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DISTRIBUTED POLYMER OPTICAL FIBRE SENSING OF MOISTURE AND PH IN SOILS: FEASIBILITY FOR E-AGRICULTURE

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Abstract: Measurements along the length of an optical fibre sensitised to pH and moisture will enable monitoring of spatial differences around the root systems of developing plants. Mapping of spatial variations and temporal changes in moisture and pH provides a methodical approach for imaging soil behaviour and potentially the effect of plant roots and associated soil micro-organisms, enabling optimisation of crop yield.

Key words: soil, agriculture, moisture, pH, distributed sensing, optical time domain reflectometry, OTDR, rhizosphere, rhizotron, sensor, evanescent field.

1. Introduction

The traditional unit of agriculture is “The Field”, considered as a homogeneous area for planting crops with uniform properties as a function of area and depth, but for optimal yield, “precision farming” requires mapping of spatial variations in soils on a far smaller scale, since the soil within a field is heterogeneous [1]. Variations in soil properties such as pH, nutrients, salinity and organic matter, can occur over distances of centimetres or even millimetres near the root system. Nitrogen, phosphates and potassium are macro-nutrients essential for crop growing and are transported in water, but local variations are caused by rate of uptake by plants, leaching or chemical soil treatments such as liming. Properties of soil that vary spatially include structure and texture which affect gas diffusion, water permeation and root development [1]. Spatial variations in soil structure are caused by the local geological conditions, whereas texture can be influenced by soil cultivation.

Fig.1: Left: Schematic of a rhizotron [3]. Right: Diagram of air and water contained in soil pores [4]

There is a generic need to monitor non-invasively soil properties below the surface, since the quality of the leafy “above surface crop” is controlled by the interactions that occur between the fauna, soil structure, moisture, nutrients and root bundle below the ground. The sub-surface environment is highly inhomogeneous and dynamic but is difficult to monitor and control. To date, subsurface monitoring involves extraction of the specimen plant or crops, washing of the root bundle and dissection of the resulting mass. Non-invasive monitoring includes high cost micro X-ray Computed Tomography (CT), which is limited in the size of plant to be studied, and involves sampling specimens for analysis in an off site centralised laboratory analyser with limited capacity to sense the
chemical changes in the bulk soil and rhizosphere. Plants require water to grow, but the uneven natural
distribution of rain water requires farmers to control water and nutrient distribution to crops precisely. New wireless sensor technologies and miniaturized sensor devices enable automatic environment monitoring and control [2] for large and small agricultural systems ranging from pots and greenhouses to field systems. On a very small scale, the rhizosphere refers to the zone of soil in the immediate vicinity of the plant root where the biology and chemistry of the soil are influenced by the root. This zone is about 1 mm wide, but has no distinct edge, and is a volume of intense biological and chemical activity influenced by compounds exuded by the root, and by microorganisms feeding on the compound and can affect changes in soil properties at distances in the order of centimetres. In order to monitor root plant growth, an underground laboratory system called the rhizotron (exemplified in Fig. 1: Left), enables access to enclosed columns of soil containing the root system or rhizosphere by means of transparent plastic or plastic windows which permit viewing, measuring, photography and image analysis [3], but this environment is artificial and the confined geometry and edge effects distort the normal behavior of the plant root system. Fig.1 (Right), indicates that soil consists of particulates with spaces or pores of varying sizes that can be filled with water or air [4].

Measurement along the length of an optical fibre sensitised to moisture and pH, will enable accurate spatial monitoring of spatial differences around the root systems of developing plants since the fibre has similar dimensions to the rhizosphere. This paper evaluates the feasibility of using distributed optical fibre sensing techniques, such as Optical Time Domain Reflectometry (OTDR), to map spatial variation and temporal changes in moisture and pH, providing a method to image soil behaviour and the effect of root systems and associated micro-organisms. Using distributed sensing, moisture and pH variations over large areas such as fields or sets of fields can be measured. The distributed sensing system can be utilised in conjunction with water and nutrient delivery to optimise agricultural production.

2. Distributed sensing for crop monitoring using optical fibres

Optical fibre distributed sensing using OTDR is of interest to e-agriculture due its ability to sense changes remotely at sensitised points along an optical fibre by interrogation from a single end. Fibre sensing is intrinsically safe for wet environments since all instrumentation used can be located remotely from the experimental area, and the fibre itself is chemically and physically passive. Work involving the development of fibre based sensors for pH and humidity has been previously described but the sensing methods rely on hydrogels [5,6]. The fibre size is similar in dimensions to the plant root system, and evanescent field sensing is enabled by decladding the fibre and exposing the core to the analyte of interest. Thus the volumes interrogated for measurement are limited to small regions within micrometres from the fibre. OTDR involves sending sharp pulse from a light source down a length of optical fibre and measuring the back scattered signal. The shape of the latter gives information about the status of the fibre. The lengths of fibres involved can range from tens of metres to many kms depending on the intrinsic fibre attenuation and the loss per sensing point, and number of sensing points along the fibre. By sensitising the fibre to a measurand or analyte, the losses experienced can be related to their status. The aim of this project is to develop a capability for interrogating a length of polymer fibre with a pulsed laser diode light source and recording the resulting light for the evaluation of the fibre as a distributed sensing system, that is sensing over its whole length.

2.1 Aims and Objectives

Nutrient uptake by plant roots is highly influenced by soil moisture and by the interactions between roots, their associated microflora and soil and consequent effects on soil pH amongst other properties. The initial feasibility work aims to measure variations in both soil moisture and pH within a 3D spatial distribution around a single root system or rhizosphere, in a pot or rhizotron (less than 1 m³) rather than over lengths of many metres. Fast data recording techniques and signal processing will differentiate signals returned from at least 2 points along the fibre yielding spatial resolutions below 30cm. Arrangement of the fibres geometrically, e.g. in a spiral, could yield higher special resolution with respect to the soil profile.

2.2 Soil moisture definition

The response of sensor points to soil moisture will be measured initially. Soil moisture or Water Content is classified as the water removed via heating of soil for at least 24 hours, at a temperature of 105°C, and is expressed as a percentage (w/w);

\[
\text{soil water content (\%)} = \frac{\text{weight of water}}{\text{weight of oven dry soil}} \times 100
\]  

(1)
Tests are planned on wet and dry soils with moisture levels ranging between 10 and 40% w/w. to characterise moisture-time profiles in different soils, wetter soil drying down over several days.

Soil moisture content is influenced by soil composition including aggregate size and porosity. The soil retains water as a thin layer around the soil particles, and within pore spaces, and ideal soils have a high porosity between and within aggregates, facilitating movement of air, water and nutrients around the soil [7,8].

2.3 Soil states and types
There are three soil states, defined by their observed effect on the plant and soil appearance: known as Soil Saturation, Field Capacity and Wilting Point. For different types of soils and plants, these specific states occur at different moisture content and cannot be defined precisely.

- Wilting Point (WP) defines the minimum amount of soil moisture a plant requires to avoid wilting, and depends both on the soil type and the plant. Soil with moisture levels above the WP, retain water stored in both the thin layer around the soil particles, and the soil pores. Soils below the WP store water in micropores and generally inaccessible to plant roots.

- Soil Saturation occurs when excess water enters the soil from rainfall or irrigation and fills all the soil pores with water, displacing air from these pores, so that the soil is at its maximum retentive capacity. This causes crop roots to die due to lack of air within the soil [7,8] except under special circumstances e.g. rice cultivation. The air-filled pore space must be approximately 10% by volume for most roots to survive [8,9].

- Field Capacity (FC) is the remaining water content in soil after it has been saturated and allowed to drain freely.

Soil water is lost in two ways, plant growth and evapotranspiration and the water content available to the crop to survive, is the amount present in the soil in between the two limits of Field Capacity and Wilting Point. Agricultural soils vary in texture and moisture holding capacity (Figure 2). Furthermore, their drying and wetting characteristics under climatic change (rainfall, hot, dry weather etc.) vary accordingly. It is therefore useful to have a general system for monitoring soil water content.

Fig. 2: Left: Water available in soil for Different Soil Textures and types of soil [7]. Right: Hysteresis between Drying and Wetting of Clay Samples [7].

Fig. 2 shows hysteresis for wetted and dried clay; the solid clay line indicates desorption (drying), and the dotted clay line indicates sorption (wetting). Reasons for the hysteresis include entrapment of air as the soil is rewetted, causing some pores to clog, and preventing effective contact between soil pores; also soil colloids returning a different formation between being wetted and dried, giving a different structure to the soil [7].

3. Characterisation of Single POF Sensor Element
Polymer optical fibre (POF) was selected over glass optical fibre (GOF) as a soil sensor, due to its ruggedness and increased sensitivity to evanescent field attenuation, when the cladding is removed to expose the core. For evanescent field sensors, the proportion of light available to interact with the measurand in the evanescent field, is described by the fraction, r, of total guided power, present in the cladding region. Values of r greater than 50% occur in single moded fibres, but r values less than 1 % are obtained for weakly guiding highly multimoded fibres such as PCS fibre, in which the core and cladding refractive indices are similar in value [13,14]. The large diameter of POF, typically 1 mm, will support tunnelling rays in addition to bound rays [11,12], which increase the value of r significantly. We have previously demonstrated that for POF evanescent field sensors, tunnelling rays contribute an extra 50% to the energy available for modulation by the measurand in the evanescent field, and up to 66% of power is contained in the bound modes and 33% in tunnelling modes. For POF sensors, we
have shown that maximum modulation of the transmitted signal of typically 5% and up to 13% has been observed, indicates that well over 10% of the total power can be exploited for sensing purposes in the evanescent field [10].

Large diameter, multimode, plastic optical fibre with the cladding removed over 3 to 6 cm and replaced by a liquid measurand, is sensitive to refractive index and suspended particulates, providing a low cost, easy to handle, and rugged throwaway sensor for a range of applications including water and beverage processes and quality monitoring. Figure 2 shows that the decladded POF sensor characteristic has two distinct regions; The accuracy of the POF sensor is ±0.007 refractive index units (to 2 standard deviations) or 0.5% between 1.33 and 1.4 and ±0.002 refractive index units (2 standard deviations) or 0.15% above 1.4 [11,12]. Although not shown in the graph, the normalised output optical power through the fibre, can be extrapolated for a refractive index of 1 (air), indicating an optical change estimated at 5 to 10%.

![Fig. 3: Normalised plot of stripped cladding plastic optical fibre versus refractive index of solution in contact with the stripped region \[11,12\]](image)

Therefore this decladded POF sensor is suitable for soil moisture measurement since soil consists of particulates with gaps in between the particles that can be filled with water or air as shown in Fig. 1.

### 3.1 Methodology and work schedule

In order to characterise a single sensor element, a 1 metre length of 1mm diameter step-index (POF) (Toray Industries; PGR-FB1000), with a sensing region created by stripping the cladding over a range of lengths. Initial interrogation is carried out using a red high brightness LED light source but a laser will eventually be used. Both a sample and a reference fibre are used so that common mode drift and noise effects induced by the light source and ambient environmental are removed. Initial tests are used to examine the stability of the dual fibre arrangement. The transmission of the decladded sensor element when exposed to water and air is measured to evaluate the difference corresponding to a refractive index change of 1.0 and 1.33 for a range of different decladded lengths with sensitised areas from 1.7 cm to 7.3 cm. The maximum change in transmitted light power observed is in the region of 15%. This proportion indicates that the light power transmitted through the fibre is modulated via evanescent field attenuation.

The air/water interface is then be replaced with a range of dry foam sponges which are weighed and wetted, according to equation 1 to define the percentage foam/ water content (w/w). Foam sponges including domestic and florist oasis types are sourced from a range of suppliers. These provide a clean porous material which can mimic soil with small pores capable of capillary action. The weighing and wetting methodology is refined prior to using real soil. Finally wet soil and dry soil will then be used in order to determine the sensitivity and resolution of a single sensor element to soil moisture. The experimental details are shown in section 4.

Tests are performed on a range of wet and dry soils with moisture levels between 10 and 40% W/W, and then wetted soil drying over several days, so that the sensor response to realistic changes in soil moisture can be elucidated. Finally, sensitization of POF sensors to pH using colorimetric claddings incorporating pH indicators will be undertaken. In soils, pH is a bulk property arising from aqueous transport of hydroxyl ions which exhibit concentration changes in all directions. Field sites may have soil where changes by one pH unit over a few metres can be experienced while overall, the actual pH value may vary from 5 to 8 pH units. Developing root systems within a rhizosphere have been shown to affect rapid changes in pH. Therefore, measurements for pH with a resolution better than 0.1 pH unit are required.

### 4. Preliminary experiments using a single sensor based POF

In order to assess the feasibility of the methods put forward, experiments have been carried out to elucidate the following:

1. Obtain the optimum value for the length of the decladded region along the fibre
2. Compare wet and dry environments for a single fibre sensor
3. Measure a POF sensor output in an environment with intermediate levels of hydration

The optimum length for the sensor is obtained by removing the cladding over a range of lengths along similar fibres. Using a water filled container the de-cladded area of each fibre is immersed while measurements are taken in both dry and wet states. Throughout this study all water used is distilled and deionised. A non-decladded fibre is used as a reference and all measurements are taken from the dry state prior to immersion in water. A high brightness 5 mm diameter red LED source (type OVL5528) is fed through a beam splitter to the sensitized (decladded) as well the non-decladded reference fibre. The optical signal is recorded using a dual channel Ando AQ2140 power meter where the analogue outputs are fed to a Labjack UE6 16 bit ADC inputs for recording on a computer. As outlined earlier, common mode effects are removed using differential measurement. Figure 4 shows the recorded output for a single fibre immersed in water from a dry state. The initial data obtained using fibre with a 5cm decladded region is appropriate for the task at hand. The step response in Figure 4 recorded demonstrates the relative dynamic range for the sensor. Therefore, the requirement for measuring the sensor response through various levels of moisture content can be expected to follow a region stretching the calibrated 0 to 100% of the normalized values shown. The step response recorded shows the “Open Loop” gain for the control system comprising the sensitized fibre with water as an input.

It is found that the time constant for such a system is fairly small (a few seconds for a rise to 2/3 of the maximum output) and this is considerably fast for the processes considered. However the saturation value exhibits a lengthy time to reach the maximum value from the top 5% (>1000 seconds compared to the earlier ~2-3 seconds).

To assess the response to a sustained continuous stimuli using water, the same setup used earlier is subjected to a controlled water process running at 0.2 ml/s while the differential output is recorded continuously. Figure 5 shows the output recorded. The small but fixed quantity of water added regularly from dry until saturation helps assess the intermediate ranges for the sensor response within an increasingly wet environment. Although the sensor used demonstrates the feasibility of the method, more experiments are required in order to produce and optimize further the observations made. The signal variations recorded span a range which is under 50mV at present. Moreover, these depend heavily on the optical source used. Fluctuations in the latter require appropriate signal averaging. The dynamic range is to be improved through appropriate analogue amplification and the use of a laser diode source with a higher power and stability. This will then help with the assessment of a distributed POF sensor. Some effects which probably caused by gravity or migration of water from one area of the sponge to another may lead unexpected temporary drops or increases in the recorded output. These require further study particularly in the case of soils.

Note: The main interest in this initial study is the assessment of fibres for sensing moisture content within a given medium. pH sensitization and investigation will be described under a separate undertaking.

5. Optical Time Domain Reflectometer

Once the modulation range and sensitivity of individual sensor elements are characterised, they can be incorporated into an OTDR system. This enables evaluation of their response within a dynamic environment.
A length of polymer optical fibre (POF) with the cladding removed to expose the core at a initially one and then two points along its length, is used with a pulsed visible laser diode light source and Avalanche Photo Diode detector, to interrogate the status of the sensor elements. By exposing the fibre core or sensitising the fibre cladding to a measurand or analyte, the back reflected loss in the fibre can be related to the status and spatial position of the measurand. The measurements at the detector are observed using a fast transient recorder. This enables a number of sensing points to be interrogated along the length of the fibre so that the status of each sensor point can be determined and related to a spatial position in the field or around the plant root system.

4.1 The data acquisition process
A visible light source emitting transmits light through the sensing fibre. This “excitation” source is triggered repeatedly at a suitable rate (0.1 Hz to 1kHz) and the backscattered response from the fibre is recorded, using an avalanche photodiode which feeds a synchronously enabled data capture channel of an oscilloscope or ADC card. After small signal amplification, the signal recorded is passed to a Lecroy Waverunner LT354L oscilloscope (8bit dynamic range). The data acquisition process is synchronized to the pulsed light source using a SRS DG535 pulse generator providing a phase relationship with an accuracy better than 50ps. Fig. 4 shows a schematic diagram for the setup described.

![Schematic diagram showing the main building blocks used during the assessment of sensitised fibres.](Image)

Fig. 6: Block diagram showing the main building blocks used during the assessment of sensitised fibres.

![Schematic timing diagram showing the process involved in acquiring and recording signals during data acquisition.](Image)

Fig. 7: A schematic timing diagram the process involved in acquiring and recording signals during data acquisition. (A): Synchronisation pulse for DAQ (locked with a delay to the laser pulse), (B) Recorded waveform, (C): Selection of a sample 2 areas of interest. The area under the selected section is calculated in real time, (D) and (E) recorded trend waveform obtained for 2 sensitised areas of a fibre.

Custom data acquisition and control software interfaces are used to synchronize and collect raw waveform data for the data capture device. The waveform recorded is first averaged and then visually inspected in order to identify areas which correspond to the sensitized regions of the fibre in the time domain. Since light progresses through the fibre at a fixed velocity (speed of light in the fibre medium), the instants at which the sensitized areas of the fibre experience the passing of the light pulse will be separated by constant delays equivalent to the distance between the points divided by the speed of light in the fibre. The waveform recorded is averaged over a number of cycles (presettable at up to 1000) before transfer to the signal processing computer.

The software interface enables individual areas of the acquired waveform to be selected and processed separately at each optical pulse cycle. Initially, a direct numerical integration of each of the areas is undertaken but further signal processing can be implemented if needed. Each sensing point in the fibre will then yield an intrinsic curve outlining changes in moisture or pH in that specific area. Fig. 5 shows a scenario including 2 sensing points in the acquisition process for a high speed system.
Since the distributed sensing points have a fixed phase within the recorded waveform, the areas of interest are selected from within software interface at an early stage in the experiment by viewing the trace waveform obtained under OTDR conditions. As outlined earlier, the areas matching the phase where each sensor is located are each integrated before graphical representation as a single point outlining an instantaneous measure of a specific environmental variable in the time domain. Subsequent recording of such areas provides a datalogging capability which elucidates the measurand variation over a given period of time (Fig. 5). This yields a transfer characteristics for the sensor considered.

While this method will work with high speed systems with data sampling rates in the GHz region (1GHz sampling would resolve a 20cm region within a medium with a refractive index equal to 1.5), slower data acquisition would enable monitoring of signal trends caused moisture changes; would only requires slow acquisition speeds of a few Hz and represents an simple method for initial setup and calibration.

6. Conclusion
This paper examines the feasibility of constructing a distributed sensor system to operate in the visible region of the spectrum to detect moisture and chemical features in soil using low-cost plastic optical fibres with a spatial resolution of just a few centimetres. Applications include operating as a single sensor modality (e.g. for moisture, pH, and eventually phosphorus, potassium or nitrates) within small volume lysimeters and operating over many 10s of metres with localised clusters of sensors to operate along the length of the fibres to interrogate specific regions in the bulk soil. The exact engineering specification can be tailored to the end-user, with respect to chemical features, specificity, accuracy, precision, spatial resolution and response times. Key to success will be the signal-to-noise ratio, as well as the number and spacing of sensor segments that maybe readily accommodated on a fibre at a viable cost, as this will dictate the number of unique measurement nodes. Picosecond time-resolution is required to achieve a sub 5cm spacing can be achieved, for rhizosphere research, to enable any location in the soil may be monitored with a spiral of fibre, or similar topography, snaking down through the root bundles.

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References