Monitoring of an Aeroponic Greenhouse with a Sensor Network

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Abstract
This paper describes the design and implementation of a wireless sensor network for greenhouse environment monitoring. The sensor network was deployed in a commercial aeroponic greenhouse that produces lettuces in a tropical environment. The sensor node was developed using off-the-shelf components and consists of sensors, a micro-controller and a low-powered radio module. Real-time data enabled the operators to characterise the operating parameters of the greenhouse and also to respond immediately to any changes in the controlled parameters. The sensor network achieved data transmission rates of more than 70%.
Keywords: *Wireless Sensor Network, Greenhouse monitoring, Precision Agriculture*

1. Introduction

This project was initiated to provide a highly detailed micro-climate data for plants within a greenhouse environment where an innovative method of growing temperate crops in a tropical environment using aeroponic is practiced. The roots of the plants are sprayed with a chilled nutrient solution to ensure that the root zone is kept cool. The stem and leaves are exposed to ambient temperatures in the greenhouse and do not seem to suffer any damage. The greenhouse was previously equipped with conventional wired sensors that provide readings of the air temperature, light intensity and nutrient solution temperature in the mixing tank. The acidity and concentration of the nutrient solution were manually measured, and require human intervention to either adjust the acidity level or to top up the nutrient solution. It has been suggested that high resolution data, collected with the deployment of a network of wireless sensors would be able to provide sufficient data to develop a model for the growth of these crops under aeroponic conditions.

2. Background

A recent survey [1] of the advances in wireless sensor network applications has reviewed a wide range of applications for these networks and identified agriculture as a potential area of deployment together with a review of the factors influencing the design of sensor networks for this application. The basic components of a sensor network consist of one or several sensors that are connected to a micro-controller and a radio module. When a large number of these tiny sensor nodes are deployed either randomly or in regular grid, they shall act collectively to perform sensing over a large area or in inaccessible terrains.

Intel Corp. was one of the main proponents of the use of wireless sensor networks for agriculture with a study [4] in 2002 which assessed the potential for sensor networks and a trial installation of 18 temperature sensor nodes for a period of several weeks in an Oregon vineyard. Its main application was to monitor the temperatures during the winter nights and to determine the time to pick the grapes. This was followed by another project [3] with 65 temperature sensor nodes arranged in a grid with a fixed network topology to determine the duration of exposure to extreme cold and to correlate the recorded temperatures to the ripening parameters.

Research on the use of WSN in agriculture is mainly focused on two major areas: (i) experimental or simulation work on various routing protocols and network topologies to increase data transfer rates whilst maintaining or reducing power consumption [5,8,12,13], and (ii) proof-of-concept applications to demonstrate the efficiency and efficacy of using sensor networks to monitor and control agriculture management strategies [7,11,16,17,18,19,20,21].

In this aeroponic greenhouse, the operators cultivate temperate plants in tropical conditions by cooling and subsequently misting of the nutrient solution to the root zone [10,14]. The plant seedlings are anchored into a planting hole on the top panels where the shoots are exposed to sunlight and the root protrude into the trough. Chilled nutrient solution is piped into the trough and

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pumped out through special misting nozzles to provide the root zone with water and nutrients at regular intervals. Unabsorbed nutrient solution flows back to the nutrient tank under gravity flow for recirculation providing a highly efficient system for water and nutrient use.

3. Design and Development of the Sensor Nodes

The plant scientists recommended that the following parameters be monitored: sunlight intensity (measured as photosynthetic photon flux density), temperatures of the leaf and root zones, acidity and concentration of the nutrient solution. The sensors were selected to function at the same supply voltage as the micro-controller and radio module, and to consume as little power as possible to ensure that these sensor nodes operate over long periods of time. The sensors were designed to be robust as it may be occasionally handled by farm operators untrained to deploy such sensitive electronic equipment.

A precision integrated-circuit temperature sensor LM61 (TO-92 package) was sealed in a watertight copper tube to ensure that the electrical connections are not damaged by the feed solution. As the LM61 operates from as low as 2.70 V and consumes less than 125 µA of current, it can be directly powered from the I/O pins and its output connected to the ADC port.

Plants are sensitive to a portion of the light spectrum that ranges between 400 nm to 700 nm wavelength. The density of the photosynthetic photon flux is measured in micro-moles per square metre per second (µmol $m^{-2}s^{-1}$). The SQ-200 sensor was factory calibrated for sunlight to provide an output of 1.00 mV per µmol $m^{-2}s^{-1}$ [2]. Maximum sunlight of 2000 µmol $m^{-2}s^{-1}$ will produce an output of 2.0 V.

The acidity of the nutrient solution is measured with a pH sensor. The temperate crops in this study require a mildly acidic nutrient solution at a pH level ranging from 5.5 to 5.9 for optimum absorption of magnesium and zinc salts, and other micro-nutrients. The CSIM11 probe eliminates the need for an extremely high-impedance voltmeter with a built-in pre-amplifier powered by two internal lithium-ion batteries, which powers the probe for a period of up to 5 years [6].

The concentration of the salts in the nutrient solution was monitored by measuring the electrical conductivity using the WQ301 conductivity probe [9]. An electrical conductivity reading of 2500 µS cm^{-1} correlates to an optimum nutrient concentration for the plants. WQ301 requires a 12 V excitation voltage and provides a 4-20 mA current output which is converted to a voltage signal by routing the current through a 100 Ohm resistor. An auxiliary power supply was provided to the wireless node to power up the EC probe. A low powered EC probe will have to be sourced for future projects to reduce the power consumption.

TABLE 1: TYPE AND SPECIFICATION OF ALL SENSORS

Parameter	Sensor, Manufacturer	Part No.	V_{out}	V_{supply}	I_{drain}
Temperatures	Temperature sensor, National Semiconductor Corporation	LM61 – TO92	0.0 – 1.60 V	2.7 – 10 V	285µA
Light intensity	Quantum sensor, Apogee Instruments Inc.	QSO-2.5S	0.0 – 2.50 V	2.5 – 5.5 V	285µA
Acidity	pH probe, Campbell Scientific Inc.	CSIM11	0 – 0.413V	2 nos. 3.0 V *	0 mA
Salt concentration	EC probe, Global Water Instrumentation Inc.	WQ301	4 – 19mA	12.0 V	6.5 mA + (4 – 19mA)

* powered by two internal lithium batteries

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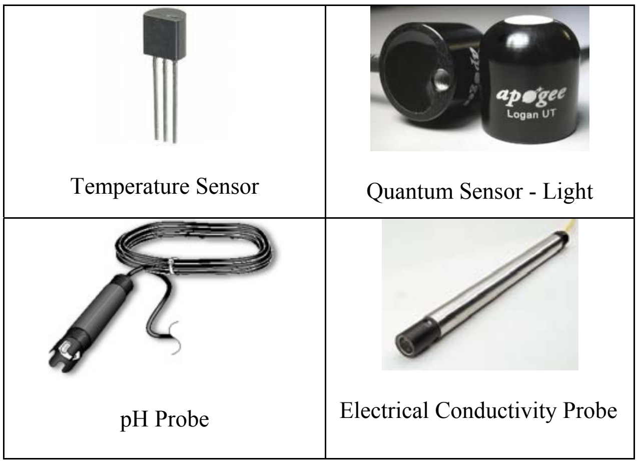

Fig. 1: Sensors for Temperature, Light, pH and Conductivity

 Node A – Temperature and Light sensors	 Node B – Temperature and pH sensors	 Node C – Temperature and Conductivity Sensors

Fig. 2: Wireless Sensor Nodes A, B and C

The iDwaRF-168 wireless module procured from chip45.com combines a Cypress CYWUSB6935 2.4 GHz Direct Sequence Spread Spectrum (DSSS) radio transceiver with an Atmel AVR ATmega 168 microcontroller. The iDwaRF has separate transmit and receive antennas integrated in the PCB that has a communication range of up to 50 metres with 62.5 kbit/s data throughput. A connector board was designed and built to connect the output of the sensors directly to the 10-bit ADC ports of the microcontroller, to provide regulated 3.30 V to the iDwaRF module from four high capacity alkaline batteries, to power the sensors with the output of a signal pin, to indicate radio activity with a single LED, and to provide a reset push-button. An additional ADC port was used to monitor the battery voltage via a voltage divider. The modular design of the connector board allows for a single board to be used for a combination of sensors, leading to the connection of two temperature probes and a light sensor for sensor Node A, temperature and pH probes for sensor Node B, and temperature and conductivity for sensor Node C. The Hub node consists of an identical iDwaRF module connected to a Hub-Board procured from chip45.com [15].

The iDwaRF sensor node samples data from the sensors at pre-determined intervals, processes the information internally, packs into a string which includes the node ID, sensor types, sensor readings, and checksum bytes, and forwards the data packet to the radio module. When the receiving hub receives the data string, it will send an acknowledgement to the sensor node. A sample of the communication strings is shown in Figure 3.

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S5 : ID  0  NID   7 T   2 C1  27 T1   0 T2   0 Vb 6084 C5 1 B:: 7
S5 : ID  1  NID   2 T   1 C1   0 T1  70 T2  77 Vb 6187 C5 1 B:: 7
S5 : ID  2  NID   9 T   8 C1  58 T1   0 T2   0 Vb 5980 C5 1 B:: 7
S5 : ID  0  NID   7 T   2 C1  27 T1   0 T2   0 Vb 6084 C5 1 B:: 7
S5 : ID  1  NID   2 T   1 C1   0 T1  70 T2  76 Vb 6187 C5 1 B:: 7
S5 : ID  2  NID   9 T   8 C1  58 T1   0 T2   0 Vb 5980 C5 1 B:: 7
```

Fig. 3: Sample data packets transmitted by the sensor nodes

Although the receiving hub possesses substantial processing capabilities, the data received is not processed but mainly re-transmitted via the serial connection to a PC for recording and further processing. A Microsoft VisualBasic 6.0 program inserts a time-stamp on all the data strings received, and then appended to a text file labelled as **yyyymmdd.txt** which corresponds to the year, month and day the data is recorded. The user is able to change the sensor node sampling interval and this instruction will be sent out to all the nodes during the next communication cycle.

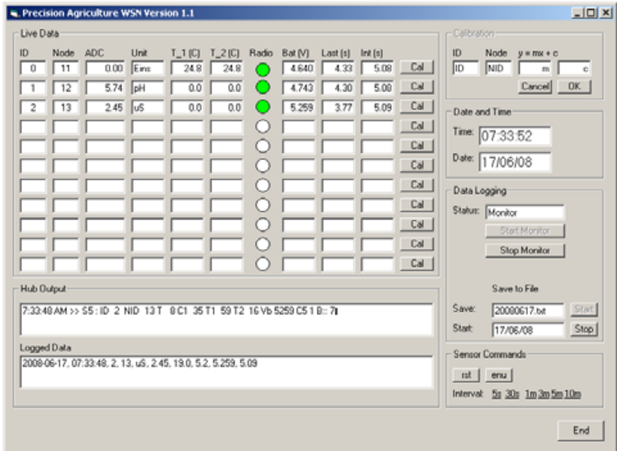

Fig. 4: Sample screenshot of the Graphical User Interface

4. Deployment of the Sensor Network

The wireless sensor network was deployed at the 640 sq.m R&D greenhouse in Labu, Negeri Sembilan between 27 May and 25 June 2008. The greenhouse was covered with a 0.2 mm thick polyethylene sheet and equipped with a 10-HP chiller unit that provides chilled feed water to nine planting troughs, a nutrient tank of 300 litre capacity for each trough, and four 1 HP ventilation fans. Each trough contains approximately 300 lettuce plants which will grow in the trough for approximately one month before harvest.

Fig. 5: Greenhouse with four ventilation fans and planting troughs inside

Sensor Node A, which consists of two temperature sensors and one light quantum sensor, was inserted into the trough in place of a lettuce plant. Sensor Nodes B and C, which were designed to measure the acidity and concentration of the nutrients in the feed solution were initially intended to be connected to the pipes supplying the solution to the nozzles, but were later placed at the feed tank to reduce the amount of piping modifications at the trough.

Fig. 6: Planting trough, Node A, Node B and Node C as installed

5. Results and Discussion

A. Sunlight

Figure 7 shows photon flux densities received inside the greenhouse for sunny and cloudy days. The cumulative duration of the light intensity is shown in Figure 8 for both these days: total duration of light intensity exceeding 300 μmol m^{-2} s^{-1} is 7 and 1.5 hours, respectively for sunny and cloudy days. This light intensity data can be used as the basis for providing additional lighting, and to determine the duration and intensity of supplemental lighting, if necessary.

B. Temperatures

Two temperature sensors recoded the air temperature in the greenhouse (T1) and in the planting trough (T2). The air temperature is what the leaves of the plant are exposed to and the temperature in the planting trough is the temperature of the root zone of the plants. It was observed that T1 changes in accordance with the weather; a hot afternoon at full sunlight without ventilation can raise the air temperature in the greenhouse to a maximum of 50°C whereas a heavy rainfall during the night can cause the temperature to drop to a minimum of 21°C. The root zone which is cooled by the chilled nutrient mist was observed to fluctuate between 21°C and 30°C depending on the ambient temperatures. The measurement of the root zone temperature is a significant improvement over the existing monitoring system which only recorded the temperature of the feed solution as it flows out of the chillers. These sensor nodes now measure the temperature directly in the root zone.

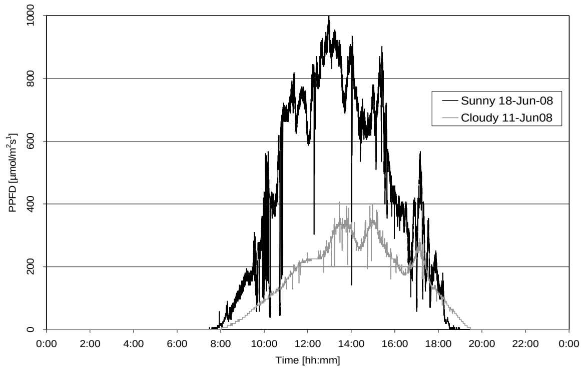

Fig. 7: Comparison of light intensity readings for sunny and cloudy days

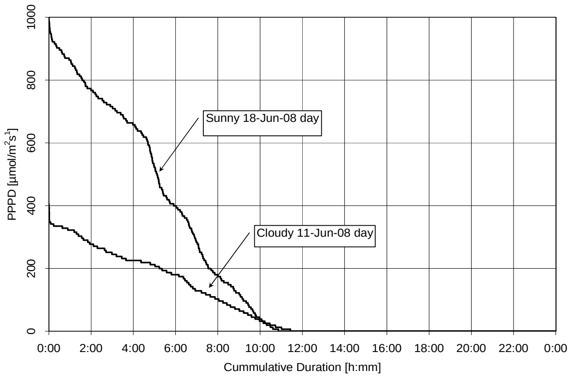

Fig. 8: Cumulative light readings for sunny and cloudy days

Figure 9 shows that the greenhouse temperature (T1) starts to increase at 7.30 am when the sun shines strongly into the greenhouse and continues to rise to a peak during the mid-afternoon. With continued ventilation, T1 hits a maximum of 40°C between 1.00 to 4.00 pm. After 4.00 pm the light intensity declines, T1 drops gradually and remains constant at about 25°C from 8.00 pm until the next morning.

At 6.30 am, the root zone temperature (T2) drops from 25°C to 22°C when the chillers are turned on. T2 fluctuates following T1 but with a 10 minute lag. T2 reduces from about 4.00 pm to a minimum of 22°C at about 8.00 pm. After 9.00 pm when the chillers are turned off, T2 is observed to gradually increase to the ambient greenhouse temperature T1 at about 11.00 pm. From figure 10, it can be seen that T2 occasionally rises to higher than 25°C when the greenhouse temperature T1 exceeds 40°C. This occurs even though the chillers are operating at full capacity. Obviously, the heat gain in the greenhouse is greater than the cooling capacity of the chillers, and action may be required to either reduce the greenhouse temperature or to increase the cooling capacity of the chillers to maintain the root zone temperature to below 25°C.

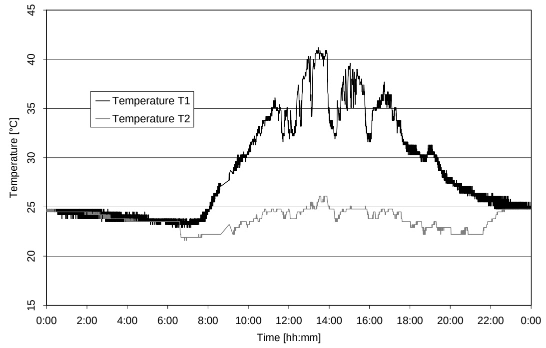

Fig. 9: Temperature readings T1 and T2 for 20-Jun-08

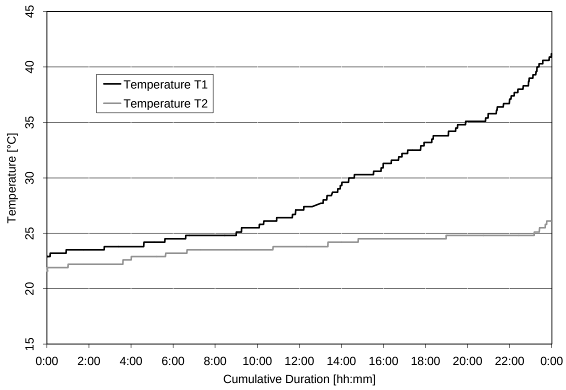

Fig. 10: Cumulative temperatures T1 and T2 data for 20-Jun-08

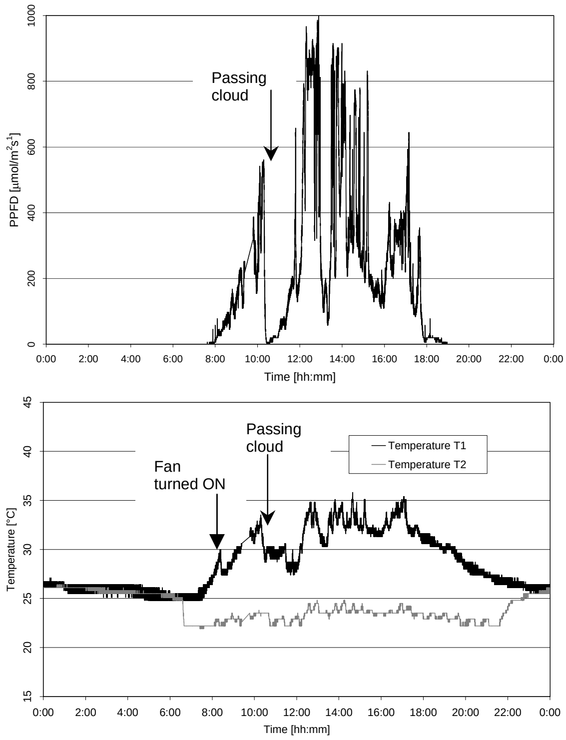

Fig. 11 Light intensities and temperatures on 10-Jun-08

Figure 11 shows the correlation between the light and temperature data in the greenhouse. The temperature inside can rise quickly to a temperature higher than the external air temperate if the ventilation fans are not turned on. At sunrise, T1 increases from about 25°C at 7.30 am until 30°C about 8.30 am and immediately drops to 27°C as the ventilation fans are switched on. T1 continues to increase as the sunlight intensifies but is observed to decrease whenever the sunlight is blocked by a passing cloud; e.g. at about 10.15 am. The drop in T1 is almost immediate.

C. Acidity and Concentration of Nutrient Solution

The current operating procedures dictate that the operators manually measure the acidity and concentration of the nutrient solution three times a day at approximately 8.00 am, 12.00 noon, and at 4.00 pm each day. Based on these test results the acidity may be adjusted, water level topped up, or additional nutrient solution added, accordingly. Throughout the deployment period of the wireless monitoring system at the R&D greenhouse, the operators continued to conduct daily manual measurements and tests on the nutrient solution.

Nodes B and C for pH and conductivity, respectively, were inserted directly into the nutrient solution tank. Figure 12 shows that the pH was about 6.05 from midnight until 7.30 am. The reduction in acidity at 9.30 am was due to the addition of water into the nutrient tank by the operator. The sharp increase in acidity at 4.00 pm was due to the addition of hydrochloric acid to the nutrient solution tank to bring the pH value back into range. The fluctuation of the acidity over time is not immediately correlated to any one parameter, and is attributed to the metabolism of the crops as suggested by the operators. Previously recorded data indicate that the pH value changed throughout the whole crop cycle. Continuous data from these wireless sensors is expected to assist the farm operators to better understand the metabolism mechanisms for the crop throughout the entire crop cycle.

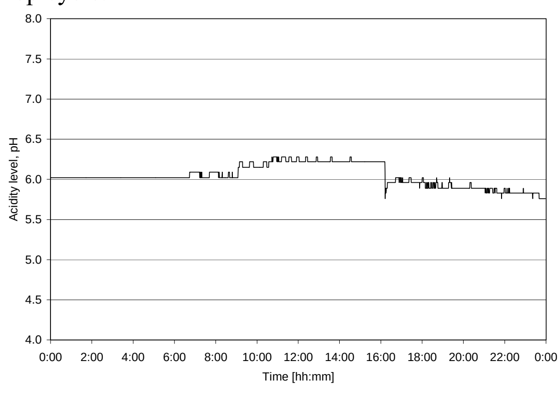

Fig. 12: pH readings in the nutrient tank on 2-Jun-08

The concentration of the nutrients in the feed solution is one of the most important parameters in the management and control of aeroponic agriculture. The concentration was determined by measuring the electrical conductivity as it directly correlates with the concentration of ions in the feed solution.

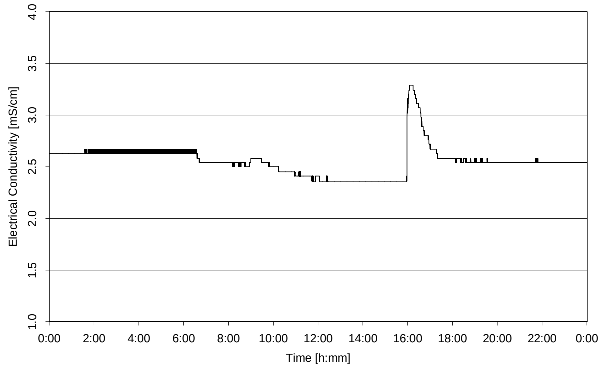

Fig. 13: Electrical Conductivity readings in the nutrient tank on 21-Jun-08

The plants in the trough are maturing rapidly and absorbing the nutrients very quickly as shown in Figure 13. The conductivity can be observed to drop from 2.6 mS/cm to 2.4 mS/cm during the first half of the day. When additional nutrients were added at 4.00 pm, the conductivity increased suddenly but eventually dropped back to 2.55 mS/cm after the nutrients are properly mixed into the solution. The frequency and/or quantity of nutrient top-up is expected to increase according to the growth rate of the plants.

6. Reliability of Data Transmission

A total of 4 sensor nodes were deployed during this project and placed in two separate planting troughs. The interval was nominally set at 30 seconds to obtain data with a higher degree of redundancy and also to collect sufficient data to determine the appropriate interval for future deployments. The nodes were operating in a star network as the distances were less than 50 m.

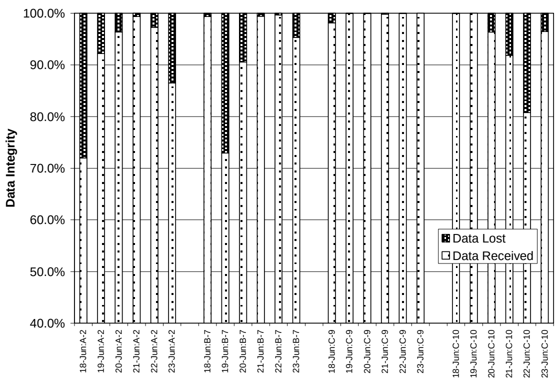

Fig. 14: Reliability of the wireless communications

Figure 14 shows the percentage of data packets received from each of the sensor nodes in the lettuce trough for each day. Although there is some variability in the performance of the network, the minimum success rate was 70%. This included data packets that were sent after a few unsuccessful attempts.

7. Conclusions

A prototype wireless sensor monitoring system for aeroponic agriculture was developed and deployed in a commercial greenhouse, offering a range of information which was required by plant scientists to provide a greater understanding of how these environmental and nutrient parameters are correlated with plant growth. The real-time information obtained from these sensor nodes may be utilised to optimise strategies to control the temperatures and the properties of the nutrient solution. This data set will also form the basis for future monitoring regimes, and is expected to contribute towards the development of a crop model for the lettuce under aeroponic conditions.

The reliability of the star network was relatively high, with many nodes performing with a data transmission rate above 90%. The minimum data transmission rate for all the nodes was 70%.

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REFERENCES

[1] Akyildiz, I.F., Su, W., Sankarasubramaniam, Y., Cayirci, E., "Wireless sensor networks: a survey", *Computer Networks*, vol.38, pp.393-422, 2002.

[2] Apogee Instruments Inc., "*Owners manual model: SQ-200 Series*", 2008.

[3] Beckwith, R., Teibel, D., Bowen, P., "Unwired wine: sensor networks in vineyards", *Proceedings of IEEE Sensors 2004*, pp.561-564, 2004.

[4] Burrell, J., Brooke, T., Beckwith, R., "Vineyard computing: sensor networks in agricultural production", *IEEE Pervasive Computing*, vol.3, no.1, pp.38-45, Jan-Mar, 2004.

[5] Camilli, A., Cugnasca, C.E., "From wireless sensors to field mapping: Anatomy of an application for precision agriculture", *Computers and Electronics in Agriculture*, vol.58, no.1, pp.25-36, Aug 2007.

[6] Campbell Scientific Inc., "*Using CSIM pH and OPR probes with Campbell Scientific dataloggers*", (Rev 1/08), 2008.

[7] Dinh, T.L, Hu, W., Sikka, P., Corke, P., Overs, L., Brosnan, S., "Design and deployment of a remote robust sensor network: experiences from an outdoor water quality monitoring network", *32nd IEEE Conference on Local computer Networks*, pp.799-806, 2007.
[8] Galmes, S., "Lifetime issues in wireless sensor networks for vineyard monitoring", *IEEE International Conference on Mobile Adhoc and Sensor Systems (MASS)*, pp.542-545, Oct 2006.
[9] Global Water Instrumentation Inc., "*User manual for WQ301*", 2001.
[10] He, J., Lee, S.K., Dodd, I.C., "Limitations, to photosynthesis of lettuce grown under tropical conditions: alleviation by root-zone cooling", *Journal of Experimental Botany*, vol.52, no.359, pp.1323-1330, Feb 2001.
[11] Kim, Y.Y., Evans, R.R.G., Iversen, W.W.M., "Remote sensing and control of an irrigation system using a distributed wireless sensor network", *IEEE Transactions on Instrumentation and Measurement*, vol.57, no.7, Jul 2008.
[12] Konstantinos, K., Apostolos, X., Panagiotis, K., George, S., "Topology optimization in wireless sensor networks for precision agriculture applications" *Int'l Conference on Sensor Technologies & Applications*, pp.526-530, Oct 2007.
[13] Langendoen, K., Baggio, A., Visser, O., "Murphy loves potatoes: experiences from a pilot sensor network deployment in precision agriculture", *20th Int'l Parallel & Distributed Processing Symp.*, Apr 2006.
[14] Lee, S.K., Cheong, S.C., "Inducing head formation of iceberg lettuce (*Lactuca Sativa L.*) in the tropics through root-zone temperature control", *Tropical Agricuture*, vol.73, pp.34-42, 1996.Lins, E., "*iDwaRF-168 Info Sheet*", 2008.
[15] Marino, P., Fontan, F.P., Dominiguez, M.A., Otero, S., "Environmental monitoring based on emerging wireless technologies", *Fourth Int'l Conference on Networking and Services*, pp.30-34, Mar 2008.
[16] Narasimhan, V.L., Arvind, A.A., Bever, K., "Greenhouse asset management using wireless sensor-actor networks", *International Conference on Mobile Ubiquitous Computing, Systems, Services and Technologies*, pp.9-14, Nov 2007.
[17] Pierce, F.J., Elliott, T.V., "Regional and on-farm wireless sensor networks for agricultural systems in Eastern Washington" *Computers and Electronics in Agriculture*, vol.61, no.1, pp.32-43, Apr 2008.
[18] Wietrzyk, B., Radenkovic, M., "Energy efficiency in the mobile ad hoc networking approach to monitoring farm animals", *Sixth International Conference on Networking*, Apr 2007.
[19] Yoo, S., Kim, J., Kim, T., Ahn, S., Sung, J., Kim, D., "A^{2}S: automated agriculture system based on WSN", *IEEE International Symposium on Consumer Electronics*, 2007, pp.1-5, Jun 2007.
[20] Zhou, Y., Yang, X., Guo, X., Zhou, M., Wang, L., "A design of greenhouse monitoring & control system based on ZigBee wireless sensor network", *International Conference on Wireless Communications, Networking and Mobile Computing*, pp.2563-2567, Sep 2007.

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