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A novel low-cost smart leaf wetness sensor

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ABSTRACT

Foliar wetness plays an essential role in plant disease cycles and epidemic development yet no cost-effective leaf wetness sensors (LWSs) are available that could be deployed within large areas to better understand that role. Electronic LWSs comprise an artificial leaf and the electronic circuitry able to measure electrical impedance changes due to water film or drops on the leaf surface. We propose a simple, compact and low-cost electronic interface circuit (EIC) for artificial leaves based on capacitance changes. The circuit relies on the charge-transfer capacitive sensing method and it is implemented by a microcontroller unit (MCU), which offers computation and communication capabilities currently missing in commercial LWSs, This EIC can be used in custom and commercial artificial leaves hence suits studies that require a close emulation of particular plant leaves.

1. Introduction

Between 2003 and 2012, about 12.5 million hectares were allegedly disturbed by plant diseases, mostly in Asia and Europe (Lierop et al., 2015). To mitigate this problem, several disease-warning systems have been developed that rely on mathematical, empirical or hybrid models that need leaf wetness duration data (LWD) (Rowlandson et al., 2015). Leaf wetness can result from dew, fog, rain, and overhead irrigation. It is a meteorological variable with no formal definition neither there is any recommended method to measure it (Madeira et al., 2002). This notwithstanding, electronic leaf wetness sensors (LWSs) are widely accepted and are the current technology of choice for LWD determination (Rowlandson et al., 2015). LWSs measure the change in the electrical impedance of a wire grid on the leaf, a clip attached to the leaf, or, more commonly, an artificial leaf (Sentelhas et al., 2004), and yield an output signal that changes according to the sensor's surface wetness. The dry/wet thresholds to determine LWD from that output signal are mostly empirical (Wichink Kruit et al., 2004), so that current LWSs are intended to be connected to external devices such as data loggers for further data processing to determine LWD.

Artificial leaves are usually built from a rectangular-, circular- or oval-shaped electrical insulator such as an electronic printed circuit board (PCB) or a ceramic plate, and are based on either resistive or capacitive grids. Resistive artificial leaves use a grid built from two interdigitated electrodes covered by hydrophilic material so that water accumulated on the surface, as drops or a film, reduces the electrical resistance between the electrodes (Fig. 1, left). Capacitive artificial leaves also use interdigitated electrodes but coated with dielectric material, hence water deposited on the surface affects the capacitance measured between the electrodes. Capacitive LWSs are more accurate and robust against surface contamination than their resistive counterparts but tend to be more expensive (Fig. 1, right). Further, leaf shapes and sizes available are limited and their cost, in excess of 100 USD, hinders their wide use in experimental studies that should involve many units, for example to assess the effect of sensor location and orientation, or in a disease-warning sensor network to be deployed within a wide area.

In this paper we describe a low-cost smart LWS that comprises an artificial leaf built on a PCB that emulates existing commercial models, and a novel electronic interface circuit (EIC) for capacitive sensors that is based on the charge-transfer capacitive sensing method and a low-end microcontroller unit (MCU). First, the sensitivity to different wetness conditions of the artificial leaves (custom and commercial) is assessed. Then, leaf wetness measurement performance is compared in two different setups: (i) using the novel EIC with the custom leaf design and with a commercial unit, and (ii) using the proposed smart LWS (electronic interface plus custom-designed artificial leaf) and a commercial LWS that includes an electronic interface with voltage output. Performance tests have been carried out in lab and outdoor conditions.

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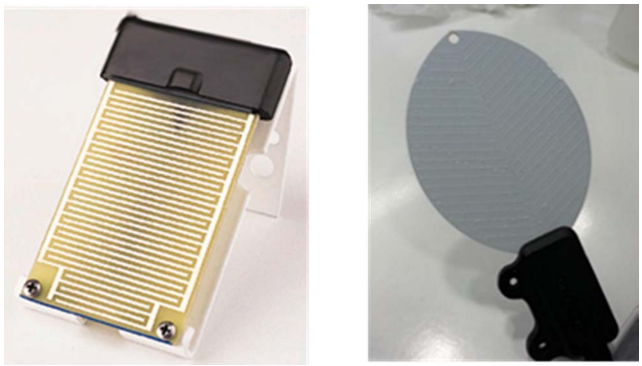

Fig. 1. LWS types: Resistive (left) (Davis Instruments) and Capacitive (right) (Decagon Devices).

2. Development of a leaf wetness sensor

2.1. Capacitive artificial leaf

We have designed two capacitive artificial leaves with rectangular (RECT) and oval (OVAL) shapes, printed on a 1.6 mm thick fiberglass plate, the usual PCB substrate, and whose dimensions are shown in Fig. 2. Capacitive leaf wetness sensors rely on the high value of the relative dielectric constant of water ($\varepsilon_r \approx 80$) with respect to fiberglass ($\varepsilon_r \approx$ 3–6). Thus, the capacitance between two electrodes underneath the "leaf" surface will depend on the presence of water drops or film on the top fiberglass surface and on the shape and dimensions of the sensor. Both sensors have interdigitated electrode patterns to increase their effective area hence the capacitance between them. The penetration depth of the electric fields above the interdigitated electrodes is proportional to the spacing between the centerlines of the sensing and the driver fingers (Mamishev et al., 2004).

The PCB electrode side is covered with a 25 μm protective coating (Clear Protective Lacquer CPL200 H – Electrolube) while the other side is left unprotected. The coating protects the PCB substrate against humidity hence fulfilling one key requirement of electronic LWS (Lau et al., 2000). Electrode width and gap are different for each sensor: 2.5 mm and 1 mm for the RECT sensor (Fig. 2, left) and 0.4 mm and 0.4 mm for the OVAL sensor (Fig. 2, right).

The accuracy of electronic LWSs is mainly limited by their physical characteristics (material, dimensions and shape) and their location and spatial orientation when deployed. Commercial LWSs are designed to mimic the thermodynamic properties of a standard plant leaf whose specific heat is about 3750 J kg^{-1} K^{-1}. Since average leaf density is about 0.95 g/cm^3 and its thickness is about 0.4 mm, the leaf's heat capacity is about 1425 J m^{-2} K^{-1}, that can be closely emulated by a 0.65 mm fiberglass plate whose heat capacity is 1480 J m^{-2} K^{-1} (Campbell Scientific). We have used a thicker plate because of availability hence our custom sensors will have a larger heat capacity that translates into dry/wet thresholds different from those of commercial sensors. The PCB coating effect on thermal conductivity is unknown because the coating's thermal properties are not specified.

To obtain results that truly represent events in a large area, LWSs must be placed in a suitable position because sun and wind exposure heavily affect dew deposition and evaporation hence the impedance measured. Schmitz and Grant (2009), for example, investigated the variability of dew duration in resistive sensors in a soybean canopy and found that there was a vertical gradient of wetness during dew events, and that wetness duration at the top of the canopy was longer for dew events than for rainfall events. In the middle of the canopy, the frequency of wetting was also higher for dew than rain, but wetness due to rain lasted twice than wetness due to dew. At the bottom of the canopy, wetness duration because of dew was rarely seen. Therefore, the deployment of several LWSs at different heights within the canopy could surely provide a more accurate picture of leaf wetness duration.

2.2. Electronic interface circuit design

Interface circuits for capacitive sensors are available wherein the sensor is directly connected to an MCU that converts capacitance to a digital value without any previous signal conditioning stage or analog-to-digital converter, which makes those circuits simple, compact, and low cost. They are based on the charge-transfer method (Philipp, 1999), where the unknown capacitance is calculated by counting the number of charge-transfer cycles needed to charge a reference capacitor to a threshold voltage via the capacitive sensor (Fig. 3, left). C_x is the sensor capacitance and C_r is a reference capacitor whose value is selected to be much greater than C_x. Pins PX.0 and PX.1 are standard input/output digital pins configurable as inputs (high-impedance input), or as outputs that provide V_{OL} and V_{OH} output voltage levels that correspond to a digital "0" and "1" respectively. V_x and V_r are the voltages across C_x and C_r respectively.

The unknown capacitance C_x is measured in a three-stage sequence controlled by the MCU:

(1) *Reset* (only at the beginning of each new measurement cycle). PX.0 and PX.1 are both set as outputs that provide a digital "0" ($V_{OL} \approx$ 0 V). Therefore, C_r is discharged towards V_{OL}, so that $V_r[0] \approx 0$.
(2) *Charging stage*. PX.0 changes to a digital "1" (V_{OH}) and PX.1 is set as an input port (high-impedance state). C_x charges exponentially towards V_{OH} (Fig. 3, ascending lines).
(3) *Charge-redistribution stage*. PX.0 is now set as an input port while PX.1 is set as an output at V_{OL} so that charge redistributes between C_x and C_r. V_x decreases and V_r increases (Fig. 3, rising lines). The control program starts to increment the number of charge-transfer cycles N_x and goes back to the charging state. The charging and charge-redistribution stages are repeated until the voltage across C_r reaches the input threshold V_T at PX.0. Since V_r [0] = 0, after N_x cycles the unknown capacitance can be approximated by (Fig. 3, right) (Gaitán-Pitre et al., 2009).

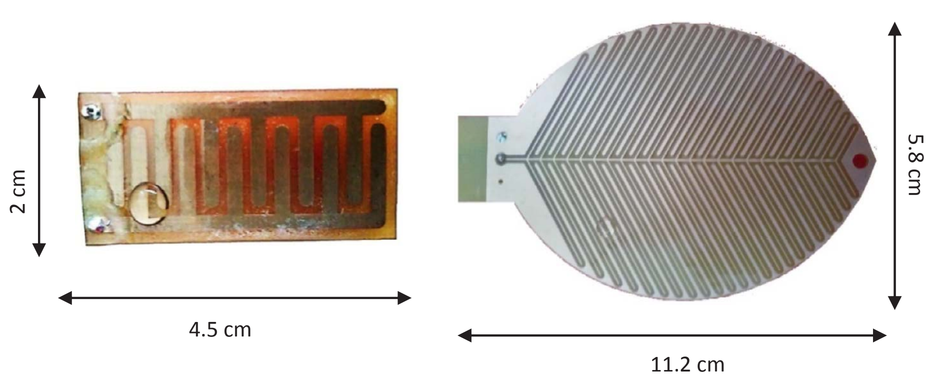

Fig. 2. Custom RECT (left) and OVAL (right) capacitive leaf wetness sensors (not to scale).