

## **A Low-cost Multihop Wireless Sensor Network, Enabling Real-Time Management of Environmental Data for the Greenhouse and Nursery Industry**

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### **Abstract**

A low-cost multi-hop wireless sensor network has been developed, deployed and are tested that enables the capture and synthesis of real-time root zone substrate and environmental data, on a wide-area basis in the field. Plant water requirements can vary by day, season and microclimate, depending on any number of environmental and plant developmental factors. Irrigation and nutrient applications can be more precisely scheduled by using the plant to integrate environmental and growth differences over time, and by accurately monitoring the real-time water use of plants with substrate moisture, temperature and electrical conductivity sensors. This should reduce water use, leaching of nutrients and overall runoff from intensive plant growing operations. Additionally, other sensors that simultaneously measure air temperature, canopy relative humidity, leaf wetness, and photosynthetically active radiation will allow us to model and better predict plant stress and disease pressure. Data can be provided at any time to anyone at any place with internet access, since all data is managed through a web-based graphic-user interface. These sensor networks are entirely portable, allowing rapid deployment of the sensors in specific areas of the facility, to optimize the utility and cost of the sensors. These networks are also scaleable, since additional nodes are easily added which allows the plant production facility to grow and/or improve their sensor network at any time.

### **INTRODUCTION**

The general availability and reduction in the cost of micro-sensors and low-power wireless communications has enabled the deployment of densely distributed sensor / actuator networks for numerous environmental monitoring applications. These applications range from urban to wilderness environments, within interior and exterior sites, and they encompass a variety of sensors including acoustic, image, and the remote sensing of various chemical and physical properties of materials (Burrell et al., 2004). Sensor nodes can perform significant signal processing, computation, and network self-configuration to achieve scalable, robust and long-lasting networks. However, much of the sensor network technology that is currently commercially available still lacks the reliability and environmental robustness required for

applications in hot, wet and high ultraviolet (UV) light environments, characteristics of many plant production systems.

We are specifically focused on developing a robust capability to monitor and control water content and nutrient applications to plants in large-scale greenhouse and nursery (both field and container) operations, up to 50 ha in size. Our goal is to deploy sophisticated, low-cost wireless networks that have the above-mentioned capabilities, as well as the ability to integrate various types of environmental sensors, including air and soil temperature, relative humidity, leaf wetness, light (photosynthetically-active radiation), water and electrical conductivity sensors, among others. Sensor nodes must be rugged (water- and UV-proof), lightweight and portable, mobile anywhere in the operation to monitor “trouble-spots”, and assist with irrigation scheduling and monitor and control other systems (e.g. heating and cooling) to optimize plant growth. Providing a suite of real-time environmental data via the internet to a grower’s desktop will enable the more efficient management of resource and increase the profitability of operations.

The six essential priorities for any environmental sensor network are: The user should be able to rapidly deploy sensors in any area of the growing facility, to maximize the utility (and minimize the real cost) of those sensors; Sensors and wireless networks should be scalable, thereby allowing an operation to begin with a small system and grow/improve the sensor network, over time; The data from sensors should be reliably transmitted using wireless connections to the base station computer, with little or no interference over distances from 100 - 1000m and with low (battery) power requirements; The monitoring function of the network should automatically log data from sensors, presented in a form which provides the user with an easily interpreted view of that data such as a spreadsheet, or preferably in a customized graphical output; The control function of the network should include minute, hourly and /or daily sensor data that is integrated by the system, to actuate irrigation solenoids or other controlling switches; A small network for an initial user should cost less than US\$5,000 to purchase and install. Supporting documentation and easy-to-follow instructions with “plug and play” operation should allow for implementation entirely by the grower.

## **BACKGROUND**

A number of researchers have published information over the last decade about the potential of computerized sensors which have the ability to directly sense the water status of soils in the field (Leith and Burger, 1989). Relatively sophisticated systems are being used at similar scales in vineyards and forestry nurseries for similar purposes (Burrell et al., 2004). While these sensors may perform relatively well, these systems are usually expensive, and have other limitations for many growers, including power and communication issues in rural areas. Higher-tech greenhouse irrigation systems (Testezlaf et al., 1999) have been in use for some years, but most of these systems do not provide a control system to manage irrigation scheduling based upon daily plant water use. They mostly monitor and control water quality information such as pH and EC (by adding acid and/or nutrients), or they control irrigation solenoids with a time-clock, similar to advanced nursery irrigation management systems. Some sophisticated greenhouse systems monitor the weight of the water in the root zone (e.g. rockwool slab systems) which integrates daily water use and loss data for computerized irrigation control. These systems are typically expensive to install and maintain, and are specifically designed for use in monoculture-type production systems, such as for large tomato, cucumber and pepper production greenhouses. They are difficult to modify and install in diverse ornamental container-production greenhouses and nurseries, and they are not cost-effective or management-effective for small growers. Affordable systems that monitor and control these functions over large

distances are essential – since real-time information will greatly improve the quality of the management decisions made using that data.

## **NETWORKING CAPABILITY**

The Carnegie Mellon University (CMU) sensor network (Zhang et al., 2004) is composed of battery-powered sensor nodes, each consisting of a small rugged waterproof box that measures approximately 76 x 127 x 178 mm (Fig. 1). Each node contains a microprocessor, a radio for wireless communication, and an interface board that provides for multiple sensor interfaces. When the nodes are deployed in the field (Fig. 1), they use radio cards to automatically find one another and form an ad-hoc wireless network (Fig. 2). This network can then be used to relay real-time data from sensors attached to the nodes to a central computer. Each node achieves upwards of a 12-month battery life through a synchronized, low-duty-cycle, geographical forwarding routing scheme.

The CMU sensor network has three main features that distinguish it from other wireless data collection systems: (1) the communications are multi-hop; (2) the network is self-configuring and (3) the nodes can be used to actuate switches, which allows for automated monitoring and control capabilities. The first feature allows transmission of data over distance longer than the range of a single radio: if a node is not within range of the central computer, it automatically finds another node to act as a relay (Fig. 2). The second feature means that the network is easy to install and that it can be reconfigured by simply moving the nodes around. It also means that the system can withstand single-point failures – i.e., if the transmission from a single node is blocked, the network automatically re-routes the data transmission through alternative nodes. The third feature makes it possible to go beyond sensing and use the nodes to monitor and control devices automatically or from remote locations.

These nodes therefore have a unique capability to dynamically route any data gathered by the sensors, to a base node, which has a high-power wireless network card for long-range data transmission (>1km). All nodes are waterproof, lightweight and durable, and can be quickly moved with the sensors to another location. This allows a grower to start with a small network and add nodes, when necessary. A small network is easier to manage and use, and this ad-hoc networking capability allows for cost-effective additions of sensor nodes over time, that takes advantage of the initial infrastructure cost.

## **GRAPHIC USER INTERFACE**

Visualizing large data sets which vary both temporally and spatially is a challenge. A small 12-node network (Fig. 1) generates 70,000 data points, by monitoring 48 sensors every minute. A flexible graphical user interface (GUI) will allow users to easily generate customized views of the data (Fig. 3). The WebSensor software is easy to use, customizable (i.e. can accommodate specific calibration curves for various substrates), and integrates with a web-version that allows for data sharing over the internet. The simplest view to generate is the real time data, which is simply a list of the most recent sensor readings, where the list entries change in real time as new sensor readings arrive. A tool can be used to sort data by location, sensor type, or other variables (e.g. sensor depth), and then provide the capability to automatically sort the list on each selectable field. Additionally, we intend to develop a map-based interface that allows the user to select and view specific node locations, generate customizable historical plots of sensor data and to export to any file format. Finally customizable alarms are planned, which automatically notify the user when the selected data is off-nominal or within range.

## SENSING CAPABILITY

### Previous Research

Recently we showed that by making irrigation decisions based on plant need (using time domain reflectometry, TDR sensors), that water use and nutrient runoff can be reduced by 60-85% in a nursery system that was open to rainfall for 9 months of the year (Ristvey, 2004). For a typical container-nursery operation using overhead sprinklers, this reduction could equate to a reduction in runoff of up to 595 kg of N and 88 kg of P per ha / year (Ristvey et al., 2007) and water savings from 9,353 – 18,706 m<sup>3</sup> per ha / year, depending on container size (Ristvey, 2004).

**1. Moisture Relations in Soilless Substrates.** Horticultural soilless substrates generally have low water-holding capacities and smaller ranges of easily-available water (EAW) for optimum plant growth (deBoodt and Verdonck, 1972). Easily-available water can be sensed and measured, based on the matric potential ( $\Psi_m$ ) of the substrate. Soilless substrates generally hold EAW in a  $\Psi_m$  range from 0 to -10 KPa, with the majority of free water available from 0 to -5 KPa (deBoodt and Verdonck, 1972). This  $\Psi_m$  is between 10 and 100 times lower than similar plant-available water tensions in soils, which means that that standard method of using water tension to measure soil moisture content does not apply well to non-soil substrates.

**2. Moisture Sensor Research.** A number of researchers have examined the use of time domain reflectometry (Topp, 1985) and capacitance sensors (Arguedas et al., 2007a, b; van Iersel et al, 2005) for irrigation management in soilless substrates. This research has shown that these sensors perform well in soilless substrates, but only if calibration and placement issues are resolved (Murray et al., 2004). Shorter sensors have a higher percent of the total sensor area in air spaces within the substrate, reducing accuracy and the maximum waveguide length is constrained by container height and sensors less than 7 cm in length have shown reduced accuracy in heterogeneous substrates (Kelly et al., 1995).

Multiple TDR sensors must be used in organic substrates, to provide an accurate and repeatable measure of water content. Murray et al. (2004) determined that a minimum of four TDR sensors per plant block (900 plants in 11.6 L containers) were necessary to ensure accurate estimation of water content in pine bark and other porous organic substrates. The use of various container sizes will probably require the use of sensors of multiple lengths and/or configurations. A TDR network was deployed for three years to monitor and control irrigation scheduling in a container nursery environment (Ristvey, 2004). This deployment of soilless substrate moisture sensing technology has been shown to significantly reduce water consumption (up to 50%), as well as to significantly reduce nitrogen and phosphorus leaching from container-nursery production systems open to rainfall (Ristvey et al., 2004).

### Current Research

The focus of our group's research efforts has been on the individual container, to retain a greater proportion of irrigated and/or rain water in the plant root-zone (container); thus water is conserved, nutrient runoff minimized and plant growth optimized. Our current focus is to integrate substrate water, temperature and electrical conductivity (Ech<sub>2</sub>0-5, Ech<sub>2</sub>0-20 and Ech<sub>2</sub>0-TE), relative humidity sensors from Decagon Devices (Pullman WA) into the CMU network system. A low-cost quantum sensor (Apogee Instruments Logan, UT) that measures instantaneous PAR has also been integrated. We will therefore be able to monitor four of the most important environmental data streams for plant growth and productivity, on a continuous basis. The 20-cm and 5-cm Ech<sub>2</sub>0 sensors have been calibrated for a number of commercial substrates (Arguedas et al., 2007a, 2007b). The sensors can precisely measure water contents at very low substrate  $\Psi_m$  (Figs. 4a and 4b), such that solenoid valves can switch off and on at set points anywhere between -1 and -10 kPa (respectively), and thus regulate the amount of water

leaching from the container. With this system, control of the leaching fraction from water applications, to minimize nutrient runoff from plant production systems can be achieved without water stress. The variability of the sensor data is higher in substrates with higher air-filled porosities. With very porous substrates, it will be necessary to use greater numbers of sensors, to obtain more precise mean values for automatic set-point control.

The nodes have been configured to work with a combination soil temperature and electrical conductivity (Ech<sub>2</sub>O-TE) sensor from Decagon Devices, although there are still calibration issues to resolve between the measurement of bulk and pore-water EC in soilless substrates. The possibility of monitoring the EC in real time will enable the measurement of continuous changes in substrate EC for the first time, which currently are very difficult to measure. Scoggins and van Iersel (2006) recently compared the performance of four commercially-available EC sensors in several soilless substrates. This study did not include the Ech<sub>2</sub>O-TE and furthermore, none of the sensors tested had the ability to provide real-time data (i.e. they were stand-alone sensors). They determined that the EC measured with these probes was highly correlated with the three standard substrate extraction (pour-through, 1:2 dilution and saturated media extract) methods over a range of fertilizer concentrations, at operating standard temperatures. They also published EC conversion guidelines that could be used to convert readings from any of the in-situ probes, although they indicated that the substrate water volumetric content should be above 35% for these measurements to be valid. Having a simultaneous (and accurate) measurement of soil moisture and temperature (as with the Ech<sub>2</sub>O-TE probe) would therefore provide a level of confidence that no other EC sensor currently provides.

## **DICUSSION AND CONCLUSIONS**

The focus of this research is to provide affordable, reliable and scaleable sensor networks to the industry. Currently the CMU nodes can be constructed and programmed for about \$500 each. Given that the cost of many individual sensors is less than \$100 (Ech<sub>2</sub>O-20 and Ech<sub>2</sub>O-5 are currently \$60 each for quantities >10), means that a grower can configure a small 5-node, 25-sensor starter network for approximately US\$5,000. Each node has the capability to accept up to 10 digital inputs or 6 analog inputs, but nodes can also be configured to accept a combination of analog and digital sensors. Nodes also can “push” a signal to actuate solenoids for irrigation management and other environmental control functions, for ‘plant-driven’ environmental control. For these reasons, this hybrid wireless sensor network addresses all the major grower irrigation monitoring and control priorities, and it will provide for rapid implementation into commercial operations. Our current integration efforts are focused on optimizing network sensor performance in real greenhouse and nursery production systems, by resolving sensor placement issues and increasing precision, and customizing the GUI. Growers should reap an immediate financial payback through improved plant growth, reduced water and fertilizer applications, together with a reduction in problems related to over-watering (fungal infections) and runoff-related environmental impacts.

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Fig. 1. Part of a twelve-node, 48 sensor network, showing an individual CMU wireless sensor node (inset, top left).

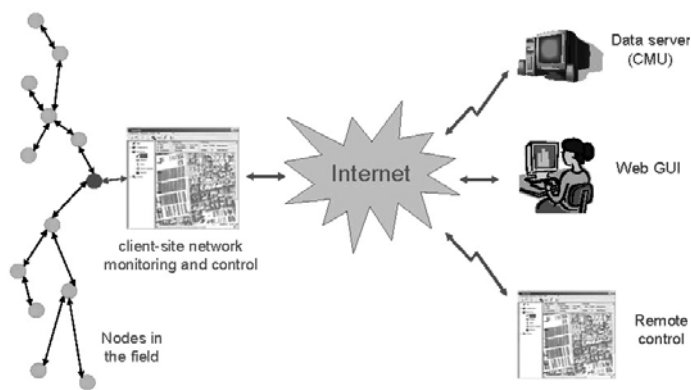


Fig. 2. Schematic of the Operational Sensor Network

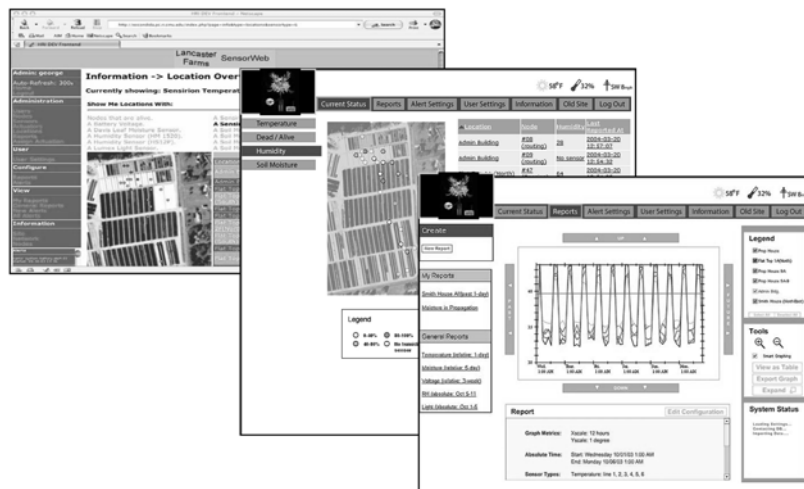


Fig 3. Computer screen capture of WebSensor graphic user interface and reporting system.

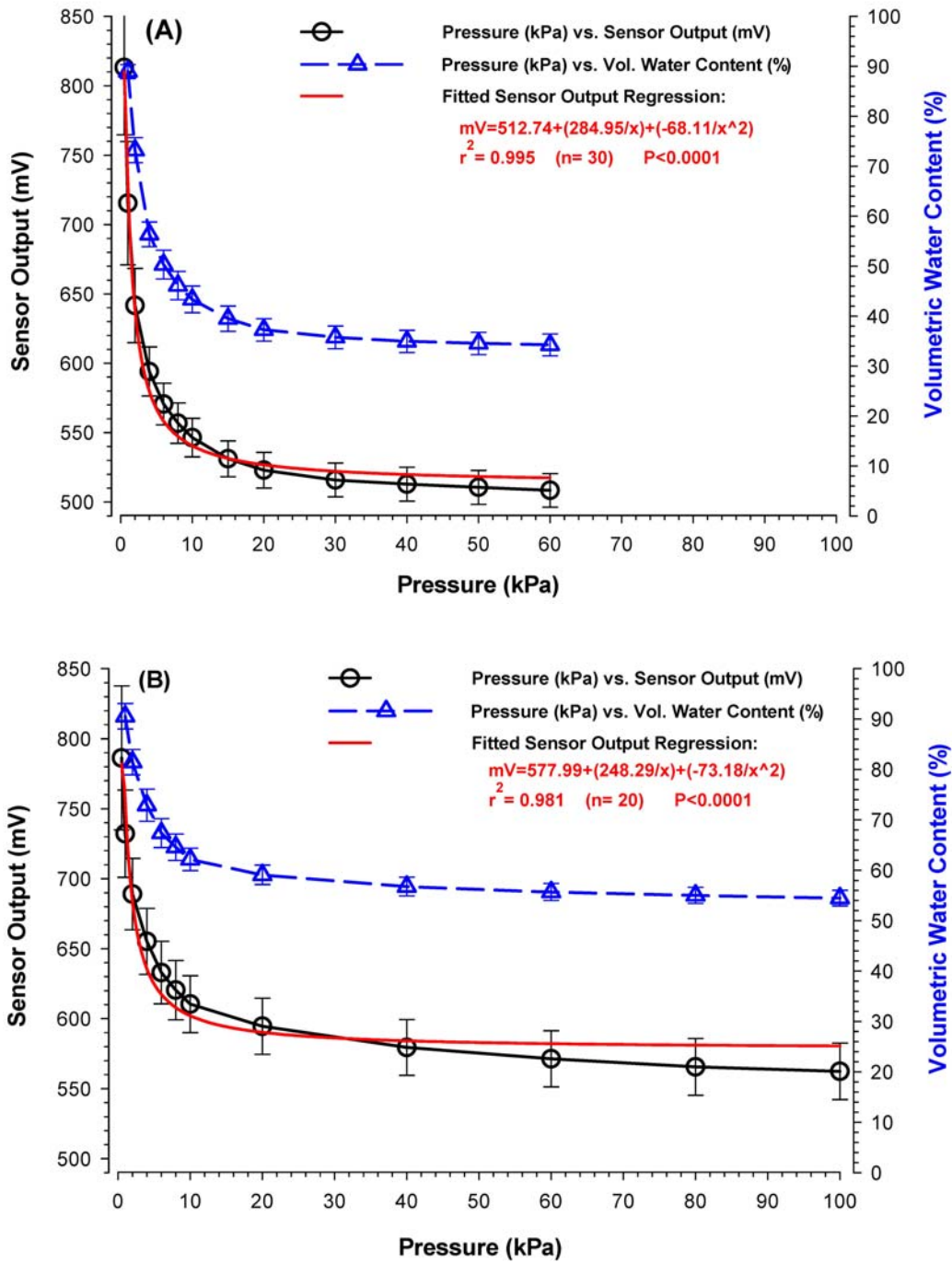


Fig. 4. Simultaneous sensor output (mV) and volumetric water content (%) vs. air pressure applied (kPa), for Ech<sub>20</sub>-5cm sensors (Fig. 4A) and Ech<sub>20</sub>-20cm sensors (Fig. 4B) in a 80% Peat : 20% Perlite commercial substrate.