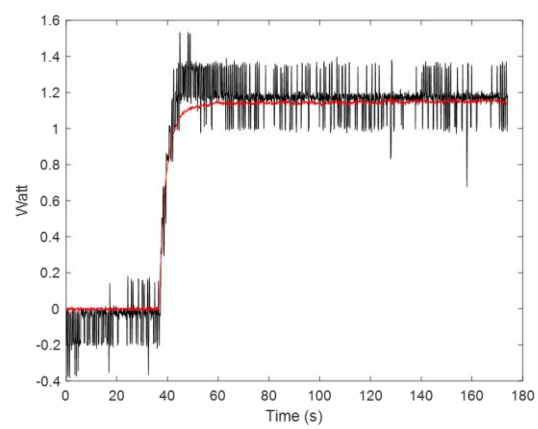

Figure 18. Power supply effort in watts to counterbalance the pressure step on the tip of the capillary: experimental response (black), and theoretical response (red).

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:

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

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 II).

TABLE II. MEDIUM AND STATUS FOR THE PH OCCURRENCE.

	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 [32][33].

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 [34]. Besides, the effectiveness of glyphosate is affected both by the pH of the medium and by the presence of cations in the spray water [35].

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 portable optical instrument for pH measurements was presented in 2011, and it makes it possible to determine pH with a colorimetric sensor array [36]. In fact, the use of four membranes containing acid-base indicators makes it possible to cover the full range of pH using the hue (H) coordinate measurements of the HSV color space. The resulting microcontroller-based system has shown to be immune to optical and electrical interferences. Besides, the authors showed that the pH response of the selected four sensing elements was modeled, and calibration curves were applied to a validation set and real samples obtaining positive correlations between the real and predicted data.

In 2013, a seawater pH data with good spatial and temporal coverage to apprehend ocean acidification phenomena studies was presented [37]. In such a way, it performed an accurate and precise autonomous in situ pH sensor for long term deployment on remote platforms. The widely used spectrophotometric pH technique was capable of the required high-quality measurements. In fact, it has been reported a key step towards the miniaturization of a colorimetric pH sensor with the successful implementation of a simple microfluidic design with low reagent consumption. The system featured a short-term precision of 0.001 pH and accuracy within the range of certified values. Likewise, the optical set up was robust and relatively small due to the use of an USB mini-spectrometer, a custom-made polymeric flow cell and an LED light source.

In addition, a portable electronic instrumentation for pH in-situ reading based on the use of a conductive polymer was also presented in literature [38]. Authors have used polyaniline, which proved to be useful to be used as a sensor for pH measurements. In such instrumentation the spectroscopy in the UV - Vis was successfully used.

Furthermore, for education purposes, in 2018 it has been presented as an open-source potentiometric instrument for pH determination experiments with Bluetooth wireless connectivity [39]. The hardware was built on a solderless breadboard and mainly composed of an Arduino Nano microcontroller, a 16-bit analog-to-digital converter, two electronic buffer amplifiers, a temperature sensor, and a Bluetooth module, i.e., a low-cost instrument. Also, the software was written in Arduino Sketch and the cross-platform Python language, both of which the students were allowed to access and modify freely. The instrument was demonstrated with a traditional glass electrode and a custom palladium/palladium oxide pH sensing electrode, and compared with a commercial pH meter. Results showed that both the accuracy and precision of the developed instrument were adequate for teaching purposes.

Recently, at Embrapa Instrumentation, 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 19).

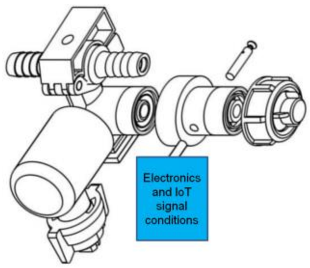

Figure 19. Technical draw of the intelligent pH sensor assembled on the nozzle for direct injection sprayer.

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 [40]. 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 III.

TABLE III. 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 Gbytes 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.

When it is being applied to a direct injection sprayer it has a typical control loop as shown in Figure 20. 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 q_{fref}, V_f, and q_m, which represent the set point for the mixture flow, controlled, and measured variables respectively.

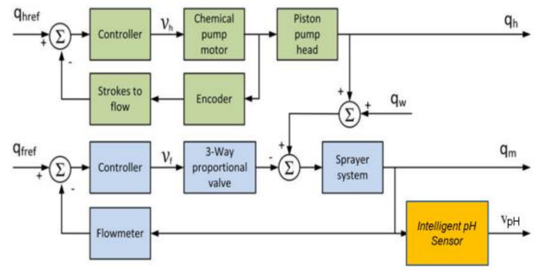

Figure 20. Block diagram for the fungicides, herbicides or insecticides, mixture control, and the intelligent pH sensor.

In this type of direct injection sprayer, the injection point is located upstream from the sprayer pump as presented in [41][42]. The water flow q_w is dependent on both the flow mixture q_m and the injection flow q_h. The intelligent sensor is assembled to measure the pH of the spray solution, which is proportional to its output denoted V_{pH}.

Figure 21 shows the flow-diagram of the algorithm for real time self-diagnostics.

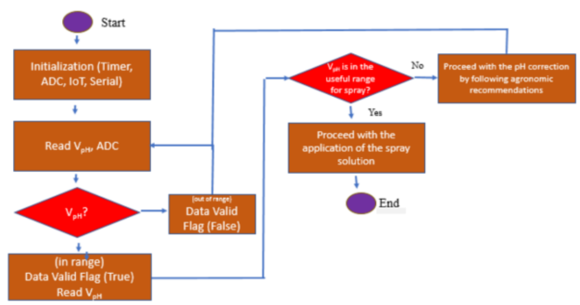

Figure 21. Computational Flow diagram for the real time measurements and flag related to the spray solution pH evaluation.

The calibration curve for the intelligent sensor for pH measurements is presented in Figure 22.

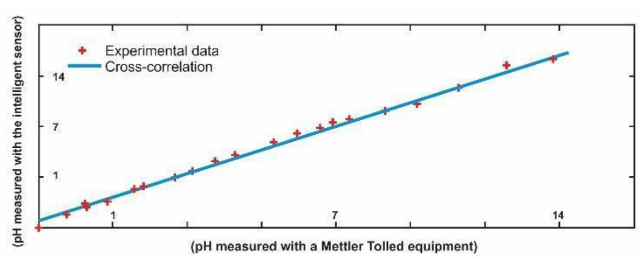

Figure 22. Calibration Curve and comparison with values obtained with prepared solutions with well-known pH values.

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. Its configurations will depend on demand and large-scale applications.

VI. CONCLUSIONS

By using the sensor developed with microwave technique in the GHz frequency, it was possible to see that the main benefits with the instrument proposed here were not only the use of a non-destructive methodology, but also easy measurement of soil water, portability, use of non-ionizing radiation, speed in the measurement, and low cost. Besides, the use of the apparent electrical conductivity of the soil has demonstrated usefulness as an important tool for precision agricultural work, since one may find its simplicity, as well as time and cost savings in carrying out decision-making in the areas of agricultural management having spatial variability. However, it is important to observe that ECa alone does not allow to answer all questions needed after the data mosaic be provided. Likewise, by supplying the physical model for the pressure probe and its improvement it has become possible an automated pressure gauge. Such a gauge is quite useful to investigate the displacement of a meniscus in the observation of the water-plant ratio, i.e., the water potential direct in agricultural crops. Furthermore, the possibility to have an intelligent sensor to measure the pH of a mixture (pesticide plus water) in spray systems contributes to decrease environmental impacts as well as in cost-reduction associated with the pest control efficiency. Finally, such affordable sensors proved to be innovative to improve production and resilience in agriculture. Future works will be focused on improvements in interoperability and real time operations to support agricultural databases and decision making based on the use of artificial intelligence.

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