Automated Irrigation System Using a Wireless Sensor Network and GPRS Module

Joaquín Gutiérrez, Juan Francisco Villa-Medina, Alejandra Nieto-Garibay, and Miguel Ángel Porta-Gándara

***Abstract*— An automated irrigation system was developed to optimize water use for agricultural crops. The system has a distributed wireless network of soil-moisture and temperature sensors placed in the root zone of the plants. In addition, a gateway unit handles sensor information, triggers actuators, and transmits data to a web application. An algorithm was developed with threshold values of temperature and soil moisture that was programmed into a microcontroller-based gateway to control water quantity. The system was powered by photovoltaic panels and had a duplex communication link based on a cellular-Internet interface that allowed for data inspection and irrigation scheduling to be programmed through a web page. The automated system was tested in a sage crop field for 136 days and water savings of up to 90% compared with traditional irrigation practices of the agricultural zone were achieved. Three replicas of the automated system have been used successfully in other places for 18 months. Because of its energy autonomy and low cost, the system has the potential to be useful in water limited geographically isolated areas.**

***Index Terms*— Automation, cellular networks, Internet, irrigation, measurement, water resources, wireless sensor networks (WSNs).**

I. Introduction

AGRICULTURE uses 85% of available freshwater resources worldwide, and this percentage will continue to be dominant in water consumption because of population growth and increased food demand. There is an urgent need to create strategies based on science and technology for sustainable use of water, including technical, agronomic, managerial, and institutional improvements [1].

There are many systems to achieve water savings in various crops, from basic ones to more technologically advanced ones. For instance, in one system plant water status was monitored and irrigation scheduled based on canopy temperature distribution of the plant, which was acquired with thermal imaging [2]. In addition, other systems have been developed to schedule irrigation of crops and optimize water use by means of a crop water stress index (CWSI) [3]. The empirical CWSI was first defined over 30 years ago [4]. This index was later calculated using measurements of infrared canopy temperatures, ambient air temperatures, and atmospheric vapor pressure deficit values to determine when to irrigate broccoli using drip irrigation [5]. Irrigation systems can also be automated through information on volumetric water content of soil, using dielectric moisture sensors to control actuators and save water, instead of a predetermined irrigation schedule at a particular time of the day and with a specific duration. An irrigation controller is used to open a solenoid valve and apply watering to bedding plants (impatiens, petunia, salvia, and vinca) when the volumetric water content of the substrate drops below a set point [6].

Other authors have reported the use of remote canopy temperature to automate cotton crop irrigation using infrared thermometers. Through a timed temperature threshold, automatic irrigation was triggered once canopy temperatures exceeded the threshold for certain time accumulated per day. Automatic irrigation scheduling consistently has shown to be valuable in optimizing cotton yields and water use efficiency with respect to manual irrigation based on direct soil water measurements [7].

An alternative parameter to determine crop irrigation needs is estimating plant evapotranspiration (ET). ET is affected by weather parameters, including solar radiation, temperature, relative humidity, wind speed, and crop factors, such as stage of growth, variety and plant density, management elements, soil properties, pest, and disease control [8]. Systems based on ET have been developed that allow water savings of up to 42% on time-based irrigation schedule [9]. In Florida, automated switching tensiometers have been used in combination with ET calculated from historic weather data to control automatic irrigation schemes for papaya plants instead of using fixed scheduled ones. Soil water status and ET-based irrigation methods resulted in more sustainable practices compared with set schedule irrigation because of the lower water volumes applied [10].

An electromagnetic sensor to measure soil moisture was the basis for developing an irrigation system at a savings of 53% of water compared with irrigation by sprinklers in an area of 1000 m^2 of pasture [11]. A reduction in water use under scheduled systems also have been achieved, using soil sensor and an evaporimeter, which allowed for the adjustment of irrigation to the daily fluctuations in weather or volumetric substrate moisture content [12].

A system developed for malting barley cultivations in large areas of land allowed for the optimizing of irrigation through decision support software and its integration with an in-field wireless sensor network (WSN) driving an irrigation

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machine converted to make sprinkler nozzles controllable. The network consisted of five sensing stations and a weather station. Each of the sensing stations contained a data logger with two soil water reflectometers, a soil temperature sensor, and Bluetooth communication. Using the network information and the irrigation machine positions through a differential GPS, the software controlled the sprinkler with application of the appropriate amount of water [13]. Software dedicated to sprinkler control has been variously discussed [14].

A data acquisition system was deployed for monitoring crop conditions by means of soil moisture and soil, air, and canopy temperature measurement in cropped fields. Data were downloaded using a handheld computer connected via a serial port for analysis and storage [15]. Another system used to achieve the effectiveness of water management was developed based on a WSN and a weather station for Internet monitoring of drainage water using distributed passive capillary wick-type lysimeters. Water flux leached below the root zone under an irrigated cropping system was measured [16]. There are hybrid architectures, wireless modules are located inside the greenhouse where great flexibility is required, and wired modules are used in the outside area as actuator controllers [17].

The development of WSNs based on microcontrollers and communication technologies can improve the current methods of monitoring to support the response appropriately in real time for a wide range of applications [18], considering the requirements of the deployed area, such as terrestrial, underground, underwater, multimedia, and mobile [19]. These applications involve military operations in scenarios of battlefield, urban combat, and force protection, with tasks of presence, intrusion, ranging, imaging, detection of chemical, toxic material, biological, radiological, nuclear, and explosive [20], [21]. In addition, sensor networks have been used in health care purposes for monitoring, alerting, assistance, and actuating with security and privacy to support real-time data transmission [22]. Vital sign monitoring, such as ECG, heart rate, body temperature, has been integrated in hospitals and homes through wearable or e-textile providing reports and alerts to personal in case of emergency and tracking the location of patients within the hospital limits [23]. WSNs have been used to remote monitor healthcare of dependent people at their homes through several biomedical sensors such as ECG, blood pressure, body temperature [24], and body motion [25].

Home applications comprised wireless embedded sensors and actuators that enable monitoring and control. For comfort and efficient energy management, household devices have been controlled through sensors that monitor parameters such as temperature, humidity, light, and presence, avoiding waste of energy [26]. Sensor networks have been used for security purposes, based on several sensors such as smoke detectors, gas sensors, and motion sensors, to detect possible risk situations that trigger appropriate actions in response, such as send an alert to a remote center through wireless communication [27].

In industrial environments, WSNs have been installed to provide real-time data acquisition for inventory management, to equipment monitoring for control with appropriate actions, reducing human errors and preventing manufacturing downtime [28], [29]. For example, industrial WSN have been implemented to motor fault diagnosis [30] and for the monitoring of the temperature-sensitive products during their distribution has been proposed [31]. In addition, there are wireless systems for structural identification under environmental an operational parameters, such as load in bridges [32].

In environmental applications, sensor networks have been used to monitor a variety of environmental parameters or conditions in marine, soil, and atmospheric contexts [33]. Environmental parameters, including humidity, pressure, temperature, soil water content, and radiation with different spatial and temporal resolution and for event detection such as disaster monitoring, pollution conditions, floods, forest fire, and debris flow is continuously monitored [34]–[36]. Applications in agriculture have been used to provide data for appropriate management, such as monitoring of environmental conditions like weather, soil moisture content, soil temperature, soil fertility, mineral content, and weed disease detection, monitoring leaf temperature, moisture content, and monitoring growth of the crop, automated irrigation facility and storage of agricultural products [37]–[39].

Various commercial WSNs exist, ranging from limited and low-resolution devices with sensors and embedded processors to complete and expensive acquisition systems that support diverse sensors and include several communication features [40]. Recent advances in microelectronics and wireless technologies created low-cost and low-power components, which are important issues especially for such systems such as WSN [41]. Power management has been addressed in both hardware and software with new electronic designs and operation techniques. The selection of a microprocessor becomes important in power aware design. Modern CMOS and micro-electro-mechanical systems (MEMS) technologies allowed manufacturers to produce on average every three years a enhance generation of circuits by integrating sensors, signal conditioning, signal processing, digital output options, communications, and power supply units [42], [43]. For example, the parallel combination of a battery and a supercapacitor has been used to extend the runtime of low-power wireless sensor nodes [44].

Energy harvesting mechanisms have been employed, in cases where it is difficult for changing or recharging batteries, hence this strategy has involved combining it with efficient power management algorithms to optimize battery lifetime. Power harvesting is a complementary approach that depends on ambient energy sources, including environmental vibration, human power, thermal, solar, and wind that can be converted into useable electrical energy [45]–[47]. On the other hand, several strategies have been implemented to reduce power consumption, such as power-aware protocols, resource and task management, communication, topology control and routing, models based on events, and congestion control mechanism to balance the load, prevent packet drops, and avoid network deadlock using a combination of predeployed group keys that allow the dynamic creation of high security subnetworks and optimizes energy efficiency of sensor networks [48], [49]. For instance, energy-saving strategies have been achieved through scheduling [50], [51], sleep or wake up schemes, and adaptive radio frequency (RF) in nodes, and choosing a network configuration [52]. There are also algorithms to maximize the network coverage ratio with a predefined balance the energy consumption in the whole WSN [53], to reduce both the transmission and the computational loads at the node level [54], and to estimate online the optimal sampling frequencies for sensors [55].

In a wireless node, the radio modem is the major power consuming component; recently, wireless standards have been established with medium access control protocols to provide multitask support, data delivery, and energy efficiency performance [56], such as the standards for wireless local area network, IEEE 802.11b (WiFi) [57] and wireless personal area network (WPAN), IEEE 802.15.1 (Bluetooth) [58], IEEE 802.15.3 (UWB) [59], and IEEE 802.15.4 (ZigBee) [60], and those open wireless communication standards for Internet protocol version 6 (IPv6) over low-power wireless personal area networks 6LoWPAN [61], [62], wireless highway addressable remote transducer WirelessHART [63], and ISA100.11a [64] developed by the International Society of Automation.

In this paper, the development of the deployment of an automated irrigation system based on microcontrollers and wireless communication at experimental scale within rural areas is presented. The aim of the implementation was to demonstrate that the automatic irrigation can be used to reduce water use. The implementation is a photovoltaic powered automated irrigation system that consists of a distributed wireless network of soil moisture and temperature sensors deployed in plant root zones. Each sensor node involved a soil-moisture probe, a temperature probe, a microcontroller for data acquisition, and a radio transceiver; the sensor measurements are transmitted to a microcontroller-based receiver. This gateway permits the automated activation of irrigation when the threshold values of soil moisture and temperature are reached. Communication between the sensor nodes and the data receiver is via the Zigbee protocol [65], [66] under the IEEE 802.15.4 WPAN. This receiver unit also has a duplex communication link based on a cellular-Internet interface, using general packet radio service (GPRS) protocol, which is a packet-oriented mobile data service used in 2G and 3G cellular global system for mobile communications (GSM). The Internet connection allows the data inspection in real time on a website, where the soil-moisture and temperature levels are graphically displayed through an application interface and stored in a database server. This access also enables direct programming of scheduled irrigation schemes and trigger values in the receiver according the crop growth and season management. Because of its energy autonomy and low cost, the system has potential use for organic crops, which are mainly located in geographically isolated areas where the energy grid is far away.

II. Automated Irrigation System

The automated irrigation system hereby reported, consisted of two components (Fig. 1), wireless sensor units (WSUs) and a wireless information unit (WIU), linked by radio transceivers that allowed the transfer of soil moisture and temperature data, implementing a WSN that uses ZigBee technology. The WIU has also a GPRS module to transmit the data to a web server via the public mobile network. The information can be remotely monitored online through a graphical application through Internet access devices.

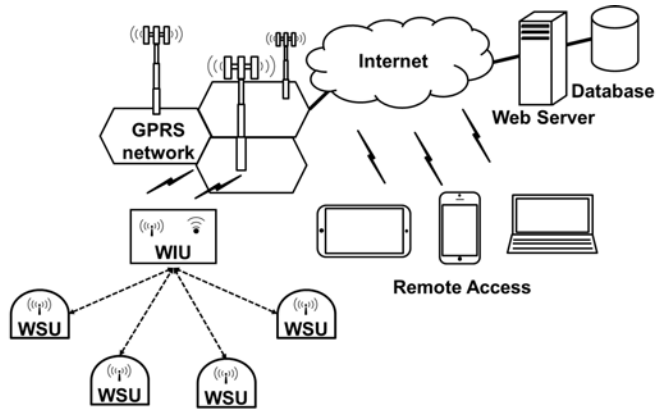

Fig. 1. Configuration of the automated irrigation system. WSUs and a WIU, based on microcontroller, ZigBee, and GPRS technologies.

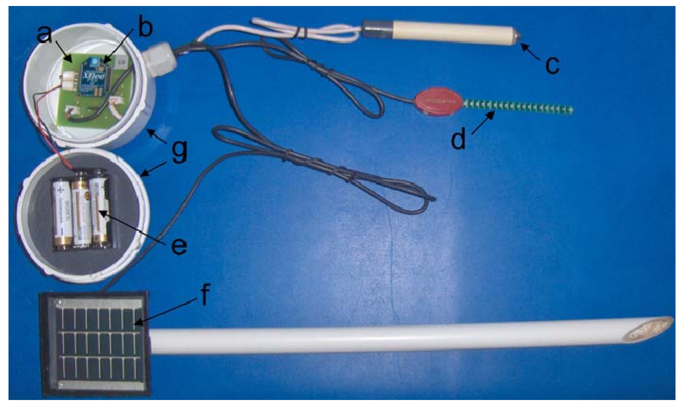

Fig. 2. WSU. (a) Electronic component PCB. (b) Radio modem ZigBee. (c) Temperature sensor. (d) Moisture sensor. (e) Rechargeable batteries. (f) Photovoltaic cell. (g) Polyvinyl chloride container.

A. Wireless Sensor Unit

A WSU is comprised of a RF transceiver, sensors, a microcontroller, and power sources. Several WSUs can be deployed in-field to configure a distributed sensor network for the automated irrigation system. Each unit is based on the microcontroller PIC24FJ64GB004 (Microchip Technologies, Chandler, AZ) that controls the radio modem XBee Pro S2 (Digi International, Eden Prairie, MN) and processes information from the soil-moisture sensor VH400 (Vegetronix, Sandy, UT), and the temperature sensor DS1822 (Maxim Integrated, San Jose, CA). These components are powered by rechargeable AA 2000-mAh Ni-MH CycleEnergy batteries (SONY, Australia). The charge is maintained by a photovoltaic panel MPT4.8-75 (PowerFilm Solar, Ames, IN) to achieve full energy autonomy. The microcontroller, radio modem, rechargeable batteries, and electronic components were encapsulated in a waterproof Polyvinyl chloride (PVC) container (Fig. 2). These components were selected to minimize the power consumption for the proposed application.

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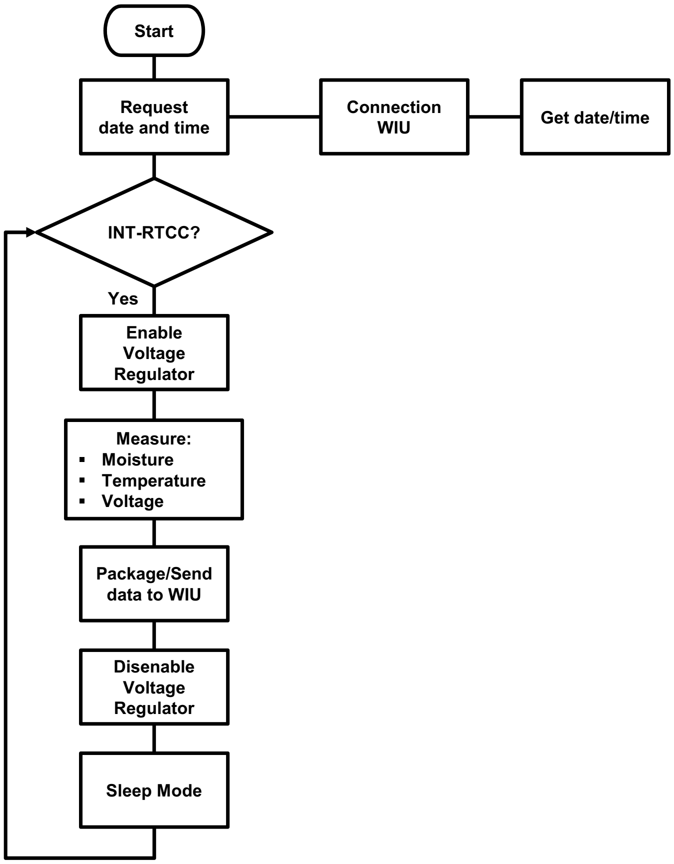

Fig. 3. Algorithm of wireless sensor unit (WSU) for monitoring the soil-moisture and temperature.

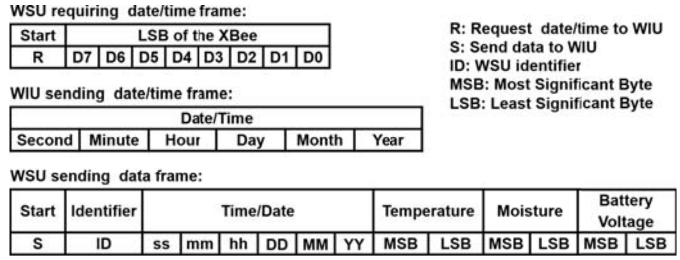

Fig. 4. Communication frames between a WSU and the WIU.

1) Single-Chip PIC24FJ64GB004: A 16-bit microcontroller with 44-pins and nanoWatt XLP technology that operates in a range 2.0 to 3.6 V at 8 MHz with internal oscillator. It has up to 25 digital input/output ports, 13-, 10-bit analog-to-digital converters (ADC), two serial peripheral interface modules, two I2C, two UART, 5 16-bit timers, 64 KB of program memory, 8 KB of SRAM, and hardware real-time clock/calendar (RTCC). The microcontroller is well suited for this remote application, because of its low-power operating current, which is 175 μA at 2.5 V at 8 MHz and 0.5 μA for standby current in sleep mode including the RTCC.

The microcontroller was programmed in C compiler 4.12 (Custom Computer Services, Waukesha, WI) with the appropriate algorithm (Fig. 3) for monitoring the soil-moisture probe through an analog-to-digital port and the soil-temperature probe through another digital port, implemented in 1-Wire communication protocol. A battery voltage monitor is included through a high-impedance voltage divider coupled to an analog-to-digital port. The data are packed with the corresponding identifier, date, and time to be transmitted via XBee radio modem using a RS-232 protocol through two digital ports configured as transmitter (TX) and receiver (RX), respectively. After sending data, the microcontroller is set in sleep mode for certain period according to the sensor sampling rate desired, whereas the internal RTCC is running. This operation mode allows energy savings. When the WSU is launched for first time, the algorithm also inquires the WIU, the date and time to program the RTCC, and periodically updates it for synchronization.

2) ZigBee Modules: ZigBee (over IEEE 802.15.4) technology is based on short range WSN and it was selected for this battery-operated sensor network because of its low cost, low power consumption, and greater useful range in comparison with other wireless technologies like Bluetooth (over IEEE 802.15.1), UWB (over IEEE 802.15.3), and Wi-Fi (over IEEE 802.11) [67]. The ZigBee devices operate in industrial, scientific, and medical 2.4-GHz radio band and allow the operation in a so-called mesh networking architecture, which can be differentiated into three categories: 1) coordinator; 2) router; and 3) end device.

From a wide range of commercial ZigBee devices, the XBee-PRO S2 is an appropriate original equipment manufacturer module to establish communication between a WSU and the WIU because of its long-range operation and reliability of the sensor networking architecture. The XBee-PRO S2 is a RF modem with integrated chip antenna, 20-pins, and 13 general purpose input/output (GPIO) ports available of which four are ADC. It can operate up to a distance of 1500 m in outdoor line-of-sight with 170 mA of TX peak current and 45 mA for RX current at 3.3 V and power-down current of 3.5 μA.

The XBee radio modem of each WSU is powered at 3.3 V through a voltage regulator ADP122AUJZ-3.3-R7 (Analog Devices, Norwood, MA) and interfaced to the host microcontroller through its serial port, a logic-level asynchronous serial, and voltage compatible UART configured at 9600 baud rate, no - parity, 1 - start bit, 1 - stop bit, 8 - data bits.

The WSUs were configured such as end devices to deploy a networking topology point-to-point based on a coordinator that was implemented by the XBee radio modem of the WIU. An end device has the following characteristics: 1) it must join a ZigBee PAN before it can transmit or receive data; 2) cannot allow devices to join the network; 3) must always transmit and receive RF data through its parent; 4) cannot route data; and 5) can enter low power modes to conserve power and can be battery powered. The least significant byte of the unique 64-bit address is used to label the information of the soil moisture and temperature for each WSU in the network. This byte is registered in the WIU as the identifier (ID) associated to each WSU. As shown in the sample frames to request date/time, receive date/time, and send data packaged to the WIU (Fig. 4).

3) Soil Sensor Array: The sensor array consists of two soil sensors, including moisture and temperature that are inserted in the root zone of the plants. The VH400 probe was selected to

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estimate the soil moisture because of low power consumption (<7 mA) and low cost. The probe measures the dielectric constant of the soil using transmission line techniques at 80 MHz, which is insensitive to water salinity, and provides an output range between 0 and 3.0 V, which is proportional to the volumetric water content (VWC) according to a calibration curve provided by the manufacturer. The sensor was powered at 3.3 V and monitored by the microcontroller through an ADC port.

Soil temperature measurements were made through the digital thermometer DS1822. The sensor converts temperature to a 12-bit digital word and is stored in 2-B temperature registers, corresponding to increments of 0.0625 °C. The temperature is required through a reading command and transmitted using 1-Wire bus protocol implemented in the microcontroller through one digital port. The thermometer has ± 2.0 °C accuracy over -10 °C to $+85$ °C temperature range and a unique 64-bit serial number. The sensor is a 3-pin single-chip and TO92 package that was embedded in a metal capsule and sealed in a waterproof PVC cylindrical container.

To calibrate the soil moisture, several samples were prepared with 1 kg of dry soil from the crop area. Its composition was loamy sand with 80% sand separate, 4.5% clay separate, and 15.6% silt separate. The soil water holding capacity was of 20.7% VWC corresponding to measured output voltages of 1.45 V. The temperature sensors were calibrated through a reference mercury thermometer CT40, with 0.1 °C divisions and a range from -1 °C to 51 °C. The thermometer and the temperature sensors were placed in an insulated flask filled with mineral oil at 10 °C and 40 °C.

4) Photovoltaic Cell: To maintain the charge of the WSU batteries, a solar panel MPT4.8-75 was employed. Each solar panel delivers 50 mA at 4.8 V, which is sufficient energy to maintain the voltage of the three rechargeable batteries. A MSS1P2U Schottky diode (Vishay, Shelton, CT) is used to prevent the solar module and to drain the battery when is in the dark. The solar panel is encapsulated in a 3-mm clear polyester film with dimensions of 94 mm $\times$ 75 mm. This flexible panel was mounted on a PVC prismatic base (100 mm $\times$ 80 mm $\times$ 3.17 mm) that is fastened in the upper part of a PVC pole allowing for the correct alignment of the photovoltaic panel to the sun. The stick is 50 cm of length and 12.5 mm of diameter; the lower end of the pole had a tip end to be buried.

B. Wireless Information Unit

The soil moisture and temperature data from each WSU are received, identified, recorded, and analyzed in the WIU. The WIU consists of a master microcontroller PIC24FJ64GB004, an XBee radio modem, a GPRS module MTSMC-G2-SP (MultiTech Systems, Mounds View, MN), an RS-232 interface MAX3235E (Maxim Integrated, San Jose, CA), two electronic relays, two 12 V dc 1100 GPH Livewell pumps (Rule-Industries, Gloucester, MA) for driving the water of the tanks, and a deep cycle 12 V at 100-Ah rechargeable battery L-24M/DC-140 (LTH, Mexico), which is recharged by a solar panel KC130TM of 12 V at 130 W (Kyocera, Scottsdale, AZ)

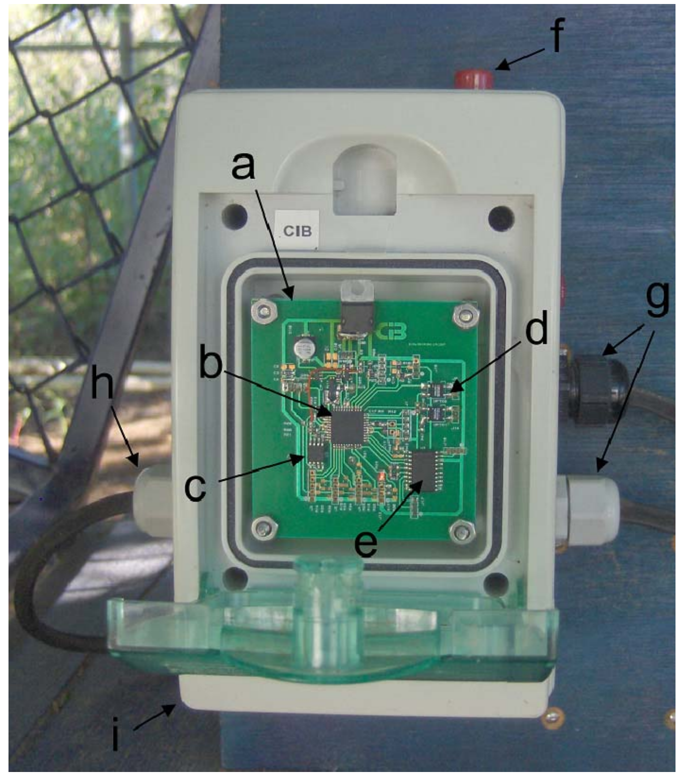

Fig. 5. WIU. (a) Electronic component PCB. (b) Master microcontroller. (c) Solid state memory. (d) Optical isolators. (e) RS-232 interface. (f) Push button. (g) Output cables to pumps. (h) Supply cable from charge controller. (i) PCV box.

through a PWM charge controller SCI-120 (Syscom, Mexico). All the WIU electronic components were encapsulated in a waterproof PVC box as shown in Figs. 5 and 6. The WIU can be located up to 1500-m line-of-sight from the WSUs placed in the field.

1) Master Microcontroller: The functionality of the WIU is based on the microcontroller, which is programmed to perform diverse tasks, as is shown in Fig. 7. The first task of the program is to download from a web server the date and time through the GPRS module. The WIU is ready to transmit via XBee the date and time for each WSU once powered. Then, the microcontroller receives the information package transmitted by each WSU that conform the WSN.

These data are processed by the algorithm that first identifies the least significant byte of a unique 64-bit address encapsulated in the package received. Second, the soil moisture and temperature data are compared with programmed values of minimum soil moisture and maximum soil temperature to activate the irrigation pumps for a desired period. Third, the algorithm also records a log file with the data in a solid state memory 24FC1025 (Microchip Technologies, Chandler, AZ) with a capacity of 128 kB. Each log is 12-B long, including soil moisture and temperature, the battery voltage, the WSU ID, the date, and time generated by the internal RTCC. If irrigation is provided, the program also stores a register with the duration of irrigation, the date, and time. Finally, these data and a greenhouse ID are also transmitted

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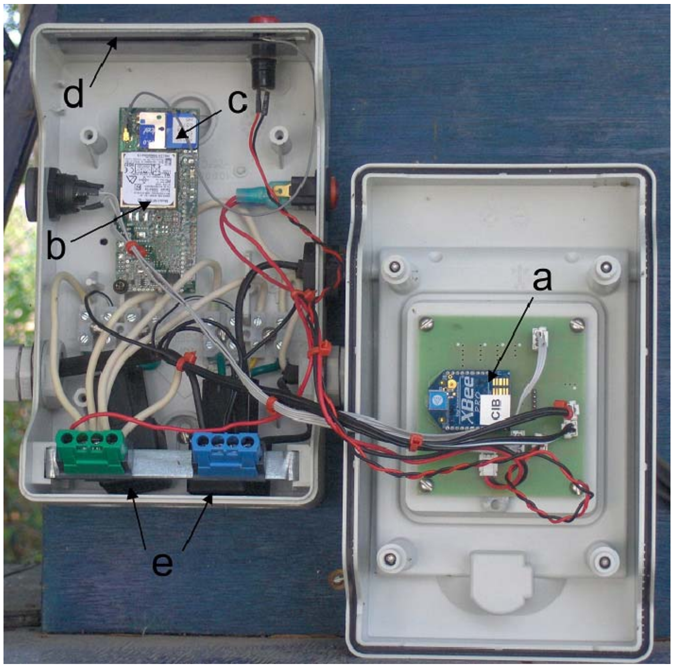

Fig. 6. Inside view of the WIU. (a) Radio modem ZigBee. (b) GPRS module. (c) SIM card. (d) GPRS PCB antenna. (e) Pumps relays.

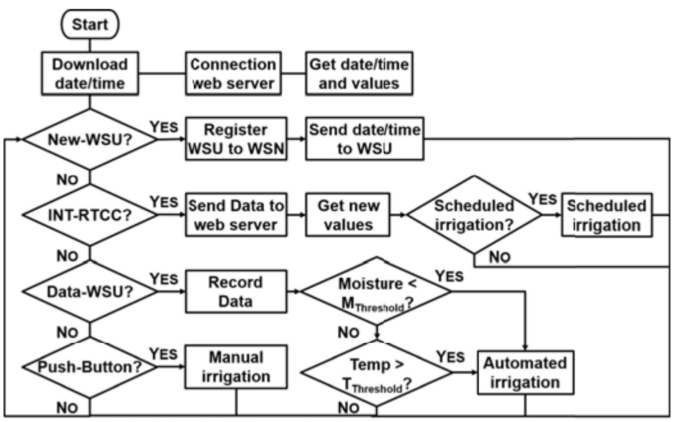

Fig. 7. Algorithm of the master microcontroller in the WIU for the automated irrigation system.

at each predefined time to a web server through HTTP via the GPRS module to be deployed on the Internet web application in real time.

When the server receives a request for the web page, it inserts each data to the corresponding field in the database.

This link is bidirectional and permits to change the threshold values through the website interface; scheduled watering or remote watering can be performed.

The WIU has also a push button to perform manual irrigation for a programmed period and a LED to indicate when the information package is received. All the WIU processes can be monitored through the RS-232 port.

The WIU includes a function that synchronizes the WSUs at noon for monitoring the status of each WSU. In the case that all WSUs are lost, the system goes automatically to a default irrigation schedule mode. Besides this action, an email is sent to alert the system administrator.

2) GPRS Module: The MTSMC-G2-SP is a cellular modem embedded in a 64-pins universal socket that offers standards-based quad-band GSM/GPRS Class 10 performance. This GPRS modem includes an embedded transmission control protocol/Internet protocol stack to bring Internet connectivity, a UFL antenna connector and subscriber identity module (SIM) socket. The module is capable of transfer speeds up to 115.2 K b/s and can be interfaced directly to a UART or microcontroller using AT commands. It also includes an onboard LED to display network status.

The GPRS was powered to 5 V regulated by UA7805 (Texas Instruments, Dallas, TX) and operated at 9600 Bd through a serial port of the master microcontroller and connected to a PCB antenna. The power consumption is 0.56 W at 5 V.

In each connection, the microcontroller sends AT commands to the GPRS module; it inquires the received signal strength indication, which must be greater than −89 dBm to guarantee a good connection. In addition, it establishes the communication with the URL of the web server to upload and download data. If the received signal strength is poor, then all data are stored into the solid-state memory of the WIU and the system try to establish the connection each hour.

3) Watering Module: The irrigation is performed by controlling the two pumps through 40-A electromagnetic relays connected with the microcontroller via two optical isolators CPC1004N (Clare, Beverly. MA). The pumps have a power consumption of 48 W each and were fed by a 5000-l water tank.

Four different irrigation actions (IA) are implemented in the WIU algorithm:

1) fixed duration for manual irrigation with the push button;
2) scheduled date and time irrigations through the web page for any desired time;
3) automated irrigation with a fixed duration, if at least one soil moisture sensor value of the WSN drops below the programmed threshold level;
4) automated irrigation with a fixed duration, if at least one soil temperature sensor value of the WSN exceeds the programmed threshold level.

C. Web Application

Graphical user interface software was developed for real-time monitoring and programming of irrigation based on soil moisture and temperature data. The software application permits the user to visualize graphically the data from each WSU online using any device with Internet (Fig. 8).

Besides the soil-moisture and temperature graphs, the web application displays the total water consumption and the kind of the IA.

The web application also enabled the user direct programming of scheduled irrigation schemes and adjusting the trigger values in the WIU according to the crop species and season management. All the information is stored in a database. The web application for monitoring and programming was coded in C# language of Microsoft Visual Studio 2010. The database was implemented in SQL Server 2005.

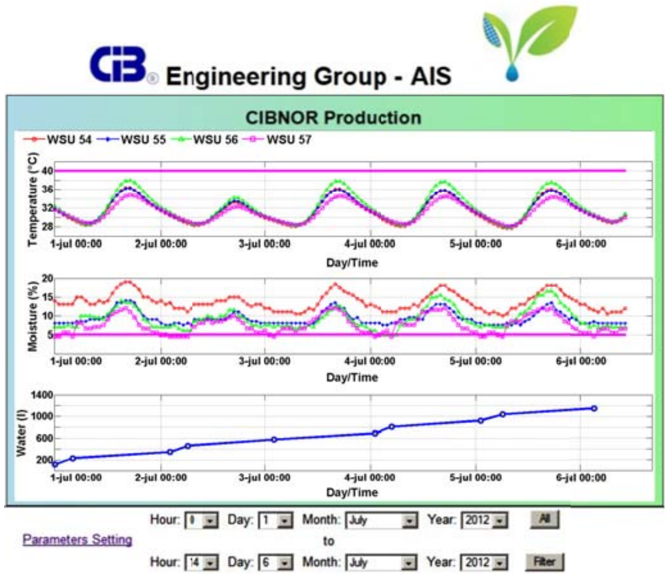

Fig. 8. Web application of the automated irrigation system to remotely supervise the soil moisture and temperature of each WSU and change the threshold values and the scheduled irrigation.

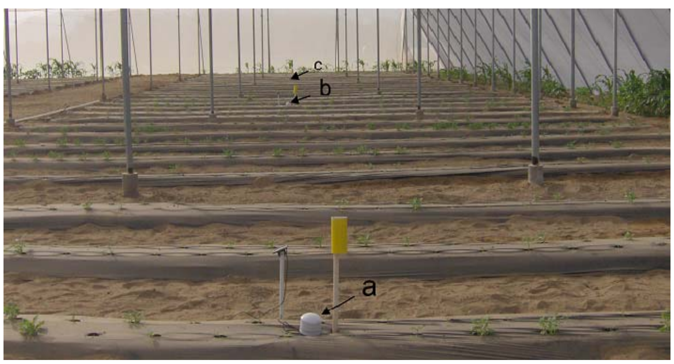

Fig. 9. Greenhouse for organic sage production with WSUs located arbitrarily in different cultivation beds. (a) WSU-55 on bed 2. (b) WSU-56 on bed 12. (c) WSU-57 on bed 23. WSU-54 was on bed 1.

III. Irrigation System Operation

The system was tested in a 2400-m^2 greenhouse, located near San Jose del Cabo, Baja California Sur (BCS), Mexico (23° 10.841' N, 109° 43.630' W) for organic sage (Salvia officinalis) production. The greenhouse had 56 production beds covered with plastic. Each bed was 14-m long and had two black polyethylene tubes with drip hole spacing of 0.2 m. The automated irrigation system was used to irrigate only 600 m^2, which corresponded to 14 beds; whereas, the remaining 42 beds were irrigated by human supervision to compare water consumption with the traditional irrigation practices in this production place. Four WSUs labeled by the last significant byte of the unique 64-bit address (WSU-54, 55, 56, and 57) were located in the greenhouse at arbitrary points (Fig. 9).

The WSU-57 unit was used to measure the soil moisture and temperature in the area (bed 23) where the traditional irrigation practices were employed. The other three units (WSU-54, 55, and 56) were located in beds 1, 2, and 12 to operate the automated irrigation system with their corresponding soil moisture and temperature sensors situated at a depth of 10 cm

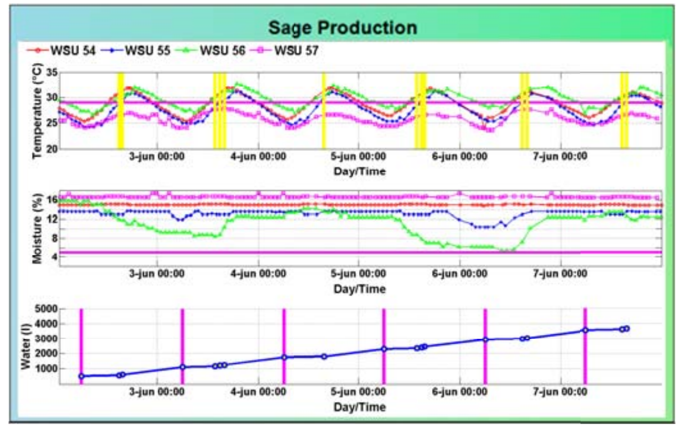

Fig. 10. Gathered data of the WSUs, in the web application of the automated irrigation system: soil temperatures, soil moisture, and water supplied (vertical bars indicate automated and scheduled irrigation).

in the root zone of the plants. These three units allowed data redundancy to ensure irrigation control. The algorithm considered the values from the WSU-54, 55, and 56, if one reached the threshold values the automated irrigation was performed.

The pumping rate provided 10 ml/min/drip hole, which was measured in the automated irrigation zone in six different drip holes.

In accordance with the organic producer's experience, a minimum value of 5% VWC for the soil was established as the moisture threshold level and 30 °C as the temperature threshold level for the automated irrigation modes (IA-3 and IA-4, respectively). Initially, the scheduled irrigation (IA-2) of 35 min/week was used during the first six weeks. After that, the scheduled irrigation was set at 35 min three times per week. Sage cultivation finalized after 136 days.

During the cultivation, several automated irrigation periods were carried out by the system because of the soil-moisture (IA-3) or temperature (IA-4) levels, regardless of the scheduled irrigation (IA-2). All data were uploaded each hour to the web server for remote supervision. For instance, data of five days are shown (Fig. 10). The first graph shows soil temperatures. The vertical bars indicate automated irrigation periods triggered by temperature when soil temperature was above the threshold value (30 °C). The second graph shows soil moistures that were above the threshold value (5.0% VWC), and thus the automated irrigation was not triggered by soil moisture. Finally, the last graph shows the total water used by the sage with the corresponding scheduled irrigation vertical bars for the IA-2. The dots denote the automated and scheduled irrigation.

Automated irrigation triggered by soil moisture for four days are shown in Fig. 11; when the soil moisture value fell below the threshold level of 5.0% VWC, the irrigation system was activated for 35 min according to IA-3, whereas the soil temperature remained below the threshold level. Similarly, Fig. 12 shows automated irrigation triggered by soil temperature; when the temperature was above 30 °C, the irrigation system was activated for 5 min according to IA-4, whereas the soil moisture remained above the threshold level.

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

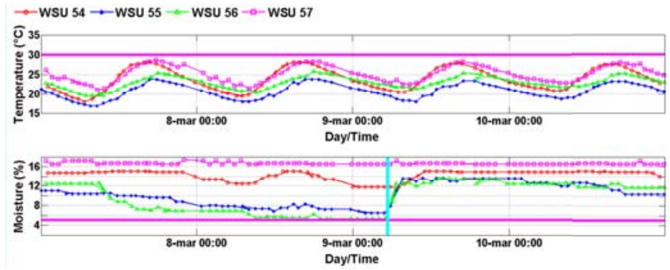

Fig. 11. Automated irrigation (vertical bars) triggered by the soil moisture threshold $\leq$ 5% VWC.

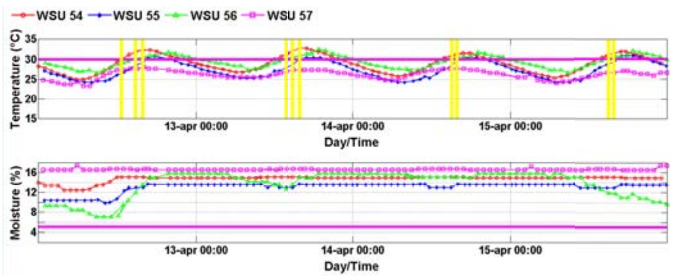

Fig. 12. Automated irrigation (vertical bars) triggered by the soil temperature threshold $\geq$30 °C.

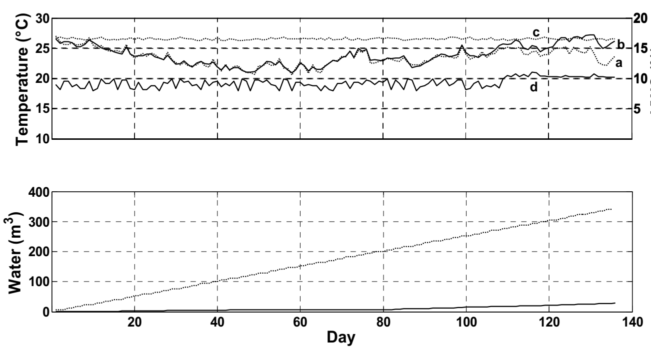

Fig. 13. Daily mean soil temperature (a: traditional; b: automated), daily mean soil moisture (c: traditional; d: automated), and accumulated water irrigation volumes (dotted line: traditional; solid line: automated) over the entire sage cropping season.

Water consumption with the organic producers' traditional irrigation procedure consisted of watering with a 2" electrical pump during 5 h three times per week for the whole cultivation period. Under this scheme the volume flow rate measured on site was 10 ml/min/per drip hole, giving a total of 174 l/drip hole, whilst the automated irrigation system used 14 l/drip hole. In the entire greenhouse, the sage plants presented similar fresh biomass regardless of the irrigation procedure during the whole production period. The average biomass per cut was 110 pounds for the traditional irrigation system corresponding to 42 production beds and 30 pounds for the automated irrigation system corresponding to 14 beds.

The automated system was tested in the greenhouse for 136 days (Fig. 13). Daily mean soil moisture and temperature are shown, as well as the accumulated water used for both systems. Both mean temperatures presented similar behavior for the production period, except for the last 30 days, where the soil temperature for the traditional irrigation practice

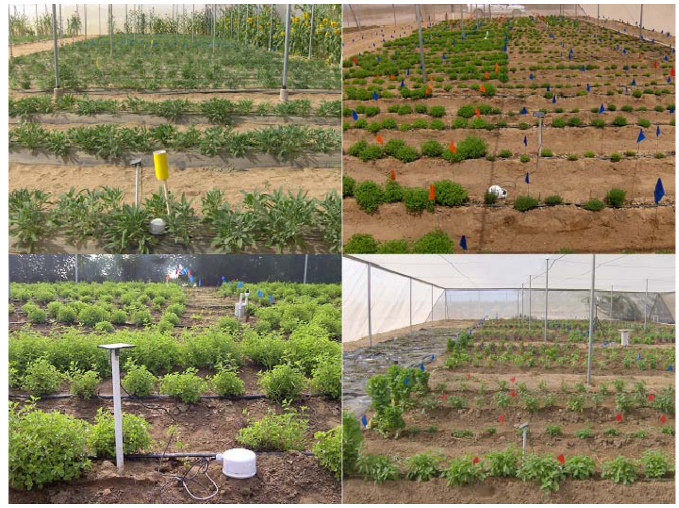

Fig. 14. Automated irrigation systems for the experimental production of: sage (top left), thyme (top right), origanum (bottom left), and basil (bottom right) in San Jose del Cabo, Los Arados, El Pescadero, and El Comitan, respectively.

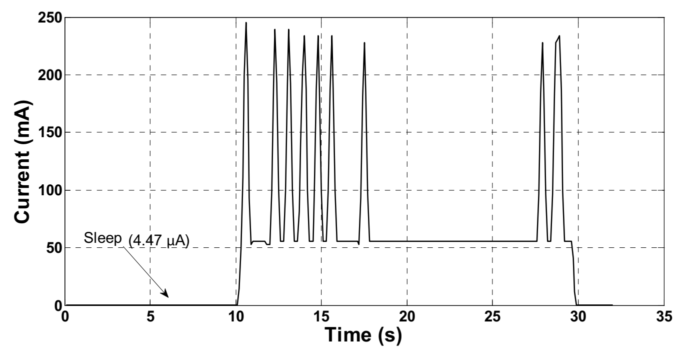

Fig. 15. WSU current consumption in monitoring and sleep modes.

(curve a) was lower than the automated irrigation (curve b). The daily mean VWC for the traditional irrigation practice (curve c) was almost constant >16%, whereas that for the automated irrigation (curve d) was below 10%. In addition, the accumulated water used are shown corresponding to 14 beds for each irrigation system. The total water requirement was 341 m^3 for the traditional one and 29 m^3 for the automated one. Then, the automated irrigation used ~90% less water with respect to the traditional irrigation practice.

Another three automated irrigation systems (Fig. 14) have been tested along 18 months in other places in BCS, Mexico: El Pescadero (23° 21.866' N, 110° 10.099' W), El Comitan-CIBNOR (24° 7.933' N, 110° 25.416' W), and Los Arados (24° 47.1' N, 111° 11.133' W). In these three places, programmed irrigations (IA-2) were compared with triggered irrigations (IA-3 and IA-4), water savings ~60% were obtained.

For cases such as Los Arados, it was found that the signal receiving strength was too low and the Internet connection could not be established, hence in this case all data were stored into the solid state memory of the WIU.

Power consumption of a WSU was measured through current oscilloscope (UNI-T UT81B) in the monitoring and sleep operational modes (Fig. 15). Each hour, the soil-moisture

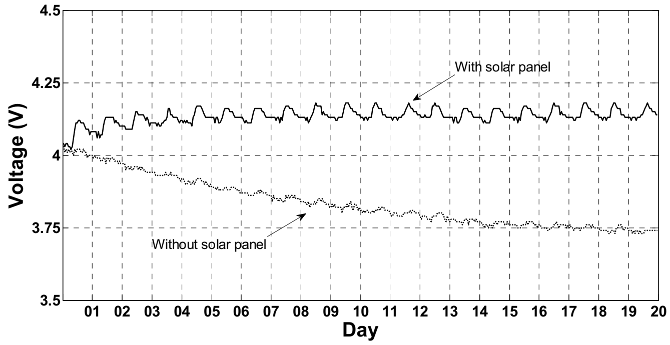

Fig. 16. Battery charge–discharge cycle of a wireless sensor unit (WSU).

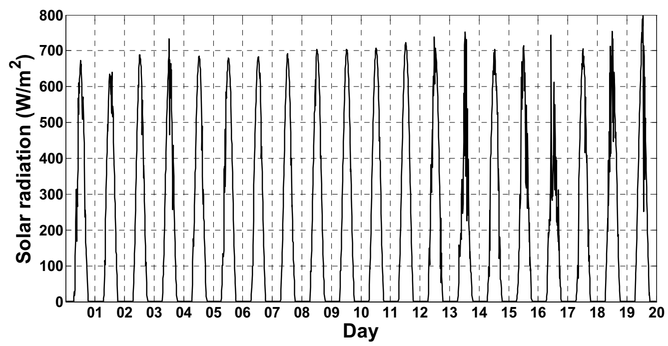

Fig. 17. Solar radiation along the experiment of charge-discharge cycle of a wireless sensor unit (WSU).

TABLE I
COMPONENTS FOR WSU

Description	Part number
Microcontroller	PIC24FJ64GB004
Transceiver	XBee Pro S2
Soil moister sensor	VH400
Soil temperature sensor	DS1822
Panel solar	MPT4.8-75
Batteries (3)	AA 2000 mAh Ni-MH
Miscellaneous (voltage regulators, connectors, capacitors, resistors, pcb, etc.)	

A WSU is comprised of a radio frequency (RF) transceiver, two sensors, a microcontroller, power sources, and electronic miscellaneous.

and temperature data were transmitted to the WIU. Before transmitting the data, the XBee of the WSU was powered on through the voltage regulator that was enabled for a period of 20 s by the microcontroller, which was a long enough time for the radio modem to wake up and transmit the data. Then, the total average power consumption was kept at 0.455 mAh. The charge-discharge cycle of the batteries is shown for 20 days in the winter with the solar panel connected and disconnected (Fig. 16) using the data registered by the battery voltage monitor. The solar radiation for those days is shown in Fig. 17. Thus, the photovoltaic panel and the batteries provide sufficient energy to maintain the WSU running for the whole crop season at almost any latitude, due the low energy consumption.

The WIU average current consumption because of the electronic components was of 80 mAh in operational mode. However, the total average power consumption was ~4 Ah per day considering the two irrigation pumps.

TABLE II
COMPONENTS FOR WIU

Description	Part number
Microcontroller	PIC24FJ64GB004
Transceiver	XBee Pro S2
GPRS module	MTSMC-G2-SP
Miscellaneous (voltage regulators, connectors, capacitors, resistors, pcb, RS232 transceiver, relays, PVC box, etc.)	
Panel solar	KC130TM
Battery	L-24M/DC-140
Charger controller	SCI-120
Livewell Pumps (2)y	1100 GPH
Tank 5000 l	

The WIU is comprised of a microcontroller, a RF transceiver, a GPRS module, power sources, two pumps, a tank, and electronic miscellaneous.

The automated irrigation system implemented is a cost-effective alternative for agriculture; the cost of each WSU is ~100 U.S. dollars (Table I), and the WIU cost is ~1800 U.S. dollars (Table II).

IV. CONCLUSION

The automated irrigation system implemented was found to be feasible and cost effective for optimizing water resources for agricultural production. This irrigation system allows cultivation in places with water scarcity thereby improving sustainability.

The automated irrigation system developed proves that the use of water can be diminished for a given amount of fresh biomass production. The use of solar power in this irrigation system is pertinent and significantly important for organic crops and other agricultural products that are geographically isolated, where the investment in electric power supply would be expensive.

The irrigation system can be adjusted to a variety of specific crop needs and requires minimum maintenance. The modular configuration of the automated irrigation system allows it to be scaled up for larger greenhouses or open fields. In addition, other applications such as temperature monitoring in compost production can be easily implemented. The Internet controlled duplex communication system provides a powerful decision-making device concept for adaptation to several cultivation scenarios. Furthermore, the Internet link allows the supervision through mobile telecommunication devices, such as a smartphone.

Besides the monetary savings in water use, the importance of the preservation of this natural resource justify the use of this kind of irrigation systems.

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