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Data Acquisition System and Irrigation Controller Based on CR10X Datalogger and TDR Sensor

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ABSTRACT

The objective of this paper was to develop, test and describe a data acquisition system and irrigation controller (DASIC) using commercially available devices from Campbell Scientific, Inc., Logan, UT: datalogger (CR10X), control-port expansion (SDM-CD16), single-ended/differential channel multiplexer (AM416), switch-closure input module (SDM-SW8A), and CS615 water content reflectometer. The controlled irrigation system was a subsurface drip irrigation (SDI) system. Two drip tape depths (23 and 33 cm) and two different irrigation-scheduling strategies (time-based and sensor-based scheduling) were combined into four SDI treatments that were tested in a sweet corn (*Zea mays* L.) experiment. Each treatment and a non-irrigated control plot were replicated four times. Sprinkler irrigated plots, controlled by an independent device, were also included. In two out of the four replications, two sensors were installed on the SDI plots, one 5 cm above the drip tape and one 61 cm below the ground surface. The CR10X was programmed to collect soil moisture content data every 15 min from 16 sensors, through the multiplexer, and to act on solenoid-valves through a parallel-port relay board, according to internal decisions based on either predetermined time or sensor strategy. Data were downloaded from the CR10X memory once a week. The sensor-based strategy permitted easy control of water application, showing great potential for automatic irrigation management, given locally adequate threshold. The DASIC performed both data acquisition and irrigation control tasks very well, permitted the observation of irrigation system behavior, and allowed the weekly evaluation and adjustment of the irrigation strategies.

INTRODUCTION

On a global scale, more efficient use of fresh water for irrigation is an increasing concern due to the unrestricted use of the available water that leads to depletion and degradation of natural water resources. Reduced availability of ground water in extensive areas of the globe aggravates this situation.

Annual rainfall in Florida ranges from 1100 to 1500 mm (435 to 59 in). However, most crops require supplemental irrigation for optimal yields due to the poor water holding capacities of most Florida soils and non-uniform rainfall distribution. Smajstrla and Haman (1999) showed how the irrigated acreage has increased from 1954 to 1998, reaching 902 000 ha (2.23 million acres) in 1998. Increases in residential water use, mainly due to increasing in population, will further reduce future availability of fresh water for the irrigation of agricultural crops.

It is possible to significantly increase the efficiency of irrigation and reduce water usage if new methods, such as precision irrigation based on electronics and information technologies, are used in the automation of irrigation systems. This aspect is particularly important for regions with variable climatic conditions.

The automatic control of water application in irrigation systems has been improved with the use of computers, hydraulic valves, sensors, electro-mechanical, and electronic actuators. The sensors most widely used are those that measure soil moisture and climate variables. These sensors allow varied levels of automation according to local conditions. In general, common tasks such as cleaning filters, turning on and off pumping systems and opening and closing irrigation valves, are automated. These tasks are often based on water volume, timing, or feedback from sensors. Sensors that measure crop water status, sap flow, transpiration, and other parameters are used too. However, their use is normally restricted to greenhouses due to the high cost of these sensors.

A software-based user-interface is used to interpret and process information obtained from sensors. The information processing is done based on irrigation management instructions and in response to soil moisture change detected by a sensor. Design of the user interface must account for the fact that the system operator is usually not an irrigation and computer expert.

Time Domain Reflectometry Technology

Time domain reflectometry (TDR) technology has been employed successfully in a variety of applications, such as monitoring of rock mass deformation and subsidence in a variety of geometries, and measurement of water level, water pressure, and soil moisture content (Huang and Dowding, 2000). The TDR method measures the travel time of an electrical pulse in a transmission line buried in the soil to detect soil water content. The travel time is directly affected by the soil dielectric constant (Campbell and Anderson, 1998), which is predominantly a function of free water content (SRPRT, 2000). The large dielectric constant of free water (81), relative to dry soil (between 3 and 8), allows for accurate measurement of soil moisture content (SRPRT, 2000) and to register small changes in water content (as small as 0.006 m^3m^{-3}) (Campbell and Anderson, 1998).

According to Noborio (2001), applications of TDR techniques to measure water content and electrical conductivity in soil have improved greatly over the last two decades. He listed some instruments developed based on TDR techniques: 1502/B/C (Tektronix, Inc., Beaverton, OR), TRASE Systems (Soilmoisture Equipment Corp., Goleta, CA), TRIME (IMKO GmBH, Ettlingen, Ger-

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many), Moisture Point (ESI Environmental Sensors Inc., Victoria, British Columbia, Canada), Theta Probe (Delta-T Devices Ltd., Burwell, Cambridge, UK) and others.

Laurent et al. (2001) compared the performance of several independent soil moisture measurement methods with the TRIME-tube method, which is a system designed for vertical water content profiling. The field calibration, which is similar to that of a neutron probe, can produce accurate and sensitive readings well suited for long-term profile monitoring.

Herkelrath and Delin (2001) reported that the CS615 reflectometer probe performed better than the CS605 TDR probe in both laboratorial and field testing, even during power supply shortages and harsh weather conditions. Over a prolonged period of time, the reflectometer probes provided more dependable and accurate data, than the TDR probes. However, regardless of the sensor type, sensors installed beneath the water table or within the capillary fringe eventually failed. Furthermore, a large discrepancy in calibrations was noted between those supplied by the manufacturer and those using soil from the field site. The reflectometer probes were also more sensitive to electrical storms. Vertical installation of TDR probes apparently created a preferential pathway that caused moisture content to increase near the probes, yielding higher soil water readings.

Souza et al. (2001a) found TDR multi-wire probes with electrical impedance discontinuities to be useful in the determination of the wetting front in drip irrigation applications. Souza et al. (2001b) found that Topp's equation is inadequate for tropical soils. Using soil-deformed samples in laboratory conditions, they reported difficulties in obtaining a calibration curve containing the total range of moisture used in irrigation management. In field conditions, the readings of apparent dielectric constant were greatly affected by the soil-bound water. More satisfactory results were obtained when the experimental data from laboratory and field methodologies were combined.

Hardware for Irrigation Management and Control

Recent developments in electronic and information technologies have resulted in the development of powerful electronic measurement instruments, which are more reliable than mechanical models. These instruments can generate greater amounts of data that can be transmitted to a computer or automatic data collection equipment (Espinosa and Aguilar, 1996).

With such equipment, it has become possible to automate microprocessors, which will allow automatic irrigation programming for extended periods of time, including an automatic estimate of irrigation needs. The decision for the ideal automation level should be made considering technical and economic criteria and the preferences of farmers. Decisions should consider the training of individuals responsible for operating the system and the availability of replacement parts and maintenance services (Lopez et al., 1992).

According to Pizarro (1987), high frequency micro-irrigation systems are easily automated because they consist of a network of fixed pipe lines, are operated with low flow rates, have relatively large irrigation subunits, are not influenced by atmospheric factors such as wind, and do not interfere with most field operations. Testezlaf et al. (1996) developed an automatic computerized control system for handling irrigation of plants grown in vases inside greenhouses using soil moisture sensors and a microcomputer with software and an input/output card.

Software for Irrigation Management and Control

According to Sontag (1998), three things are necessary to make an intelligent irrigation system: 1) an interface to enable easy access and control devices throughout the system, 2) a way to gather and analyze environmental conditions, and 3) a decision-making process to adjust the control devices based on current information.

Several programs for irrigation scheduling were developed using climate, soil and crop data to calculate the crop water requirements and irrigation timing. In Brazil, a good example of an irrigation software system is Sistema de Suporte a Decisão Agrícola (SISDA) (Agricultural Decision-Making Support System), developed by the Agric. Engineering Dep. of Federal Univ. of Viçosa. The main goal of the program is irrigation management using both stored and current local data. The SISDA also allows crop development simulation throughout the entire crop cycle. The program uses database information related to the climate, soil, irrigation systems, and equipment (Mantovani et al., 1997).

Leib et al. (2002) reported the development of Washington Irrigation Scheduling Expert (WISE) software to meet the needs of farmers. The WISE software was written to allow easy access to reference evapotranspiration (ET) from Washington's 59 Public Agriculture Weather Stations, and employs a short-term water balance routine that can be adjusted for soil moisture conditions. The graphical user interface is intuitive and helps the user input their field specific parameters such as crop type and planting date, soil moisture and irrigation system specifications. The WISE software is also an educational tool that teaches the principles of irrigation scheduling, since it displays irrigation scheduling calculations.

Torre-Neto et al. (2000) developed an automated system based upon fixed instrumentation which used soil probes with temperature and matric potential sensors to measure spatially-variable soil conditions. They also used a controlled microsprinkler irrigation system on a spatially-variable basis by both local and remote operation using a RS-485 network and RS-232 radio-modem transmission. The software system used to control the system was based on LabVIEW (National Instruments Corp., Austin, TX).

The objective of this paper is to present a data acquisition system and irrigation controller (DASIC), developed initially for the specific purpose of controlling subsurface drip irrigation events in a sweet corn and peanut (*Arachis hypogaea* L.) rotation experiment. The

DASIC was based on the following devices: CR10X datalogger, SDM-CD16 control port expansion with drivers, AM416 relay single ended/differential channel multiplexer, SDM-SW8A switch closure input module, CS615 water content reflectometer, and a parallel port relay board. Soil moisture data were collected from 16 TDR sensors through a multiplexer and stored in CR10X memory. The same set of data was used for internal decisions such as turning the valves on or off, based on both sensor scheduling and time scheduling.

MATERIAL AND METHODS

The field site is located at the Univ. of Florida Plant Sci. Res. and Educ. Unit, near Citra. A subsurface drip irrigation system was used to irrigate the experimental plots of a sweet corn and peanut rotation experiment, where DASIC was tested. In the first season, sweet corn was planted on 21 Mar. 2002, at 5-cm depth using a mechanical planter.

There were 32 plots each 15.2 m by 4.6 m (50 ft by 15 ft) arranged in four replicated blocks (Table 1). Out of eight plots in each block, four were subsurface drip irrigation (SDI) treatments which were controlled by the DASIC, one was a sprinkler treatment and was not part of the DASIC, one was the control that was not irrigated, and two were borders for the sprinkler irrigated treatment. The borders were irrigated by surface drip irrigation that was controlled on a time basis. The SDI system was designed to supply water for four treatments that were a combination of two irrigation-scheduling strategies (time-based and sensor-based) and 23- and 33-cm (9 and 13 in) installation depths.

The drip tape used was Typhoon 630 (Netafim USA, Fresno, CA) with an emitter spacing of 30 cm (12 in), 330 μm (13 mil) thickness, and a flow rate of 0.98 L h^{-1} (0.26 gph) at 70 kPa (10 psi). The installation of the drip tapes was accomplished using a subsoiling shank, which could be adjusted for various installation depths. Each plot consists of six rows spaced 76.2 cm (2.5 ft) apart with one drip line directly under each crop row.

Two irrigation-scheduling strategies were used in the experiment. They consisted of (1) time-based irrigation, in which the events were triggered and run for a predetermined time and (2) sensor-controlled irrigation, where the sensors controlled both the start and the end of irrigation events (Table 1). Sensor installation was the same for both strategies.

Each set of sensors consisted of two sensors, a "shallow" and a "deep" sensor (Fig. 1). The shallow sensors were installed 5 cm (2 in) above the drip tape, and the deep sensor was installed 63 cm (24 in) below the ground surface. The deep sensors measured the soil moisture content below the crop root zone and were used to indicate excessive irrigation. The shallow sensors measured the soil moisture content in the root zone and were used for irrigation decisions. Two out of four replications of all four SDI treatments were instrumented with TDR sensors at two depths, totaling 16 TDR sensors in the experimental area.

The DASIC allowed threshold moisture levels to actuate irrigation valves. The moisture level was calculated as an average of soil moisture content read by the upper sensors, which were collected at the same depth in two different replications of the treatment. This value was compared to the threshold, and the irrigation decision for that treatment was made.

The lower and the upper limit for the soil moisture content (SMC) were established based on soil properties. With the purpose of testing the DASIC functionality, two sets of thresholds were analyzed in this paper configuring two field situations: (1) 60 min every day for the time-based strategy and soil moisture content limits of 0.10 cm^3cm^{-3} to turn ON and 0.14 cm^3cm^{-3} to turn OFF; and (2) 45 min every day and 0.07 cm^3cm^{-3} ON and 0.12 cm^3cm^{-3} OFF, respectively. The DASIC program compared readings from a treatment to these thresholds every minute. Although readings occurred every minute, 15-min averages were stored for post processing. For the time-based strategy, an application time that simulates farmer practices was used (e.g., irrigate 1.0 h daily), and the sensor readings were used to monitor soil moisture content. This time-based strategy can be defined by the irrigation manager to be daily, every other day, or every third day, starting at any time during the day.

Distribution and control of the water to all treatments, was accomplished via a distribution manifold. The main components of the manifold were ball valves and solenoid valves, flow meters, pressure regulators, pressure gauges, and inlets for chemical injections. Chlorine was injected to clean the lines periodically, using a peristaltic pump. From the manifold, the water was delivered through a polyethylene pipeline network (Fig. 2).

The DASIC components were installed in two boxes: the control box and the power box. The power box contained a 12 V battery, an automatic charger for

Table 1. Treatment identification, scheduling strategies, type of irrigation control and automation system used to test the DASIC.

Treatment	Treatment name†	Irrigation scheduling	Irrigation control	Automation
1	SDI-23T	Time Schedule	Time	DASIC
2	SDI-23S	Sensor Schedule	TDR sensor	DASIC
3	SDI-33T	Time Schedule	Time	DASIC
4	SDI-33S	Sensor Schedule	TDR sensor	DASIC
5	Sprinkler	Time Schedule	Time	Independent Device
6	Control	None	None	None
B	Border	Time Schedule	Time	DASIC

†SDI-23 and SDI-33 = Subsurface Drip Irrigation with drip tape installed at 23 and 33 cm (9 and 13 in), respectively.

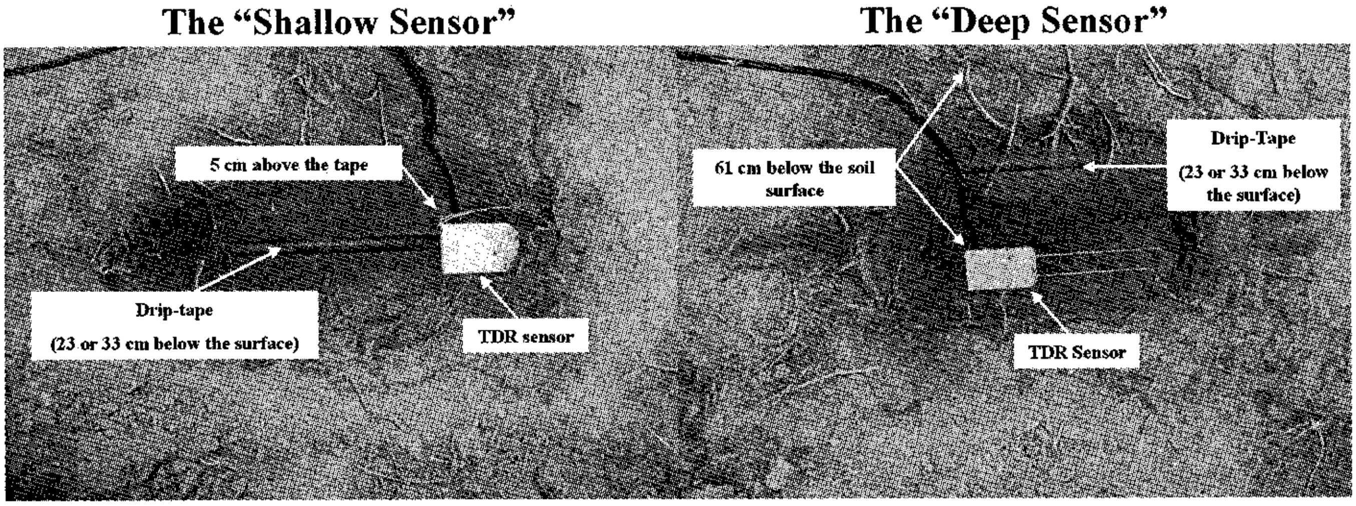

Fig. 1. Position of installation of drip tape and sensors for SDI treatments.

the battery, and a 120 V × 24 V power transformer for supplying 24 V to the solenoid valves. In the control box there were data acquisition and irrigation control devices: datalogger (Campbell Scientific CR10X), control port expansion with drivers (Campbell Scientific SDM-CD16), single ended/differential channel multiplexer (Campbell Scientific AM416 Relay Multiplexer), switch closure input module (Campbell Scientific SDM-SW8A), and a parallel port relay board. The control box with the DASIC components is shown in Fig. 3.

The diagram in Fig. 4 shows the connections among the DASIC components. In order to get information from all 16 single-ended TDR sensors to the CR10X datalogger a multiplexer was required. Similarly, a switch closure input module was required to acquire the data from all five flow meters, which contain pulse type sensors. In addition, a control port expansion was used to supply control ports to control the solenoid valves. The PC relay board was used to interface the CR10X and the solenoid valves. The relays in the board were energized from control ports and enabled the 24 V power supply for the solenoid valves.

To control the system, the CR10X datalogger needs a specific program in the memory. The program structure was based on three different sections called "Table 1", "Table 2", and "Table 3", which are not tables, but only subdivisions of the programming area. "Table 1" and "Table 2" include the main instructions of the program. The first parameter defined in these two "Tables" is the time interval used to execute its instructions. This parameter can be understood as resolution time for all the instructions in the "Table". "Table 3" is used for the subroutines that can be called from any part of the other "Tables". The most important instructions used in the DASIC program were "Excitation with Delay" (P22), that allows reading the TDR 1-16 through the multiplexer, "Period Average (SE)" (P27), that reads the single-ended channel, and "Polynomial (P55)", that converts the time information from the TDR sensors into soil moisture content using a polynomial calibration.

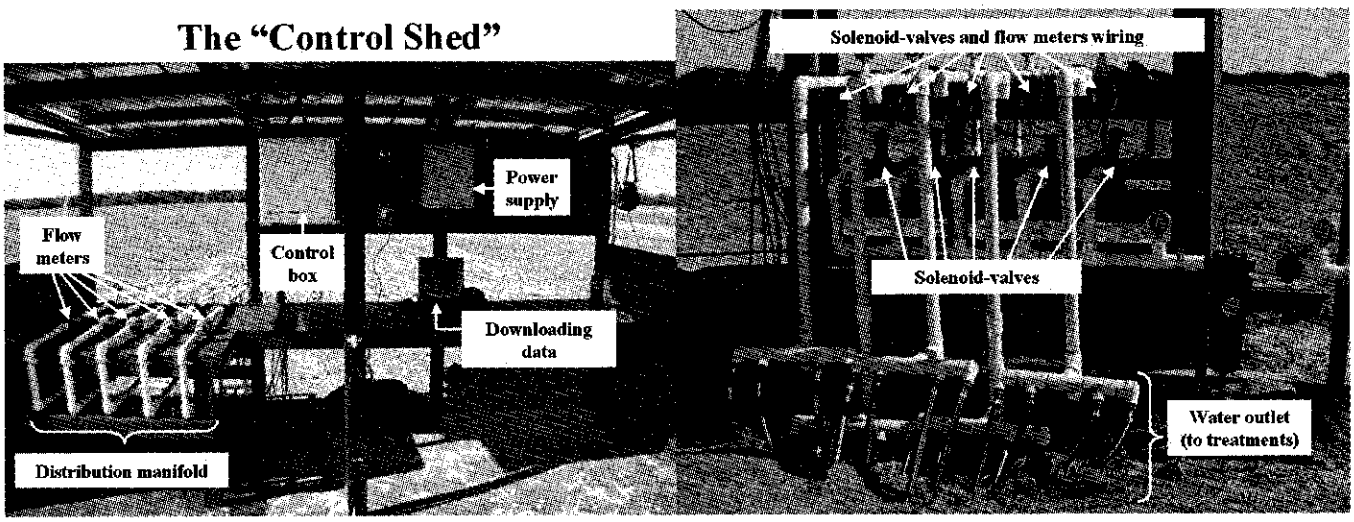

Fig. 2. Components of DASIC and the manifold for water distribution and control.

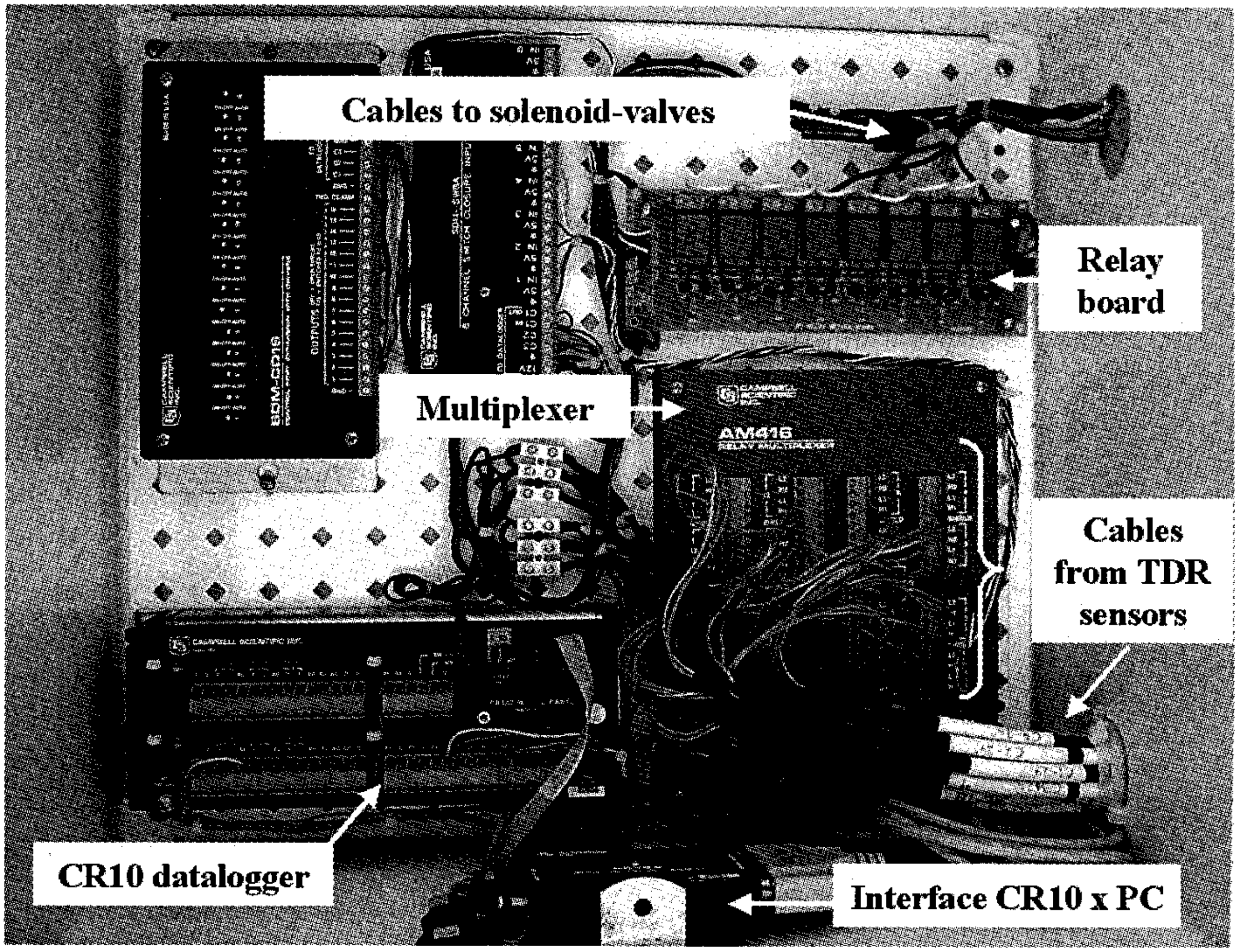

Fig. 3. DASIC components housed inside the control box.

The DASIC program used instructions to acquire data from the sensors, and convert and store data for further use and download. Decision instructions were included to perform continuous comparisons between irrigation thresholds and the acquired data. The irrigation decisions were used to actuate the solenoid-valves. Irrigation thresholds were defined to be the upper limit and the lower limit of soil water content suitable for that crop in that growth conditions, according to soil information and prior experiences in that agricultural environment.

The DASIC has been installed and has been operating the irrigation system as described. The data stored in datalogger memory was downloaded at least once a week as a comma-separated text file, which can be imported by different software for processing, including spreadsheet software to show the behavior of the variables with time.

RESULTS AND DISCUSSION

A 15-d period was chosen for the discussion on the DASIC performance because it illustrates different aspects of irrigation management. Two rainfall events (4 and 11 mm), a chlorine application and the change in the soil moisture thresholds were registered by the DASIC as shown in Fig. 5. The graph of the soil moisture content registered by the TDR sensors right above the drip tape in all four treatments SDI-23T and SDI-33T (time-based), and SDI-23S and SDI-33S (sensor-based) demonstrates the DASIC ability as a useful tool to monitor very closely how the system behaves. With a temporal resolution of 15 min for all four SDI treatments, the plotted information permits the irrigation manager to get very detailed information from the system, which is quite helpful for the decision making process, mainly if it is a research project. For practical applications, this level of resolution may not be necessary, unless the irrigation system has a high level of automation.

In general, the time-based strategy produced similar behavior for both SDI-23T and SDI-33T treatments following a pattern of alternating peaks and valleys. The small differences observed between peaks and valleys of these two graphs are mostly due to the soil characteristics of the layers where the sensors were placed in each treatment. Changing daily the application time from 60

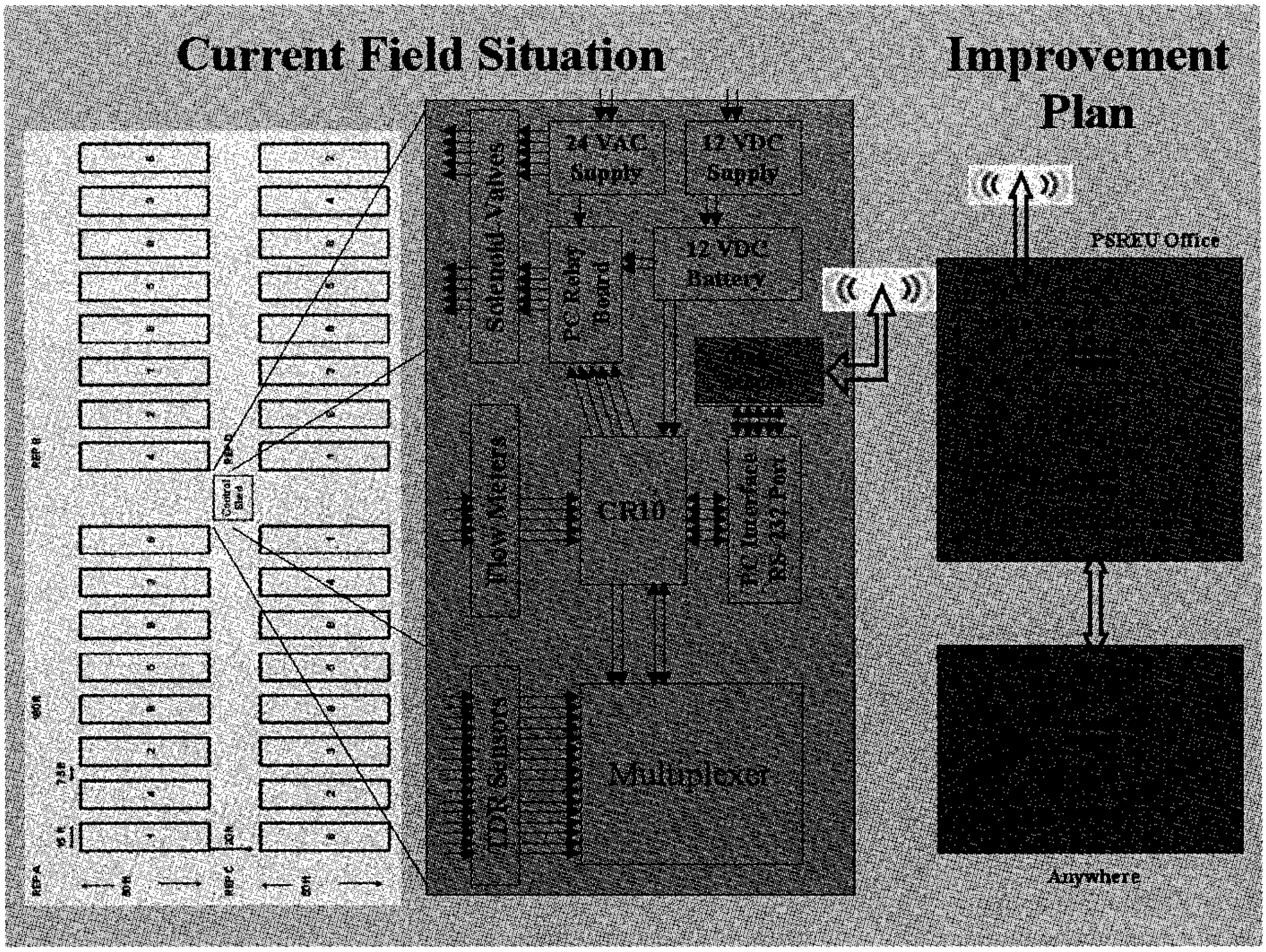

Fig. 4. Diagram of connections for DASIC components and future improvements.

to 45 min slightly changed the amplitude of the irrigation cycles, from ≈0.045 to 0.035 cm³cm⁻³ of water content. This change was observed only in the deeper treatment (SDI-33T) and almost no difference was seen in the shallower treatment. In addition, a greater increase in moisture content with the same amount of applied water can be observed in treatment SDI-23T compared to SDI-33T, indicating a difference in the soil moisture characteristics of the two layers.

The sensor-based strategy behaved differently from the time-based strategy in both SDI-23S and SDI-33S treatments. Initially, the irrigation threshold was set at 0.10 cm^3cm^{-3} ON to 0.14 cm^3cm^{-3} OFF, but later on it was changed to 0.07 cm^3cm^{-3} ON to 0.12 cm^3cm^{-3} OFF. Before modifying the irrigation set-point, the water application was excessive for the shallower treatment, promoting excessive drainage, which resulted in water loss below the root zone. Furthermore, the deeper treatment did not initiate any irrigation cycle with the same thresholds, which indicates the different soil characteristics in that layer. When the lower limit of the volumetric moisture content in both treatments was changed from 0.10 cm^3cm^{-3} to 0.07 cm^3cm^{-3}, the irrigation cycle was not activated during a 15-d period. Without irrigation events, both treatments showed a constant decrease in the moisture content with a tendency to stabilization. At "steady-state", soil moisture was around 0.07 cm^3cm^{-3} for the SDI-23S treatment and around 0.11 cm^3cm^{-3} for the SDI-33S treatment, respectively. The difference in these values was probably related to the differences in physical characteristics of the soil layers. In addition, plants were too small and root systems too shallow to deplete residual soil moisture at greater soil depths.

Two rainfall events occurred during this 15-d period. The first rainfall was only 4 mm and did not greatly affect the soil moisture content, however it was large enough to skip one irrigation cycle in the SDI-23S treatment. This probably only happened due to the higher moisture thresholds at the beginning of the period. The second rainfall event of 11 mm was large enough to cause an increase in soil moisture content as can be seen clearly on the graphs for both depths of sensor-based treatments (SDI-23S and SDI-33S), but not so clearly for both depths of time-based treatments (SDI-23T and SDI-33T).

The chlorine application appeared as an isolated irrigation event in the middle of the selected period and

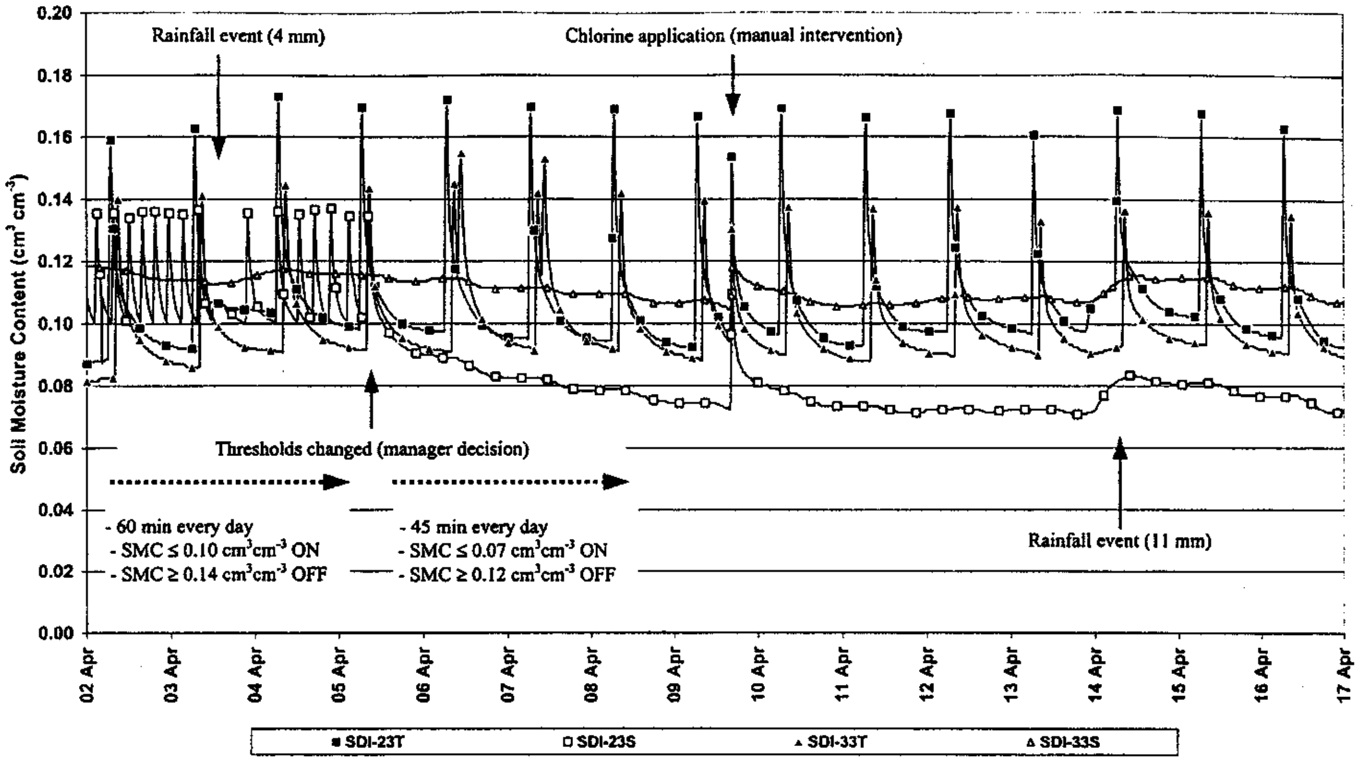

Fig. 5. Average across two replications of TDR sensor readings of soil moisture content (SMC) at a depth of 23 and 33 cm (9 and 13 inches) from four SDI treatments controlled with DASIC. For complete description of treatments see Table 1.

between two automatic events for time-based treatments, because it was manually activated. The amount of water applied by this manual event slightly raised the moisture content, but the moisture content stabilized again after 24 h.

Overall, evaluating the activity of the irrigation system throughout this 15-d period, regarding water and energy consumption, it can be concluded that both sensor-based treatments are potentially superior to the time-based treatments. Both sensor-based treatments did not irrigate after adjusting moisture levels. On the contrary, both time-based treatments resulted in 11 irrigation events, which could mean in certain situations loss of water in the deeper layers (deep percolation).

A graph of 15-min averaged soil moisture content from the TDR sensors installed at the 63-cm (24-in) depth illustrates the behavior of soil moisture content in a layer below the crop root system during the same period of 15 d for all four treatments (Fig. 6). These TDR sensors were not used in the control program for irrigation decisions. This monitoring was used to verify the result of the irrigation manager decisions. Both curves of time-based strategy (SDI-23T and SDI-33T) treatments demonstrate that the soil moisture content was increasing constantly, at a rate of almost 0.005 $cm^3cm^{-3}d^{-1}$, until the manager changed the application time from 60 to 45 min, and became more stable after that. The cycles of peaks and valleys in both curves reflect the effect of the daily irrigation cycles. The differences of ~0.02 cm^3cm^{-3} in soil moisture observed between the two treatments of this strategy are likely related to the variability in physical characteristics of the soil layers (water retention) and not related to the effect of the treatments. Besides, this sensor has an accuracy of ±2% over the water content range, according to the manufacturer.

Considering the sensor-based strategy, apparently both treatments are consistent in showing the effect of excessive irrigation on the decrease and stabilization of soil moisture content. When the shallower treatment (SDI-23S) operated with the initial higher threshold limits, some deep percolation occurred as shown by high readings for the deeper sensors (Fig. 6). After that, there was a gradual decrease in moisture content until it stabilized, indicating that the soil layer probably reached its field capacity. The deeper treatment (SDI-33S) presented a slight rate of decrease in moisture content during the first seven days of the studied period. After that, it seems that the moisture content stabilized, indicating that it also reached field capacity.

The rainfall events that occurred during the 15-d study period were not large enough to affect the soil moisture content at the 63-cm (24-in) depth (Fig. 6). Only the higher rainfall (11 mm) seems to have slightly affected the soil moisture at this depth, appearing in the curves on the subsequent day. The effect of the manual irrigation for chlorine application in the moisture content was quite visible on all curves.

Based on the results of all four treatments, it can be inferred that the daily supply of water for both time-based treatments (SDI-23T and SDI-33T) promoted a constant rate of percolation losses. On the contrary, both sensor-based treatments (SDI-23S and SDI-33S)

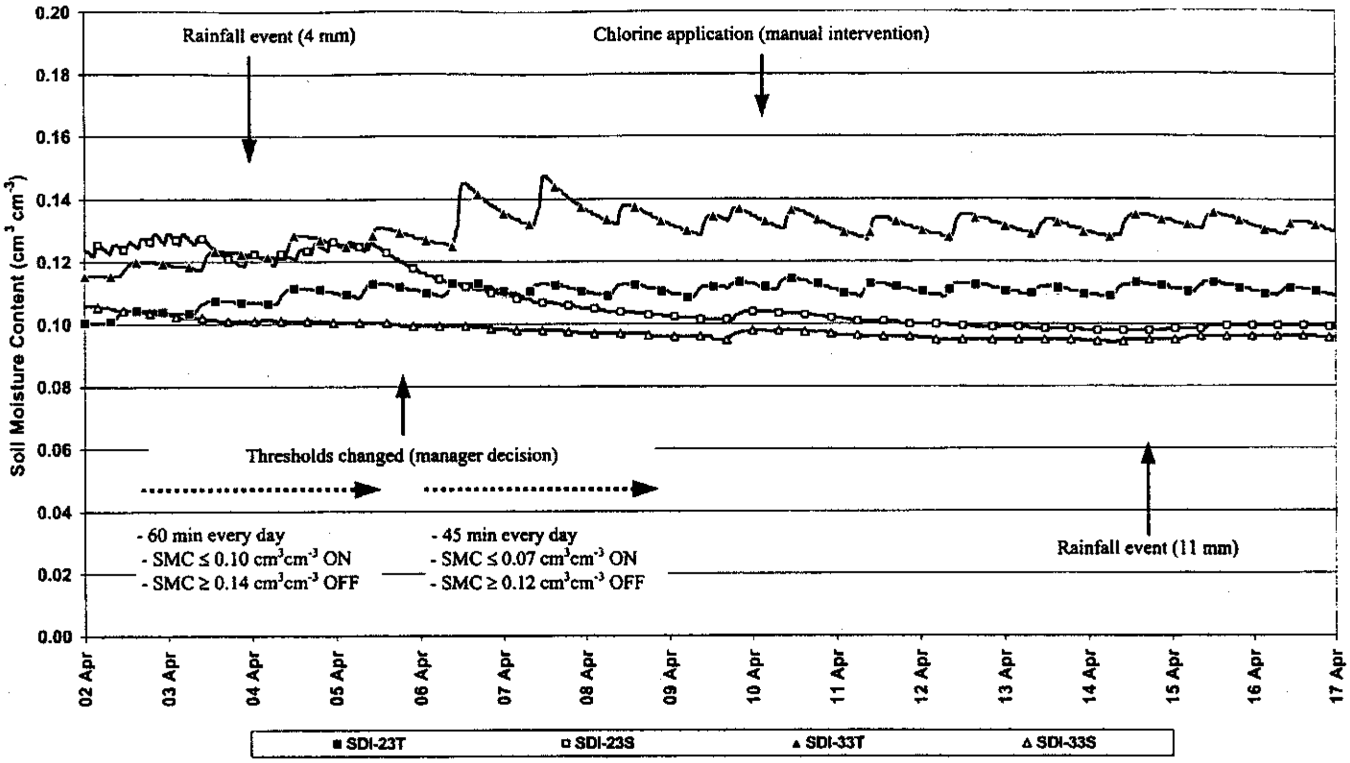

Fig. 6. Average across two replications of TDR sensor readings of soil moisture content (SMC) at 63 cm deep (24 inches) from four SDI treatments controlled with DASIC. For complete description of treatments see Table 1.

had the ability to save water and electricity. The DASIC permitted a thorough analysis of the system behavior, based on continuous readings of soil moisture content, and allowed for rapid decision making to correct possible problems in water management.

As an important improvement for DASIC, the authors recommend its connection to an office computer, using wireless communication technology, and to the Internet in order to remotely control the data acquisition and the irrigation management. To accomplish that, it is necessary to invest in a set of communication devices and specific software, which are already available on the market.

CONCLUSIONS

The DASIC proved to be an efficient tool for irrigation management. It collects data and controls the irrigation events according to predefined irrigation strategies. It allows for controlling the individual (or group of) solenoid valve enabling/disabling the irrigation events anytime in any treatment (irrigation zone), based on either sensor readings or predefined time schedule. It allows for continuous monitoring of external events and permits the adjustment of the thresholds as needed, according to the soil and crop conditions. It permits a complete analysis of the irrigation system behavior, based on continuous readings of soil moisture content, thus allowing for a rapid decision making to correct possible problems in fulfilling the crop water requirements. It can be upgraded to remotely control the data acquisition and irrigation management through wireless devices and Internet communication facilities.

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