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Analysis of In Vivo Plant Stem Impedance Variations in Relation with External Conditions Daily Cycle

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***Abstract*—World population growth and desertification are the most severe issue to agricultural food production. Smart agriculture is a promising solution to ensure food security. The use of sensors to monitor crop production can help farmers improve the yield and reduce water consumption. Here we propose a study where the electrical impedance of green plants' stem is analyzed in vivo, along with environmental conditions. In particular, the variations associated with the daily cycle are highlighted. These analyses lead to the possibility of understanding plant status directly from stem impedance.**

I. INTRODUCTION

At the beginning of the 19th century, about 1 billion people were living on the planet, while nowadays, this number reached the amount of 7,7 billion [1]. Temperature rising, the reduced soil water retention potential, the reduction of weather precipitation, and the water consumption needed for crop growth caused a mechanism called land desertification: fertile and florid soils are becoming arid and sterile. World population growth and climate change are the main issues impacting food security nowadays. Furthermore, water consumption is expected to be amongst the most important future challenges, as reported in the 'Food and Agriculture Organization' of United Nations [2].

Smart Agriculture is a possible solution. It aims to improve farmers' food production by integrating their knowledge with data collected by sensors and automatizing agricultural processes as the ultimate goal. Different examples of plant monitoring are available in the literature. Data collection of various parameters from the surrounding plant environment, such as temperature, humidity, soil moisture, etc. is depicted in [3]–[5]. However, these parameters are not a direct indication of plant status: the surrounding environment is causing plants reaction, but it is important to measure the plants directly. In [6], a review on Electrical Impedance Spectroscopy (EIS) in agriculture is presented. Impedance variations, both in roots and stems, are correlated with different parameters. However, no examples are reported of in vivo measurements: the samples are always removed from the plant and processed before measuring the impedance spectrum. EIS is also used in food quality check and leaves measurements to understand watering status [7].

In [8], we proposed to monitor the plant stem impedance changes and showed correlation and causality relation with its hydration status. Here, we implemented an updated version of the monitoring system able to measure in vivo plant stem impedance. It can measure up to four plants simultaneously. Furthermore, a wireless sensor node is described as an improvement of the one presented in [9]. The new sensor system enabled a more in-depth analysis of the plant stem impedance shown here. In this paper, the impedance variations due to the daily cycle are evaluated and described.

II. EXPERIMENTAL SETUP

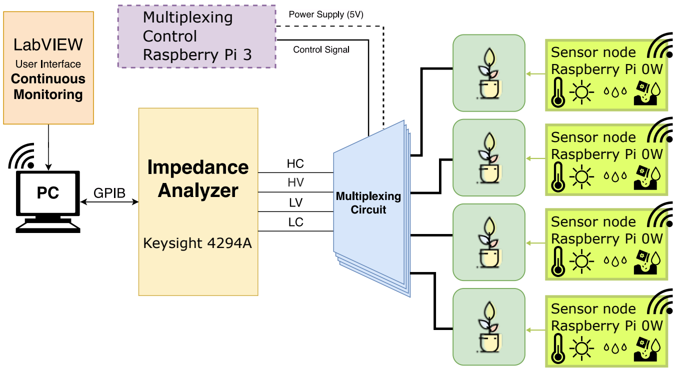

Fig. 1. Full system architecture showing impedance measurements and environment sensors connection.

A block diagram of the developed measurement and data processing system is shown in Figure 1; currently, up to 4 plants can be monitored in parallel. In this study we used tobacco plants. It is composed by modular, wireless, small and low-cost data acquisition nodes, featuring environmental sensors (temperature and humidity, light intensity, and soil moisture). Nodes have been developed around the Raspberry

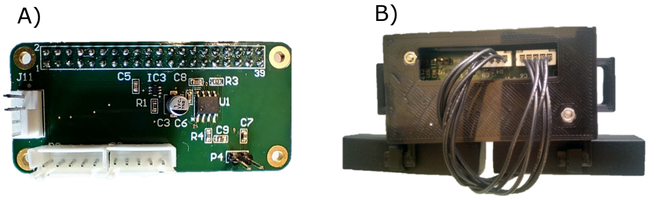

Fig. 2. Sensor node picture. A) custom PCB to be mounted on top of the Raspberry Pi. B) Plastic case holding the sensor node. The side components connected trough wires hold the light and temperature sensors.

Pi Zero W [10], with a custom PCB stacked on top of it comprising all the electronic circuits needed for interfacing with the sensors; further sensors could easily be added as an expansion thanks to the available I^{2}C bus. Thanks to this design we were able to provide each plant with a complete data acquisition node, thereby greatly simplifying the overall deployment of the measurement system in case of multiple plants to be independently monitored in parallel. Figure 2 shows the developed sensor node. Four point electrical impedance measurements (discussed in [11]) are performed by an expensive but accurate instrument, a Keysight 4294a impedance analyzer [12], and the overall process is controlled by a LabView [13] software interface, running on a common PC. In order to measure different plants during the experiment, a multiplexing system (shown in Figure 3) has been implemented. Four analog BNC multiplexer, produced by Hasseb [14], are used to switch the four measurement cables among the plants. Each multiplexer, an analog BNC multiplexer produced by Hasseb [14], comprises four relays, each one used to internally connect one of the available BNC channels to a single common BNC connector. A Raspberry Pi 3 [15] controls all the multiplexers: the channels are correctly selected on all the modules with the same timing, in turn controlled by the LabView interface. Furthermore, a webcam connected to the Raspberry Pi is used to visually monitor the plants under measurement, taking a picture synchronously with the impedance measurements.

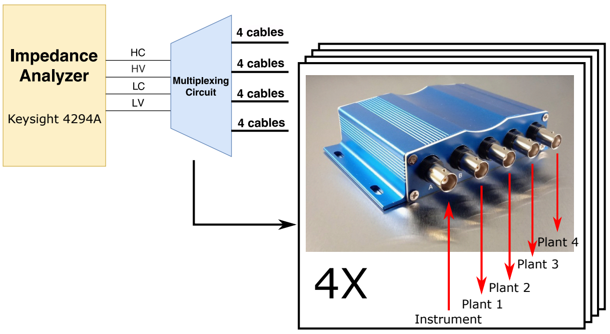

Fig. 3. Schematic view of the multiplexing system. Four instances of the Hasseb multiplexer are used to connect the four wires of the impedentiometer to the plants under test.

Environmental data are sampled every 30 minutes, while the impedance spectrum is analyzed every 15 minutes, multiplexing across four different plants. Impedance spectrums are measured over frequencies ranging from 40 Hz to 1 MHz (distance between measurement electrodes on the stem of 5 cm). Overall, each plant stem impedance data is saved every hour. Physiological timing of the plants, in particular reactions to environmental conditions/changes, are so long that the implemented sampling time and synchronization among data acquisition subsystems are not an issue, in particular not requiring any tight synchronization (however, to be on the safe side, data recorded with time differences greater than 30 minutes are not considered). At the same time, such a “low” sampling time enable to record data for very long periods without incurring in common problems due to the very large data size to be stored and then processed. This, in turn, allowed us, for example, to properly track long period of induced water stress, a key test in investigating the relation between stem electrical impedance and the physiological condition of the plants.

III. MEASUREMENTS AND RESULTS

Figure 4 shows an example of the impedance spectrum variation due to soil drying. Each curve in the figure refers to the complete spectrum measured at the same time every day. The variations are not uniform all over the spectrum. Therefore, as a primary analysis, the optimal frequency for this analysis was investigated. Figure 5 shows impedance modulus and phase variations during time compared with the environmental data. The plot covers two weeks with a watering event after ten days. The watering event is visible in the

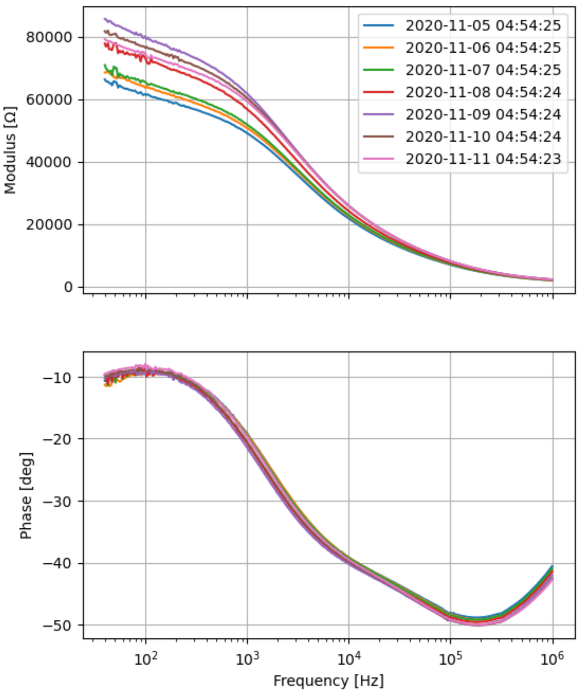

Fig. 4. Impedance modulus and phase of a tobacco plant variations during a week after watering.

Moisture chart in Figure 5: the soil moisture decreases and reaches a minimum value that represents completely dry soil. Then, the steep increase in December, the 11th shows the watering event. The most important aspects of these charts are that the colored lines available in the first two plots show the trend of the impedance values at different frequencies. In particular, the blue line is related to a frequency of 863 Hz. This is the lowest frequency considered for this analysis since noise injection was more severe for values below this one. The other curves are related to different frequency values. From a visual inspection, it is possible to see that lower frequencies are associated with higher variations. However, it can be seen that some curves are noisy, in particular the phase ones. A good trade-off is available at 10 kHz (the red curve): it shows moderate variations in relation to environmental conditions with a smooth outline. The aforementioned analysis is valid for the impedance modulus. Regarding the phase, it is possible to observe different results. In particular, lower frequencies are related to lower changes: The blue line (863 Hz) is almost flat, while the pink one (205 kHz) shows notable variations. However, noisy edges are also clearly visible in the phase charts.

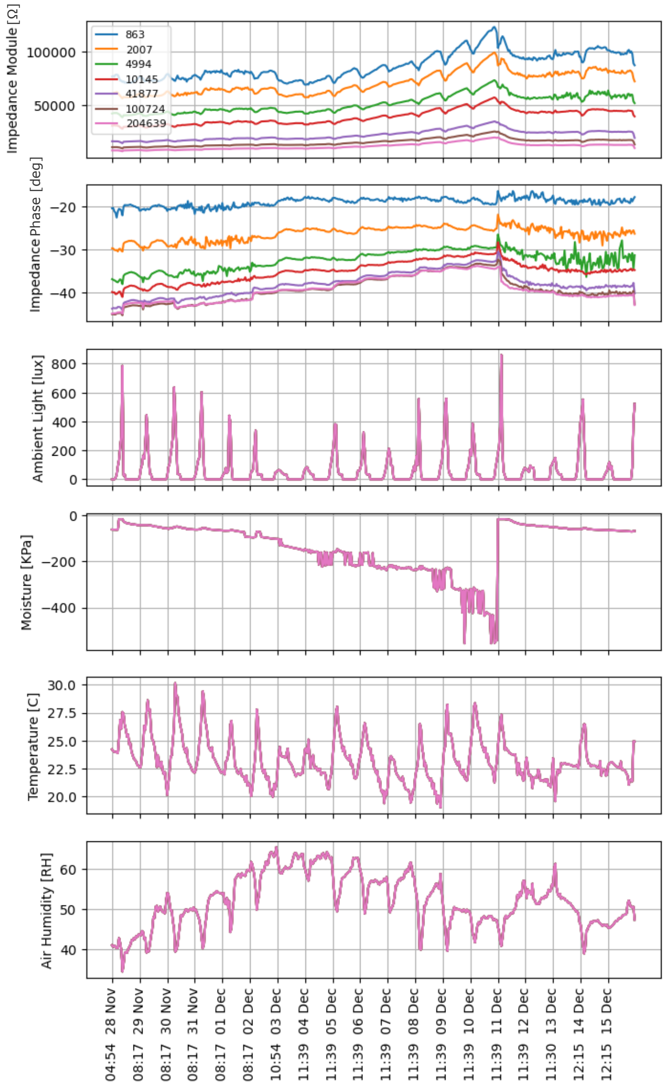

Fig. 5. Impedance modulus and phase trend at different frequencies over two weeks with environmental data(ambient light, temperature, relative humidity, and soil moisture).

These analyses show that an ideal frequency for the impedance measurement does not exist. Lower frequencies are more suitable for measuring the modulus, while higher ones better monitor the phase. A fair trade-off for both modulus and phase seems to be a frequency of 10 kHz, where the noise effect is reduced, and the variations are significant for both the values.

IV. ANALYSIS OF THE DATA

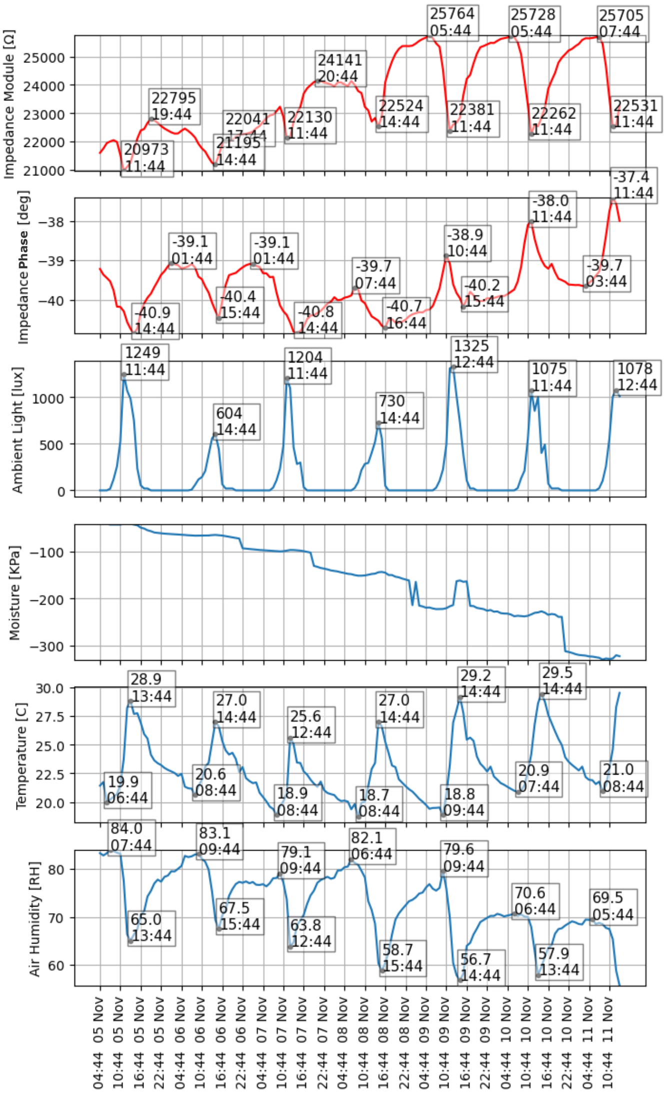

Fig. 6. Impedance modulus and phase of a tobacco plant over a week with environmental data(ambient light, temperature, relative humidity, and soil moisture).

The relation between soil moisture and water condition was already discussed in [8]. Figure 5 shows the main impedance

Fig. 7. Picture of a tobacco plant under test during a day. The first is taken at 10 a.m. and the others every two hours.

modulus trend due to soil moisture variations. In particular, it is possible to see a slow but steady increase before the watering event for all the frequency curves. After the watering, the trend of the impedance values start to decrease.

We want now to focus on the relation between the stem electrical impedance and the daily cycle. In Figure 6 impedance values at 10 kHz and environmental data are plotted. In this case, the data cover a time range of a week. Impedance modulus and phase are showed maximized to highlight their trend.

Furthermore, labels are placed in correspondence with minimum and maximum values in all the curves. The trend, clearly visible in the environmental chart, is related to the daily cycle. Sensors are placed near a window inside a laboratory. Therefore, the light intensity has its maximum peak around midday. The weather in the considered week was sunny. Temperature data confirm weather information. Thus, maximum temperature values correspond to light peaks. Furthermore, the average and minimum temperature values are relatively high. Finally, relative humidity has an opposite trend to temperature, with the maximums in correspondence of temperature lower peaks and vice versa. From the visual inspection, it is clear that the impedance modulus and phase show a trend linked with the environmental condition. Daily changes are superposed to the overall trend due to water conditions. In the red curves in Figure 6, the labels show the peaks reached during a day by modulus and phase. Both high and low peaks follow the general expected trend, based on the water condition. The plant soil is drying, and both the curves are growing. Furthermore, the red curves' peaks are aligned with the peaks in ambient light, temperature, and humidity curves. It is possible to define two separate cases in the charts: before November 8th, and after. In the first portion, the plant hydration is normal. Here, when the temperature is starting to rise, the impedance curves change their trend. Therefore, the maximum peaks of the impedance modulus and phase always follow the temperature's minimum peaks. The plants react to high temperature and light intensity closing the stomata and reducing the amount of water and the sap flow in the stem. The reduction of the fluids in the stem causes an impedance increase. When the temperature starts to decrease, the plants start the photosynthesis process, collecting water from the roots and moving it to the leaves. This trend is visible in the impedance modulus curve. After the temperature peak, typically in 1 hour, both modulus and phase show their minimum peak and then start to increase. In this condition, both modulus and phase show the same shape. Something different is visible when the soil moisture falls below -150 kPa. Modulus and phase curves show a completely different shape: high flat portion separated by narrow negative peaks for the modulus and low flat portion with high peaks for the phase. The modulus stays high during the night and then shows a steep fall as soon as light is available. The high-temperature impacts the plant condition, and the modulus rises again: this time, due to the water stress condition, the process begins far before the temperature peak. On the contrary, the phase shows exactly the opposite behavior, with minimum values in correspondence with modulus maximum. This behavior is also visible in the plants' leaf condition. Figure 7 shows the same plant during different hours of the same day. The pictures are taken every two hours, starting from 10 a.m. up to 6 p.m. Leaves are in normal conditions in the morning. After two hours, the temperature has reached its peak, and the leaves start to lose their turgor. This effect is evident in the central picture. Starting from 4 p.m., the leaves begin to rise, reaching the regular aspect again before 6 p.m.

V. CONCLUSIONS

In this paper, we showed the relation between the plant stem's electrical impedance and the daily cycle. Environmental conditions, in particular light and temperature, induce changes in the impedance modulus and phase that are superposed to the trend given by water stress conditions. These results are an additional step towards the possibility of understanding plant status measuring only the stem electrical impedance, possibly at a specific frequency.

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