Advances in design and construction of leaf wetness sensors

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Advances in design and construction of leaf wetness sensors

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***Abstract*—The majority of fungal infections are caused by leaf wetness, due to excessive humidity, mist, rain or irrigation. Leaf wetness duration (LWD), the total number of hours per day in which water is present on the foliage, can be monitored through a leaf wetness sensor (LWS). In this paper, an innovative procedure to manufacture a precise, low power and low cost electronic sensor is proposed to provide a tool for agronomic exploitation. The measurement subsystem consists of a two-side capacitive leaf wetness sensor, where a water presence varies the dielectric constant of the surrounding medium. The data acquisition subsystem exploits a capacitance-to-digital converter. Experimental results in controlled and real environments confirm reliability.**

***Index Terms*—Fungal infection, leaf wetness, low power, low cost, capacitive leaf wetness sensor, capacitance-to-digital converter.**

I. INTRODUCTION

Nowadays, crop disease represents one of the main concerns in agriculture, having a strong impact on the final yield. The majority of fungal infections are due to leaf wetness, i.e. the presence of water on the leaf surface, occurring in case of excessive humidity, mist, rain or irrigation. Thus, the parameter of leaf wetness duration (LWD), which indicates the total number of hours per day in which water is present on the foliage [1], is significant in early detection and prevention. A leaf wetness sensor (LWS) plays a crucial role in monitoring all these conditions.

II. STATE-OF-THE-ART

Historically, the first LWSs were mechanical, where a change in the amount of water present on the leaf determined a change in the weight or size of the sensor [2]. Other LWSs were static [3], being only able to determine whether a leaf was dry or wet [4].

Today, miniaturization and improved robustness make electronic sensors a preferable choice. LWD can be indirectly measured using temperature and humidity sensors by calculating the period during which the difference between the temperature and the dew point is below a predefined threshold.

On the other hand, electronic LWSs represent the first choice for the direct measurement of LWD. Two types of LWSs exist:

- resistive, through two metallic conductors, usually gold plated, whose ohmic resistance changes with humidity;
- capacitive, measuring the dielectric constant of the material between two electrodes, which in turn changes the sensor capacitance due to the fringing field [5].

Both typologies are characterized by greater stability and reliability, compared to mechanical and static ones, but might be less affordable off the shelf [3], especially capacitive sensors, despite their extraordinary efficiency [6]. Indeed, high precision can be reached by introducing a hydrophobic coating that might increment manufacturing costs [7].

III. PROPOSED SOLUTION

An innovative leaf wetness sensor was designed and implemented with these aims:

- low manufacturing cost;
- easy replication;
- minimum energy consumption.

To this purpose, a capacitive solution has been selected.

Data are retrieved through a capacitance-to-digital converter, which can be easily found off the shelf at cheap prices and allows to perform capacitance and frequency instead of voltage measurements, the last ones being power consuming.

A. Design

The sensing part of the capacitance LWS was designed as a two-side, four layers printed circuit board (PCB). The upper and lower layers contain a set of alternate strips printed in a quasi-circular pattern, as it is shown in Fig. 1.

To design the intermediate layer, an analytical formulation has been developed, leading to a mathematical formula that allows an easy and selectable design of leaves with any dimension, consequently applicable to any crops. The analytical computation will be presented in a dedicated publication.

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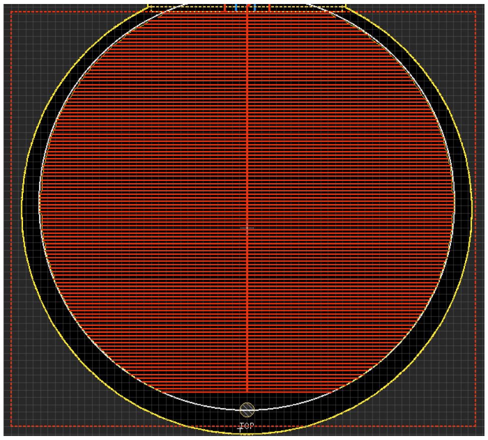
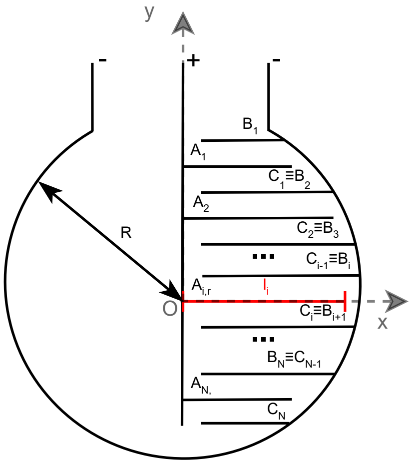


(a) PCB schematics



(b) Strips pattern

Fig. 1. Sensing surface configuration

The two intermediate layers contain floating ground planes, which guarantee adequate separation between the upper and lower part. The PCB is coated to prevent damages to the strips. In this way, two distributed capacitances are formed, one between the alternated strips printed on the top layer, the other one between the strips on the bottom one. Capacitance varies, depending on the dielectric constant of the medium that surrounds the coating (either air or water).

For what concerns the data acquisition, the FDC2112 [8] from Texas Instruments was adopted as frequency to digital converter, which provides high resolution and the possibility to use two independent channels for each sensor side, respectively for the upper and bottom layers of the electronic leaf. Its high-speed rate, up to 13.3 ksps, allows to further reduce the power consumption. Moreover, the support for a wide excitation frequency range (10 kHz - 10 MHz) ensures sufficient dynamics in the capacitance variation and, consequently, an adequate precision in the measurement.

Differently from the most common LWSs available on the market, the minimum required supply voltage is only 2.7 V, against the usual 5 V, lowering the energy demand.

The FDC measures the oscillation frequency of an L-C resonator, with a digital output value, proportional to frequency and converted to an equivalent capacitance.

An I^{2}C interface is used for the digital communication with a microcontroller.

Our measurement configuration, as it is shown in Fig. 2, consists of an L-C circuit, with a constant inductance value constant L_c and the total capacitance equal to the unknown capacitance of the leaf face, plus a constant offset C_c, which optimizes the frequency excitation variation range.

B. Implementation

The sensor capacitance on each surface depends on the geometry and thickness of the electrodes, the distance between two adjacent electrodes, the number of electrodes and the material used as dielectric.

The material chosen for the PCB prototype is FR-4 TG130, whose dielectric constant is ϵ_r = 4.29 and thickness h = 0.36 mm.

To properly dimension the sensing device, a trade-off between sensor capacitance, which must be sufficiently high, and the PCB production costs of strips with small gap and width values must be taken into account.

To accomplish the requirement of the sensor excitation frequency range, a suitable choice is represented by $L_c =$ 10 mH and $C_c =$ 15 pF, which ensures a sufficient sensing range.

C. Materials

The application of transparent polyurethane conformal coating is necessary for both sides of the leaf wetness sensor, as it is shown in Fig. 3a, to improve the resistance to chemicals products and to avoid corrosion.

A plastic case, realized in 3D printer, was filled with epoxy resin to protect the circuital part.

After the manufacture process, the device was initially tested in a controlled environment. To this end, the humidity generator system Thunder 2500 from Thunder Scientific was used. The sensor was inserted in the chamber (Fig. 4), generating different percentages of humidity. Consequently, for each sensor a calibration curve was computed, proving the linearity between capacitance and leaf wetness percentage.

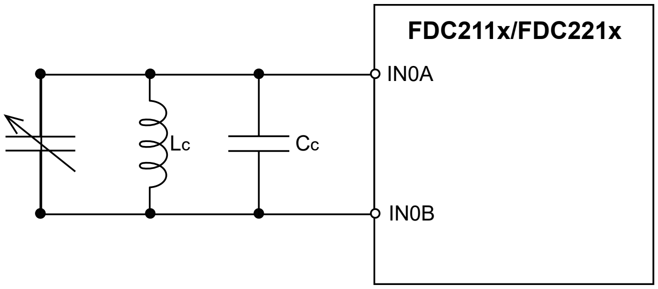


Fig. 2. Sensor Configuration

(a) Prototype of the LWS (b) LWS on the field

Fig. 3. Final LWS prototypes

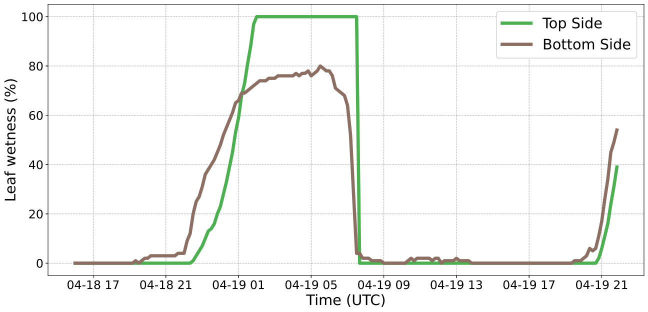
Fig. 4. Ambient chosen for the LWS characterization

An NFC tag was inserted to include a sensor identification number and calibration parameters.

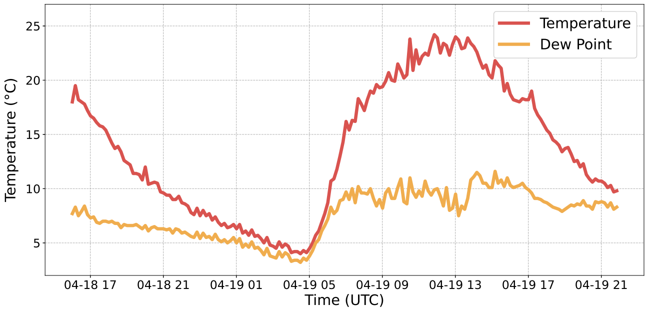
IV. RESULTS

The final prototype was installed in a vineyard as it is shown in Fig. 3b, combined with humidity and temperature sensors, through which the dew point was calculated and used as a reference.

Fig. 5a shows the wetness percentage on both leaf sides on 19^{th} April 2023. It can be seen that the highest percentage of wetness was reached during the night, from midnight until 9am, which is perfectly coherent with the data shown in Fig. 5b, where the computed dew point is referred to the air temperature. When the ”thermal difference”, computed as the distance in temperature between the two curves, is less than 1°C, dew forms.

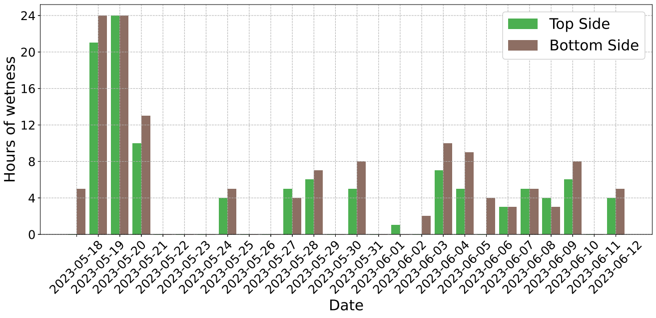


(a) Leaf wetness

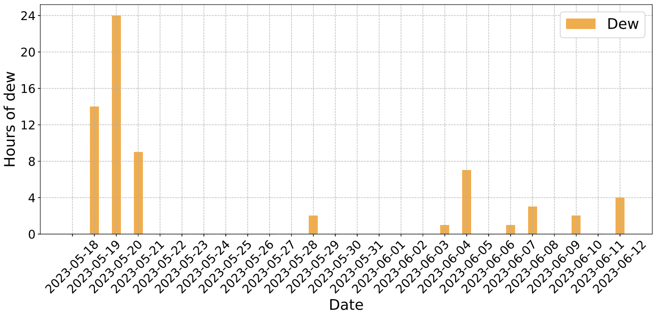


(b) Dew point

Fig. 5. Measurements over a typical day



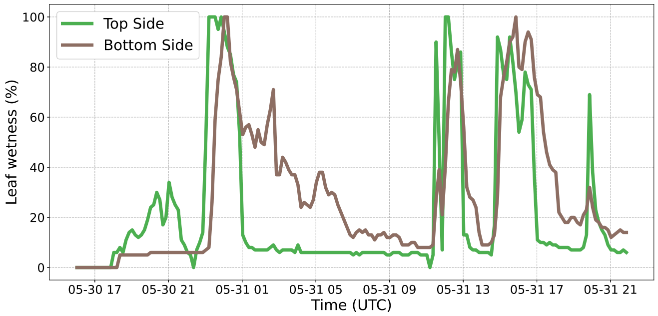
(a) Leaf wetness hours per day



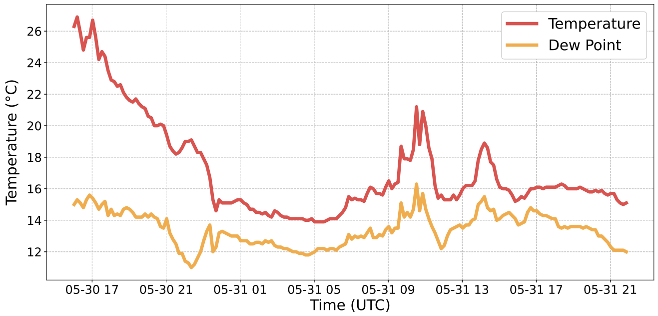
(b) Dew hours per day

Fig. 6. Measurements over May 2023

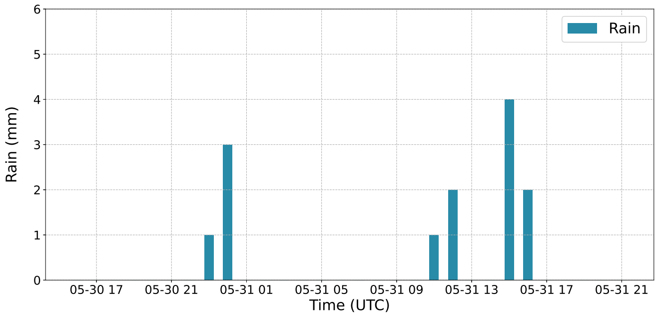
Fig. 6a represents the daily amount of hours in a month when leaf wetness was larger than 50%, while Fig. 6b daily amount of hours in the same month characterized by presence of dew, according to the dew point computed from temperature and humidity measurements. The two graphs correspond. Some differences are present, e.g. on May 31^{st} (Fig. 7a) when wetness was recorded on both faces with no computed dew (Fig. 7b), due to a rainfall (Fig. 7c), which caused additional



(a) Leaf wetness 31/05/2023



(b) Dew point 31/05/2023



(c) Rainfall measured with a rain gauge on 31/05/2023

Fig. 7. Experimental results

wetness. The LWS recognizes cases that are not detected with a simple dew point calculation.

In terms of power requirements, the FDC measurement has required only 5.15 mWs, minimal if compared to off the shelf available solutions.

The energy cost was evaluated by means of a power source set at 3 V and a current probe amplifier, which converts the current to a voltage signal that can be easily visualized and stored using an oscilloscope. The power consumption was then computed through the integral over the period of time of the FDC measurement.

CONCLUSIONS

An innovative leaf wetness sensor was designed, realized and tested firstly in a controlled room capable to generate different levels of leaf wetness and finally deployed in the crops.

The obtained performance and results are coherent with the expectations and the data collected by other sensors. Experimental results demonstrate that LWS is able to provide information not easily detectable by mathematical estimators, allowing more accurate agronomic decisions.

Further results about the power consumption compared to commercial devices and the theoretical study involved in the design of the measuring system will be presented in future works.

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