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Sensor System for Water Stress Detection Using In-Plant Transmitted Signal Amplitude Evaluation

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***Abstract*—Environmental sustainability has become a significant topic, especially in recent years. Extreme natural phenomena and food insecurity related to the rising world population have highlighted the need for a new approach to agriculture. Smart Agriculture solutions may represent a viable answer to boost productivity, reduce emissions, and optimize human labor through the utilization of several new technologies and techniques in the climate-change scenario. From this perspective, the following paper proposes a sensor system capable of evaluating the plant's health status based on stem electrical impedance from a local and global point of view. In particular, the receiving system is able to sense the global stem impedance, monitoring the amplitude of a signal transmitted inside the plant itself. The system injects a square wave into the plant, and thanks to the proposed sensor, it is possible to read a frequency proportional to the amplitude of this signal collected from another point of the stem. The developed system has been tested on a tobacco plant, showing correlations of 0.94 and -0.97, respectively, for the local sensor and global sensor with respect to the soil water potential.**

***Index Terms*—Impedance Monitoring, In-vivo Monitoring, Smart Agriculture, Water Stress, Sensor System**

I. Introduction

In recent years, awareness of environmental sustainability has grown due to frequent extreme natural phenomena worldwide. According to the WMO State of the Global Climate Report 2022 [1], these events are increasingly common due to rising greenhouse gas concentrations, global temperatures, and sea levels, causing deaths, food insecurity, migrations, and economic losses impacting social stability and international relations. The agri-food sector significantly impacts emissions despite a downward trend in agricultural emissions over thirty years [2]. Given rising global food demand, a shift in agricultural management is needed to reduce environmental impact and enhance sustainability. Smart agriculture aims to boost productivity, improve resilience, reduce emissions, and optimize labor through new technologies, addressing food demand and climate change. This is possible thanks to sensors to monitor the crops connected to ultra-low-power consumption and low-cost devices with a wireless connection for data transmission. Electrical Impedance Spectroscopy (EIS), the study of the interaction of the passive electrical properties of a sample with an AC current (or voltage) applied over a range of frequencies, is an interesting approach to the agrifood sector [3]. It can be applied to every part of the plant: roots [4], stem [5], leaves [6], and fruits [7]. Furthermore, it is possible to study the electrical impedance variations to detect different types of stresses affecting the crops. EIS is performed on a range of frequencies. Useful information can also be extracted at a fixed frequency, as shown in [8]. Variations in the electrical impedance of the plant stem are associated with stress conditions. A custom device monitoring the electrical stem impedance was presented in [9]. This device utilizes a stem frequency sensor based on a square wave oscillator with the plant stem in its feedback loop. Although it lacks precision due to harmonic interference, it effectively detects variation trends in the plant using simple, low-complexity, and low-power circuits, eliminating the need for expensive components. However, impedance measurements are limited to a portion of the stem where the electrodes are inserted. In the same paper, the authors showed that it is possible to transmit a signal inside the plant stem. A signal traveling inside the plant is affected by the stem impedance. The plant stem attenuates the transmitted signal since it is not a perfect conductor. In this paper, we show a sensor system where the receiving system monitors the attenuation of a signal transmitted into the plant. This quantity is related to the impedance of the stem used as a communication channel, enabling the possibility to monitor the entire stem of the plant. We propose a sensor system for monitoring stem electrical impedance based on off-the-shelf components, which is low-cost and compatible with a microcontroller.

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II. Proposed Design

The proposed design wants to demonstrate the working principle of a smart sensor system to detect plant water stress by sensing the stem impedance of a Plant Under Test (PUT) both in a local and a global region of the plant, using the conductive paths of the plant itself, respectively, sensing the local component close to the sensing point and the global output at the base of the plant. This will not be possible using a

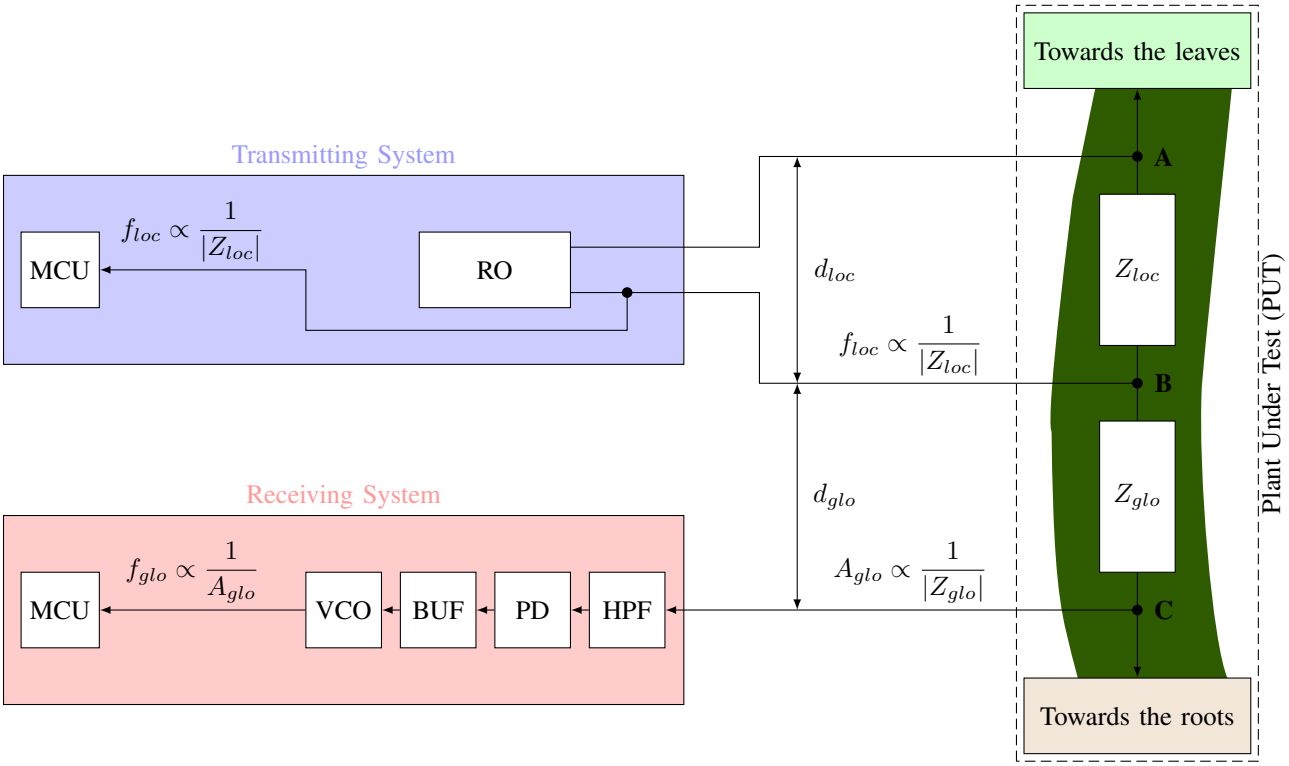


Fig. 1. Block diagram of the sensor system to measure local and global impedance moduli of the Plant Under Test (PUT).

commercial high-precision impedance converter system, such as the AD5933 (Analog Devices, Wilmington, Massachusetts, USA), because it only allows local measurements. As a result, placing the transmitter in the tree crown and the receiver at the base of the tree, using the tree as the communication channel, will not be feasible.

Our solution includes a transmitting system similar to the one presented in [9] and a novel receiving system. Fig. 1 shows the block diagram of the sensors network. The transmitting system is mainly composed of a Relaxation Oscillator (RO) circuit based on LMC555 (Texas Instruments, Dallas, Texas, USA), a 555-series general-purpose timer, and a low-power microcontroller (MCU), named STM32WL55 (STMicroelectronics, Geneva, Switzerland), having a timer to estimate the frequency of the generated square wave from RO. In this way, the transmitting system provides a frequency output inversely proportional to the impedance modulus $|Z_{loc}|$ of a stem track equal to d_{loc} distance between two electrodes (track **A**-**B**). Generated square wave from the transmitting system, in point **B**, could be read in other points, as point **C** of the stem plant, influenced by the new stem track considered (track **B**-**C** equal to d_{glo}). In point **C**, if we consider a generic impedance Z_{glo}, a square wave generated in point **B** will be distorted, attenuated, and shifted. In this work, we focused on the attenuation factor, inversely proportional to the impedance modulus $|Z_{glo}|$. Moreover, a higher impedance modulus leads to a lower amplitude A_{glo} of the resulting square wave in point **C** due to a greater attenuation factor. This can be measured by a receiving system using the following elements: a High-Pass Filter (HPF) is used to filter out the environmental noise from the input signal below 10 kHz and to set the bias point at half of the supply voltage (assuring an always-positive signal at peak detector input), a Peak Detector (PD) circuit (composed by an operational amplifier, a Schottky diode, and a storage capacitor), a buffer (BUF) implemented as unity-gain amplifier and a LMC555-based Voltage-Controlled Oscillator (VCO). The result of this electronic chain is a square wave output signal f_{glo}, whose frequency is inversely proportional to amplitude A_{glo} of the square wave in point **C**. Moreover, f_{glo} is directly proportional to the impedance modulus $|Z_{glo}|$. This frequency is acquired by a microcontroller (MCU) as in the case of the transmitting system.

III. Results and Discussions

The proposed sensor system was tested on a PUT, a *Nicotiana Tabacum L.* cultivar. In particular, it used a set of 1 cm-long 0.4 mm-diameter stainless steel electrodes as in [9], both for two electrodes composing transmitting system and the single electrode of the receiving system. This preliminary work on a single plant will be tested in a new experiment with a group of crops under the same conditions to achieve statistical validation. These electrodes are placed at a distance d_{loc} of 10 cm between point **A** and **B** for transmitting system and at a distance d_{glo} of 5 cm between point **B** and **C** for receiving system. The electrode in point **C** is placed at the height of 10 cm with respect to the base of the plant. It is useful to note that it was not possible to increase additionally d_{glo} due to

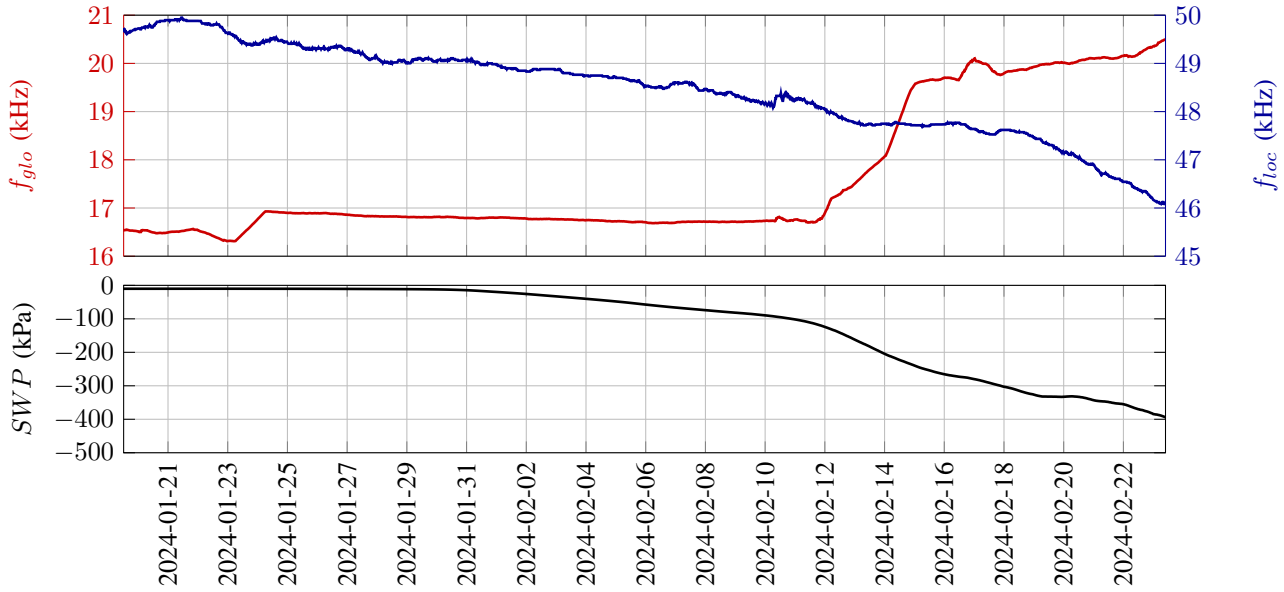


Fig. 2. 24-hour moving average frequency of the transmitting and receiving systems compared to the matric potential in the soil.

the fact that the total stem height of the PUT is approximately 25 cm. A greater d_{glo} is possible in higher plants. Finally, it was measured the Soil Water Potential (SWP) to correlate plant water stress measured by the stem impedance using a commercial digital soil sensor named TEROS 21 (METER Group, Inc., Pullman, Washington, USA) using a low-power, long-range electronic system able to communicate with it [10]. SWP, typically expressed as kPa, identifies the potential energy that the plant needs to overcome to extract water from the soil using its roots. A filtering process on the data has been performed to appreciate the frequency variations of both transmitting and receiving systems: data are sampled each 20 min, and it has been performed a moving average of 72 samples, corresponding to a 24-hour moving average. This step was performed to extract information about the general trend of plant filtering out noise and the superimposed harmonic due to the circadian rhythm of the plant, which corresponds to 24 hours. The experiment lasted from 19/01/2024 to 23/02/2024, approximately one month, starting from an irrigation event on 19/01/2024 on a mature PUT. The experiment started a few days after the electrode mounting step. This has been done in such a way that the plant has had sufficient time to heal the wound, guaranteeing more stable frequency measures. Fig. 2 shows the results of the experiment: as a reference, it is possible to note the mean soil water potential close to −10 kPa, confirming a wet soil in the flowerpot of the tobacco PUT. Day after day, mean SWP tends to have more negative values, which means drier soil. On 23/02/2024, the last day of the experiment, SWP sensor shows a mean −397 kPa value. The receiving system starts with a mean frequency of 16.54 kHz and the transmitting system with a mean frequency of 49.72 kHz. The final values, at the end of the experiment, are 20.51 kHz and 46.04 kHz, respectively,

TABLE I
CORRELATION COEFFICIENT MATRIX.

	SWP	f_{loc}	f_{glo}
SWP	1		
f_{loc}	0.94	1	
f_{glo}	-0.97	-0.86	1

for receiving and transmitting systems. These values depend on a chosen set of passive components realizing RO for the transmitting system and VCO for the receiving system. An increasing and a decreasing frequency value occurred, respectively, for receiving and transmitting systems. Table I shows the correlation coefficient matrix among SWP, f_{loc} and f_{glo}, computing the Pearson correlation coefficients. In particular, f_{loc} and f_{glo} have, respectively, a direct correlation (0.94) and an inverse correlation (-0.97) with respect to SWP. This behavior confirms the hypothesis of the proposed design about the sensor system to detect abiotic stress, such as plant water stress.

IV. CONCLUSIONS

In this study, we developed a novel sensor system to monitor plant water stress by measuring stem electrical impedance in a *Nicotiana Tabacum L.* cultivar. The system uses both local and global impedance measurements, allowing for detailed monitoring of specific plant areas or overall stem impedance. Changes in frequency outputs from the transmitter and receiver correlated with soil water potential, indicating that stem impedance reflects the plant's water status. This suggests that the system can detect water stress, making it a useful tool for smart agriculture. Future work could optimize the system for other plant species and expand its ability to detect various stresses.

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