Optical Sensors for Monitoring Water Uptake in Plants

Sillas Hadjiloucas, Lucas S. Karatzas, David, A. Keating, and Mike. J. Usher

Abstract—The monitoring of water uptake in plants is becoming increasingly important. Optical sensors offer considerable advantages over conventional methods and several sensors have been developed including an optical potometer that monitors water uptake from individual roots, the detection of xylem cavitation using audio acoustic emissions with an interferometric force feedback microphone, and an optical fiber displacement transducer that detects changes in leaf thickness in relation to leaf-water potential.

I. INTRODUCTION

The development of plants is strongly affected by adverse environmental parameters, collectively known as water stress. Moderate stresses have the potential for inducing reversible growth inhibition, whereas more severe stresses may produce irreversible cell injury. Crop plants in many dry-land crop areas are regularly exposed to water stress, which can be of great practical significance in reducing crop yield.

Recently, as the expansion of irrigation into new areas has become limited by the availability of water resources and more salinity problems have been reported in existing irrigated areas, greater attention has been given to the study of water stress in the hope of finding ways of limiting these effects. Clearly, the quantitative study of both moderate and severe water stress may provide information that can help to increase plant growth under field conditions.

At the present time, most measuring devices and the associated techniques are either bulky or invasive, making continuous monitoring of the water status of the plants difficult and time consuming. Optical fiber sensors offer a number of advantages: 1) increased sensitivity over existing techniques; 2) geometric versatility so that sensors can be configured in arbitrary shapes; 3) a common technology base from which devices to sense various physical perturbations (acoustic, magnetic, temperature, displacement, polarization, etc.) can be constructed; 4) dielectric construction so that they can be used in electrically noisy or high temperature environments; and 5) inherent compatibility with optical fiber telemetry technology. Progress in demonstrating these advantages has been substantial over the past few years with many different sensor types being developed, but there is still little use in the plant physiology area, since suitable devices are not presently available “off the shelf.”

Our main concern is with the utilization of optical fiber sensors to monitor water movement within plant tissues when these tissues are under water stress. The plant parameters of interest to be measured are: 1) the water uptake rate of the roots; 2) the leaf thickness as related to the leaf-water potential; and 3) the degree of blockage of the xylem conducting vessels due to cavitation at periods of moderate water stress. Emphasis is given to noninvasive techniques, as these offer the advantage of continuously monitoring changes in water content of individual tissues.

II. DESCRIPTION OF SENSOR SYSTEMS

A. The Optical Fiber Potometer

Potometers are generally used in transpiration studies and as a calibration instrument for sap flowmeters. In its simplest form, a potometer is comprised of a sensing tube whose water body is continuous with that of the plant system, as shown in 1. The rate of volume uptake by the plant is proportional to the time change in water column length in the sensing tube. Normally, the potometer tube is refilled from a reservoir. Potometers have been adapted for studies with small intact plants and studies with excised shoot systems. However, the necessity of regular observation of the meniscus position renders the basic potometer unsuitable for the continuous monitoring of volume flow rate over extended time periods.

With a vertical sensing tube, as water is withdrawn there is a change in height $\Delta h$ of the meniscus, and a corresponding variation $\Delta \Psi$ in water potential at the base of the cut shoot: $\Delta \Psi = h_{\text{max}} \rho g - h_{\text{min}} \rho g$ where $h_{\text{max}}$ and $h_{\text{min}}$ define the vertical limits of meniscus movement in the tube, $\rho$ is the density of water and $g$ is the acceleration due to gravity. The value of $\Delta \Psi$ is small, typically $0.979 \text{ kPa}$ for a $100 \text{ mm}$ meniscus transition. This could be important in modifying shoot water potential in small shoots with otherwise small gradients of $\Psi$; therefore $\Delta h$ must be kept as small as possible. Volume resolution of $10^{-5} \text{ L}$ and sensitivity of $0.5 \times 10^{-3} \text{ L/ V}$ was obtained by McDonald, Jordan, and Ford [1]. In their design, they used a variable capacitance liquid level sensor [2]. The main problem with such sensors is that under dynamic conditions, the gas-liquid surface is not always a well defined plane. Typically, the surface is flat enough as liquid rises around the sensor element, but as the liquid...
recedes, it leaves a film on the sensor which may cause the system to indicate a liquid level higher than the mean level (flowback phenomenon). Such complications suggest that an optical fiber transducer may be advantageous for this particular application.

Using optical fibers in a potometer permits the capillary containing the sensor tip to be narrower. As a result, a higher resolution, due to smaller volumetric changes, may be obtained. Furthermore, a fiber-optic sensor is, small in size, light, flexible, robust, and low in energy requirements. Also, the sensor allows for future integration with developments in optoelectronics. Another major advantage of using an optical fiber displacement transducer is that there is no need for recalibration when used with solutions of different salt concentrations (the sensor's output can be easily normalized). The new automatic optical potometer, described in Fig. 1, can be easily adapted for physiological work, continuously measuring water uptake (transpiration studies) or axial and radial hydraulic resistance from individual roots [3], [4], with the use of multiplexed sensors.

Another example of potometer usage is the calibration of sap flowmeters. A cut shool with attached flow transducers is inserted in the potometer assembly and the flowmeter output is calibrated for volume flow rate for potometric data. The automated potometer facilitates the repeated, simultaneous measurement of volumetric flux and flowmeter output. It is particularly useful in identifying steady state flux, at which time the flowmeter output may be measured.

Fig. 2(a) shows a simple reflective optical fiber displacement transducer as described in [5], [6]. The polymer cable (PMMA) has a core-cladding diameter of 1.00 mm, a core refractive index \( n_1 \) of 1.49, and a clad refractive index \( n_2 \) of 1.42, giving a numerical aperture (NA) of 0.47, an acceptance angle \( \theta_{a2} \) of 27.85°, and a critical angle \( \theta_c \) of 71.76°. In order to improve the responsivity of the transducer, a simple way is to cut the emitter \( (T_e) \) and receiver \( (R_a) \) fibers at an angle \( (\alpha) \), so as to make full use of the critical angle. This ensures improved coupling and, therefore, better signal-to-noise ratio (SNR). The condition for \( \alpha \) is the one for which the ray emerging from the fiber is parallel to its sloping face, and using Snell's law to cut the fibers

\[
\frac{n_0 \sin \theta_0}{n_2 \sin \theta_1} = \frac{n_1 \sin (18.24° + \alpha)}{n_2 \sin \theta_c}
\]

gives \( n_0 \sin 90° = n_1 \sin (18.24° + \alpha) \) so \( \alpha = 23.84° \). This value is used for the reflectance displacement transducer shown in Fig. 2(b), where the fibers are placed next to each other.

A further improvement in performance can be obtained by cutting the fibers twice, at angles of 24° and 66°, as shown in Fig. 2(c) [7]. The advantage of the double-cut configuration is that it maximizes the amount of the reflected light that enters the receiving fiber and minimizes the light that is lost in all other directions. To avoid any thermal drifts of the LED source, the techniques of amplitude modulation, intensity referencing, and phase-sensitive detection (PSD) are used in a local feedback path to stabilize the LED source and eliminate the nonlinearities in the forward path (Fig. 3). The two receivers with the corresponding PSD and filter must be matched as closely as possible if a unity gain of the overall system is desired.

The responses of the three configurations when a mirror is used as a reflector are shown in Fig. 4. It can be seen in Fig. 4(c) that a significantly better response is obtained with the double-cut configuration. After having established the relative responses, the reflector is replaced by water, in which case the reflected optical waves are dependent on the angle of incidence, for both perpendicular and parallel polarization of the optical waves. In the double-cut configuration, some of the light is coupled inside the fiber and the rest is reflected at various angles. As the liquid level varies, light from different reflection angles is detected, increasing the overall responsivity. Using a thin opaque film (paint) between the two fibers minimizes light directly coupled from the emitter to the receiver. Thus, the linear part of the response curve is extended. Fig. 5 shows the relation of the output voltage with volumetric changes in liquid level in the linear part (front slope) of the transducer operation.

The dominant noise source in the system is the shot noise of the output photodiode. This is given by \( i_n = (2eBi)^{1/2} \) where \( e \) is the electronic charge, \( i \) is the diode current, \( B \) is the bandwidth (Hz) and \( i_n \) is the rms noise current. The SNR is then defined as the standing current at the operating point (mid-point of the linear region) divided by the noise current \( i_n \).

The collective results for responsivity, SNR, least detectable signal (LDS), and linear range are shown in Table 1, with mirror or water as a reflector. At its highest resolution, the system employs a capillary with internal diameter of 2 mm. With the double-cut configuration, this gives a range of \( 3.14 \cdot 10^{-10} \) m³ to \( 3.14 \cdot 10^{-2} \) L for a liquid level drop of 10 mm. This is particularly useful in studies of previously stressed or low transpiring plants.
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Fig. 3. System overview, with local feedback for thermal stabilization of the emitter.

TABLE I

<table>
<thead>
<tr>
<th>Sensor Type</th>
<th>Response (V/m)</th>
<th>SNR (dB)</th>
<th>LDS (m)</th>
<th>Linear Range (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uncut</td>
<td>183.3</td>
<td>62.5</td>
<td>4.27x10^-10</td>
<td>1200x10^-6</td>
</tr>
<tr>
<td>Single-Cut</td>
<td>769.2</td>
<td>64.6</td>
<td>1.4x10^-10</td>
<td>650x10^-6</td>
</tr>
<tr>
<td>Double-Cut</td>
<td>11880</td>
<td>67.8</td>
<td>1.7x10^-11</td>
<td>80x10^-6</td>
</tr>
</tbody>
</table>

Fig. 4. Response curves for (a) uncut, (b) single-cut, and (c) double-cut fibers using a mirror as a reflector.

B. Changes In Leaf Thickness In Relation To Leaf-Water Potential

Since 1950, thermocouple psychrometers and pressure chambers have been employed to measure leaf-water potential. More recently, commercial displacement transducers have been used for measurements of diurnal variation in leaf thickness (typically between 30 and 55 μm) having a sensitivity of the order of 0.1 μm, and range 100 μm. Recent studies have shown that although leaf thickness at a given relative water content (RWC) varies between plants, it increases linearly with leaf RWC; the rate of change being similar in leaves of plants of the same age and species [8]. Due to this relationship, the construction of a pressure-volume curve makes possible the estimation of leaf-water potential, which is the driving force for water movement. In this case, a calibration curve is needed for each population studied. The versatility and simple construction of optical fiber sensors makes them particularly promising in such applications.

The single-cut and double-cut reflectance displacement transducers described so far may also be used for low albedo targets such as leaves; e.g., measuring changes in leaf thickness. For the double-cut configuration, the corresponding, least detectable signal and the linear range are 6.1 \cdot 10^{-11} \text{ m} and 80 \text{ μm}, respectively [9]. It is an inexpensive noncontact method that offers a resolution superior to most commercial LVDT devices, which must also compensate for the effect of leaf temperature. A further advantage of the optical fiber sensor is that it does not interfere with the measurand due to pressure variation on the contracting surface. The complete system is comprised of two transducers, which are aligned opposite each other (Fig. 6). For a known total distance between the two transducers, the change in leaf thickness \( \Delta x_2 \) can be calculated from their signal output [Figs. 7(a)-(c) and 8(a)-(c)]. Guides are used to ensure that the leaf is properly mounted on the sensor, although, for more detailed measurements, simple feedback based on algorithms described in [10] can be employed to compensate for possible angular misalignment of the leaf with respect to the normal of the two sensors. Normalized intensity at both sides is used to compensate for the different reflectivities at each side of the leaf. Again, the techniques of amplitude modulation, intensity referencing, and phase sensitive detection are used.

In another configuration, a system of two receivers and one emitter may be used to detect displacement [11] at each side of the leaf, so that the ratio of the sum and difference of
the signals is used. With such a configuration, resolution and dynamic range may be altered, making the sensor scaleable for leaves with different thicknesses.

C. An Optical Force-Feedback Microphone For The Detection of Xylem Cavitation Acoustic Emissions

1) Cavitation Events in Plants: Water inside plants moves due to potential differences, the sucking action arising from the chemical potential of water in the presence of solutes. From cohesion theory, the water inside the xylem is at a negative pressure, or tension. The vascular system that is responsible for water transport consists of dead, stiff-walled capillary tubes that are interconnected by pores. There are several ways by which these water columns might become disrupted when under tension. A cavity in the water may arise de novo, a bubble may form from the growth of an existing microscopic bubble on the wall of the tube, or air may be drawn into the xylem from the outside environment as a result of leakiness of the tissues. At periods of water stress, plant cell walls are pulled inwards and start vibrating when cavitation occurs, producing audio acoustic emissions (AAE) and ultrasonic emissions (UAE). When plant conduits cavitate they must lose water through their minutely porous walls. Air cannot enter if the pores are wet and sealed by surface-tension via a film of water, but if the strain becomes significantly severe, gas could be drawn through a pore. A single tiny bubble inside the conduit would instantly produce total disruption because, once it entered, it would immediately expand until the strain within the encircling walls would be relieved. The second phase, which could be observed with appropriate microscopic preparation, would be when the bubble continued to enlarge, relatively slowly, until it completely filled the conduit with gas at near vacuum pressure.

Detection of the frequencies of emission depends upon attenuation by tissues and on the resonant properties of conduits. Generally, the counting of AAE’s is ultimately limited by the SNR of the equipment, as the counter depends on detecting a voltage signal against a background of electronic noise (Fig. 9) emanating from the sensor itself [12]. The main problem with conventional microphones is that a small capsule must be used to pick up AAE’s at close proximity to the stem, and therefore, commercially available microphones have a large self-noise. Improvements in the self-noise of the sensor illustrated in Fig. 10 and optimization of the counting procedure can provide an almost perfect agreement between counts and number of tracheids, leading to the notion that one cavitation causes one signal only [13]. Information from spectra of cavitation processes can be related to volumetric flow of water through stems in many ways, e.g., using the Hagen-Poiseuille equation. Such accurate observations of cavitation events can only be possible if the sensing microphone has a predictable frequency response along the frequencies of interest. Therefore, a high gain-bandwidth product is necessary if quantitative information on the volumetric water flow towards the leaves at periods of water stress, is to be measured. An optical force-feedback microphone with these characteristics has been constructed for this purpose.

2) Description of the Optical Force-Feedback Microphone: The application of force-feedback to the diaphragm in a conventional microphone leads to significant advantages in terms of linearity, frequency response, and dynamic range. Feedback is applied electrostatically by two electrodes on either side of the diaphragm [14]. However, this makes the normal technique of measuring the diaphragm displacement (dc excitation and change in capacitance) very difficult to apply. The use of
optical interferometry avoids these problems. The Fabry–Perot arrangement is convenient, because its "in-line" geometry allows the optical sensor to be inserted in a microphone housing. This interferometer has increased sensitivity and the response is more linear than the Michelson [15].

In a conventional Fabry–Perot interferometer (FPI) the light passes through the partial mirrors, interacts with itself in the cavity that is formed within the two mirrors, and the interference pattern observed outside the cavity (usually transmitted) is sensitive only to the changes in the separation of the two mirrors. In the modified version [16] however, light is reflected totally back (since the microphone membrane acts as a near perfect mirror). The polarizing beam splitter (PBS) divides the beam into two paths. A polarizing type is employed so that, when used in conjunction with a quarter-wave plate (λ/4), optical isolation (of the order of 90 dB) may be achieved. This also allows all the reflected light from the cavity to reach the output photosensor (OP). The OP is part of the electrostatic force-feedback loop applied to the microphone diaphragm. The light is split equally between the laser control photosensor (LCP), and the interfering cavity in such a way as to minimize the noise caused by the laser and the OP. The ratio by which
The reflected intensity (normalized) is given by

\[ r_1^2 = 0.5 \]

\[ r_2^2 = 0, 1, 0.2, \ldots, 0.9, 0.99 \]

Fig. 11. Intensity response for (a) optimal and (b) normal capsules.

light is split is chosen so that the standing currents in the two photodiodes (OP and LCP) are equal.

The first mirror (fixed) can be of an ordinary type, while the second is the actual (moving) diaphragm of the microphone. The values of the reflectivities for the two mirrors \( R_1, R_2 \) is dictated by the required responses. The most critical aspect in a Fabry-Perot configuration is the absolute parallelism of the two surfaces causing the interference. There are many different ways to ensure that this is so, but in this particular application, a spacing ring of an ultra low expansion material (Zerodur or Invar) with a thickness of 25 \( \mu \)m, and its two faces parallel to better than \( \lambda/6 \) in 7.5 mm is adequate.

The response of a Fabry-Perot can be calculated from the multiple reflections and transmissions that light undergoes in the cavity [17]. It can be shown that the amplitude variation of the reflected light \( A \) with respect to path-length-difference \( d \) (twice the mirror-membrane separation) is given by

\[ A = \frac{R_1 + R_2 e^{i\varphi}}{1 + R_1 R_2 e^{i\varphi}} \tag{1} \]

where \( \varphi = 2 \pi d/\lambda \) is the phase variation of light in air, and \( \lambda \) is the wavelength of the laser. It can be shown that the condition \( R_1 = R_2 = (0.5)^{1/2} \) produces the best response in terms of slope, range and SNR. Such intensity response against path length difference is shown by line (a) in Fig. 11, in our configuration, however, line (b) was used. A useful linear range is \( \lambda/8 \), which corresponds to \( \lambda/16 \) of mirror movement. For \( \lambda = 780 \text{ nm} \), the maximum linear range on open loop corresponds to 48.75 \( \text{nm} \) of membrane movement.

The standing current at OP for bias at 0.25 is 0.3 mA. This results in a noise current of 1.39 nA rms, which corresponds to a displacement of the membrane of 69.6 fm rms. Therefore, the self noise is \(-3.15 \text{ dB SPL} \) (ref \( 10^{-13} \text{ m rms} \), CALREC microphone), or \(-8.15 \text{ dBA SPL} \) (A weighted). Adding 3 dB, due to the LCP noise, yields a final total self noise figure of \(-5.15 \text{ dBA SPL} \), which is very good. The corresponding dynamic range is 115.71 dB.

An important consideration in the development of the microphone is laser noise. Because the path length difference in the FPI is of the order of a few nanometers, when the force-feedback is applied, the phase noise of the laser is minimized [18], and the intensity noise dominates. Such noise can be minimized by applying feedback to the laser driver. Conventionally, laser current loops are designed for dc operation of the laser and many such designs are described in the literature. On the other hand, in the microphone configuration, the resulting gain should be as flat as possible across the frequencies of interest, and this can only be achieved by using a very large gain-bandwidth product. A compensator was designed to meet these characteristics [19]. The frequency response obtained for the magnitude and the phase is shown at Fig. 12.

On an open loop of a typical capacitor microphone, the diaphragm moves several micrometers at the highest sound pressures, while in the Fabry-Perot configuration, the diaphragm movement that corresponds to the linear range is only about 50 nm. The motion of the movable diaphragm must therefore be controlled using electrostatic force-feedback, applied through the microphone feedback system. If a voltage is applied across the plates of a parallel plate capacitor, then the resultant force \( F \) is proportional to the square of the applied voltage and is given by

\[ F = AV^2/2a^2 \tag{2} \]
Several optical sensors suitable for monitoring water uptake and translocation in plant tissues have been described, and each offers substantial advantages over conventional devices. The field of plant physiology is rapidly expanding and optical sensors are being developed for many applications. One important area is the local adaptability of manipulators for automatic grasping applied in the fields of agricultural robotics and laboratory instrumentation. Growth monitoring proximity sensors and edge detectors for automatic in situ evaluation of leaf area index are particularly useful in transpiration studies and photosynthesis research. Localized pattern recognition in leaves with salinity or nutrient deficiency problems and disease diagnosis is also possible. Recent advances in new polymer optical fibers using ARTONTM (Japan Synthetic Rubber Company, Ltd.) in conjunction with the double-cut configuration sensor implemented on a Peltier-cooled, gold-plated mirror element, offers the possibility of an improved dew-joint sensor; particularly useful for atmospheric moisture studies, transpiration studies, and measurements of moisture content of crops and food products.

The long term stability will be exceptional because the response depends only on \( s \) and \( V_p \), neither of which is likely to change.

### III. DISCUSSION

Dynamic range for a capacitor microphone is 120 dB; therefore, it is clear that the optical microphone is far superior.

Using feedback in the microphone offers many advantages. It reduces the diaphragm displacement by a factor of \((1 + \text{loop gain})\) and reduces distortion by the same factor, so linearity is improved. The frequency response of the microphone is controlled by the feedback electronics; not by the behavior of the diaphragm. Also, the problem of accurate path length difference setting is alleviated, and the dynamic range is increased. Therefore, it can be said that the combination of optical techniques with force-feedback results in a microphone with wide dynamic range and predictable frequency response.

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REFERENCES


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