A HIGH-RELIABILITY DATABASE-SUPPORTED MODULAR PRECISION IRRIGATION SYSTEM

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ABSTRACT

Reliability and flexibility of sensor network-based systems are real concerns in precision irrigation systems in places where fault repair is slow and where farms have a wide range of sizes and irrigation methods. A database-supported modular precision irrigation system was designed and developed at the Arab Open University in collaboration with the University of Alexandria. The system consists of isolated, self-contained modules for the weather station, valve control assemblies and soil sensor pods with well defined interfaces. Water release decisions for a given crop in a given locality are made based on the data received from the sensor network, information retrieved from a historical crop and weather database, manually, or by using hybrid methods based on combinations of those sources/methods. Preliminary results indicate that the database-support allows system operation with faulty sensors for longer periods until repairs can be made in the field, and stronger potential for more precise irrigation that is less sensitive to abnormal weather fluctuations. Furthermore, the modularity of the system allows reduction in system costs due to exclusion of unwanted modules, system augmentation by plugging in new modules, simpler customization, more flexible and scalable design and better suitability to a wider range of use conditions. The system is useful for application to varying farm sizes from small family farms to large organized farms and to different irrigation methods (sprinkler, drip and flood). In the Nile basin, where water is a contested commodity, the availability of home-grown systems with lower costs, more robustness and better flexibility is a much needed and promising direction of research and development.

Keywords: Modular Systems, Precision Irrigation, Sensor Networks, Reliability

INTRODUCTION AND MOTIVATION

Irrigation is the dominant user of fresh water. Worldwide about 70% of water use is for agriculture, with a much higher figure (85%) in low and middle income countries, where agriculture is a major economic sector (World Bank, 1992). In Egypt, Agriculture consumes about 80% of available fresh water. Egypt obtains most of its supply of fresh water from the Nile River, which it shares with nine other countries in the Nile basin, with a fast-growing total population of over 350 million. Egypt faces a potential reduction in its water share from the Nile river headwaters due to water contention. The performance of irrigation systems remains a central issue in water management (Perry, 2003). Irrigation systems, particularly in developing countries including Egypt, have generally been performing far below their potential. Thus, the levels of agricultural production and irrigation benefits are reduced making some of the systems financially and economically unattractive. This necessitated new methods for the irrigation planning and development (Raju and Kumar, 1999).

An efficient irrigation schedule is the application of water in the correct amount and only when needed. Over-irrigation tends to have environmentally costly effects because of wasted water and energy, leaching of nutrients and/or agricultural chemicals into groundwater supplies, degradation of surface water supplies by sediment-laden irrigation water runoff, and erosion (Ley, et al., 1994).

The aim of this paper is to present out ongoing work in constructing a home-grown automated system to provide a dynamic and smart scheduling of irrigation to match water use efficiency with commercial productivity in farms. The system is intended to deliver the optimum amount of water depending on weather conditions, crop type, its development stage and other factors.

BACKGROUND

Most of the existing methods for irrigation control can be classified either as a feed-forward application of the crop water needs estimated by water balance, or as a feedback control aimed at keeping the soil moisture or the plants' water stress within a range. The system described in this paper belongs to the latter category.

In the feed-forward group, the most widely used approach is to deliver the amount of water required to compensate for crop evapotranspiration (ET_c) (Casadesús, et al., 2012). Irrigated crop production is particularly well served by an irrigation scheduling program that predicts when to irrigate and the amount to apply precisely. Adopting such programs has reduced irrigation amounts without reducing yields, and has also decreased the problem of nitrate leaching to the groundwater (Feibert, et al., 1998, Shock, et al., 2001, Shock, et al., 2004, Wright and Stark, 1990). Most scheduling programs are based on estimating reference evapotranspiration (ET_o) through various procedures and the simulation of available soil water within the root zone. Many factors can affect the amount of ET_o occurring for any particular crop. Under non-limiting, irrigated conditions, daily ET_o rates for individual crops are directly related to the meteorological processes affecting evaporative demand, and to the current stage of plant development, and percent crop cover. Many direct and indirect methods have been developed and evaluated to estimate the maximum crop ET_o at a given site (Stanley and Maynard, 1990). Increasing irrigation efficiency can be achieved by irrigation timers. Irrigation time clock controllers are an integral part of an automatic irrigation system. In the feed-forward group, an Open Control Loop (OCL) timer is used. OCL systems apply a preset action, as is done with simple mechanical irrigation timers.

In the feedback group, to which our system belongs, a Closed Control Loop (CCL) timer is used. In a CCL timer system, the system receives feedback from one or more sensors, makes decisions, and applies the results of these decisions to the irrigation system (Zazueta, et al., 1993). Using a CCL timer proceeds by first setting up a general strategy in the timer, then, the control system takes over and makes decisions of whether or not to apply water based on data from the sensor(s). For example, readings from soil moisture sensors can result in avoiding over irrigation when adequate soil moisture is detected, readings from rain sensors can result in avoiding over irrigation during or after significant rain, readings from wind sensors can result in a decision to stop the system when a speed-threshold is surpassed, and readings from water pressure sensors can result in a decision to shut down the system if the pump is not primed or to initiate flush cycles in filters, preventing pump damage. (Boman, et al., 2002, Zazueta, et al., 1993).

The measurement of the soil water content (θ) through in situ dielectric methods are being used more frequently. Some of the techniques based on dielectric methods have been classified as time domain reflectometry (TDR), time domain transmissometry (TDT), and frequency domain reflectometry (FDR) (Blonquist Jr, et al., 2005, Topp, 2003). Of the three types, it is generally recognized that TDR provides more accurate readings. Our current system uses this type of sensor technology among other types.

A Granular matrix Sensors (GMS) is a type of sensor that is commonly used to estimate θ. This device measures soil electrical resistance, which is then converted to calibrated readings of soil water tension. A GMS device is buried in intimate contact with the soil, and allowed to reach equilibrium with the soil water content. Since the development of the GMS, many researchers have used it in irrigation scheduling. However, in soils with coarse textures (i.e. sand) reduced soil/sensor contact may result in incorrect estimation of soil water tension (Irmak and Haman, 2001). In addition, GMSs exhibit hysteretic behavior (Thompson, et al., 2006) and a high variability of readings (Intrigliolo and Castel, 2004, Taber, et al., 2002), so individual sensors should be calibrated for accurate readings (Leib, et al., 2003). However, they can be appropriate when a relative indication of soil wetness is sufficient. Examples of their successful use are reported in monitoring θ in urban tree-landscapes (Connellan, et al., 2000), and for irrigation scheduling in onion (Shock, et al., 1998), potato (Shock, et al., 1998), tomato and walnut trees (Hanson, et al., 2000). Due to these factors, our current system utilizes both

GMS-type sensors in addition to TDR dielectric method sensors. This allows more accurate readings under varying conditions.

Although irrigation water savings under field conditions have been published (Cardenas-Lailhacar, et al., 2008, Cardenas-Lailhacar, et al., 2010, McCready, et al., 2009, Zotarelli, et al., 2009), performance of a database-supported modular precision irrigation system has not been implemented. Hence, the objectives of this research were to: develop smart precision irrigation system (SPIS), which consists of a software application, a database and hardware interface, that's: collect data from database and sensors, calculates the specific water requirements for crops, scheduling the crop water requirements in the specific time needed, controlling water valves applied in the field according to the crop schedule. This paper describes an umbrella project to develop an extensible home-grown system for smart computer-controlled precision irrigation system based on accurate sensor readings and that can serve also for supporting precision irrigation research. As an umbrella project, the system described has an ambitious plan and set of requirements. The current paper describes both the aims of the umbrella project and the current status of the implementation of the system, both in hardware and software.

SYSTEM COMPONENTS, APPROACH AND METHODS

In this section, we provide an overview of the components of system developed, its approach for water scheduling and its methods for calculating the including the various parameters that affect the irrigation scheduling decisions. Specifically, we discuss the system database, the system hardware, the sensors, the valves, and the methods used to calculate the crop evapotranspiration (ET_c), the reference crop evapotranspiration (ET_o), and the crop coefficient (K_c).

The main requirement of precision irrigation system (PSI) is to reduce the water used in irrigation by applying exactly the crop water requirement, in a specific real time soil situation. We aim to achieving this is as follows:

1. Building the system database from data imported from FAO's climatic and crop information databases and adding to it farm information (blocks, valves and irrigation system), hardware interface cards and sensors settings data, plants properties, and soils properties.
2. Building a software application to carry out the following tasks:
    a. Collecting data from both sensors and the database
    b. Calculating crop water requirements using the data collected,
    c. Real-time controlling of the water released using the data collected from all the available sources: the FAO database the weather sensors and the soil sensors.
    d. Reporting current and previous status and actions done by the system.
    e. Allowing manual intervention when necessary

The System Database

The climatic and crops database was implemented in MS SQL Server 2008 and contains information imported from the FAO databases of CLIMWAT (Grieser, 2006) and CROPWAT (Swennenhuis, 2009). In addition, it acts as a repository for all locally collected data. The system database serves two important functions:

1. As a standard reference to aid water scheduling decisions, and
2. As a research repository for future data mining and knowledge discovery.

The system database also contains information of:

- Crops characteristics and needs.
- Historical climate records.
- Farm, block and node configurations.
- Soil properties.
- Weather and soil sensor characteristics.
- Interface configurations and calibration data.
- Weather and soil sensor data records.
- Valve characteristics.

The database application programs were implemented in C#.net with the Object Relational Mapping language (Linq to SQL) used to simplify the integration between C# and SQL.

System Hardware

Personal Computer (PC)

PC used having the following minimum requirements: PIIII 1 GHz processor with 512 RAM, a parallel port, and USB ports.

Interface cards

PIS hardware contains four type of interface cards. There are:

1. inter12 Bit PC Based DAQ (Data Acquisition) kit with parallel port interface having Max186 microcontroller based (eight analog inputs, four digital outputs). This is used to connect sensors with 12 Bit resolution.
2. NI-6008 USB Interface card (12-bit) resolution, which has 10 Ks/s low-cost multifunction DAQ (Data Acquisition) kit, 8 analog inputs (12-bit, 10 kS/s), Bus-powered for high mobility, and Built-in signal connectivity.
3. USB interface Input / Output Controller, which contains 8 Relay Outputs, Switching at 230/5A. This to connect to valves, water pump, flow indicator and excitation voltage to sensors. It has 4 Opto. Isolated inputs to receive signal from flow indicator weather there is water flow or not, 2 Analog Inputs (0-5V or 0-20mA), 10 Bit resolution to connect temp sensor. As

resolution needed is 8 or 10 bit, and 1 PWM Output to apply excitation to flow indicator.

4. Kt-5220 USB interface Input / Output Controller for Relay Outputs Switching at 230/5A. It is containing 4 Opto-Isolated Inputs, 2 Analog Inputs (10 bit) 0-5V or 0-20mA, 1 PWM Output (8 bit), Screw Terminals, Jumper Selectable, Power Indicator LED, and Visual Basic DLL.
5. Em-50 Data logger for Pre-calibrated.

Sensors

Weather sensors

Weather station has been assembled in our system to have real-time records for climate conditions (e.g. air temperature, relative humidity, solar radiation, wind speed and rain gauge). Air temperature Sensor with radiation shield was made by Velleman Co. with model of VM132: Universal Temperature Sensor with -20 C to +70 C sensitivity. Anemometer manufactured by Davis Instruments, has been used for measuring wind speed and direction with an accuracy of ±5% for wind speed and 7° for direction. It has measurement range from 58m/s to 209km/hr. Air relative humidity was observed with an accuracy of 2% and measurement range from 0 to 100%. Solar Radiation Sensor (Pyranometer) measures the solar radiation flux density in w/m^2 (made by Decagon Devices) (Decagon Devices, 2010).

Soil sensors

The volumetric water content θ of each soil node was monitored with two frequency domain reflectometry probe Decagon's 5TE and 10HS Decagon Devices, Inc. (Decagon Devices, 2010) which were buried diagonally, at 15 cm from the surface, and at 30 cm. The soil mister sensors SMS were connected to micro-loggers or interface card and readings were recorded every 10 min. Before the beginning of the experiment, calibration of the SMS was performed at the research site using the gravimetric soil sampling method described by (Gardner, 1986). Three probes were installed in the field and connected to a micro-logger. Undisturbed soil samples were collected from the field (using a core sampler of 137.4 cm^3) less than 20 cm from the probes, and at the probe burial depth and measured their θ at laboratory. As well as, Decagon's 5TE was used to measure θ, it was used for measuring soil temperature, and soil salinity (EC).

Soil water potential of each soil node was observed by MPS-1 Dielectric Water Potential Sensor (Decagon Devices, Inc). It was also used for irrigation monitoring and control.

Electric solenoid diaphragm valves

The water supply has been controlled by Hunter electric solenoid valves 24 volt AC, with pressure regulator in order to control water flow.

Parameter Calculation Methods

Calculation of crop evapotranspiration (ET_c)

ET_c was calculated under standard conditions. This is the ET_c from disease-free, well-fertilized crops, grown in large fields, under optimum soil water conditions and achieving full production under the given climatic conditions. The effects of various weather conditions on evapotranspiration are incorporated into ET_o as following.

Calculation of reference crop evapotranspiration (ETo)

In case of weather data are collected by an automated weather station, which include air temperature, relative humidity, wind speed, wind direction, solar radiation, barometric pressure, and soil heat flux. ET_O is calculated from the Penman–Monteith equation described in FAO-56 (Allen, et al., 1998) as follows:

$$\boldsymbol{ET_o} = \frac{\mathbf{0.408}\Delta(\boldsymbol{R_n} - \boldsymbol{G}) + \boldsymbol{\gamma}\dfrac{\mathbf{900}}{\boldsymbol{T} + \mathbf{273}}\boldsymbol{u_2}(\boldsymbol{e_s} - \boldsymbol{e_a})}{\Delta + \boldsymbol{\gamma}(\mathbf{1} + \mathbf{0.34}\boldsymbol{u_2})}$$

where ET_o is the reference crop evapotranspiration (mm/day); R_n is the net radiation at the crop surface (MJ m^{-2} day^{-1}); G is the soil heat flux density (MJ m^2/day); T is the mean daily air temperature (°C); u_2 is the daily wind speed at 2 m height (m/s); e_s is the saturation vapor pressure (kPa); e_a is the actual vapor pressure (kPa), Δ is the slope of the saturation vapor pressure versus temperature curve (kPa $°C^{-1}$); and γ is the psychrometric constant (kPa $°C^{-1}$).

In case of some weather variables are missing, they have been estimated using basic weather data as described by (Allen, et al., 1998). Details of these intermediate calculations are too long to be reproduced here and the reader is referred to numerous excellent publications on the subject e.g. (Allen, et al., 1998). Although the PM-ET_o is the recommended benchmark, other largely empirical models have evolved that cater for situations where only a subset of the needed data for driving the PM-ETo is available. Thus, a comparative analysis of the PM-ET_o and four commonly used empirical evapotranspiration models, namely Hargeaves (Hargreaves and Samani, 1985), FAO Blaney-Criddle (Doorenbos and Pruitt, 1975), and Jensen-Haise (Jensen and Haise, 1963), were carried out. Details of these models are summarized as follows:

Hargreves equation: $ET_o = 0.0023(T_{mean} + 17.8)(T_{max} - T_{min})^{0.5}R_a$

where R_a is the extra-terrestrial radiation (mm/day water equivalent).

FAO-Blaney-Criddle: $ET_o = a + b[p(0.46T_{mean} + 8.13)]\left[1 + 0.1\left(\frac{Elev}{1000}\right)\right]$

$$a = 0.0043RH_{min} - (n_s/N_s) - 1.41$$

$$b = 0.82 - 0.0041RH_{min} + 1.07(n_s/N_s) + 0.066u_2 - 0.006RH_{min}(n_s/N_s) - 0.0006RH_{min}u_2$$

where p is mean daily percentage of total annual daytime hours for a given time period and latitude; $Elev$ is the site elevation above mean sea level (m); RH_{min} is mean daily minimum relative humidity (%); (n_s / N_s) is mean ratio of actual to possible sunshine hours.

Jensen-Haise: $ET_o = R_s(0.025T_{mean} + 0.08)$
where R_s is measured solar radiation (mm/day water equivalent).

The crop coefficient

The crop coefficient, K_c, is basically the ratio of ET_c to the reference ET_o, and it represents an integration of the effects of major characteristics that distinguish the crop from the reference ET_o. These characteristics are crop height (affecting roughness and aerodynamic resistance); crop-soil surface resistance (affected by leaf area, the fraction of ground covered by vegetation, leaf age and condition, and soil surface wetness); and albedo of the crop-soil surface (affected by the fraction of ground covered by vegetation and by the soil surface wetness). K_c is defined for perfect conditions having no water or other *ET* reducing stresses. Actual ET_c, denoted as $ET_{c\ act}$ is calculated in FAO-56 (Allen, et al., 1998) as:

$$ET_c = K_{c\ act}\ ET_o$$

where $K_{c\ act}$ is is the actual crop coefficient.

In PIS software program, two forms for K_c are presented: the "singular" K_c and the "dual" K_{cb} and K_e form introduced in FAO-56. Details of these intermediate calculations were carried out according to FAO-56 (Allen, et al., 1998).

SYSTEM INSTALLATION AND OPERATION

In this section we outline the steps taken during the software installation and the subsequent operation in the farm. Note that italics indicate parameter entry and starred operations can be done in parallel (concurrent operations).

1. Farm Installation
    - *geographic location*
    - *Total area*
    - *Number of blocks in farm*
2. Blocks installation (for each block in the farm)
    2.1. Block configuration
    - *Block area*
    - *Number of valves in block*
    - *Block soil type*

    2.2. Valve installation (for each valve in the block)

    2.2.1 Valve configuration
    - *Valve size diameter*
    - *Valve flow rate*
    - *Operating pressure at valve*
    - *Irrigation method served by valve*

    2.2.2 Configuration of irrigation method served by valve
    - Sprinkler Irrigation
    - Drip Irrigation
    - Surface irrigation

2.3. Node configuration (for weather station and each soil sensor module)
 2.3.1. Weather station configuration *
 2.3.2. Soil sensor module (node) configuration *
2.4. Software installation of hardware
 2.4.1. Sensor Calibration (for each sensor in the farm) *
 2.4.2. Interface card configuration (for each interface card in the farm) *
2.5. Operation (Planting)
 2.5.1. Irrigation scheduling *
 2.5.2. Monitoring *
 2.5.3. Manual Control (Intervention) *
 2.5.4. Reporting *

Since the last step (Planting) is at the heart of system operation, it will be the screen that is mostly viewed by the system operator. It is worth illustrating the system control screen for this phase which will be used for of longest duration. Figure 1 shows this screen.

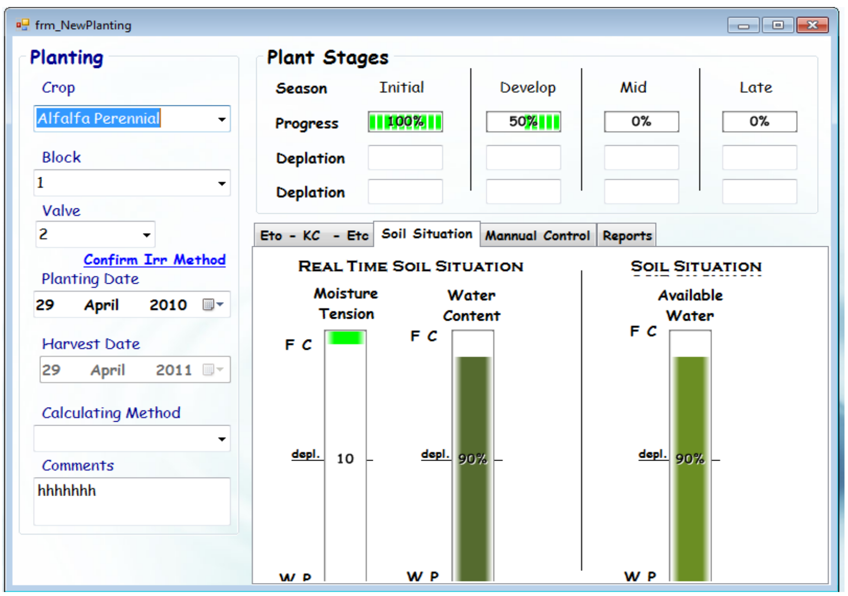

Figure 1. The main system operation control screen, showing the crop type, the current planting stage, Irrigation scheduling, soil situation monitoring, manual control and reporting tabs.

DISCUSSION AND CONCLUSIONS

In this paper, we described a system that has been in development since September 2009 as part of an active collaboration project between researchers in the Faculty of Computer Studies at the Arab Open University, Egypt Branch and the Faculty of Agriculture at Alexandria University. The system has witnessed two successive implementations, the first completed in June 2010 and the second competed in June 2011. The project aims were to develop an extensible and modular home-grown automated irrigation system. The system is intended to improve the efficiency and effectiveness of agriculture in terms of reduced manpower, water, and energy consumption, with simultaneous improvement in yield and quality of crops. In addition, the system is intended to be suitable for a variety of farm sizes and to act as a test bed and research tool for the irrigation protocols under varying conditions, including different crops, soil types, weather conditions, and operating environments.

From an Engineering point-of-view, the system aims to provide a highly modular system to control costs, improve maintainability and provide easy extensibility and flexibility under varying user requirements.

In order to achieve those aims, the system takes the approach of grouping the basic system components in such a way that will maximize the benefit of the modularization. The system modules are designed in such a way to make all components active in any size/configuration of farm with a minimum of unnecessary components. The following factors contributed to the final modular design:

1. The weather station can cover a very large area that is much larger than the area covered by the ground sensor pods. As a result, one may need to add many ground sensor pods before needing to add another weather station.
2. Data loggers often have a limited capacity of inputs. As a result, whenever we will need to add a new ground sensing pod, or a new weather station, we will need to also add a matching controller.
3. Reliability and serviceability will be enhanced if we keep the dependencies of major system components to a minimum. For example, using one power supply for both the weather station and ground sensor will make the system highly susceptible to failures in the power module.

Initially, we admit to create system with high modularity in order to enhance the reliability and usability so we cut the system into 3 individual independent components as follow:

1. Weather-station modules: consist of Data logger and weather sensors.
2. Soil node modules (pods): consist of high resolution interface card and 3 levels of sensors.
3. Valve Module: consist of interface card and electronic valve.

To allow more sophisticated data mining and knowledge elicitation techniques.

Future Work

Current and future work includes extending the system to administer fertilizers through the irrigation water, in order to allow numerous questions regarding fertilization protocols to be investigated. It also includes more precise measurements of administered irrigation water through flow feedback from the valve network, more filed testing, and better data mining of the project database to illicit useful knowledge. In addition, we plan to enhance the database to allow network access to a centralized information resource (an irrigation cloud) and to allow more data types to serve additional system functionalities, including feedback water flow measurements, fertigation , chemigation, sensor maintenance and battery replacement records.

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