In-Situ Performance and Usability of a Distributed, Wireless Sensor Network via Mesh Connectivity at a Production Container Nursery

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TECHNICAL NOTE:

IN-SITU PERFORMANCE AND USABILITY OF A DISTRIBUTED, WIRELESS SENSOR NETWORK VIA MESH CONNECTIVITY AT A PRODUCTION CONTAINER NURSERY

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ABSTRACT. *Many nurseries are considering soil moisture sensor networks to improve water application efficiency. Due to the necessarily wide distribution of sensors at a nursery, a wireless network is easier to install, more flexible, and can be scaled up as needed without re-design as compared to a traditional wired sensor network. When choosing a wireless network, a matter of critical importance is the network reliability. This study examined the reliability and usability of a commercially available, mesh-style wireless network used at a container nursery. We found that the network failed to record approximately 20% of scheduled sensor readings and that usability was limited due to a fixed 15-min reading interval. However, the system function was sufficient for calculating irrigation set-time and monitoring net irrigation and evapotranspiration when overhead irrigating containerized nursery crops. Results led to discussion of optimum characteristics of a wireless monitoring network system and to what extent this system embodied each of them.*

Keywords. Wireless network, Nursery, Network reliability, Mesh network, Sensor networks, Container nursery.

Recent technological advancements in wireless data transmission, environmental sensors, solar power supplies, and decreased hardware costs have made it possible to remotely monitor agricultural crops using web-based devices. This study examined the use of a wireless soil water content measurement system at an ornamental container nursery in Yamhill, Oregon (Bailey Nurseries Inc.).

Several studies have utilized custom wireless networks to transmit sensor data to a computer (Cayanan et al., 2008; Lea-Cox et al., 2010). Although studies have been conducted in controlled laboratory environments (Cayanan et al., 2008), commercial greenhouse operations (Lea-Cox et al., 2010), and field sites (Cardell-Oliver et al., 2005, few have used real-time sensor data on wireless networks to make on-demand irrigation management decisions (process control).

Cayanan et al. (2008) used a non-commercial wireless transmitter ("Poseidon" Wireless Module, University of Guelph, Guelph, Ontario, Canada) in conjunction with a custom Matlab PC interface. The Matlab program sent data requests to the wireless modules every 20 min. The system controlled water delivery via drip irrigation lines based on volumetric water content (VWC) of the coconut coir substrate using capacitive sensors (ECH$_2$O-TE, Decagon Devices, Pullman, Wash.). The University of Guelph system was able to be configured to accommodate many different irrigation schemes; however, the Matlab software utilized was not conventional and could be difficult to teach to users with limited computer skills. It also relied on non-rechargeable batteries with a lifetime of approximately two weeks requiring the user to replace the batteries in each wireless module many times during the course of the growing season.

Lea-Cox et al. (2008a, 2008b, and 2010) utilized a non-commercial wireless system developed by Carnegie Mellon Robotics Institute (Pittsburgh, Pa.) with ECH$_2$O series sensors (Decagon Devices) at a commercial cut-flower greenhouse operation. The battery and solar powered wireless nodes activated the sensors once every minute and recorded the average every 5 min.

In contrast to Cayanan and Lea-Cox, we evaluated commercially-available network products in a commercial, open-air, container nursery with overhead irrigation. The objective of this study was to use a system currently available to nursery operators and to test its performance as a soil moisture monitoring tool. We first describe the characteristics of an "ideal" sensor network system, including human interface. Then we compare the installed system performance with this ideal.

MATERIALS AND METHODS

The experiment consisted of eight data-collection nodes (eKo Node 2120, Memsic Corporation, Andover, Mass.) communicating wirelessly with a single solar-powered base station (BaseStation, PureSense Environmental, Inc., Fresno, Calif.). The eKo Nodes were distributed in two groups, four per irrigation zone. All nodes were between 80 and 220 m from the BaseStation; in each group eKo Nodes were between 20 and 50 m apart. Nodes were installed about 1.5 m above the ground, well above the height of the small shrubs they were monitoring. The BaseStation collected the data from the eKo Nodes and transmitted them over a cellular modem to the PureSense servers, which allowed access to the data via a web page interface to a database.

Each solar powered eKo Node was capable of monitoring up to four instruments, but for this study only two instruments were monitored per node. Each node was used to monitor both a load cell (15kg RL1042, Rice Lake Weighing Systems, Rice Lake, Wis.) and a volumetric soil moisture sensor (EC-5, Decagon Devices, Inc., Pullman, Wash.). The load cell was attached to the eKo Node using an interface cable and an analog signal conditioning board (es9100, Memsic Corporation, Andover, Mass.); a configuration file was also added on the eKo Node following the instructions provided by Memsic Corporation. Two eKo Nodes also monitored a weather station (ES2000v6, Memsic Corporation, Andover, Mass.), one in each irrigation zone, that collected wind speed and direction, irrigation and rainfall, temperature, relative humidity, solar radiation, UV radiation, and barometric pressure. Figure 1 shows a simplified network diagram of the system. One of the advantages of the eKo Nodes over similar devices was their capability to communicate to the BaseStation via another node; if a node was too far from the BaseStation to communicate directly, the node could pass its data to a nearby node that was able to communicate with the BaseStation. This ability, called mesh networking [Ferrari, 2010; now being finalized into IEEE wireless stan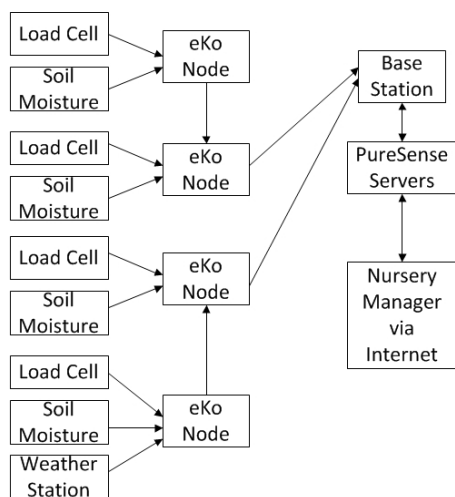dard 802.11s (Camp and Knightly, 2008)], enabled the network to extend far from the BaseStation by utilizing intermediary nodes.

The network collected data over a period of nine weeks (18 July to 21 September 2010) during the active production season for the nursery. Between 21 July and 24 August 2010, at any given time the BaseStation did not properly receive and record data from at least one of the eight nodes; however, a firmware update to the BaseStation provided by PureSense on 24 August corrected most of these transmission problems. Therefore, the network reliability analysis will focus only on the dates between 24 and 28 August, 2 to 9 September, and 13 to 21 September. Missing dates are due to power losses at the BaseStation. Under normal operation the nodes were designed to communicate with the BaseStation every 15 min to transmit sensor data. For the purposes of this study, a transmission is the collection of all sensor data with the same time-stamp received from a single node and is considered a single data point or packet. A transmission was not repeated once the current 15 min period had elapsed; data was not saved locally on the node in the case of transmission failure, nor was a full acknowledgement and retry procedure implemented in the system. Upon network startup, each node went through an initialization process during which it transmitted once every 30 s for 60 min. Periods of initialization were not considered normal operation and are excluded from the results.

Because these were young, woody shrubs, the plants and containers were small to medium size and placed close together. The close spacing and frequent moving by nursery staff made use of individual drip irrigation impractical and thus the site was irrigated by overhead impact sprinklers, operating once per day for approximately 2 h per "set."

Figure 1. Simplified network representation showing possible transmit paths.

RESULTS

Between 24 August and 21 September the system collected 10,353 data points out of the expected 13,766, a transmission success rate of 75.2%. Of the data collected the majority (80.9%) were received as expected (approx. every 15 min.), but a significant minority (19.1%) were collected after at least one missing interval (15.2% were collected after one missing interval, 2.8% after two missing intervals, and 1.1% after three or more missing intervals). These data show that occasionally the system failed to record data at the BaseStation at the expected time, thus decreasing data density and sample size available to the nursery manager to make irrigation management decisions.

DISCUSSION

Although the transmission success rate of 75.2% was better than the 63.8% reported by Cardell-Oliver et al. (2005) on their custom wireless network, it illustrates that the system tested was still far from the reliability necessary for an active-control implementation. An active-control system would be one which relies directly on sensor readings to determine when to shut off irrigation.

Let us consider a system that has perfect transmission reliability and a plant that needs 2 h of irrigation to reach a functional saturation point. If the saturation point is reached just a few seconds before the wireless node powers up the sensors and takes the measurement, the system will turn off the irrigation and the water application efficiency (WAE) of the system is 100% (water needed/water delivered; here irrigation time is a proxy for volume of water assuming a constant irrigation rate). But if the saturation point is reached a few seconds after the 2 h measurement, the system will continue irrigating for an extra, and mostly unnecessary 15 min; the WAE then is 89% (2/2.25). If the system fails to record what should be the ending data point, the WAE decreases. Combining the observed transmission success with expected WAE and finding a weighted WAE, the long-term WAE of the observed system could range from 87% to 97%. If the data collection period were reduced from 15 to 10 min (and transmission success rate profile remains the same), the long-term WAE range would be 91% to 98%. If the no-gap transmission success (no missing interval) was increased to 95% (with one, two, and more missing intervals being 4.0%, 0.7%, and 0.3% respectively, the same proportion as observed), the WAE range would only increase to 88% to 99%.

It is profitable to compare the system tested to what might be taken to be an ideal system. Most of these characteristics are at least mentioned in Burrell et. al (2004) and Lea-Cox et al. (2008a, 2008b), but have not previously been considered in a unified manner to address the needs as often encountered at an outdoor container nursery with overhead irrigation.

IDEAL CHARACTERISTICS OF AN AUTOMATED SYSTEM

1. Sufficient temporal data density to not significantly reduce WAE due to reporting interval. A shorter reporting interval allows for greater control over the irrigation cycle and higher utilization of water, even moving into controlled soil-moisture deficits for desired biological effects such as flowering or dormancy. Sensor resolution is an important factor in determining the effectiveness of reducing the reporting time interval. If the reporting time is reduced below the time needed for the sensor reading to increase one increment under the expected rates of irrigation application (e.g., in our study, the average weight step was 17.83 g and the average volumetric step was 0.0038 cm³/cm³), then the field node would be sending unnecessary data to the BaseStation. Alternatively, a system could be designed to take field measurements at short intervals, but only transmit to the BaseStation on a sensor change; this is called a reactive system, such as the one used by Cardell-Oliver et al. (2005). A second alternative would be to take measurements more frequently during irrigation to ensure data density, and then less frequently during draw down, conserving power supplies.

2. Network transmission reliability to prevent data loss. If the end of an irrigation cycle depends on measured values, transmission reliability is critical. An irriga-

tion system that reduces its dependency on data transmission would be a more robust option (i.e., timer fail-safes). Also, transmission acknowledgment signals between base station and distributed nodes would be a very desirable feature with unacknowledged transmission data stored on the node for some period of time.

3. Redundancy to ensure a representative sample. A container nursery with overhead irrigation has many variables in irrigation, such as outlier performance of a single plant, a mixture of container sizes, and species. At least one sensor per irrigation zone, per species, per size of container is recommended.

4. Sensor accuracy and proper installation. If the end of an irrigation cycle depends on measured values, sensor accuracy is important. Sensor accuracy often depends on proper installation. Also, if containers are frequently moved, the sensor may need to be adjusted and recalibrated.

5. Robust power management. The design of a wireless sensing system must always balance energy supply (solar panel output and battery capacity) with energy consumption (dominated by the radio usage).

6. Outputs to control irrigation pumps. Remote operation of the entire irrigation system is the end goal of such an automated system. This can only be accomplished with output relays integrated into the system to control the flow of water.

7. Inputs from other data sources such as meteorological instruments and system water use, while not absolutely necessary, would provide additional data for making accurate irrigation decisions.

8. Easy to use data display and control interface. A data-reliant system is effectively useless if the nursery manager cannot easily access the data and control set-points for irrigation.

9. Durability of network components. System components necessarily would be exposed to adverse weather, solar radiation, the accidental run-in with nursery machines, and even employee misuse. Components should be able to withstand these conditions for multiple years.

CURRENT SYSTEM PROVISIONS

The PureSense BaseStation and Memsic eKo Node system monitored in this study provided the following benefits, some of which are solutions to points outlined above. PureSense provided both an easy-to-use web site and a custom computer application (not shown) for monitoring environmental and soil water conditions. The eKo Nodes and PureSense BaseStation used solar-recharged batteries making them maintenance free throughout the growing season. The eKo Node wireless mesh network allowed for widespread distribution of sensors without the expense of burying communication cables. Because the sensors used only a short cable to connect with the eKo Node, the sensors and eKo Nodes could be easily moved to monitor a different section. The system provided a reliable estimate of the soil-moisture status in the hour prior to irrigation (with 99% probability).

Further, with over 80% reliability, we could expect to obtain the weight within 15 min of the end of irrigation, and with 98% probability the weight an hour after irrigation. We believe that 15 min between sensor readings with 80% reliability is sufficient to monitor soil moisture during draw-down and that these data allowed us to: 1) reliably determine when container saturation achieved a threshold value; and 2) verify that the full water holding capacity of the system was achieved after an irrigation cycle.

Under situations requiring only one irrigation cycle per day, the evaluated system would be sufficient to: 1) determine when to start irrigation; 2) compute an irrigation time duration sufficient to achieve field saturation; and 3) verify that the plants obtained field saturation.

Furthermore, in most instances (over 80% of the cases) these data would allow observation of over-irrigation as evidenced by plateau in weight during the final period of the irrigation set and a significant drop in weight immediately following the end of irrigation (drainage to field capacity). These data would be very valuable to irrigation management even without automated irrigation because the irrigation manager would be able to calculate how much water the plants needed day to day and adjust for optimal irrigation time, thus reducing electricity use and fertilizer leaching loss.

CURRENT SYSTEM LIMITATIONS

The system does have limitations which must be taken into account when developing an irrigation control system for container nurseries based on this approach to monitoring. We now see important limitations presented by the unchangeable reporting intervals (15 min); power limitations of the eKo Nodes (one reason for unchangeable reporting intervals); limited selection of sensors; lack of output relays for control of external systems; multiple points of potential failure in the data path; and most importantly, the unexplained loss of over 20% of data.

It is the opinion of the authors that 15 min between sensor readings with 80% reliability is not sufficient to actively control irrigation (also called process control). If using process control, a shorter interval of 10 min would seem prudent so as to not needlessly apply water due to lack of current data (as shown at the beginning of the discussion); however, reporting at intervals shorter than the ability of the irrigation rate to increase a sensor measurement leads to other interesting problems such as inefficient use of node power supplies and requiring a more complicated method to determine if the set point has been reached. But with a higher sample rate, the system could tolerate a higher percentage of data loss.

One of the problems with the network was power loss at the BaseStation. This could have been a problem with poor siting; the BaseStation was placed in a location that was shaded in the afternoon by a two story building. Since it wasn't receiving full sun all day, it could have had difficulty recharging the battery. This could have been resolved with a larger solar panel combined with a larger-capacity battery or improved siting.

CONCLUSION

The system tested had distinct advantages over many other soil moisture monitoring strategies. Most other solutions require changing batteries periodically or providing electricity at the sensor site; both would be costly (in wiring and/or maintenance effort) and could cause such systems to have failures which would be unacceptable in a production nursery environment. However, missing one in five readings should be cause for more serious thought about the implementation of the current system to control irrigation. An automated irrigation system that relies on the current system should be time based as opposed to sensor based. In its current implementation, the system of PureSense BaseStation and Memsic eKo Nodes is designed for periodic monitoring and not for process control management as would be required by an automated system. But it is still possible to employ this system to manage irrigation. We know that successive irrigation sets follow very similar patterns, so knowledge of the degree of depletion prior to irrigation, as well as having a history of the relationship between irrigation duration and net water accumulation, may be sufficient information to schedule the duration for each irrigation event as computed prior to onset of water application (time-based instead of sensor-based). Thus, while not quite satisfying all of the characteristics of an ideal monitoring system, the benefits and robustness of using an eKo Node system with a PureSense BaseStation may yet provide sufficient functionality to improve irrigation performance.

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