

Final Report
**Precision Fertigation in Orchards:
Development of a Spatially Variable Microsprinkler System**
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Statement of Objectives

In order to address the unique needs of individual trees in an orchard, we developed a spatially variable microsprinkler system. The specific objectives were to

- 1) design and develop electronic hardware for individually controllable microsprinklers along a drip tubing irrigation line,
- 2) develop the communication network and software for control of the drip tubing irrigation lines by a master computer,
- 3) experimentally evaluate the system performance and potential problems caused by operation in the field, and
- 4) develop potential fertigation control strategies to optimize orchard production.

Abstract

Precision management of irrigation and fertigation in orchards is compromised by the physical constraints of traditional sprinkler and drip systems, which are designed for uniform nutrient delivery and ignore the reality that demand varies across fields and between individual trees. Trees that die from flooding or other damage are replanted and do not have the same water and fertilizer requirements as older trees. When applied uniformly, water and fertilizer may leach in light textured soils and pool in heavy soils. Emitter clogging and irrigation line damage further compound the problem of delivering water and fertilizer based on demand. Controlled application of water and dissolved fertilizer through a network of intelligent microsprinklers could lessen these problems.

A microsprinkler system was developed to provide spatially variable delivery of water and fertilizer, and a prototype was installed in a nectarine orchard at the University of California in Davis. Fifty individually addressable microsprinkler nodes, one located at every tree, each contained control circuitry and a valve. Low-cost microcontrollers were programmed to communicate on a wired network laid along each row of the orchard. Latching valves provided a low-energy means of controlling flow to each microsprinkler. Pressure sensors connected to some of the nodes provided lateral line pressure feedback. A small computer board in the field (i.e., drip line controller) stored schedules and issued commands to each node. The nodes and drip line controller were operated on a single battery with solar-powered recharger. The system was programmed to irrigate individual trees for specific durations, to apply a specific volume at each tree, or to irrigate in response to soil water demand. Time-based schedules demonstrated the ability to provide microsprinkler control at individual trees, but exhibited discharge variation due to pressure differences between laterals. Volume-based schedules used pressure sensor feedback to more accurately control the volume applied by individual microsprinklers, and the average error in application volume was less than 4%. The

coefficient of variation for application volume improved from 4.1% for time scheduled control to an average of 2.5% for volume scheduled control. Soil-moisture-based schedules showed how an individual or a group of microsprinkler nodes could be triggered using a soil moisture sensor to irrigate at specific thresholds. Fault detection was used to check for damaged drip lines and clogged or damaged emitters. A pressure monitoring routine automatically logged errors and turned off the microsprinklers when drip line breaks and perforations caused pressure loss. Emitter diagnosis routines correctly identified clogged and damaged microsprinkler emitters in 359 of 366 observations.

The system was effective for spatially variable control but suffered from trouble with wiring connectors, difficulty of installation, and the potential for problems associated with long-range wired communication and damage from animals and machinery. To alleviate these problems we explored the possibility of wireless communication between nodes. A prototype node was developed and results indicate that wireless control could be a feasible alternative to a wired system.

Project Details

The results from this research project are summarized in two manuscripts, which have been submitted to two different journals for publication. The technical details of the microsprinkler system are described in the manuscript "Design of a System for Individual Microsprinkler Control" included in Appendix A, which is under review for Transactions of the ASABE. The results from evaluation of the system are summarized in the manuscript "Control of Individual Microsprinklers and Fault Detection Strategies" included in Appendix B, which has been published in Precision Agriculture (Vol 7, Issue 2, pp. 85-99). Findings from preliminary research on wireless communication are in a conference paper "Wireless Network for Individual Emitter Control in Irrigation" included in Appendix C, which will be presented at the 2006 Agricultural Engineering World Congress in Bonn, Germany.

Project Evaluation

When this project was conceived, we did not anticipate the difficulty of valve selection. There is very little availability of simple, robust, and low cost valves. Since valves are a critical part of this system, commercial efforts to improve valve design are needed. As part of a summer internship in our laboratory, a student researched valve technology and developed an alternative design to those available commercially. Similar efforts by large companies could result in a small, rugged, and inexpensive valve. Spatially variable control of individual trees in an orchard would demand millions of units and this could be a potent driving force for innovation and commercialization.

A concern often expressed by growers and other researchers is that of cost. The per-node cost in this research project was about \$70 since the units were assembled in small quantity. The latching valve was about a quarter of the total node cost. In large quantity, the circuits would be relatively inexpensive and continue to decrease in cost as technology advances. Our rough estimate for the per-node cost of 100,000 units is about \$15, with half for the valve. Less expensive valves and a refined circuit design could reduce cost further. Still, this cost per microsprinkler may not be feasible for orchards, unless substantial savings in water or fertilizer or increased profit can be demonstrated.

However, landscapes, nurseries, and greenhouses could benefit from this system even at \$15 per unit. A single valve for groups of neighboring emitters could be an alternative to individual emitter control, further reducing the expense of a complete system.

The use of wiring for power and communication in this system could be problematic in an orchard environment. Machinery and animals can damage the wires and the installation of nodes can be time consuming. However, this system could be used in nurseries and greenhouses where wiring is less obtrusive. With an extension from FREP, we also conducted preliminary research on the use of wireless communication and determined that this approach is feasible. It will be the subject of future study.

Evaluation of time, volume, and soil moisture based control strategies provided useful information that can be used for precision fertigation. Information on fertilizer movement within the irrigation system can be combined with the ability to control individual microsprinklers to optimize fertilizer delivery. The next step is to implement fertigation trials wherein these strategies can be tested and the effect on orchard performance quantified.

Outreach

Outreach for this project included technical publications, conference presentations, and field demonstrations. Some of the activities were:

February 2004, poster. American Society of Agricultural Engineers (ASAE) CA-NV section meeting, Tulare, California.

May 2004, demonstration. Nickels Field Day, Arbuckle, California.

August 2004, conference paper and presentation. "Precision Irrigation/Fertilization in Orchards," paper no. 042249. 2004 ASAE Annual Meeting, Ottawa, Canada.

September 2004, poster. "Spatially Variable Microsprinkler System." AgEng2004: International Conference on Agricultural Engineering, Leuven, Belgium.

November 2004, progress report and demonstration. "Precision Fertigation in Orchards: Development of a Spatially Variable Microsprinkler System." 12th Annual FREP Conference, Tulare, California.

March 2005, presentation. "Precision Irrigation in Orchards: Development of a Spatially Variable Microsprinkler System." CalGIS conference, Bakersfield, California.

June 2005, M.S. thesis and presentation by Robert W. Coates. "Precision Irrigation in Orchards: Development of a Spatially Variable Microsprinkler System." Biological and Agricultural Engineering, UC Davis, Davis, California.

July 2005, conference paper and presentation. "Precision Irrigation and Fertilization in Orchards," paper no. 052214. 2005 ASAE Annual Meeting, Tampa, Florida.

September 2005, conference paper and presentation. "Precision Irrigation in Orchards: Development of a Spatially Variable Microsprinkler System," paper no. 23. 7th Fruit, Nut and Vegetable Production Engineering Symposium (FRUTIC), Montpellier, France.

November 2005, progress report and demonstration. "Precision Fertigation in Orchards: Development of a Spatially Variable Microsprinkler System." 13th Annual FREP conference, Salinas, California.

February 2006, journal paper. "Design of a System for Individual Microsprinkler Control." Transactions of the ASABE, submitted.

March 2006, journal paper. "Control of Individual Microsprinklers and Fault Detection Strategies." Precision Agriculture 7(2): 85-99.

February 2006, trade newspaper. "Trees and Vines: Profiting from Pinpoint Irrigation." Ag Alert, California Farm Bureau Federation, Feb 22 2006, pp 9-10.

June 2006, presentation. "Wireless valve control network for orchards, landscapes, and nurseries," Wireless Networks and Sensors in Agriculture Symposium, Davis, California.

2004 - 2006, industry contacts. Motorola, Netafim, Agilent, and InTime have expressed interest in the system.

DESIGN OF A SYSTEM FOR INDIVIDUAL MICROSPRINKLER CONTROL

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ABSTRACT. A new microsprinkler system was developed to allow spatially variable delivery of water and fertilizer. A prototype was installed along 50 trees in a nectarine orchard. Individually addressable microsprinkler nodes were located at each tree, and a drip line controller which stored the irrigation schedule and issued commands to each node was installed at one corner of the orchard. Each microsprinkler node included a standard microsprinkler emitter, latching solenoid valve, and control circuit. A master computer allowed remote access to the drip line controller using a wireless modem. Tests were conducted to evaluate power consumption, valve and communication reliability, wireless range, and individual microsprinkler control. A lead-acid battery with solar-charger powered the system for ten continuous days with no decline in average daily voltage. While testing prototype reliability, four communication errors and three valve errors occurred out of 10,250 operations. Wireless communication range between the master computer and drip line controller was 600 m with line-of-sight and 130 m with obstructions. The ability to provide microsprinkler control at the individual tree level was demonstrated by operating the emitters for different durations.

Keywords. *Irrigation, latching valve, microsprinkler, network, orchard, precision agriculture, site specific, spatially variable, variable rate application.*

Our research in pistachio orchards shows that significant variation in yield occurs among sites within an orchard. For example, within a uniformly irrigated and fertilized 32 ha orchard, individual tree yields ranged from 9 to 80 kg (Rosenstock and Brown, 2005). Even within a single row, there is significant yield variability between individual trees. Possible causes of variability include tree stress, soil type, water and nutrient availability, diseases and pests, tree size and age, alternate bearing, and individual tree genetics. Current irrigation systems supply a uniform amount of water and nutrients

31 throughout the orchard. Consequently, actual tree demand is not taken into account and some trees
32 may receive more or less water and fertilizer than needed, resulting in a loss of productivity. By
33 addressing water and nutrient availability at an individual tree level, we believe that yield, nutrient and
34 water use efficiency, and crop value could be increased.

35 Spatially variable irrigation refers to the differential application of water based on variable
36 field conditions. It has been tested in center-pivot and linear-move systems for field crops (Camp et
37 al., 1998; King et al., 1999; King and Kincaid, 2004), but these technologies cannot be cost-effectively
38 applied to microirrigation systems because the number of emitters in microirrigation is much greater.
39 In addition, most systems used high voltage networks, which could be dangerous in an unprotected
40 orchard. Few spatially variable systems have been developed for microirrigation. In a spatially
41 variable microsprinkler system designed for citrus trees, each orchard row had latching solenoid valves
42 controlling water flow to two laterals (Torre-Neto et al., 2000). Each lateral uniformly irrigated a
43 management zone consisting of half the trees (large and small trees) in a given row. A computer
44 communicated with microcontrollers at each row to operate the valves. In another site-specific
45 microirrigation system, microcontrollers responded to soil moisture feedback along individual rows
46 (Rodrigues de Miranda, 2003). In this system, each management zone consisted of one lateral with
47 three plants each. Similar to the system for citrus trees, valves controlled water flow to individual
48 laterals, ignoring variability between individual plants. These systems have an advantage over uniform
49 irrigation because they allow delivery of water and fertilizer based on the demands of a group of plants.
50 Control of multiple zones along a single orchard row would, however, require branching or addition of
51 microirrigation tubing (Torre-Neto et al., 2000). By controlling each individual emitter, no
52 modifications are required. Further, management zones should be as small as possible in order to
53 minimize water and fertilizer waste. Individually controllable valves at each tree could realize this
54 goal and allow management schemes to be altered as individual tree demand and local environmental
55 conditions changed. The presence of intelligent valves throughout the field would also provide a
56 platform for distributed sensing and response. Recently, a citrus study showed that variable rate

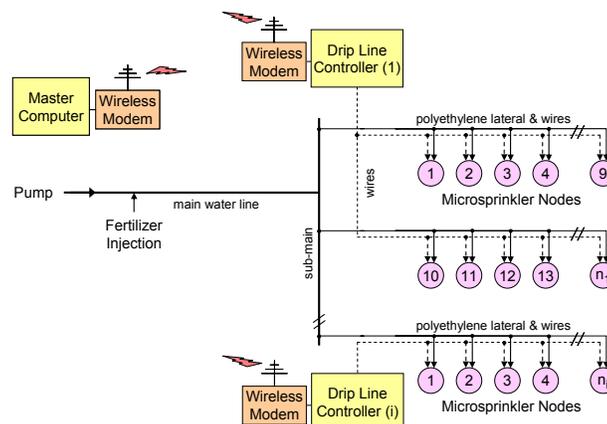
57 application of granular fertilizer based on individual tree size reduced overall nitrogen application by
58 38-40% compared with conventional treatment (Zaman et al., 2005). Similar benefits could be
59 expected from spatially variable application of injected fertilizer through microsprinklers (fertigation).

60 The objectives of this research were to (1) design electronic hardware for individually
61 controllable microsprinklers along a microirrigation line, (2) develop the communication network and
62 software for control of the microsprinkler network by a drip line controller and master computer, and
63 (3) experimentally evaluate the system operation and potential problems caused by operation in the
64 field.

65 MATERIALS & METHODS

66 SYSTEM DESIGN

67 The spatially variable microsprinkler system consisted of four components: the microsprinkler
68 node, drip line controller, communication and power network, and master computer (fig. 1). Each
69 microsprinkler node had a valve to control water discharge, independent of all other nodes in the field.
70 The nodes received water through drip irrigation tubing and were powered through a wired network.
71 The drip line controller stored the irrigation schedule and communicated with the individual
72 microsprinkler nodes and the master computer. Our prototype system used only one drip line
73 controller, but multiple independent controllers are possible.

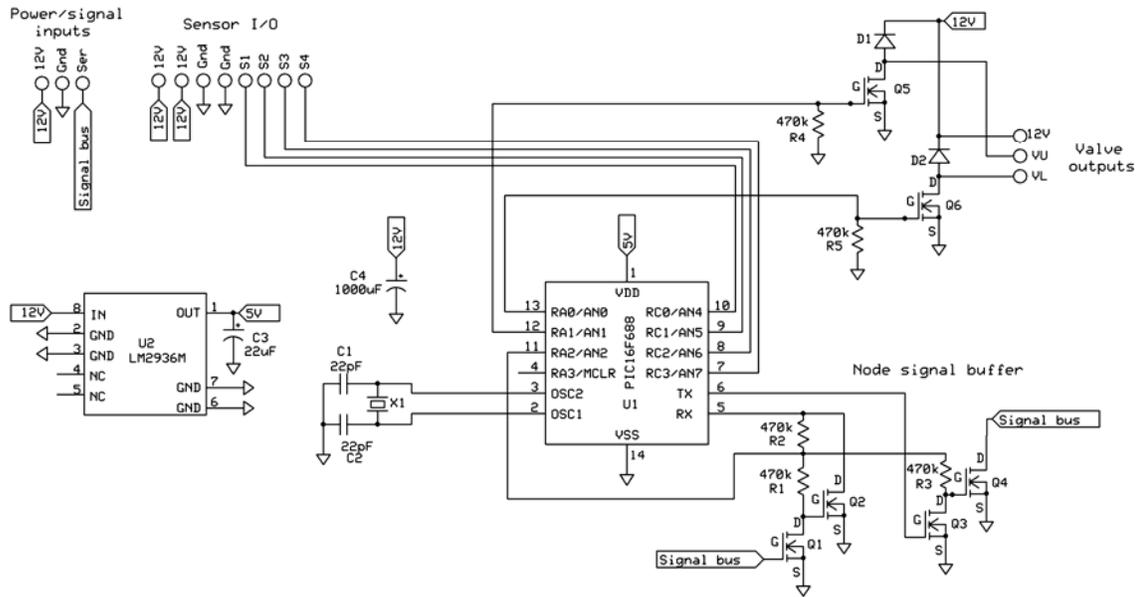


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75 **Figure 1. General layout of the microsprinkler system with drip line controllers 1 to i, microsprinklers nodes 1**
76 **to n_i for each, and a master computer.**

77 ***Microsprinkler node***

78 Each node consisted of an electronic circuit, latching solenoid valve, and orchard microsprinkler.
79 The electronic circuit (fig. 2) was designed with a compact, low power, 8-bit microcontroller
80 (PIC16F688, Microchip Technology, Chandler, Arizona), U1. The operating frequency was set at
81 1.8432 MHz using a crystal oscillator, X1. A linear voltage regulator, U2, converted 12 V from the
82 power/signal network to 5 V for powering the microcontroller. A latching solenoid valve (Series 400
83 #621-411N, Evolutionary Concepts, San Dimas, California) was selected because it required only a
84 brief pulse of current to open or close. The valve inlet was connected to the drip line and a
85 microsprinkler with a 1.0 mm orifice rated for 40 L/h at 172 kPa (Ultra-Jet 6900, Olson Irrigation,
86 Santee, California) was connected to the valve outlet using vinyl distribution tubing (7.2 mm OD).
87 The valve was actuated with a 50 ms, 12 V pulse by low-side switching through n-channel
88 enhancement metal-oxide-semiconductor field-effect transistors (MOSFET). The node had two high-
89 current MOSFETs, Q6 for opening the valve and Q5 for closing it. Pull-down resistors, R4 and R5,
90 prevented the MOSFETs from turning on during microcontroller power-up and initialization. Diodes,
91 D1 and D2, protected the MOSFETs from inductive voltage spikes caused by the solenoid. A boost
92 capacitor, C4, stored energy from the power/signal network to assist with valve actuation. This was
93 required to overcome voltage-drop caused by the network wire resistance.



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Figure 2. The microsprinkler node circuit contained a microcontroller (U1), signal buffer (Q1-Q4), valve switching circuit (Q5-Q6), and boost capacitor (C4).

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The analog-to-digital (A/D) converter on the microcontroller was used to measure signals from external sensors that were connected to the node circuit board through short wires. Drip line water pressure was measured using a pressure transducer powered by a digital output on the microcontroller.

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A granular matrix sensor was used to measure soil moisture. Details of the design and testing are given by Coates (2005).

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Three 14 gauge (AWG) wires (12 V, common, and signal), each 300 m in length, formed the network that interconnected nodes in the prototype system. Valve switching behavior was analyzed to guide selection of a boost capacitor value, C_b (C4 in fig. 2). The system was modeled as a switched RLC network (fig. 3). The 12 V and common wires were modeled as a single resistance, R_w , and the latching valve was modeled as a series resistance, R_v , and inductance, L_v . Wire capacitance and inductance were neglected in the model and computer simulations later verified that their effect on valve behavior was minor.

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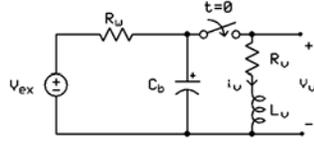
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Figure 3. The network wires, boost capacitor, and latching solenoid valve were modeled as a simple RLC network.

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112 Valve current, i_v , was given by the second-order differential equation,

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$$\frac{d^2 i_v}{dt^2} + \left(\frac{R_v}{L_v} + \frac{1}{R_w C_b} \right) \frac{di_v}{dt} + \left(\frac{1}{C_b L_v} + \frac{R_v}{R_w C_b L_v} \right) i_v = \frac{v_{ex}}{R_w C_b L_v}, \quad (1)$$

114 with C_b charged to an excitation voltage, v_{ex} , for $t < 0$, and $i_v = 0$ and $\frac{di_v}{dt} = \frac{v_{ex}}{L_v}$ at $t = 0^+$. Lab

115 experiments showed that a large C_b would be required, so equation 1 was solved for the under-damped

116 case, giving the current through the valve solenoid,

117
$$i_v(t) = \frac{v_{ex}}{R_w + R_v} + (A_1 \cos \omega_d t + A_2 \sin \omega_d t) e^{-\alpha t}, \quad (2)$$

118 and the voltage across the solenoid,

119
$$v_v(t) = \frac{v_{ex} R_v}{R_w + R_v} + (R_v A_1 + L_v \omega_d A_2 - L_v \alpha A_1) \cos(\omega_d t) e^{-\alpha t}, \quad (3)$$

$$+ (R_v A_2 - L_v A_1 \omega_d - L_v \alpha A_2) \sin(\omega_d t) e^{-\alpha t}$$

120 where

121
$$\omega_d = \sqrt{\omega_n^2 - \alpha^2}, \quad (4)$$

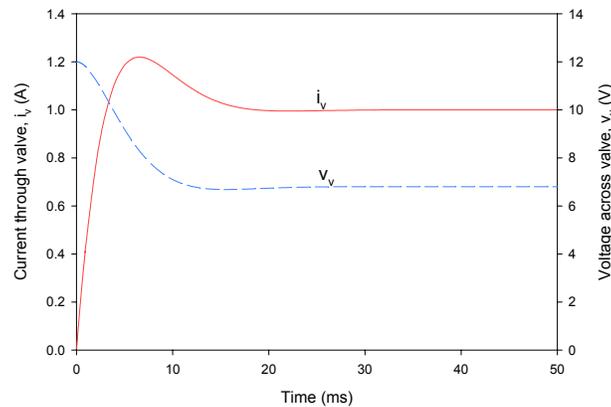
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$$\omega_n = \sqrt{\frac{1}{C_b L_v} + \frac{R_v}{R_w C_b L_v}}, \quad (5)$$

123
$$A_1 = -\frac{v_{ex}}{R_w + R_v}, \quad (6)$$

124
$$A_2 = \frac{v_{ex} - \frac{v_{ex} L_v \alpha}{R_w + R_v}}{L_v \omega_d}, \text{ and} \quad (7)$$

$$\alpha = \frac{\left(\frac{R_v}{L_v} + \frac{1}{R_w C_b}\right)}{2} \quad (8)$$

126 R_v was measured with a digital multimeter and L_v was experimentally determined by observing the
 127 transient response to a 12 V step input. Equations 2 and 3 were plotted as a function of time (fig. 4) for
 128 $v_{ex} = 12$ V, $C_b = 0.001$ F, $R_w = 5.2 \Omega$ (14-gauge, 12 V and common wires each 300 m), $R_v = 6.8 \Omega$, and
 129 $L_v = 0.023$ H. The results showed that the peak current through the valve was about 1.2 A and the
 130 voltage across the valve dropped to about 6.8 V. Peak current was determined for values of C_b ranging
 131 from 0.0001 to 0.05 F (fig. 5). From the eigenvalues, the system was over-damped for $C_b > 0.0032$ F
 132 (solution not shown). As capacitance increased, the peak current approached that obtained from valve
 133 operation with $R_w = 0$ ($i_v = v_{ex}/R_v = 1.76$ A). In laboratory experiments, 0.00067 F was the smallest
 134 capacitor that would allow valve operation over the network wires. In order to reduce physical size
 135 and expense, a 0.001 F boost capacitor was chosen for the final design.



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 137 **Figure 4. The current (i_v) through and voltage (v_v) across the valve during switching, predicted from equation 1.**

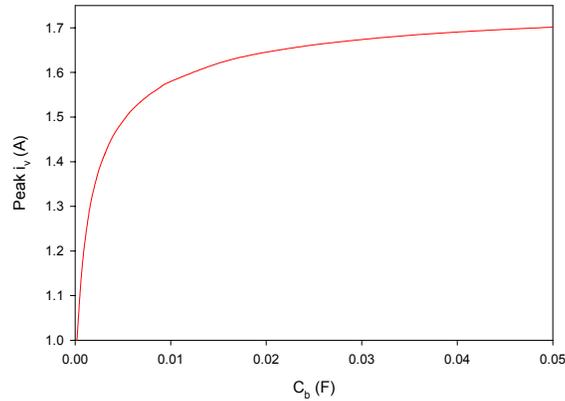


Figure 5. Peak current through the valve for boost capacitors between 0.0001 and 0.05 F.

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The communications hardware was designed to operate over a single signal wire (referenced to the common wire). By developing our own hardware and protocol, we avoided the time and expense of implementing commercial networking standards (e.g., CAN, AS-i, X-10). This also simplified the installation process since insulation displacement connectors were used to tap the signal line, instead of cutting the wires at each node as required by networks using twisted pair cable. The microcontroller used a built-in serial communications interface (SCI) configured for half-duplex, asynchronous communication at 600 baud. The transmit pin of the microcontroller, which was high (5 V) when idle, could not be connected directly to the network signal bus because it would be unable to pull the line low (0 V) for communication if all other nodes on the same bus were driving the line high. Therefore, it was desired to have the transmit pin connected to the bus when transmitting and isolated when idle. This was accomplished by connecting the SCI of each node through a signal buffer composed of four n-channel enhancement MOSFETs, Q1-Q4. The signal bus was connected to the gate of Q1 for receiving and the open drain of Q4 for transmitting. A 2.2 k Ω pull-up resistor at the drip line controller held the bus voltage high when units were not transmitting. The signal buffer also solved a problem caused by the input impedance of the SCI receiver. With 200 receivers connected directly to the signal bus, each having an input impedance of approximately 380 k Ω , the parallel impedance would be 1.9 k Ω . This would create a voltage divider with the signal pull-up resistor and the idle bus voltage would be only 2.3 V, which is an indeterminate logic level. Using the signal buffers in which the MOSFETs

158 were assumed to have input resistances of 200 MΩ, the idle signal voltage would be 4.99 V with 200
159 nodes connected.

160 The finished circuit boards were mounted in polycarbonate enclosures (NEMA 4X) with sealed
161 ports for the signal, valve, and sensor wires, which were soldered directly to the circuit board. The
162 other ends of the signal wires were fitted with male disconnects and plugged into female taps on the
163 power/signal network. A completed node is shown in figure 6.

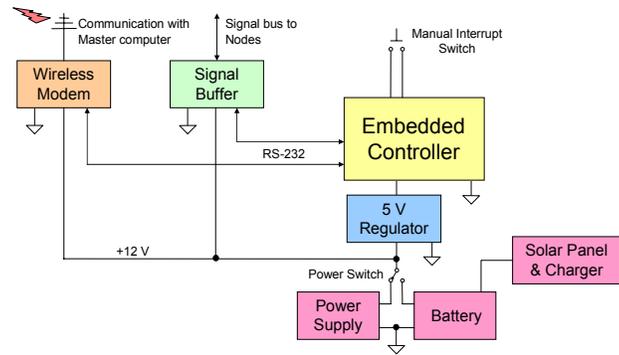


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165 **Figure 6. Microsprinkler node with circuit connected to power/signal network, and valve and microsprinkler**
166 **connected to drip line.**

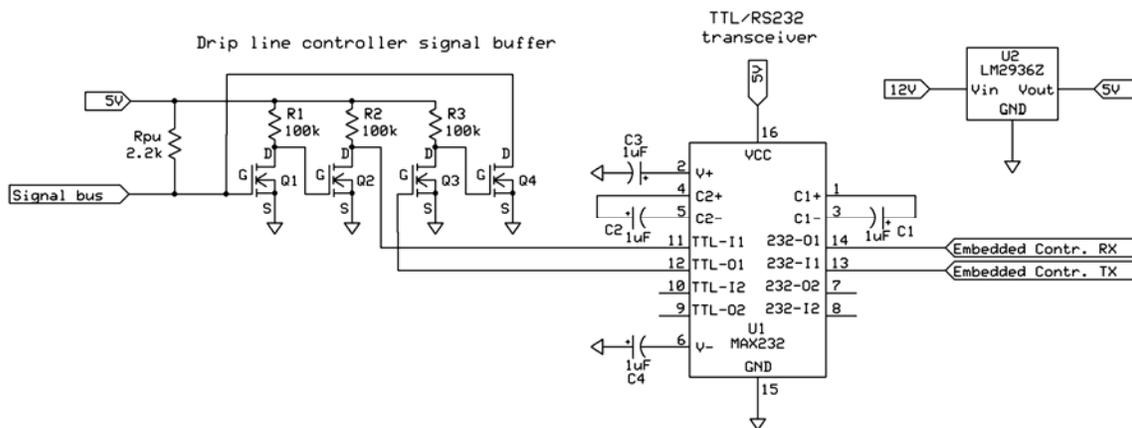
167 *Drip line controller*

168 The drip line controller consisted of an embedded controller (TD40, Tern, Davis, California),
169 signal buffer, multiple power sources, and wireless modem (fig. 7). The embedded controller stored
170 and executed an irrigation schedule and retrieved sensor data from the microsprinkler nodes. A liquid-
171 crystal display provided visual feedback during testing and a keypad allowed manual control of the
172 system. A 900 MHz wireless modem (9XStream-PKG-R, Maxstream, Orem, Utah) was connected to
173 one of the serial ports on the embedded controller, allowing remote access from the master computer.
174 The modem communicated with the embedded controller at 9,600 baud and with the master computer
175 modem over the air at 9,600 baud. The second serial port of the embedded controller was connected to

176 the signal bus through an RS-232 level transceiver, U1, and a signal buffer, Q1-Q4 (fig. 8). A 2.2 k Ω
 177 pull-up resistor, R_{pu}, held the idle bus at 5 V.



178
 179 **Figure 7. The drip line controller consisted of an embedded controller, power supplies with solar charger,**
 180 **voltage regulator, signal buffer, and wireless modem.**



181
 182 **Figure 8. The drip line controller had an RS-232 transceiver (U1), voltage regulator (U2), and signal buffer (Q1-**
 183 **Q4) with pull-up resistor (R_{pu}).**

184 The nodes and drip line controller were powered by a 12 V, 35 Ah lead-acid battery connected to
 185 a solar-panel charger. A 12 V switching power supply was also installed on the drip line controller for
 186 use when AC power was available. A high-efficiency switching regulator (LM2675, National
 187 Semiconductor, Santa Clara, California) supplied 5 V to the embedded controller. The drip line
 188 controller and network of 50 microsprinkler nodes consumed 201 mA while executing tasks and 45
 189 mA while in power-save mode. Assuming that the system was executing tasks for one hour per day
 190 and in power-save mode otherwise, 1.2 Ah/day at 12 V would be required to operate the system. The

191 average solar insolation in Davis, California gives the equivalent of 6.1 hours of full sunlight per day
192 during summer and 3.3 hr/day during winter. A 10 W solar charging system rated for 0.59 A output
193 would thus provide 3.1 Ah/day during summer and 1.7 Ah/day during winter (including a 15%
194 derating for cable and charge controller losses), which is sufficient for year-round operation of our
195 prototype.

196 Normal schedule execution could be interrupted remotely from the master computer or in the
197 field at the drip line controller. Transmitting a signal from the master computer to the embedded
198 controller caused a serial port interrupt, allowing remote operation. The user could also press a push-
199 button switch connected to an external interrupt line on the embedded controller and then enter
200 commands from the keypad.

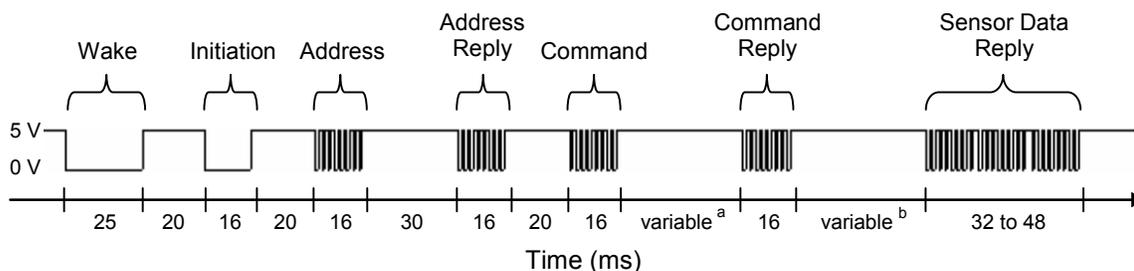
201 *Master computer*

202 The master computer was a laptop computer that provided an interface for the user to store
203 irrigation schedules, monitor system status, retrieve sensor data, and manually control the network. A
204 12 V, 1.2 Ah lead-acid battery powered the wireless modem connected to the laptop serial port. The
205 master computer used a terminal program to remotely interface with the drip line controller. To initiate
206 a session, the user simply opened a connection and pressed any key. This caused the drip line
207 controller to enter master-mode, and a text based menu of options was transmitted to the master
208 computer. The user could then select an option and follow the on-screen prompts.

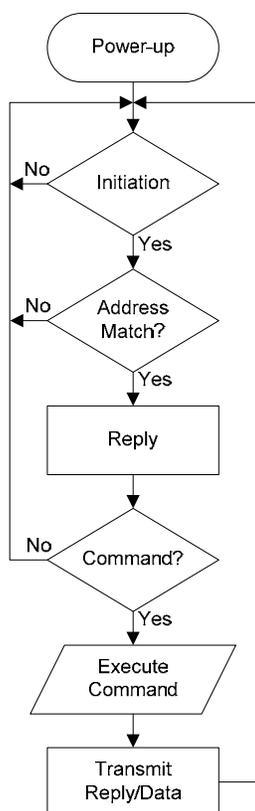
209 *Node software and communication protocol*

210 The node microcontrollers were programmed in assembly language using the manufacturer's
211 development environment and chip programmer (MPLAB IDE v7.10 and PICSTART PLUS,
212 Microchip Technology, Chandler, Arizona). Each chip was individually programmed with one of 254
213 unique addresses between 01_{hex} and FE_{hex} . Zero was reserved for communication initiation and FF_{hex}
214 was a broadcasting address. More addresses could be made available by using multiple address bytes.

215 Using standard non-return-to-zero encoding, each byte was preceded by a start bit and followed
 216 by a stop bit. A logic-1 bit was represented by a high signal (5 V) and a logic-0 by a low signal (0 V).
 217 A master-slave protocol was developed in which the drip line controller initiated all communication
 218 with the microsprinkler nodes. The protocol included a wake signal, initiation byte, address byte, and
 219 command byte transmitted by the drip line controller, with replies transmitted by the addressed node.
 220 Figure 9 shows the communication timing diagram and figure 10 shows the basic program execution
 221 followed by each node. To begin communication, the drip line controller transmitted a wake signal by
 222 holding the signal bus low for 25 ms, allowing time for the nodes to exit sleep mode. Next, the
 223 initiation byte (00_{hex}) told the nodes that an address and command would follow. The address was
 224 received by all nodes connected to the network, but only the node with the matching address
 225 responded, sending a confirmation reply. After the correct address reply, the command was
 226 transmitted by the drip line controller. The command could be to open or close the valve, measure
 227 input from an external sensor, or run a fault diagnosis. The node executed the command and then
 228 replied. In the case of sensor measurement or fault diagnosis, the resulting data were transmitted by
 229 the node after the command reply. If the drip line controller transmitted the broadcasting address
 230 (FF_{hex}) instead of a single node address, all nodes listened and executed the subsequent command, but
 231 did not reply, since this would have caused a signal bus conflict.



232
 233 **Figure 9. Signal voltage during communication between drip line controller and node using non-return-to-zero**
 234 **encoding. Depending on the command, delays between node replies varied (^a31 to 80 ms, ^b30 to 2930 ms).**



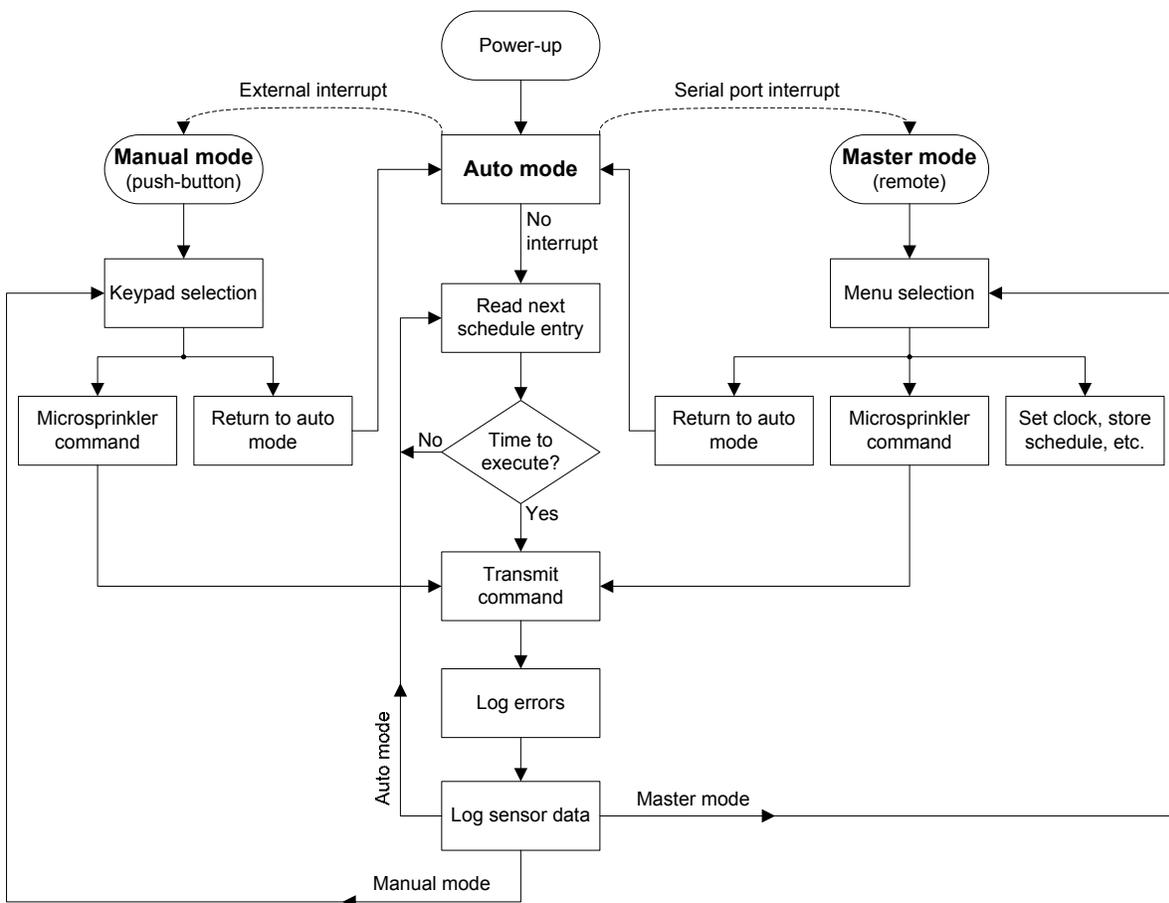
235

236 **Figure 10. The node microcontroller program checked for an initiation byte, address, and command, and then**
 237 **replied to the drip line controller after address reception and execution of the command.**

238 ***Drip line controller software and operational modes***

239 The embedded controller was programmed in C++ (Paradigm C++ Lite: Tern Edition, Tern,
 240 Davis, California) and operated in one of three modes: auto, master, or manual (fig. 11). On power-up,
 241 the controller entered auto mode and the irrigation schedule stored in memory was executed. Each
 242 schedule entry contained a node address, execution time, and command. The command in each entry
 243 was transmitted to the appropriate node at the scheduled time. Errors that occurred during
 244 communication, pressure monitoring, or fault detection were recorded in an error log. Data transmitted
 245 by the nodes were stored in data logs. The user could suspend auto-mode with the master computer or
 246 push-button switch and execute other operations such as storing a new schedule, setting the internal

247 clock, manually sending commands to a specific microsprinkler node, downloading sensor data, or
 248 reading the error log.



249
 250 **Figure 11. The drip line controller executed irrigation schedules in auto mode, keypad selections in manual**
 251 **mode, or menu selections in master mode.**

252 **SYSTEM EVALUATION**

253 Various tests were conducted on the prototype system to evaluate its operation and identify
 254 potential problems. Fifty microsprinkler nodes were installed along four rows in a research orchard of
 255 nectarines at the University of California, Davis. Polyethylene drip tubing (17 mm OD) delivered
 256 water to the microsprinklers in each row. The drip line controller was installed at one corner of the
 257 orchard and the power/signal network interconnected it with the microsprinkler nodes. The network

258 wires were laid alongside the laterals in each row, buried between rows, and the excess length
259 remained on a spool.

260 ***Power consumption***

261 The power consumption test was used to evaluate the ability of the solar panel charging system to
262 maintain the battery. Battery voltage was monitored with a datalogger (21X, Campbell Scientific,
263 Logan, Utah) during 10 days of operation in August. A simple irrigation schedule was created in
264 which the drip line controller and microsprinkler nodes were awakened between 11 AM and noon and
265 then returned to power-save mode on each day of operation. Voltage was plotted over time to
266 determine if the battery maintained charge during operation.

267 ***Reliability***

268 Valve and communication reliability were tested by cycling each of the 50 microsprinkler valves
269 open and closed 205 times. Commands were issued to each node by the drip line controller and water
270 flow at each microsprinkler was visually monitored to check that valves opened and closed properly.
271 The drip line controller display was monitored for communication errors.

272 ***Wireless range***

273 The maximum range of the wireless link was measured for line-of-sight conditions and with
274 orchard obstructions. In this report, line-of-sight refers to *visual* line-of-sight, as opposed to *RF* line-
275 of-sight in which the Fresnel zone between antennas is completely clear of obstructions, including the
276 ground. The drip line controller was placed on the ground with the wireless modem antenna inside the
277 enclosure, 75 mm above soil level. The second wireless modem, connected to the master computer,
278 was carried on the outside of a backpack, about 1.5 m above soil level. The modems were
279 programmed for five transmission retries, meaning data not received by the other modem were
280 retransmitted up to five times to reduce the number of lost data packets. While operating in master
281 mode, the drip line controller was sent requests for the current time and it was noted whether a

282 complete reply, partial reply, or no reply was received. The latter two cases indicated that data were
283 lost during transmission. The line-of-sight range was determined by walking with the master computer
284 and wireless modem across a level road. There were no obstructions within a 15 m wide corridor
285 between the computer and drip line controller. The distance at which no transmission errors occurred
286 was considered to be the maximum line-of-sight range. The maximum range in an orchard was
287 determined by placing the drip line controller at the corner of a walnut grove. The trees were about 6
288 m tall with moderate foliage. The master computer was carried through the orchard in a diagonal
289 direction. The distance at which no transmission errors occurred was considered to be the maximum
290 range with orchard obstructions.

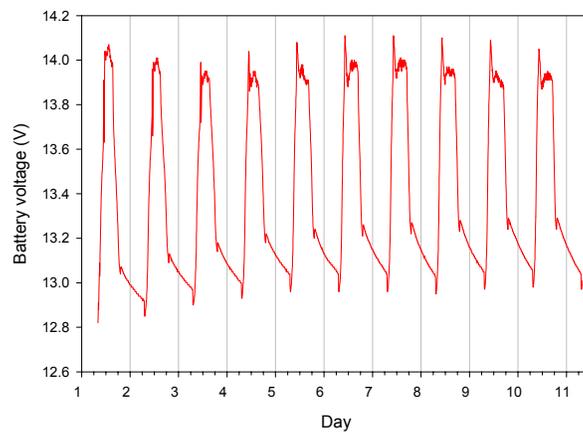
291 *Variable irrigation*

292 Three different control strategies were used in auto-mode on the drip line controller: time-
293 scheduled, volume-scheduled, and soil-moisture-scheduled irrigation (Coates, 2005). To demonstrate
294 the functionality of the system, only time-scheduled irrigation is presented here. The time-scheduled
295 field test showed how each microsprinkler was independently controllable and could run for different
296 durations. An irrigation schedule was written so that each microsprinkler would discharge water for a
297 different duration, applying a linear gradient of water across the orchard. Each day, the
298 microsprinklers were sequentially turned on every 35 seconds and then all were turned off after 30
299 minutes. Thus, the first microsprinkler ran 30 minutes and the last ran 85 seconds. The system was
300 operated continuously for four days. Water was collected from 25 of the microsprinklers each day and
301 the volume was plotted against field position to assess linearity.

302 **RESULTS & DISCUSSION**

303 **POWER CONSUMPTION**

304 The starting battery voltage was about 12.8 V (fig. 12). During daytime, the solar panel charged
305 the battery using a 14.1 V setpoint, shown by the voltage peaks each day. Daily sunrise and sunset
306 were at about 6:30 AM and 7:50 PM. The battery voltage decreased from 11 AM until noon since the
307 nodes and drip line controller were awake and drawing greater current. Charging stopped at about 4
308 PM, even though substantial sunlight was available, likely because the battery had reached full
309 capacity. After charging had finished, the battery voltage dropped to a resting value of about 13.2 V.
310 At night, the voltage declined as the battery discharged to power the system, but never fell below the
311 starting level. This showed that the solar panel charging system could supply sufficient energy for
312 summer operation.



313
314 **Figure 12. Battery voltage was recorded during 10 days of system operation in the orchard.**

315 **RELIABILITY**

316 Of 10,250 total valve cycles performed, there were seven errors. Four errors occurred during the
317 first four cycles at a single microsprinkler node due to a loose electrical connector on the
318 communication wire. The problem was fixed by re-crimping the connector and the node operated

319 correctly for the remainder of the test. Loose connectors were a recurring problem in this prototype
320 system and must be improved in future designs. The remaining three errors occurred at a different
321 microsprinkler node when a valve jammed in the open position, possibly due to debris. The valve was
322 tapped several times until it began operating properly. During several months of testing there were
323 only a few cases when the valves became jammed. Methods to detect clogging and damage at each
324 node are presented by Coates et al. (2006).

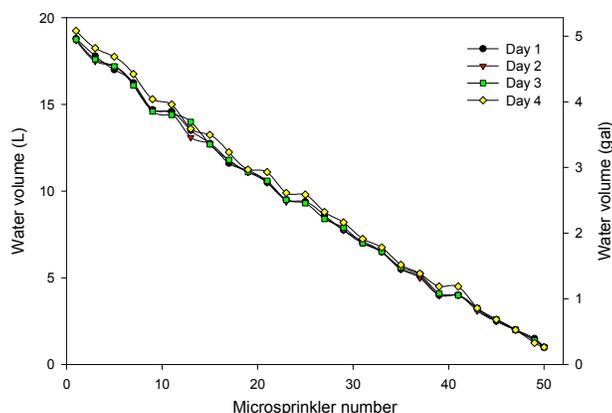
325 **WIRELESS RANGE**

326 The line-of-sight test yielded a maximum wireless range of 600 m. If the user's body was
327 between the two antennas, the range decreased. There was no specification for *visual* line-of-sight
328 range, but the rated range for these modems under *RF* line-of-sight conditions was 11 km. The
329 maximum range with orchard obstructions was approximately 130 m. The rated range in an
330 "indoor/urban" environment was 450 m, but the density and composition of obstructions in the orchard
331 probably caused greater interference than that found in an "indoor/urban" test environment. Improved
332 antenna position or higher gain would increase the maximum range under both conditions. The
333 wireless modem of the drip line controller had its antenna mounted inside the enclosure, but the
334 exterior of the enclosure would have been a better location.

335 **VARIABLE IRRIGATION**

336 Since the microsprinkler nodes were programmed to turn on sequentially, water was applied in
337 a linear gradient across the field (fig. 13). Each microsprinkler applied a consistent volume of water
338 each day, though slightly more water was applied on day 4 because the system water pressure
339 increased due to other irrigation blocks being shut off. Also, the data exhibited a slight curve because
340 of a higher water pressure at the two outside orchard rows. In spite of these effects, the results clearly
341 showed that the spatially variable system worked on the individual microsprinkler level and performed
342 consistently from day to day. However, changes in water pressure substantially affected

343 microsprinkler discharge, as evident by the day 4 readings and data curvature. Volume-scheduled and
344 soil-moisture-scheduled irrigation addressed this problem (Coates et al., 2006).



345

346 **Figure 13. Water volume versus microsprinkler position over four days, with the time of actuation a linear**
347 **function of microsprinkler position.**

348 CONCLUSIONS

349 A spatially variable irrigation system was developed, consisting of 50 microsprinkler nodes
350 controlled by a drip line controller and master computer. It was designed using simple components so
351 that, if manufactured on a large scale, nodes would be inexpensive. A prototype system was installed
352 and tested in a nectarine orchard. Power consumption tests showed that the system could be operated
353 from a solar-recharged battery, eliminating the need for external power. To operate hundreds or
354 thousands of nodes in a large orchard, further reduction in power consumption would be required to
355 prevent the solar panel and battery from becoming too large. Errors during the reliability test were due
356 to faulty connectors and a jammed valve, and both were easily fixed during the test. An improved
357 means of connection may be to use the cable-piercing connectors similar to those in landscape lighting.
358 Valve reliability should be improved and a method of detecting valve malfunction should be
359 developed. Wireless modem range was adequate for proof-of-concept tests, but a greater range would
360 be required for use in large commercial orchards. This could be achieved using higher gain antennas
361 and overhead mounting. Finally, time-scheduled irrigation showed that precision application of water

362 through individual microsprinklers was possible. Irrigation management can be further optimized by
363 using the distributed node intelligence to monitor system status (e.g., pressure, soil moisture), detect
364 emitter clogging, and improve irrigation and fertigation precision (Coates et al., 2006).

365 **ACKNOWLEDGEMENTS**

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368 **REFERENCES**

- 369 Camp, C.R., E.J. Sadler, D.E. Evans, L.J. Usrey, and M. Omary. 1998. Modified center pivot system
370 for precision management of water and nutrients. *Applied Engineering in Agriculture*, 14(1):
371 23-31.
- 372 Coates, R.W. 2005. Precision irrigation in orchards: Development of a spatially variable
373 microsprinkler system. MS thesis. Davis, California: University of California, Davis,
374 Department of Biological and Agricultural Engineering.
- 375 Coates, R.W., M.J. Delwiche, P.H. Brown. 2006. Control of individual microsprinklers and fault
376 detection strategies. *Precision Agriculture*, in press.
- 377 King, B.A., I.R. McCann, C.V. Eberlein, and J.C. Stark. 1999. Computer control system for spatially
378 varied water and chemical application studies with continuous-move irrigation systems.
379 *Computers and Electronics in Agriculture*, 24(3): 177-194.
- 380 King, B.A., and D.C. Kincaid. 2004. A variable flow rate sprinkler for site-specific irrigation
381 management. *Applied Engineering in Agriculture*, 20(6): 765-770.
- 382 Rodrigues de Miranda, F. 2003. A site-specific irrigation control system. ASAE Paper No. 031129.
383 St. Joseph, Michigan.

- 384 Rosenstock, T., and P. Brown. 2005. Integration of precision agriculture and systems modeling in
385 pistachio. Abstract. HortScience, 40(4): 1141-1142.
- 386 Torre-Neto, A., J.K. Schueller, and D.Z. Haman. 2000. Networked sensing and valve actuation for
387 spatially-variable microsprinkler irrigation. ASAE Paper No. 001158. St. Joseph, Michigan.
- 388 Zaman, Q.U., A.W. Schumann, and W.M. Miller. 2005. Variable rate nitrogen application in Florida
389 citrus based on ultrasonically-sensed tree size. Applied Engineering in Agriculture 21(3), 331-
390 335.

Control of individual microsprinklers and fault detection strategies

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Abstract Based on yield variability in orchards, it is evident that many trees receive too much or too little water and fertilizer under uniform management. Optimizing water and nutrient management based on the demand of individual trees could result in improved yield and environmental quality. A microsprinkler sensor and control system was developed to provide spatially variable delivery of water and fertilizer, and a prototype was installed in a nectarine orchard. Fifty individually addressable microsprinkler nodes, one located at every tree, each contained control circuitry and a valve. A drip line controller stored the irrigation schedule and issued commands to each node. Pressure sensors connected to some of the nodes provided lateral line pressure feedback. The system was programmed to irrigate individual trees for specific durations or to apply a specific volume of water at each tree. Time scheduled irrigation demonstrated the ability to provide microsprinkler control at individual trees, but also showed variation in discharge because of pressure differences between laterals. Volume scheduled irrigation used water pressure feedback to control the volume applied by individual microsprinklers more precisely, and the average error in application volume was 3.7%. Fault detection was used to check for damaged drip lines and clogged or damaged emitters. A pressure monitoring routine automatically logged errors and turned off the microsprinklers when drip line breaks and perforations caused pressure loss. Emitter diagnosis routines correctly identified clogged and damaged microsprinkler emitters in 359 of 366 observations. Irrigation control at the individual tree level has many useful features and should be explored further to characterize fully the benefits or disadvantages for orchard management.

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Introduction

Variability of yield within orchards is due to many factors such as tree stress, soil type, topography, water and nutrient availability, diseases and pests, tree size and age, alternate bearing, and individual tree genetics. This variability has been quantified using remote sensing (e.g., normalized difference vegetation index), soil sampling, yield monitoring, and growth measurements. Our research in pistachio orchards has also shown that there is substantial variability between individual trees. For example, within a single row, the average yield per tree was 28 kg and individual yield ranged from 1.6 to 56 kg (Fig. 1). Uniform management of the entire orchard results in some trees receiving more or less water and fertilizer than required. Therefore, it is desirable to match water and nutrient application to the needs of each tree to maximize production and minimize water and fertilizer waste.

Most orchards planted within the past 15 years use microirrigation for both water and nutrient delivery, and many older orchards that currently use flood or sprinkler irrigation are being converted to microsprinklers to reduce costs and increase efficiency. Although there has been substantial interest in site-specific management, research on spatially variable microirrigation systems has been limited. In one reported development, latching solenoid valves controlled two laterals per row in a citrus orchard (Torre-Neto, Schueller, & Haman, 2000). Each lateral uniformly irrigated half the trees in the row, which were grouped based on size (large and small trees). In another development, microcontrollers

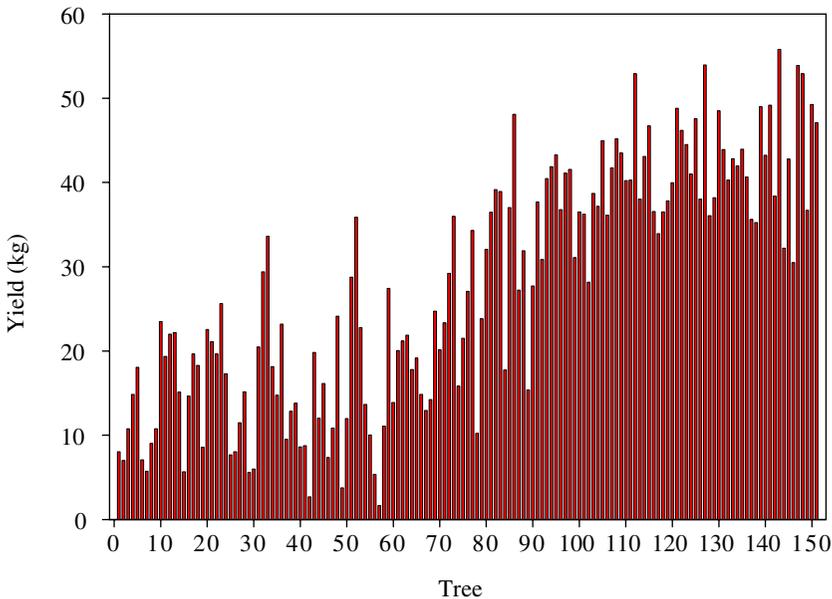


Fig. 1 The yield of individual pistachio trees along a single orchard row

responded to soil moisture feedback by controlling water flow to individual laterals, but neglected variation between individual plants (Rodrigues de Miranda, 2003). Individually controllable valves at each tree along a single drip line could maximize the benefit of spatially variable control and allow management strategies to be altered as conditions change.

Using pressure or flow sensors, water and dissolved fertilizer applications at each microsprinkler could be monitored and controlled. Feedback from these sensors could also be used to develop a method for detection of lateral line damage caused by insects, rodents, and machinery, and emitter clogging caused by insects, biological matter, and chemical precipitates. These ideas were presented in a patent for an irrigation system that would “automatically distribute a pre-established quantity of water to an agricultural area” and “diagnose breaks in the water distributing apparatus” using flow meters, pressure sensors, and valves (Barash et al., 1980). A research study also showed that pressure sensors located at each lateral could be used to detect line damage or partial clogging of 5% of the drip emitters on a single lateral (Povoa & Hills, 1994). Similar to these prior systems, some modern commercial systems use flow meters to monitor water delivery and detect unusual flow, but not at the individual emitter level.

Reduced environmental damage and increased profitability are documented benefits of spatially variable irrigation and fertilizer application. Matching nitrogen delivery with plant needs has increased the efficiency of fertilizer use and net returns in some field crops (Beckie, Moulin, & Pennock, 1997) and reduced nitrate leaching in potato crop simulations (Verhagen, 1997). Spatially variable management has been shown to increase profits from corn (Koch, Khosla, Frasier, Westfall, & Inman, 2004; Wang, Prato, Qiu, Kitchen, & Sudduth, 2003) and improve yield in potatoes (King, Reeder, Wall, & Stark, 2002) and grain sorghum (Yang, Everitt, Bradford, 2001). Variable rate application of granular fertilizer based on individual tree size in a citrus study reduced overall nitrogen application by 38–40% compared with conventional treatment (Zaman, Schumann, Miller, 2005). Spatially variable fertigation might have similar advantages. In a pistachio study, rates of potassium fertilizer applications appeared to correlate with nut yield and quality (Zeng, Brown, & Holtz, 2001), so it might be beneficial to match potassium application with tree demands more locally. No studies have yet determined the overall effect of irrigation and fertilizer management based on individual tree demands.

The aim of the work presented here was to create a tool to enable control of irrigation emitters at individual trees and to explore application control and fault detection strategies. The objectives in this research were to: (1) design electronic hardware for individually controllable microsprinklers, (2) evaluate control strategies for precise water application, and (3) develop methods for automated fault detection.

Materials and methods

System design

The spatially variable microsprinkler system (Fig. 2) consisted of four components: the microsprinkler node, drip line controller, communication and power network, and master computer (Coates, 2005). Each microsprinkler node used a valve to control water application independent of all other nodes in the field. The nodes received water through drip irrigation tubing and were powered through a wired network. The drip line controller

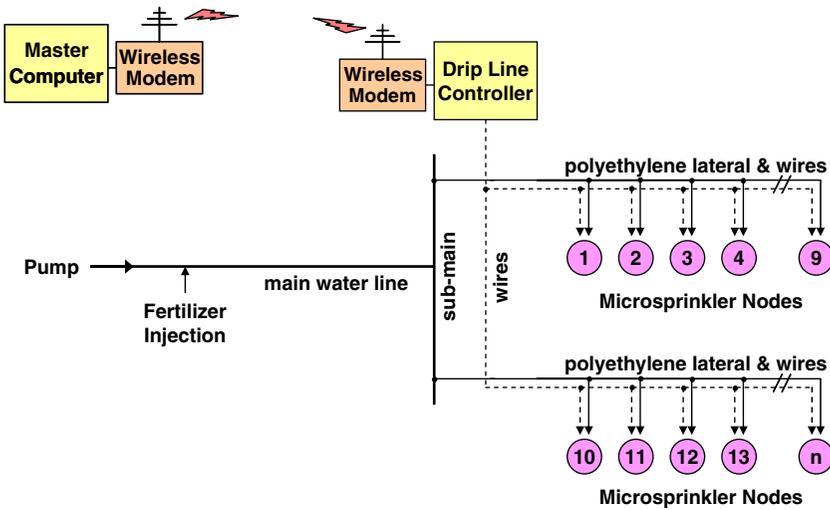


Fig. 2 Layout of the microsprinkler system, with networked microsprinkler nodes, drip line controller, and master computer

stored the irrigation schedule and communicated with the individual microsprinkler nodes and master computer.

Each microsprinkler node consisted of a control circuit, latching solenoid valve, and orchard microsprinkler (Fig. 3). The control circuit used a compact, low-power microcontroller to operate the valve, communicate on the network, and interface with sensors. Each chip was individually programmed with a unique address. A latching solenoid valve was selected because it required only a brief pulse of energy to open or close. The valve inlet had a barbed fitting for connection to the drip line and the valve outlet was connected to a microsprinkler with a nominal discharge of 40 l h^{-1} at 172 kPa (Ultra-Jet 6900, 1.0 mm blue orifice, Olson Irrigation, Santee, California). The analog-to-digital converter on the microcontroller was used to sample signals from external sensors including a pressure transducer (MPX5700DP, Freescale Semiconductor, Austin, Texas) and granular matrix soil moisture sensor (Watermark 200SS, Irrrometer Company, Riverside, California). The circuit boards were housed in polycarbonate watertight enclosures with sealed ports for the network, valve, and sensor wires.

The drip line controller consisted of an embedded controller, signal buffer, battery, and wireless modem. A liquid-crystal display provided visual feedback during testing and a keypad allowed manual control of the system. The embedded controller stored and executed the irrigation schedule and retrieved sensor data from microsprinkler nodes. The drip line controller communicated with the network of microsprinkler nodes through 14 gauge (AWG) wire and could be accessed remotely by the master computer through a wireless link. The signal buffer translated RS-232 and logic-level signals between the embedded controller and nodes. The system was powered by a 12 V lead-acid battery that was recharged with a solar panel. The drip line controller initiated all communication with the microsprinkler nodes using a simple master-slave protocol. Each schedule entry in the drip line controller contained a node address, execution time, and command. The command in each entry was transmitted to the appropriate node at the scheduled time. Errors that occurred during communication, node command

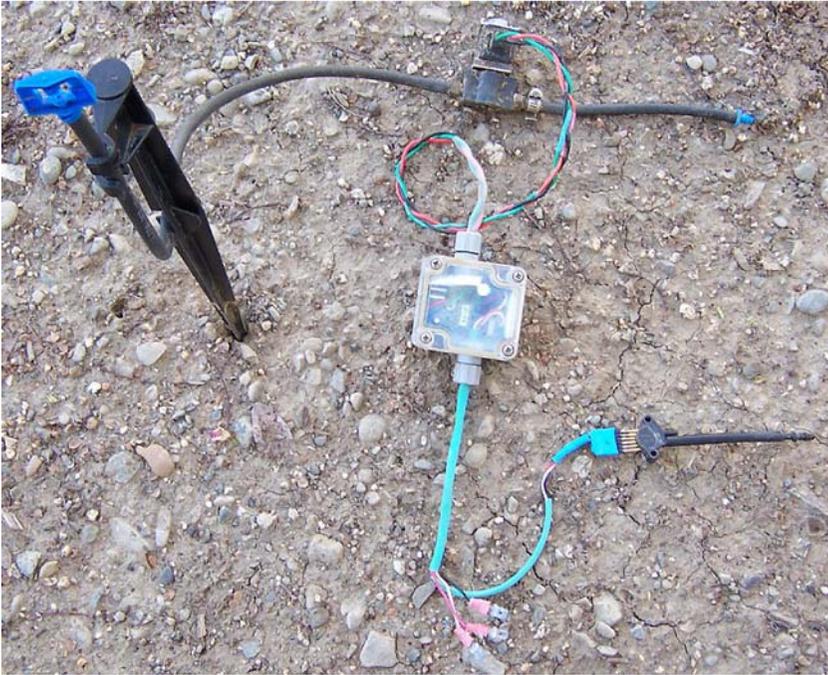


Fig. 3 Microsprinkler node with control circuit, latching valve, orchard microsprinkler, and pressure sensor

execution, or fault detection were recorded in an error log. Normal schedule execution was suspended when the user transmitted commands from the master computer or entered them using the keypad.

The master computer was a laptop computer able to communicate remotely with the drip line controller by wireless modem. It provided an interface for the user to store irrigation schedules, set the internal clock, send commands manually to individual nodes, retrieve sensor data, and read the error log. A terminal program allowed the user to select options from a text-based menu transmitted by the drip line controller.

Installation

Fifty microsprinkler nodes were installed along four rows in a nectarine (*Prunus persica* var. *nucipersica* cv. Fantasia) orchard at the University of California, Davis (Fig. 4). Polyethylene drip tubing (17 mm) delivered water to the microsprinklers in each row. The drip line controller was installed at one corner of the orchard and 300 m of network wire (power and signal) connected it with the microsprinkler nodes. The wire was laid alongside the laterals and buried between rows. The remaining wire was left on a spool to verify operation of the network through the entire length.

Flow characteristics

Emitter uniformity was analyzed using 25 new microsprinkler emitters (Coates, 2005). The average emitter flow rate at 172 kPa was 39.4 l h^{-1} with a coefficient of variation of 0.5%. The relationship between flow and pressure was fairly linear over the range of operating

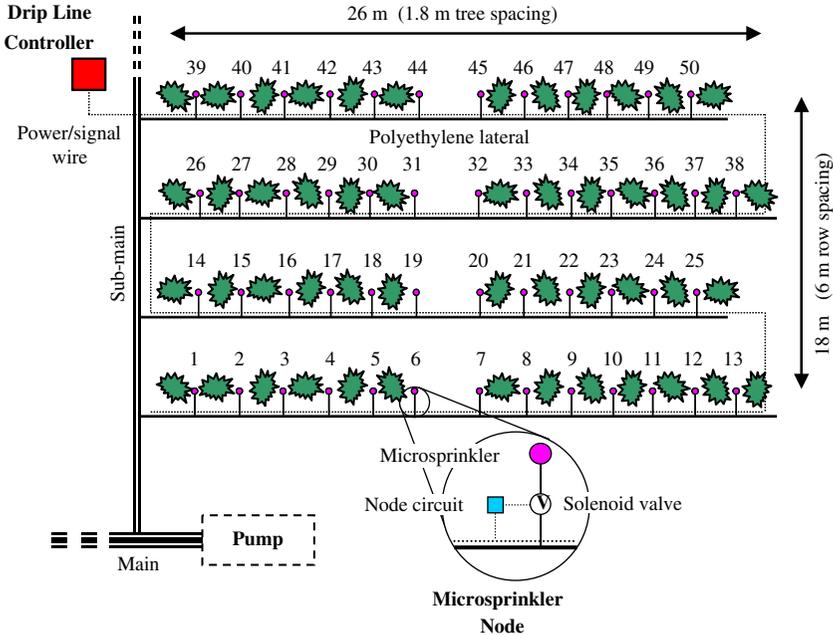


Fig. 4 The 50-node prototype system was installed along four rows in a nectarine orchard

pressures (138–207 kPa), so a linear calibration equation was determined for four units in the orchard operating at lateral inlet pressures of 108, 130, 158, and 190 kPa ($R^2 = 0.9939$),

$$Q = 0.121P + 14.01 \tag{1}$$

where Q was flow rate ($l\ h^{-1}$) and P was water pressure (kPa).

Irrigation control strategies

Three different control strategies were used by the drip line controller: time scheduled, volume scheduled, and soil-moisture scheduled. Results from the soil-moisture scheduled tests are given by Coates (2005). The time scheduled field test demonstrated that each microsprinkler was independently controllable and could discharge water for different durations. On each of four consecutive days, the 50 microsprinklers were turned on sequentially every 35 s and then all turned off after 30 min. Thus, the first microsprinkler ran for 30 min and the last one for 85 s. Water was collected from 25 microsprinklers and volume was plotted against field position. In a subsequent test, all microsprinklers were turned on for 15 min to assess the uniformity of application. Water was collected from 25 microsprinklers, volume was plotted against field position, and a coefficient of variation was calculated.

Volume scheduled irrigation addressed a fundamental problem with time scheduled irrigation: water pressure in each lateral varied with the number of microsprinklers running at a given time, causing flow rates to vary. To remedy this problem, pressure sensors were installed in the nodes at the head of each row and lateral inlet pressure was recorded when any microsprinkler was running. The irrigation schedule specified an on-time and desired

water volume for each microsprinkler. The drip line controller checked the pressure of the laterals every 10–15 s and calculated flow rates using Eq. (1). By numerically integrating the flow rate, the drip line controller calculated the volume of water applied by each microsprinkler. In this test, 50 microsprinklers were scheduled to apply 3.79, 7.57, 11.36, 15.14, or 18.93 l of water. The actual volume of water collected from each individual microsprinkler was compared to that specified in the schedule, and a coefficient of variation was calculated for data at each specified volume. Pressure measurements were recorded for all four laterals every 30 s to show the pressure differences in the system.

Fault detection

Pressure monitoring

Low-pressure warnings were used to alert the operator of possible drip line damage. Damage was simulated by incrementally opening and closing a valve at the lateral outlet and then disconnecting three nodes from the line, allowing water to spray from the punctured drip tube. Pressure was monitored while simulating damage in order to determine error-detection thresholds (Fig. 5). With all 50 microsprinklers turned off and the outlet valve closed, the maximum water pressure of the lateral inlet was 193 kPa. The first error-detection threshold was set at 90% of this value, 174 kPa. The second threshold was selected to be less than the lowest pressure obtained when all 50 microsprinklers were turned on. With the outlet valve closed and all microsprinklers turned on, the water pressure was 168 kPa (data not shown), so the second threshold was chosen to be 138 kPa (20 psi). This was considered to be the minimum allowable pressure. If the drip line pressure fell below the 90% threshold when all microsprinklers were off, an error was logged on the drip line controller. If the pressure fell below the minimum, regardless of the number of microsprinklers that were running, an error was logged on the drip line controller and all microsprinklers were turned off. If the pump had been interfaced to the

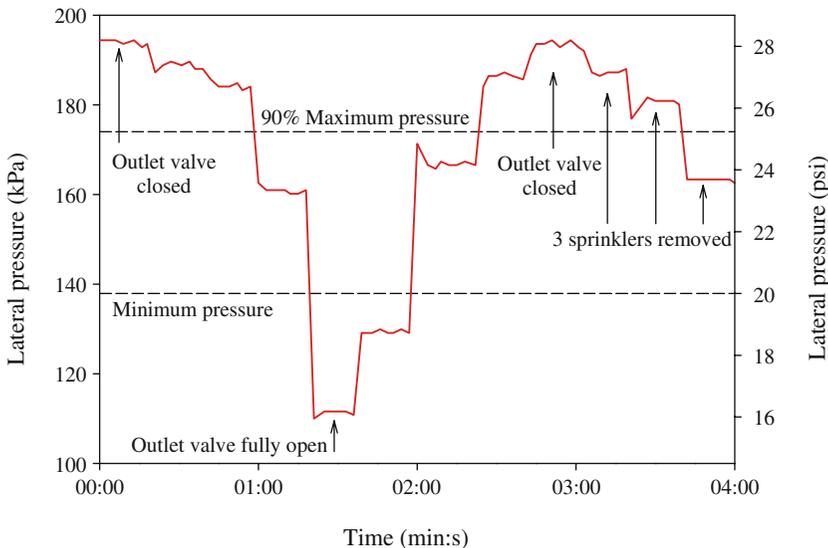


Fig. 5 Drip line pressure over time while opening and closing an outlet valve and removing three microsprinkler emitters

drip line controller, it too could have been turned off. Each entry in the error log included the address of the node that was reading the pressure sensor. The pressure in each lateral was checked every 10–15 s and the damage simulation was repeated with different numbers of microsprinklers running. The microsprinklers were visually monitored during the test to verify that they were turned off at pressures below the minimum and the error log was checked to verify that warnings were logged correctly.

Emitter diagnosis

Lateral-level and node-level diagnosis routines were developed to detect emitter clogging and damage. For both tests, pressure transducers were connected to nodes 1, 14, 26, and 39, near the inlet of each lateral (Fig. 4). All microsprinklers remained off except for the one being diagnosed. The node condition was classified as *clogged*, *normal*, or *damaged* based on pressure change features during valve cycling. *Damaged* nodes were simulated by removing the emitters from the distribution tubes. *Clogged* emitters were simulated by stuffing cellophane into the distribution tubes and replacing the emitter. Though not explicitly tested, a valve that was stuck in the open or closed position would probably respond like a clogged emitter and would be classified as such. Pressure measurements were expressed as integer values from the analog-to-digital converter of the node microcontroller, thus simplifying data storage and mathematical calculations by avoiding conversion to kilopascals. The conversion was

$$P_{\text{kPa}} = 0.7963P_{\text{integer}} - 26.1922 \quad (2)$$

In lateral-level diagnosis, a microsprinkler was tested by measuring pressure changes at the inlet of the drip line along which it was located. Pressure readings were transmitted to the drip line controller for analysis and node classification. Twenty pressure readings were taken each time before opening the valve, after opening the valve, and after closing the valve (Fig. 6). Pressure was recorded every 0.33 s (the sampling rate limited by low-rate communication between the node and drip line controller) and diagnosis of a single node took about 20 s. Pressure fluctuation was visualized by a moving average of the previous 20 readings. It is evident that a *normal* emitter produced more change in pressure than a *clogged* emitter and less change than a *damaged* one. A classification algorithm was developed from the results of several field trials. Two thresholds were selected to separate the microsprinklers into one of three classes. The classification algorithm was then tested on all 50 microsprinklers under each of the three conditions, for a total of 150 fault diagnosis observations. Actual microsprinkler condition was compared to the classified condition and error rates were calculated.

Node-level diagnosis used the same equipment as lateral-level diagnosis, but was predicated on the assumption of a pressure sensor at every microsprinkler node in the field. Instead of transmitting pressure measurements to the drip line controller, values were stored in node memory. The node microcontroller analyzed measurements locally and only the classification result was transmitted to the drip line controller, making node-level diagnosis much quicker than lateral-level diagnosis. The routine was tested on the four nodes containing pressure sensors. Forty pressure measurements were taken after cycling the valve on and another 40 after cycling it off (Fig. 7). A pressure reading was taken by the node every 10.6 ms, so diagnosis of a single node took about 0.9 s, including communication time with the drip line controller. The water pressure transients induced during valve cycling were visualized as peaks and troughs centered around the mean pressures

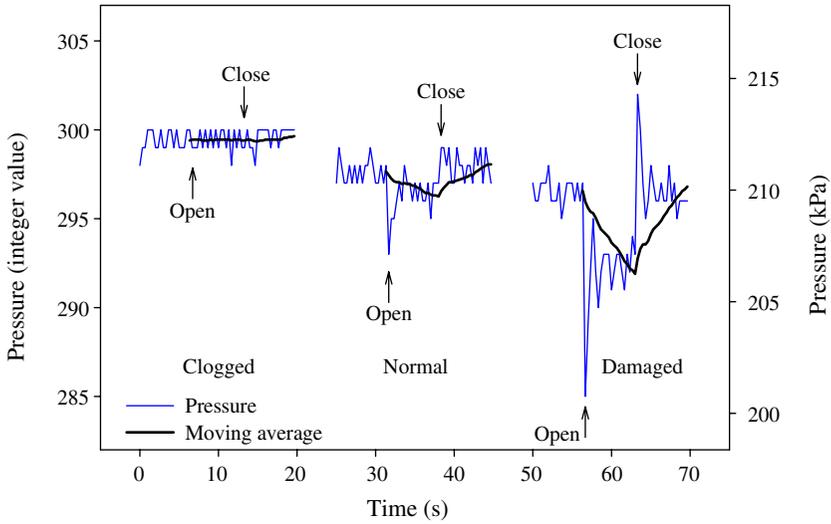


Fig. 6 Pressure measurements with a moving average of the previous 20 readings for lateral-level diagnosis for clogged, normal, and damaged microsprinklers

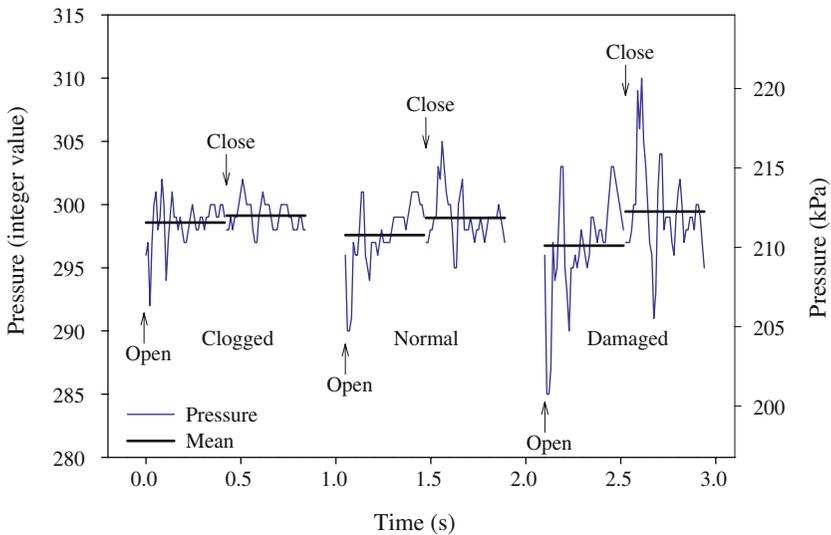


Fig. 7 Pressure measurements with average pressures after opening and closing the valve for node-level diagnosis for clogged, normal, and damaged microsprinklers

after opening and closing the valve. A classification algorithm was developed from several field trials, similar to lateral-level diagnosis. During initial testing, it became evident that air in the distribution tube could alter the pressure transients and result in an incorrect classification. One remedy was to purge air from the distribution tube by opening and closing the valve prior to the diagnosis. After the air purge, a delay was required to allow pressure transients to decay. Three air purge schemes were tested: no purge, short-delay purge (0.5 s purge with 0.4 s delay), and long-delay purge (0.5 s purge with 1.6 s delay).

A total of 216 node-level diagnosis observations were made over two days. On day one, the four nodes were tested under each microsprinkler condition three times with three different air purge schemes for a total of 108 observations. The test was conducted at a drip line pressure of 193 kPa. On day two, the four nodes were tested once under each condition at 215, 239, and 147 kPa with three different air purge schemes for a total of 108 observations.

Results and discussion

Irrigation control strategies

Time scheduled

The microsprinkler nodes were programmed to turn on sequentially, so water was applied in a linear gradient across the field (Fig. 8). Each microsprinkler applied the same volume of water on each day, although slightly more water was applied on day 4 because the system water pressure increased due to other irrigation blocks being shut off. This test demonstrated that the spatially variable system worked on the individual microsprinkler level and performed consistently from day to day.

When scheduled to run for 15 min, the discharged volume of water varied across the orchard (Fig. 9). The coefficient of variation for application volume was 4.1%. This variation was attributed to a higher water pressure in the two outer laterals. Operation for an extended duration would have lead to a larger difference in water discharge between laterals, making it difficult to irrigate and fertigate all parts of the orchard precisely. Volume scheduled irrigation was used to compensate for the unequal pressure distribution in the system.

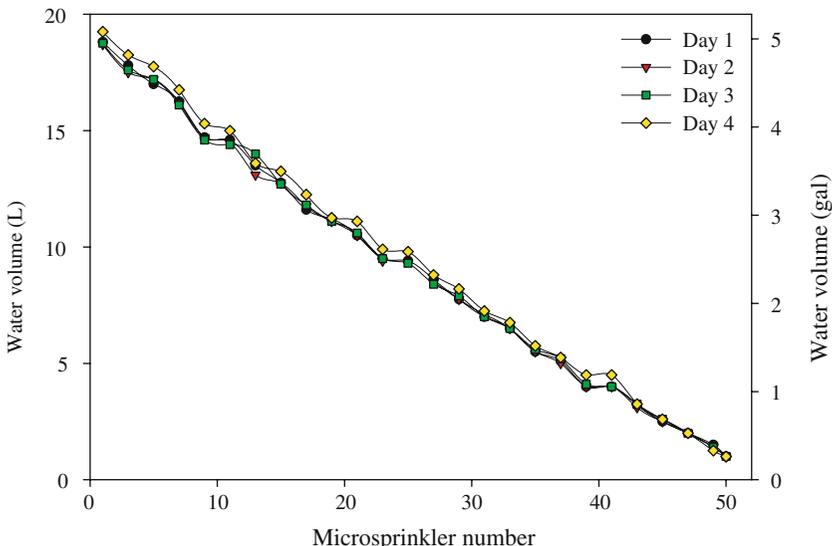


Fig. 8 Water volume vs. microsprinkler position over four days, with the time of actuation a linear function of microsprinkler number

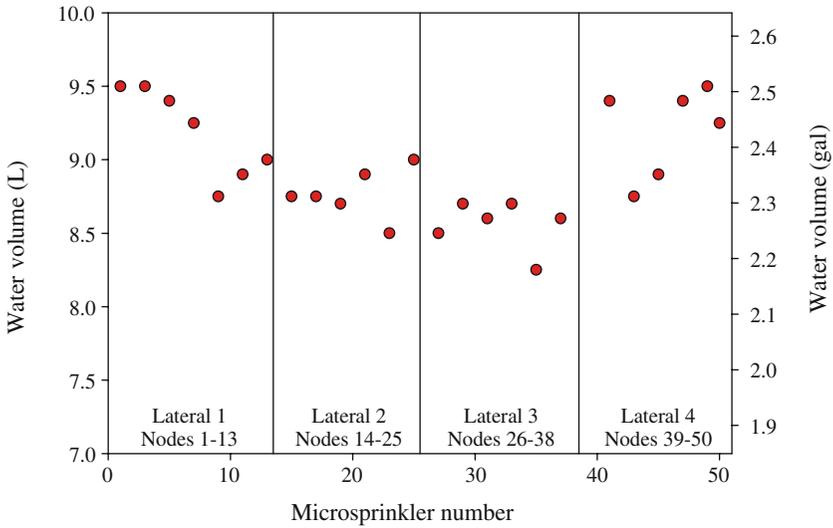


Fig. 9 Water volume versus microsprinkler position for 15 min discharge duration by all microsprinklers

Volume scheduled

The water volume specified in the schedule was compared to the actual volume collected from each microsprinkler during the volume scheduled test (Fig. 10). Water pressure in the four laterals differed between the inner and outer lines and changed as groups of micro-sprinklers turned off (Fig. 11). The two inner laterals operated at 14–19 kPa less than the

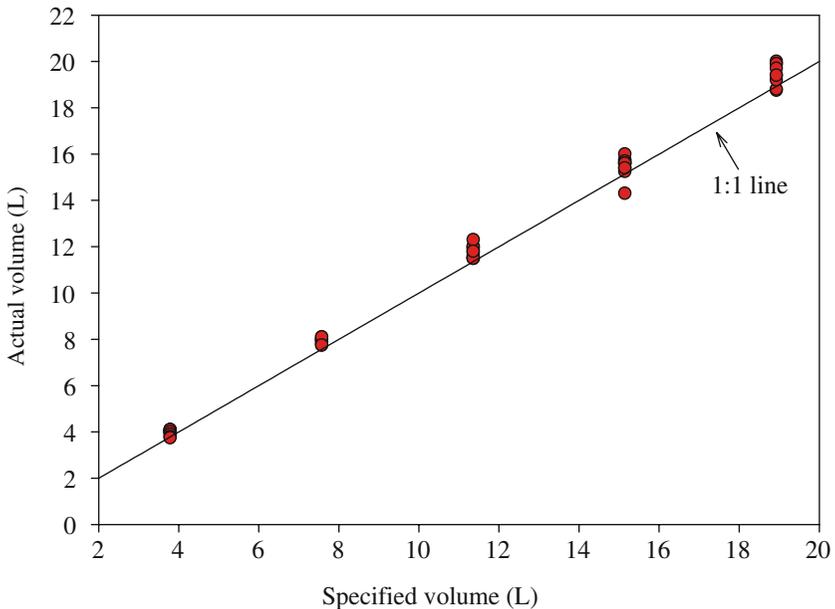


Fig. 10 Actual volume of water collected during the volume scheduled test versus the volume of water specified in the schedule

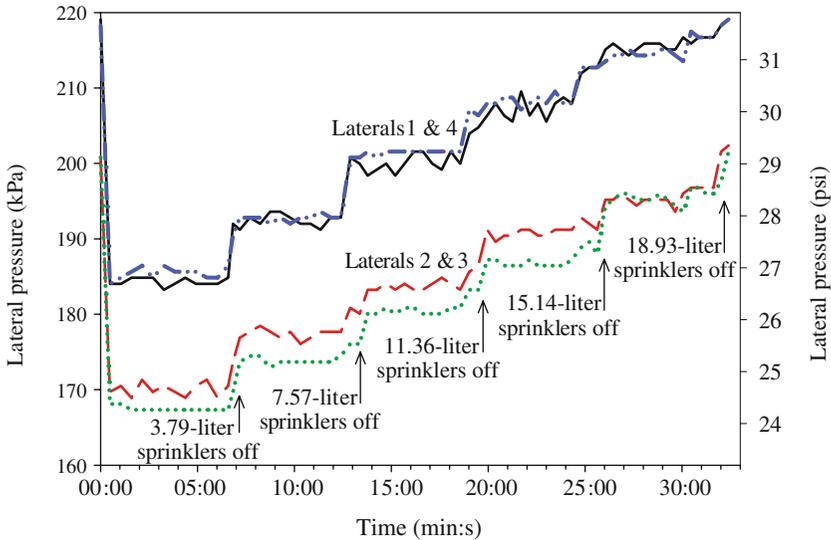


Fig. 11 Water pressure at lateral inlets during volume scheduled irrigation test

outer laterals, so the drip line controller calculated longer irrigation durations for micro-sprinklers along the inner laterals, as expected. For example, of the microsprinklers scheduled to apply 15.14 l, those on the two outer laterals were turned on for 24.3 min, but the microsprinklers on the inner laterals were turned on for 25.6 min to apply the same volume of water. The microsprinklers discharged an average of 3.7% more water than specified. The coefficients of variation of the actual volumes were 3.1, 1.7, 2.3, 3.0, and 2.4% at specified volumes of 3.79–18.93 l, respectively. The coefficient of variation at each specified volume was less than that of time scheduled control, indicating that volume scheduled control provided more precise water application. Differences between actual and specified volume could have been due to inaccuracy of flow calibration, variability in emitter manufacture, or partial clogging of the valves and emitters. In this test, lateral head loss was neglected because short laterals were used, but could be included in the calibration since the position of each microsprinkler was known. In spite of these differences, volume scheduled irrigation was useful in overcoming the effects of pressure variation by allowing more precise control of water using feedback from sensors in the field.

Fault detection

Pressure monitoring

With all microsprinklers turned off, the pressure fell below the 90% threshold once when simulating a line break and once when three microsprinklers were removed. The drip line controller recorded correctly the error type, time, pressure, and node address in the error log (Coates, 2005). When the drip line pressure fell below the minimum pressure threshold, all valves were closed and an error was recorded in the log. Since the error log included a node address for each reported error, the operator knew which lateral sustained damage. This test demonstrated that monitoring drip line water pressure could be used to detect and respond to problems at individual laterals.

Emitter diagnosis

For lateral-level diagnosis, pressure fluctuation, P_f , was quantified by,

$$P_f = (\bar{P}_{\text{closed}} - \bar{P}_{\text{open}}) - (\bar{P}_{\text{open}} - \bar{P}_{\text{before}}) \tag{3}$$

where \bar{P}_{before} was the average pressure before the valve was opened, \bar{P}_{open} was the average after the valve was opened, and \bar{P}_{closed} was the average after the valve was closed. The average and range of values from initial field trials (Table 1) were used to determine thresholds for microsprinkler classification: $P_f > 6.0$ for *damaged*, $1.5 \leq P_f \leq 6.0$ for *normal*, and $P_f < 1.5$ for *clogged*.

For node-level diagnosis, the pressure transients were quantified by the sum, S_t , of the difference between each pressure measurement and the average pressure after opening or closing the valve by,

$$S_t = \sum_{i=1}^{40} |P_{i,\text{open}} - \bar{P}_{\text{open}}| + \sum_{i=1}^{40} |P_{i,\text{closed}} - \bar{P}_{\text{closed}}| \tag{4}$$

where $P_{i,\text{open}}$ was the i th pressure reading after the valve was opened and $P_{i,\text{closed}}$ was the i th reading after the valve was closed. Classification thresholds were based on field trials at a lateral pressure of about 215 kPa. The average and range of values (Table 2) were used to determine the thresholds: $S_t > 300$ for *damaged*, $150 \leq S_t \leq 300$ for *normal*, and $S_t < 150$ for *clogged*.

Of the 150 lateral-level diagnosis observations, 146 were classified correctly, giving a 3% overall error rate (Table 3). Three *damaged* nodes were incorrectly classified as *normal* and one *normal* node was incorrectly classified as *damaged*. It is possible that partial valve clogging caused the incorrect classifications. P_f was slightly greater than the 6.0 threshold for the incorrectly classified *normal* node and much less than the threshold for the incorrectly classified *damaged* nodes. This overlap suggested that the difference between *normal* and *damaged* microsprinklers was not easily distinguished using lateral-level diagnosis. Diagnoses were not done with longer drip lines, different microsprinklers, or at different water pressures, though they could affect the accuracy of classification.

Of the 216 total node-level diagnosis observations, 213 were classified correctly, giving a 1% overall error rate (Table 4). At lateral pressures of 193 kPa (108 observations) and 215 kPa (36 observations), there were no errors. At the highest pressure, 239 kPa (36 observations), one *clogged* node was incorrectly classified as *normal*. At the lowest pressure, 147 kPa (36 observations), one *damaged* node was incorrectly classified as *normal* and one *normal* node was incorrectly classified as *clogged*. Since the diagnostic routine was developed at 215 kPa and errors occurred at the highest and lowest pressures, calibration over a range of water pressures would probably improve the accuracy of classification. Also, two of the three errors occurred when using no air purge and one

Table 1 Values of P_f for clogged, normal, and damaged microsprinklers

Condition	P_f		
	Minimum	Average	Maximum
Damaged	6.9	8.3	9.7
Normal	2.1	3.0	3.4
Clogged	-1.1	0.3	1.3

Table 2 Values of S_t for clogged, normal, and damaged microsprinklers

Condition	S_t		
	Minimum	Average	Maximum
Damaged	381	489.3	577
Normal	206	238.1	281
Clogged	52	73.2	96

Table 3 Lateral-level diagnosis results with error rates

Actual condition	Predicted condition			Total	Error (%)
	Damaged	Normal	Clogged		
Damaged	47	3	0	50	6
Normal	1	49	0	50	2
Clogged	0	0	50	50	0
Total	48	52	50	150	3

Table 4 Node-level diagnosis results with error rates

Actual condition	Predicted condition			Total	Error (%)
	Damaged	Normal	Clogged		
Damaged	71	1	0	72	1
Normal	0	71	1	72	1
Clogged	0	1	71	72	1
Total	71	73	72	216	1

occurred when using the long-delay purge. With the short-delay purge, there were no incorrect classifications, indicating that it may be more effective than the other purge routines.

It is evident that automated fault detection is possible and could be a valuable tool in irrigation system management to reduce water and fertilizer loss through damaged microsprinklers, reduce tree stress due to clogged emitters, and decrease time spent troubleshooting the system.

Conclusions

Evaluation of the spatially variable system has established that precision microirrigation on the individual emitter level is possible and has several advantages over conventional systems. With a time scheduled control strategy, a gradient of water was applied across the orchard. Changes in water pressure, however, caused variation in microsprinkler discharge. Volume scheduled irrigation overcame this problem by using pressure sensor feedback and emitter calibration to adjust microsprinkler discharge duration, thus allowing precise water application. The distributed intelligence of the microsprinkler nodes and sensors allowed automated detection of drip line damage and clogged or damaged emitters. Automated fault detection and correction has the potential to reduce labor costs associated with

troubleshooting system performance while reducing water and fertilizer loss from undetected damage.

The system described here also provides the capability for precise application of injected fertilizers, which should be tested with the control strategies we have developed. The volume scheduled irrigation strategy and emitter fault diagnosis routines could be made more effective with a differential pressure sensor across each valve to determine individual microsprinkler flow rates. Other control strategies would be possible with alternative types of sensors to measure tree water and nutrient demand and monitor system status. Long term studies should be conducted to quantify the effect of tree-level orchard management on yield, profitability, and environmental quality.

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References

- Barash, S., Brandman, Y., Cohen, Y., Shporn, S., Vishnipolsky, J., & Yanai, E. (1980). *Computer-controlled irrigation system*. U.S. Patent No. 4209131.
- Beckie, H. J., Moulin, A. P., & Pennock, D. J. (1997). Strategies for variable rate nitrogen fertilization in hummocky terrain. *Canadian Journal of Soil Science*, *77*, 589–595.
- Coates, R. W. (2005). *Precision irrigation in orchards: Development of a spatially variable microsprinkler system*. Davis, California: MS thesis. University of California, Davis, Department of Biological and Agricultural Engineering.
- King, B. A., Reeder, R. E., Wall, R. W., & Stark, J. C. (2002). Comparison of site-specific and conventional uniform irrigation management for potatoes. ASAE Paper No. 022175. St. Joseph, Michigan.
- Koch, B., Khosla, R., Frasier, W. M., Westfall, D. G., & Inman, D. (2004). Economic feasibility of variable-rate nitrogen application utilizing site-specific management zones. *Agronomy Journal*, *96*, 1572–1580.
- Povoa, A. F., & Hills, D. J. (1994). Sensitivity of microirrigation system pressure to emitter plugging and lateral line perforations. *Transactions of the ASAE*, *37*, 793–799.
- Rodrigues de Miranda, F. (2003). A site-specific irrigation control system. ASAE Paper No. 031129. St. Joseph, Michigan.
- Torre-Neto, A., Schueller, J. K., & Haman, D. Z. (2000). Networked sensing and valve actuation for spatially-variable microsprinkler irrigation. ASAE Paper No. 001158. St. Joseph, Michigan.
- Verhagen, J. (1997). Site specific fertiliser application for potato production and effects on N-leaching using dynamic simulation modelling. *Agriculture, Ecosystems, and Environment*, *66*, 165–175.
- Wang, D., Prato, T., Qiu, Z., Kitchen, N. R., & Sudduth, K. A. (2003). Economic and environmental evaluation of variable rate nitrogen and lime application for claypan soil fields. *Precision Agriculture*, *4*, 35–52.
- Yang, C., Everitt, J. H., & Bradford, J. M. (2001). Comparisons of uniform and variable rate nitrogen and phosphorus fertilizer applications for grain sorghum. *Transactions of the ASAE*, *44*, 201–209.
- Zaman, Q. U., Schumann, A. W., & Miller, W. M. (2005). Variable rate nitrogen application in Florida citrus based on ultrasonically-sensed tree size. *Applied Engineering in Agriculture*, *21*, 331–335.
- Zeng, Q., Brown, P. H., & Holtz, B. A. (2001). Potassium fertilization affects soil K, leaf K concentration, and nut yield and quality of mature pistachio trees. *HortScience*, *36*, 85–89.

Wireless Network for Individual Emitter Control in Irrigation

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Introduction

Site specific irrigation and fertilization have been proven to be useful tools for crop management. Existing technology generally limits the scale at which site management can take place since fields are divided into management units which contain multiple sprinklers or emitters. This problem is evident in orchards, landscapes, nurseries, and greenhouses. The needs of individual trees in an orchard may vary due to such things as soil condition, tree age, elevation changes, or localized pest infestations. When applied uniformly, water and fertilizer may leach in light textured soils and pool in heavy soils. Dead trees are usually replaced with young trees that have different water and nutrient requirements. For trees planted on steep slopes, maintaining irrigation uniformity is difficult. Insecticide application is usually not needed in an entire orchard since infestations often occur in small regions. Nurseries and greenhouses contain many different varieties of ornamental plants in close proximity to one another and must deal with continually changing inventory and strict environmental regulations. A single valve usually controls water flow to many emitters, and if there are plants of differing size or water requirements, some will receive too much water, while others will receive too little. Inventory movement is a problem since water is wasted in locations where plants have been removed. Irrigation control in landscapes is also important since a significant amount of water is used for turfgrass and ornamentals. Studies have shown that optimizing water delivery can conserve water and prevent run-off. Many commercial controllers have been developed in order to optimize water delivery by using reference evapotranspiration, but they only address the scheduling aspect of irrigation management and do not help with problems such as varying soil types, elevation, and diverse water requirements for plants in a single landscape.

Objectives

We propose to develop a wireless valve network capable of controlled application of water, fertilizer, and agricultural chemicals through each valve. Larger valves could control flow to multiple sprinklers or drip emitters (e.g., laterals), or smaller valves could control flow to individual plants or trees (e.g., each microsprinkler). Individual valve schedules would be different in order to match differing water and fertilizer requirements and could easily be changed to accommodate replants, disease, growth, or seasonal changes. This could improve profitability by increasing overall plant quality, while reducing water and fertilizer

waste. Environmental benefits such as reduced leaching and runoff would also be expected. Using feedback from pressure sensors, it will be possible to improve water and fertilizer application accuracy over that of fixed-duration irrigation. An added benefit is that these sensors will provide information to automatically detect line breaks, emitter clogging, and similar problems. The specific objectives are to:

- (1) design an intelligent valve controller capable of low-power, wireless communication,
- (2) design an energy management system to allow stand-alone operation of each valve controller,
- (3) develop a communication network to link the valve controllers with a central field controller, and
- (4) develop control strategies for applying water and fertilizer.

Literature Review

Reduced environmental damage and increased profitability are documented benefits of spatially variable irrigation and fertilization. Matching nitrogen delivery with plant needs has increased fertilizer use efficiency and net returns in some field crops (Beckie et al., 1997) and reduced nitrate leaching in potato crop simulations (Verhagen, 1997). Variable rate application of granular fertilizer based on individual tree size in a citrus study reduced overall nitrogen application by 38-40% compared to conventional treatment (Zaman et al., 2005). It seems logical that the benefits seen with variable rate granular fertilization would be seen for variable rate fertigation as well. Spatially variable management has also been shown to increase profits from corn (Koch et al., 2004; Wang et al., 2003) and improve yield in potatoes (King et al., 2002) and grain sorghum (Yang et al., 2001).

While there has been substantial interest in site-specific management, research on spatially variable microirrigation or sprinkler systems has been limited. In one recent development, latching solenoid valves controlled two laterals per row in a citrus orchard (Torre-Neto et al., 2000). Each lateral uniformly irrigated half the trees in the row, which were grouped based on size (large and small trees). In another development, microcontrollers responded to soil moisture feedback by controlling water flow to individual laterals for potted plants, but neglected variability between individuals (Rodrigues de Miranda, 2003). Spatially variable irrigation has also been tested in center-pivot and linear-move systems for field crops (Camp et al., 1998; King et al., 1999; King and Kincaid, 2004).

We recently developed a precision microsprinkler system for orchards under a research project supported by the Fertilizer Research and Education Program (FREP) of the California Department of Food and Agriculture (CDFA). The microsprinkler system was

designed to provide spatially variable delivery of water and fertilizer, and a prototype was installed in a small nectarine block (Coates et al., 2006a; Coates et al., 2006b). Individually addressable micros sprinkler nodes, each containing control circuitry and a valve, were located at 50 trees. A drip line controller stored the irrigation schedule and issued commands to each node. Pressure sensors connected to some of the nodes provided lateral line pressure feedback. The system was programmed to irrigate individual trees for specific durations, to apply a specific volume of water at each tree, or to irrigate in response to soil water demand. Fault detection was used to check for damaged drip lines and clogged or damaged emitters. This system could be improved by using radio-frequency (RF) communication and solar power to eliminate the use of wires in the orchard. This will improve ease of installation and reduce problems associated with long-range wired communication and damage from animals and machinery.

System Design

Since this system is intended for application in orchards, greenhouses, landscapes, and nurseries, the wireless network (Figure 1) must be versatile enough to operate in many environments. Mesh networking will allow messages to pass from one node to any other node in the network by routing it through nodes in-between. This technique allows increased network range without using high power transceivers. Another advantage is redundancy. A failed node will not disable the entire network since multiple routing paths exist between nodes. The operator will enter irrigation schedules on the central field controller, and they will be distributed to individual nodes in the network. An optional master computer would be a personal computer that provides a graphical interface, but will not be required to operate the system.

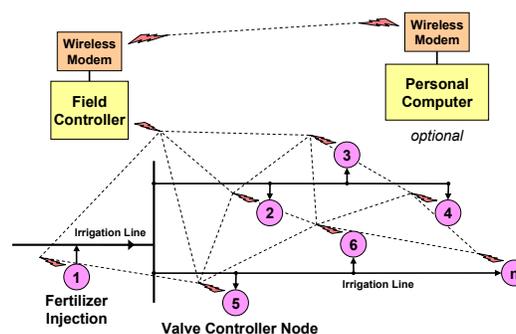


Figure 1. Layout of wireless valve network.

An early prototype for micros sprinklers was designed using commercially-available demonstration boards (Figure 2) (Microchip Technology Inc., Chandler, Arizona, USA). The board included a microcontroller (PIC18LF4620) and RF circuit (CC2420 transceiver,

Chipcon, Oslo, Norway). A latching solenoid valve was used to control water flow through the microsprinkler emitter. A latching solenoid was used since it requires only a brief pulse of energy to open or close. It was operated by N-channel metal-oxide-semiconductor field-effect transistors controlled by digital outputs on the microcontroller. A piezoelectric buzzer was connected to the microcontroller for audible feedback during node operation. The circuit board was modified for low power operation by removing an unused temperature sensor, disabling status lights, and using 1 M Ω pull-up resistors instead of the microcontroller's internal pull-ups. A 32.768 kHz crystal and load capacitors were added to the circuit for use as a real-time clock. During testing, the nodes were powered with 9 V alkaline batteries, but will ultimately be powered using rechargeable batteries and a 200 mW solar panel. Each controller will be able to measure water pressure and input from other sensors (e.g., soil moisture, run-off).

One demonstration board was not modified, but was connected via serial to an embedded controller which acted as the field controller for the network. The field controller contained a keypad to allow entry of schedules and manual operation of the remote valves, and a liquid crystal display (LCD) for viewing status information.

The node microcontrollers were programmed in C. The network communication protocol was handled by Microchip's implementation of the Zigbee wireless networking standard (<http://www.zigbee.org>). Additional code was written to pass messages between nodes, operate the latching valve and buzzer, and maintain a real-time clock. C-language code was also written to operate with field controller.



Figure 2. Prototype microsprinkler node.

Preliminary Evaluation

Communication between the field controller (with unmodified node) and two microsprinkler nodes was tested. Nodes were debugged by connecting the built-in serial port

to a computer to monitor status information sent from the microcontroller. Each node properly responded to commands to open or close its valve. Valve operation required a 50 ms pulse from the battery (2 A peak current). Real-time clock operation was verified over several days of operation and no inaccuracies were evident. Radio transmission range under visual line-of-sight conditions reached about 30 m using the printed antennas on the demonstration boards. Improved range could be achieved by using whip antennas on the microsprinkler stake.

Node current consumption during idle periods was about 35 μ A. This could be further reduced by using a more efficient voltage regulator than the one on the demonstration board. Current consumption during radio transmission and receiving was about 20 mA. To extend battery life, nodes were idle most of the time and only used the radio when data transfer was required. If the radio was used an average of 30 minutes per day, daily energy consumption would be about 11 mA-h. Solar panel performance was tested in full sunlight and full shade conditions. A datalogger recorded current from the solar panel through a 10 Ω resistor (measured by voltage drop) for several days. Peak current was about 16 mA in full sun and 1.5 mA in shade. Integration yielded a daily energy production of 52 to 81 mA-h in full sun and 6 to 10 mA-h in shade. Energy management will be critical to ensure continuous node operation.

Future Work

We plan to replace the demonstration boards with smaller, lower-power circuits. Code will be written to allow standalone schedule-based operation of each node. Sensors will be connected to the nodes for monitoring water pressure or soil moisture level. Nodes will be deployed in the field and used to develop water control and fault detection strategies. Since this system has potential applications in orchards, nurseries, greenhouses, and landscapes, the wireless controllers will be designed to operate large valves that could control flow to multiple sprinklers or drip emitters (e.g., laterals), and small valves that control flow to individual trees (e.g., each microsprinkler).

Acknowledgement

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References

- Beckie, H.J., Moulin, A.P., Pennock, D.J. 1997. Strategies for variable rate nitrogen fertilization in hummocky terrain. *Canadian Journal of Soil Science* 77, 589-595.
- Camp, C.R., Sadler, E.J., Evans, D.E., Usrey, L.J., Omary, M. 1998. Modified center pivot system for precision management of water and nutrients. *Applied Engineering in Agriculture*, 14(1): 23-31.

- Coates, R.W., Delwiche, M.J., Brown, P.H. 2006a. Control of individual microsprinklers and fault detection strategies. *Precision Agriculture*, in press.
- Coates, R.W., Delwiche, M.J., Brown, P.H. 2006b. Design of a system for individual microsprinkler control. *Transactions of the ASABE*, submitted.
- King, B.A., McCann, I.R., Eberlein, C.V., Stark, J.C. 1999. Computer control system for spatially varied water and chemical application studies with continuous-move irrigation systems. *Computers and Electronics in Agriculture*, 24(3): 177-194.
- King, B.A., Reeder, R.E., Wall, R.W., Stark, J.C. 2002. Comparison of site-specific and conventional uniform irrigation management for potatoes. *ASAE Paper No. 022175*. St. Joseph, Michigan.
- King, B.A., Kincaid, D.C. 2004. A variable flow rate sprinkler for site-specific irrigation management. *Applied Engineering in Agriculture*, 20(6): 765-770.
- Koch, B., Khosla, R., Frasier, W.M., Westfall, D.G., Inman, D. 2004. Economic feasibility of variable-rate nitrogen application utilizing site-specific management zones. *Agronomy Journal* 96, 1572-1580.
- Rodrigues de Miranda, F. 2003. A site-specific irrigation control system. *ASAE Paper No. 031129*. St. Joseph, Michigan.
- Torre-Neto, A., Schueller, J.K., Haman, D.Z. 2000. Networked sensing and valve actuation for spatially-variable microsprinkler irrigation. *ASAE Paper No. 001158*. St. Joseph, Michigan.
- Verhagen, J. 1997. Site specific fertiliser application for potato production and effects on N-leaching using dynamic simulation modelling. *Agriculture, Ecosystems, and Environment* 66(2), 165-175.
- Wang, D., Prato, T., Qiu, Z., Kitchen, N.R., Sudduth, K.A. 2003. Economic and environmental evaluation of variable rate nitrogen and lime application for claypan soil fields. *Precision Agriculture* 4(1), 35-52.
- Yang, C., Everitt, J.H., Bradford, J.M. 2001. Comparisons of uniform and variable rate nitrogen and phosphorus fertilizer applications for grain sorghum. *Transactions of the ASAE* 44(2), 201-209.
- Zaman, Q.U., Schumann, A.W., Miller, W.M. 2005. Variable rate nitrogen application in Florida citrus based on ultrasonically-sensed tree size. *Applied Engineering in Agriculture* 21(3), 331-335.