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An Automated System for Irrigation Control in Containerized Ornamental Crop Production

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Abstract

Building on existing technology that utilizes capacitance sensors and low-cost microcontrollers, we designed, assembled and tested a self-contained irrigation system for controlling substrate volumetric moisture content in container-grown ornamental plants. In the prototype system described here, compatible software is embedded within the microcontroller, real-time measurements appear on a liquid-crystal display screen, and data are stored on a secure digital card, thereby allowing irrigation threshold settings to be changed without the need for reprogramming the microcontroller. The system components are readily available and affordably priced, making the unit a useful management option for improving irrigation scheduling for growers that do not wish to invest in more costly wireless network systems. In evaluation trials using 5-week-old containerized zinnia seedlings, the automated system reliably controlled irrigation thresholds ranging from 0.155 to 0.425 m^3m^{-3}. During the trial period each threshold was maintained for 5-7 days during which time substrate VMC varied ± 0.04 to ±0.06 m^3m^{-3}, and the volume of water required to sustain each threshold (as calculated from data collected and stored on the system secure digital card) was within 3% of the actual quantity of water collected in plastic containers attached to the same irrigation line.

Keywords: Capacitance sensors; Electronic control systems; Substrate moisture content

Introduction

Proper irrigation management is a critical factor in the environmental and economic sustainability of nursery and greenhouse-grown crops [1]. With the advent of increasingly strict water-use regulations, higher water procurement costs and limited groundwater supplies, there is an increased need for growers to minimize plant-water use during the production cycle while, at the same time, maximizing water-use efficiency. Nowhere is this need more important than in the production of containerized high-value ornamental crops, where various production methods are used and numerous species are grown, many of which require different irrigation regimes [2]. While irrigation management decisions are often based on methodology as simple as using predetermined time schedules or by visually evaluating the water status of individual plantings [3], recent technology has made the use of automated systems more reliable [4]. Using capacitance sensors and frequency domain technology, the volumetric moisture content (VMC) of almost any soil or soilless substrate can be determined by measuring the dielectric constant [5,6]. Although research in automated irrigation control has largely shifted to the development and testing of costly wireless sensor networks (WSNs) designed for large scale horticultural production [2], the need still exists for an economical, portable, self-contained system with embedded software designed specifically for use in ornamental crop production [7]. This is especially true for smaller-scale growers who wish to control irrigation based on crop water usage but can't afford the expense of larger, more costly WSNs. The present study was undertaken to design, assemble and evaluate a fully automated, affordable, standalone irrigation system (including compatible software) that permits a range of irrigation management options for ornamental plant growers. In the system described here, capacitance sensors are used to monitor and log substrate VMC based on real-time measurements. But, unlike previously described systems that use open-source microcontrollers, the current prototype is a self-contained unit providing information of interest to the operator on an LCD screen, recording and storing data (CSV format) on a secure digital (SD) card, and allowing changes in irrigation threshold settings without the need for reprogramming the microcontroller. We henceforth refer to this prototype as the WaterMaster (WM) system.

Materials and Methods

Hardware

Microcontroller: While various low-cost microcontrollers are available, we selected the Mega 2560 R3 (Arduino, Ivrea, Italy) because of its simplicity, speed, and the fact that it offers a sufficient number of input/output ports. It also has board circuitry for data transmission (TX and RX) and for I^2C communication (SDA and SCL) as well as analog pins that will accept inputs from a variety of analog and/or digital sensors. In addition, instead of inputs, the digital pins can be programmed as outputs to provide 5 V DC to external equipment such as actuators, relays or LEDs. The Mega 2560 R3 also has an on-board 3.3 V regulator, which is used to provide a regulated voltage supply for more precise sensor signalling.

Shields: In the WM system, shields (auxiliary printed circuit boards) were plugged directly into the microcontroller forming a stack. Pins on the shield engage sockets on the Mega 2560 R3 to connect all input, output, power and ground functions. The system described here contains two shields. The first is an SD card shield with a real-time clock (RTC model 2.0 Adafruit.com, Adafruit, New York, NY). The second shield, the screw connector shield (#196 Adafruit.com, Adafruit, NY), contains an open area, used in our design for several circuits, which are described below in the section entitled "Circuitry".

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Relay driver: A 5V DC relay driver board with 16 relays (20-018-103; SainSmart, Leawood, KS) used to switch power to the solenoid valves in response to 5V DC signals from the microcontroller.

Display module: An LCD module (LCD2004; SainSmart, Leawood, KS) with four lines of 20 characters each, used to present information to the operator (thereby negating the requirement for a computer hookup if the WM system is used in the field).

Moisture sensors: Four capacitance soil moisture sensors (model EC-5; Decagon Devices, Pullman, WA) to measure substrate VMC; Solenoid valves. Four 24 AC ¾" NPT solenoid valves (75D V; Rainbird, Tucson, AZ) which deliver water to each of four irrigation supply lines.

Switches: The microcontroller and shield components described above are housed in a 12 × 22 × 9.5 cm water-resistant plastic enclosure (Figure 1) fitted with the following switches:

(1) A DPST switch to turn the power on and off;

(2) An SPST switch for the operator to choose either "run" or "set" modes;

(3) A BCD switch which, in the "run" mode, is used to select the irrigation cycle;

(4) A second BCD switch which, in the "run" mode, is used to select the irrigation time;

(5) Another 16-position BCD switch used to select the sensor or solenoid valve to be activated (only four positions/pins are used in the WM system, the remainder being available for system expansion);

(6) An SPDT switch which, in the "set" mode, is used to raise or lower the VMC to the desired set point;

(7) A pushbutton switch which, in the "set" mode, is used to set the desired VMC threshold.

Circuitry: The system contains the following four circuits constructed on the screw connector shield:

Figure 1: Water Master Microcontroller:

(1) DPST switch (turns power off and on);

(2) SPST switch ("set mode determines VMC level at which solenoid valves will activate);

(3) BCD switch ("run" mode select irrigation cycles);

(4) BCD switch ("run" mode selects irrigation times);

(5) BCD switch (selects solenoid to be activated);

(6) SPST switch ("set" mode raises or lowers VMC to desired set point);

(7) Pushbutton switch ("set" mode locks VMC set point).

(1) A circuit providing 3.3 V power to the VMC sensors. Since we wanted the power "on" only while reading VMC, a transistor was placed in the line from the Mega 2560 R3 3.3 V onboard supply to the sensors;

(2) A circuit providing precisely adjustable voltage to the Mega 2560 R3 AREF pin. This circuit was designed to allow an adjustable reference signal to the microcontroller AREF pin;

(3) A third circuit inverts signals to the relay board. Since the relay board is controlled by "active low" inputs (inverse logic), the relays are turned on when the input signal is low (near zero) voltage and, likewise, the relays are turned off when the input signal is at high (near 5 V) voltage;

(4) A circuit that detects the zero crossing of the 24 V AC power supply. If a solenoid valve is turned on when the voltage is other than zero, the voltage could spike, potentially causing damage to the system electronics. To prevent a voltage spike, a zero crossing detector (an IC chip) was used to provide a signal to the microcontroller indicating when the 24 V AC crosses zero and can be safely turned off.

Wiring: Since the total number of electrical components in the WM microcontroller is quite large, a detailed wiring schematic is included under Supplementary Information (Appendix A), where the components are enlarged and separated into sections for increased clarity. Where appropriate, matching the corresponding letters that appear in the margins of each diagram will provide an overview of the entire schematic. It should be noted, however, that there are connections from one shield stacked on top of another that do not show up in the schematic since there are no copper tracks or wiring between them (e.g., pin D1 on the Mega 2560 R3 is connected to pin D1 on the SD card shield and to pin D1 on the connector shield). In the interest of conserving circuit board space on the connector shield, all switch circuits are designed to be "active low". This arrangement allows use of the internal pull-up resistors on the Mega 2560 R3 to prevent voltage "float" for each switch position; otherwise an external pull-down resistor would be required for each switch position.

The cost of the microcontroller components required for assembly of the WM prototype described here, including 12 V and 24 V power supplies, shields, switches, wiring and associated hardware was 234 (USD). Costs associated with the 4-line irrigation supply system used in testing and evaluating the WM prototype (described in the section entitled Performance trials), including capacitance sensors, solenoid valve assemblies, cable connections, plumbing, wiring, tubing, emitters and mounting hardware, was an additional 661 (USD).

Software

The WM software program is embedded in the microcontroller such that the system operator needs no prior knowledge of its construction or internal operation. Presented here is a general overview of the software, the source code for which can be found in Appendix B under Supplementary Information.

The WM software program follows conventional format in that there are four sections: declarations, set-up, functional definitions and main loop. The declarations section defines the constants and variables where information is found, defining variables and pin connections to the hardware. Names of variables are chosen by the programmer, usually with a logical inference to the physical quantity the variable refers to. The set-up section defines which pins are input and which are output, then sets the initial state. This section also provides information for the microcontroller to "talk" to the various hardware components, and sets certain variables to a known start up status. The third section, functional definitions, defines the functions used repeatedly in the main program loop. The final section, the main loop, is the program section that is executed in a continuous, never-ending loop after the other sections have been executed once. The general outline of the program is to interrogate the switches during each program pass through and react as dictated by program logic. Operationally, when switched to the "run" mode, the program reads the substrate moisture sensors, determines whether or not irrigation should be initiated (via the solenoid valves), stores the data on the SD card, and displays the information on the LCD screen. When switched to the "set" mode, the program reacts to the settings of other switches to either raise or lower the VMC set point, displays the information on the LCD screen, and captures the set point value for future use, storing it in the microcontroller's EEPROM memory. In the "calibration" mode, if the capture button is not activated, the program reads the "sensor select" switch, and then reads the sensor selected and displays the reading on the LCD screen. If the capture button is activated, the program turns on the appropriate solenoid valve corresponding to the "sensor select" switch.

Performance trials

Zinnia seedlings (*Zinnia elegans* Jacq. 'Thumbelina'), started from seed, were grown in 700 cm^3 plastic pots containing soilless substrate (Ball Professional Growing Mix, BPGM; Ball Horticultural Co., West Chicago, IL) mixed with controlled release fertilizer [Osmocote 14-14-14 (14.0N-6.1P-11.6K)]. The plants were grown under lights (90 $\mu molm^{-2}s^{-1}$ photosynthetic photon flux; 12 h photoperiod) at 18-25C and 50 ± 5% RH for three weeks and watered by hand to keep the substrate moisture content at or above field capacity (-33 kPa). At the start of week 4, a capacitance sensor (EC-5) was inserted into the substrate in four of the pots, the sensor being positioned so its volume of influence was contained entirely within the substrate matrix (Figure 2). After sensor insertion, the seedlings were placed back beneath the lights for an additional week to allow time for stabilization at the sensor-substrate interface.

The WM performance trial was initiated at the start of week 5 by placing 20 potted seedlings in an irrigation system constructed from four equal lengths of plastic polytube, each length fitted with 10 equally-spaced pressure-compensating emitters (model PCP10, Griffin, Fresno, CA). Each line was capped at one end with a metal plug and the other end connected to a solenoid valve. Each solenoid valve, in turn, was connected to the WM microcontroller as shown in the wiring schematic (Appendix A). The emitters located along each irrigation line were attached to dribble rings made from plastic tubing, allowing irrigation water to flow at 1.8 mLs^{-1} with water pressure set at 20 psi. For each irrigation line, emitters at positions #1, #2, #5, #6, and #9 were connected to pots containing zinnia seedlings, with pot #2 encompassing the EC-5 sensor. For the five remaining emitter ports along each line (positions #3, #4, #7, #8 and #10), plastic containers were positioned to collect the water released from each dribble ring during every irrigation event. To start the trial, microcontroller threshold values were set at 0.125, 0.225, 0.325 and 0.425 m^3m^{-3} for irrigation lines 1-4, respectively. The trial was designed so that after the initial threshold was reached and maintained for 5-7 days, the threshold value was reset either higher or lower than the original setting. Whenever VMC fell below the prescribed set point (measured by the EC-5 sensor embedded in pot #2), the solenoid valve connected to that line was activated, releasing water through each of the ten emitter ports. Since van Iersel et al. [8] have demonstrated that substrate-specific calibrations can improve the accuracy and reliability of measuring VMC, a pre-determined substrate-specific calibration for BPGM [VMC=(voltage x 1.4670)-0.4197] was used in these studies. The BPGM-specific calibration was determined following procedures described by Cobos and Chambers [9].

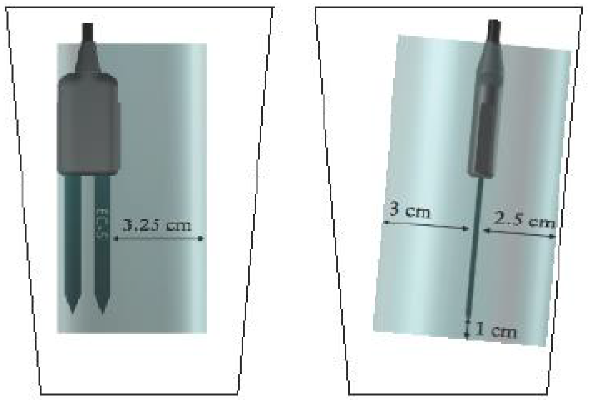

Figure 2: Scale drawing showing positioning of EC-5 capacitance sensor inside 700cm^3 plastic pots. Probe was inserted to ensure that the sensor's sphere of influence was contained entirely within the substrat matrix.

For these trials, the WM system was programmed to record the following parameters:

1. Date and real clock time, and, for each of the four irrigation supply lines;
2. The preselected VMC set point;
3. The actual real-time VMC reading;
4. The number of 5-second irrigation cycles occurring every 0.5 h. These data were subsequently used to determine the following parameters for each threshold setting:

a) The number of days to reach the threshold,

b) The number of irrigation events to reach the threshold,

c) The volume of water to reach the threshold,

d) The number of irrigation events to maintain the threshold,

e) The volume of water to maintain the threshold,

f) variation in VMC mean during a 5-7 day maintenance period.

Results and Discussion

A summary of the irrigation data collected during the WM trials and a graph illustrating day-to-day variation in VMC are found in Table 1 and Figure 3, respectively. Measurements recorded during the first series of threshold set points (Table 1) showed that the WM system effectively controlled VMC for irrigation lines #2, #3 and #4 within a range of ± 0.04 to ±0.06 m^3m^{-3}. For line #1 [the lowest VMC setting (0.125 m^3m^{-3})], the potted zinnia seedlings connected to this line exhibited signs of water stress (foliar wilt) after 10 to 12 days without water; however, substrate VMC remained above this threshold setting. These data indicated that a VMC of 0.125 m^3m^{-3} was too low to support the growth of potted zinnia seedlings without causing plant-water stress, and was likely caused by the higher wilting point range required for peat-based substrates like BPGM.

Variable	Irrigation line number			
First threshold setting (m^3m^{-3})	**1**	**2**	**3**	**4**
	0.125[y]	0.225	0.325	0.425
No. of days to reach threshold	-	8	4	1
No. of irrigation events to reach threshold	-	0	0	0
Vol. of water to reach threshold (mL)	-	0	0	0
No. of irrigation events to maintain threshold	-	9	28	36
Vol. of water to maintain threshold (mL)				
Determined from WM dataset	-	81	252	324
Actual vol. of water collected	-	81	255	328
VMC deviation during maintenance period (m^3m^{-3})	-	± 0.06	± 0.06	± 0.04
Second threshold setting (m^3m^{-3})	0.325	0.425	0.155	0.225
No. of days to reach threshold	2	1	8	5
No. of irrigation events to reach threshold	27	5	0	0
Vol. of water to reach threshold (mL)	243	45	0	0
No. of irrigation events to maintain threshold	50	49	16	34
Vol. of water to maintain threshold (mL)				
Determined from WM dataset	450	441	144	306
Actual vol. of water collected	450	437	149	298
VMC deviation during maintenance period (m^3m^{-3})	± 0.04	± 0.05	± 0.04	± 0.05

[y] Prior to reaching the 0.125 m^3m^{-3} threshold for line #1, the seedlings grown in pots connected to this irrigation line started to wilt, which necessitated increasing the threshold set point before the WM was activated.

[z] Tests conducted with 5-week-old containerized zinnia seedlings grown in 700 cm^3 plastic pots containing soilless substrate (Ball Professional Growing Mix™). Each value represents a single measurement except for the "Actual volume of water collected", which is the mean of five measurements.

Table 1: Irrigation data collected during WaterMaster (WM) evaluation trials[z].

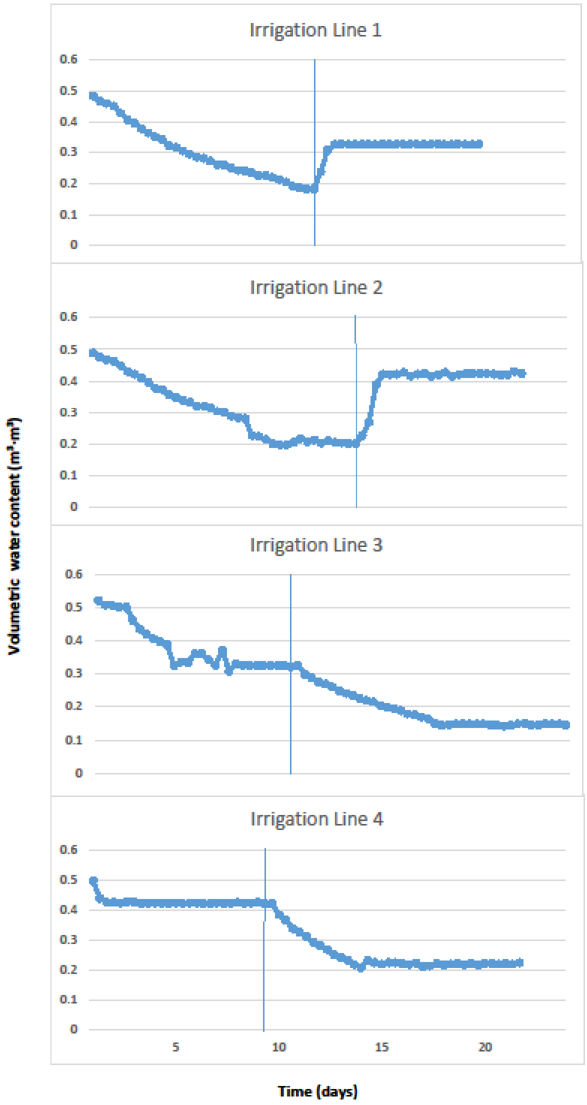

Figure 3: Graph of daily variation in substrate volumetric moisture content (VMC) in pots containing 5-week-old Zinnia elegans seedlings irrigated automatically with the WaterMaster (WM) system. VMC was monitored continuously by capacitance sensors (EC-5) placed in a single pot in each of four irrigation lines. VMC thresholds were established on day 1 for all four irrigation lines, and again on days 12, 13, 10 and 9 for irrigation lines 1-4, respectively (vertical lines in Figure 3). After reaching each threshold set point, VMC was maintained and monitored continuously for 5-7 days.

The data in Table 1 also show that the time required to reach the first series of VMC threshold settings (with the exception of line #1), varied from one day (line #4; 0.425 m^3m^{-3}) to eight days (line #2; 0.225 m^3m^{-3}). These differences reflect the time required for the substrate to dry down to the prescribed threshold setting as a result of evapotranspiration - the lower the threshold, the longer the dry-down period. Once each threshold was reached, the number of irrigation events necessary to maintain that threshold for 5-7 days ranged from 9 (line #2; 0.225 m^3m^{-3}) to 36 (line #4; 0.425 m^3m^{-3}), and, once again, the lower the maintenance threshold, the fewer irrigation events required to maintain that threshold (Table 1). One unique feature of the WM evaluation trial was the ability to compare the calculated volume of water required to maintain a given threshold (determined from the WM dataset) with the actual water volume collected in containers placed at five emitter ports along the same irrigation line. These data (Table 1) showed that the maximum difference between the calculated and actual water volumes was only 1% (4 mL).

Following completion of the first set of maintenance trials, the irrigation lines were reset to a preselected alternate VMC threshold value (Table 1 and Figure 3). Also at this time, irrigation line #3, originally designated to be reset from 0.325 m^3m^3 down to 0.125 m^3m^{-3} was, instead, reset slightly higher (0.155 m^3m^{-3}) to avoid the foliar wilt problems encountered during the first evaluation trial. Results of the second series of tests (Table 1) showed that whenever substrate VMC was increased from a lower to a higher threshold (e.g., irrigation lines #1 and #2), the number of irrigation events concomitantly increased as the sensors called for additional water. Likewise, when the threshold setting was reduced (e.g., irrigation lines #3 and #4), the corresponding solenoid valve was not activated since no irrigation was required to reach a lower VMC.

As observed in the first trial, the WM system effectively controlled irrigation for the second series of threshold settings as well (Table 1 and Figure 3). Once each secondary threshold value was reached, the number of irrigation events required to maintain that threshold varied from 16 (0.155 m^3m^{-3}) to 50 (0.325 m^3m^{-3}). Correspondingly, the volume of water necessary to maintain each threshold ranged from 144 mL (0.155 m^3m^{-3}) to 450 mL (0.325 m^3m^{-3}) and, as previously noted, the volume of water calculated from the WM dataset matched closely (maximum difference of 3%; 8 mL) with the actual volume of water collected in containers from the same irrigation line. During these evaluation trials, comparing water-use determined from the WM dataset with the actual amount collected in the containers from the same irrigation line resulted in an R^2 value of 0.99 with an intercept not significantly different from 0, and a slope of 1.002. These results illustrate the reliability of the WM system in maintaining water-use based on irrigation time and system flow rate.

In previous studies using sensor-based irrigation systems, Nemali and van Iersel [10] and van Iersel et al. [8] report finding larger fluctuations in VMC at lower threshold values. In the current study, fluctuations in VMC were not associated with either higher or lower threshold settings. These results are in agreement with those reported by Ferrarezi et al. [4], who tracked irrigation in containerized hibiscus plants. Since a certain degree of variation in VMC over time is inevitable, even for containerized crops of the same species grown under similar conditions, growers must decide for themselves on an acceptable degree of accuracy before sensor deployment. This decision will impact not only the appropriate number of sensors to use, but the optimum location of each sensor as well. Daniels et al. [11] recommend using the minimum number of sensors required to estimate the mean substrate VMC within a confidence interval of ± 5% VMC. In previous studies on sensor orientation, the same authors report that sensors placed at half the depth of the pot provide a reliable estimate of bulk VMC, and Hagen et al. [12] report that sensors placed either vertically, horizontally or diagonally, all show a strong linear relationship with substrate VMC measured gravimetrically.

Conclusions

The standalone WM microcontroller/data logger system described in this report effectively controlled substrate VMC in container-grown zinnia seedlings using capacitance sensors to trigger irrigation via solenoid valves from a pressure-controlled water source whenever VMC fell below pre-programmed threshold settings. The WM is a compact, portable, economical, autonomous system providing user information on an LCD screen, storing recorded data on an SD card and allowing irrigation threshold settings to be changed without reprogramming the microcontroller. In evaluation trials, the WM system accurately supplied irrigation water based on plant demand. The reliability of the system was confirmed by measuring the deviation in VMC over a 5-7 day maintenance period and by comparing the calculated volume of water from the WM dataset with the actual volume of water collected in containers placed along the same irrigation line. The WM system components can be purchased and assembled at a reasonable cost, making this technology affordable and useful for a wide range of growers, especially those who may not wish to invest in more expensive WSN irrigation systems.

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