Agricultural ecosystem monitoring based on autonomous sensor systems

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Abstract—**More than two-thirds of freshwater consumed worldwide are used for irrigation, and large quantities of freshwater can be saved by improving the efficiency of irrigation systems. Irrigation control systems deployed in agriculture can substantially be enhanced by implementing intelligent monitoring techniques enabling automated sensing and continuous analyses of actual soil parameters. Automatically scheduling irrigation events based on soil moisture measurements has been proven an effective means to reduce freshwater consumption and irrigation costs, while maximizing the crop yield. Focusing on decentralized autonomous soil moisture monitoring, this paper presents the design, the implementation, and the validation of a low-cost remote monitoring system for agricultural ecosystems. The prototype monitoring system consists of a number of intelligent wireless sensor nodes that are distributed in the observed environment. The sensor nodes are connected to an Internet-enabled computer system, which is installed on site for disseminating relevant soil information and providing remote access to the monitoring system. Autonomous software programs, labeled "mobile software agents", are embedded into the wireless sensor nodes to continuously analyze the soil parameters and to autonomously trigger irrigation events based on the actual soil conditions and on weather data integrated from external sources.**

Keywords—Agricultural ecosystem monitoring; agro-geoinformatics; irrigation control; smart sensing; wireless sensor networks; multi-agent technology

I. INTRODUCTION

By 2025, as the United Nations Global Environment Outlook predicts, the water withdrawals in developing countries will increase by 50% and, if the trend continues, 1.8 billion people will be living in regions with absolute water scarcity [1]. However, not only developing countries, which are facing severe health problems due to limited access to freshwater, but also the world's wealthiest industrial nations are increasingly suffering from water shortages. In 60% of the European cities with more than 100,000 people, for example, groundwater is being used at faster rates than it is replenished [2]. The water scarcity severely affects the nations' socio-economic development, because industrial and manufacturing activities require adequate water supplies. As a direct consequence, increasing water, food and energy prices as well as hampered agricultural productivity have major implications on the nations' economies. For example, the water prices in the United States are growing about 10-15% every year [3].

Main reasons for the global water crisis – besides population growth, urbanization, and climate change – are excessive water use, poor management, and inadequate irrigation. According to the United Nations World Water Development Report, 70% of freshwater worldwide is used for irrigation [4]. Conventional irrigation systems usually work on the principle of timer-based irrigation. Timer-based irrigation controllers, incorporated into the irrigation systems, are deployed to trigger irrigation events using mechanical or electromechanical timers [5]. However, timer-based systems possess several disadvantages because actual soil and weather conditions are not considered. Consequently, the amount of applied water does usually not match the requirements of the irrigated crop, and either too much or too little water is used for irrigation. Recent studies have unveiled that less than 40% of applied water is used by the irrigated crop effectively [4, 6]. Furthermore, it is well known that poorly managed irrigation systems not only contribute to water scarcity, but can also lead to significant soil damage caused by draining (due to water shortage) or leaching (due to excessive water application) entailing a further reduction in crop yield [6].

To overcome the problems caused by inadequate and expensive irrigation, "smart" irrigation controllers have been proposed as an alternative to conventional timer-based irrigation controllers [5, 7]. Smart irrigation controllers, such as weather- or soil moisture-based devices, are able to automatically trigger irrigation events depending on actual site conditions [7]. Soil moisture-based controllers, for example, trigger irrigation events based on the soil moisture content in the root zone of the crop [8]. Ensuring a soil moisture level between the field capacity of the soil and the wilting point of the crop, soil moisture-based controllers typically determine the water requirements by comparing the soil moisture measurements with pre-defined threshold values. Although smart irrigation controllers are capable of timely initiating irrigation events, there are several limitations associated with smart controllers available in the market: Many smart irrigation controllers lack the ability of automatically adjusting the irrigation runtimes, i.e. the quantity of applied water, based on real-time soil moisture measurements; rather, a preset quantity of water is applied for an irrigation event independently from the actual soil conditions [9]. In consequence, even well-designed and well-managed state-of-the-art sprinkler irrigation systems achieve maximum irrigation application efficiencies between 20% and 75% [6]. Apart from that, significant installation and maintenance costs due to wiring of the controllers arise, with at least US$ 130 per meter according to recent studies [10].

With the advancements in wireless communications and microcontroller technologies, wireless sensor networks are deployed in agriculture to overcome the functional limitations and the high costs associated with conventional (cable-based) irrigation controllers. Measuring relevant parameters from the monitored environment, wireless sensor nodes are capable of hosting intelligent software programs facilitating efficient, decentralized and low-cost irrigation control strategies. Besides the flexible and rapid deployment of wireless sensor networks, a significant reduction in installation and maintenance costs of 20-80% can be achieved as compared to cable-based systems [10]. Nevertheless, while wireless sensor networks are used for monitoring in related disciplines since many years [11-15], the deployment of wireless monitoring systems in agriculture, supporting the new concept of "precision agriculture", is still rare [16-19].

Although wireless sensor networks deployed for irrigation control in agriculture have been proven cost- and resource-efficient with water savings up to 60% [20], most systems do not integrate automated decision support functionalities providing optimum irrigation scheduling. Instead of autonomously performing data acquisition, data analysis, data aggregation and decision making directly on the sensor nodes, the vast majority of systems is designed solely for data acquisition and transmission of the data sets to connected server systems. Requiring extensive amounts of data to be wirelessly transmitted, sensor data is usually collected by the wireless sensor nodes and then sent to a central server for further processing; data analysis and decision making need to be conducted by human individuals manually. In this study, an intelligent remote monitoring system, composed of a number of wireless sensor nodes and a computer system located on site, is proposed for irrigation control in agricultural ecosystems. Data acquisition, data analysis, data aggregation and decision making are performed directly on the sensor nodes, and real-time soil moisture measurements as well as actual weather data are used to schedule irrigation events autonomously.

In this paper, preliminary results are presented illustrating the design and implementation of the wireless monitoring system. As will be shown in this paper, intelligent software programs are embedded into the wireless sensor nodes enabling (i) autonomous communications between the sensor nodes, (ii) cooperative decision making for scheduling irrigation events in real time, (iii) dynamic adaptations to changing environmental conditions, and (iv) dissemination of relevant soil information through the Internet via the computer system located on site. This paper is organized as follows: First, the design and the implementation of the prototype monitoring system are shown. Then, field validation tests are presented serving as a proof of concept of the newly proposed approach and illustrating the real-time capabilities of the monitoring system. Finally, the results are discussed, followed by concluding and future research directions are proposed.

II. A PROTOTYPE SYSTEM FOR AGRICULTURAL ECOSYSTEM MONITORING

The architecture of the monitoring system is shown in Figure 1. As shown in the figure, the observed environment is divided into two regions, labeled "Region 1" and "Region 2". Instrumented with soil moisture and temperature sensors, one wireless sensor node is placed in each region to continuously collect and analyze soil parameters obtained from the region in which the sensor node is located. The monitoring system is complemented by an on-site computer connected to the wireless sensor nodes through a base station. The following subsections briefly describe the hardware components of the monitoring system as well as the software, which is embedded into the wireless sensor nodes and installed on the on-site computer.

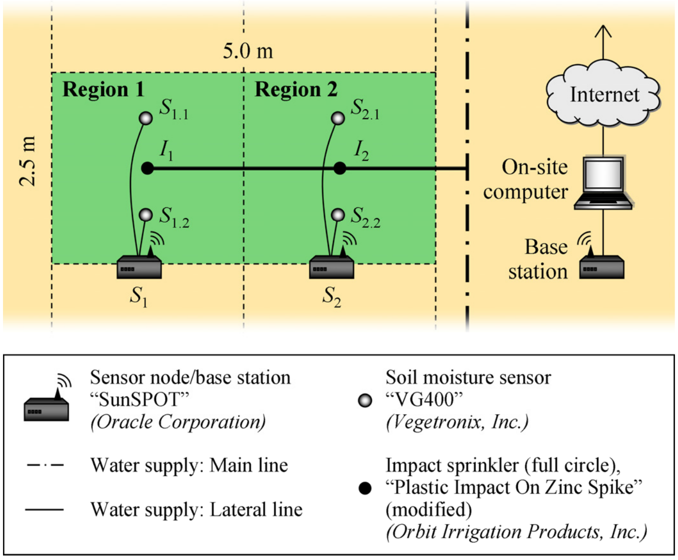


Fig. 1. Overview of the monitoring system architecture.

A. Hardware of the monitoring system

Java-based Oracle SunSPOT sensor nodes are deployed for the prototype implementation of the wireless sensor nodes and the base station [21, 22]. The sensor nodes are built according to the IEEE 802.15.4 standard, which focuses on low-cost ubiquitous communication and minimal power consumption in wireless personal area networks.Representing a distinct advantage compared to common embedded applications for wireless sensor networks that are usually written in low-level native languages, the sensor nodes comprise of a fully capable Java virtual machine compliant with the Connected Limited Device Configuration (CLDC) [24]. CLDC, a fundamental part of the "Java Platform, Micro Edition" (Java ME), defines basic libraries and virtual machine features for resource-constrained devices such as smart phones or wireless senor nodes. The most significant feature of the sensor nodes is the "Squawk" Java virtual machine running on the nodes, which executes directly out of the flash memory without an underlying operating system [25]; operating system functionalities are provided by the Squawk virtual machine. As a result, memory is saved that would otherwise be consumed by the operating system. Furthermore, whereas most Java virtual machines run a single application, the Squawk Java virtual machine can run multiple applications, which makes Squawk a powerful basis for prototyping "smart" monitoring systems for agricultural ecosystems.

The sensor nodes are provided with several integrated sensors (e.g. temperature sensors), high current output pins, general purpose I/O pins as well as analog inputs for attaching external sensors. In this study, external soil moisture sensors, type Vegetronix VG400 [26], are attached to the sensor nodes through the analog inputs. The VG400 is a low-power and robust soil moisture sensor. Specifically, it senses volumetric water content based on measurements of the dielectric constant of the soil, a technique known to provide highly accurate results. The sensor is insensitive to water salinity and can not corrode over time as, for example, traditional conductivity-based sensors [27]. With respect to the costs discussed earlier, it is worth mentioning that a VG400 sensor is currently available for less than US$ 30, and one of the wireless sensor nodes deployed in this study for about US$ 100 [28, 29].

B. Software design and implementation

The software embedded into the wireless sensor nodes is based on multi-agent technology that provides self-contained, interacting software programs ("software agents"). Representing a topic of increasing importance in science and in practice, multi-agent technology has been proven to be a powerful means to solve distributed engineering problems [31-36]. According to [37], a software agent can be described as a software program "situated in some environment that is capable of [performing] flexible autonomous action in order to meet its design objectives". Thus, a software agent acts *autonomously* without any direct intervention of humans or other software agents and has full control over its internal state. Unlike a software object which, upon being invoked by another object, has no control over the execution of its internal methods, a software agent decides for itself whether or not to perform an action upon request from another agent or human user. Additionally, a software agent is capable of executing *flexible* actions. Flexibility of software agents includes reactivity, pro-activeness, and social ability [30]:

- Reactivity: Software agents are able to perceive their environment and to timely respond to changes that occur in the environment.
- Pro-activeness: Software agents apply self-contained, goal-directed actions, instead of solely acting in response to their environment.
- Social ability: Software agents are capable of interacting with other agents (and possibly with humans) via cooperation, coordination and negotiation in order to perform specific tasks and to achieve their design objectives.

The software agents embedded into the wireless sensor nodes of the monitoring system are implemented following a mobile multi-agent approach proposed in [38]. Referred to as a "mobile software agent", each software agent is responsible for solving one specific monitoring task directly on the sensor node. As shown in Figure 2, different types of mobile agents are implemented and embedded into each wireless sensor node. For example, a *soil moisture sensor agent* and a *temperature sensor agent* are embedded for collecting different sensor data. Furthermore, a *controller agent* is embedded into every node to perform on-board data analyses and to communicate both with other sensor nodes and with the on-site computer. A controller agent, taking into account current soil and weather conditions, requests sensor data from the other agents to compute real-time diagnoses of the soil parameters. Based on the diagnoses, the controller agent sends messages to the on-site computer to propose starting or stopping irrigation events. For persistent storage, measurements taken from the soil (i.e. soil moisture and temperature) are aggregated and sent by the controller agent to the on-site computer in periodic intervals.

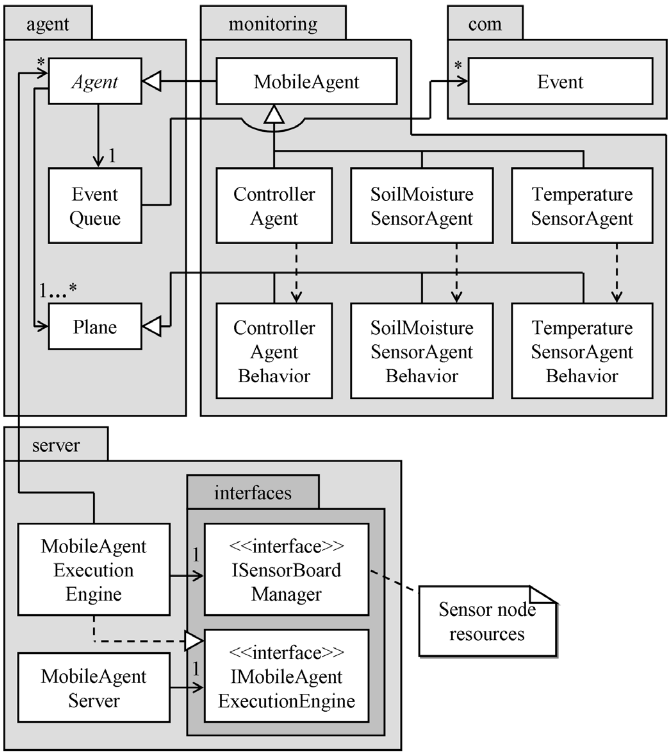
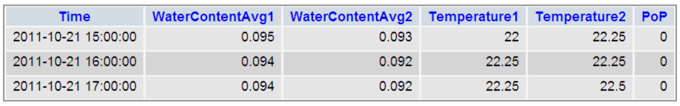


Fig. 2. Software embedded into the wireless sensor nodes (abridged UML class diagram).

Technically, the mobile software agents of the wireless monitoring system are implemented in terms of components that interact through events. The component- and event-based approach allows modeling the dynamic behavior of the agents using multi-plane state machines [39, 40]. A multi-plane state machine, in essence, consists of several functions, variables, and planes. One plane represents one behavior of an agent corresponding to the agent's distinct role in the wireless monitoring system (that is, sensing soil moisture, sensing temperature, or system control). A fundamental part of a plane is an automaton that controls the dynamic behavior of a plane – and thus of the agent – using Event-Condition-Action (ECA) rules. In the prototype implementation of the monitoring system, ECA rules are defined as the triplet $r = (E, C, A)$, where E is the event set, C is the condition set and A are the atomic actions to be taken. An action of an ECA rule, e.g. measuring soil moisture, transfers the automaton in the next state, and it is triggered when both the corresponding event is detected and the condition is satisfied. The events of an agent, triggering actions of other agents, are communicated asynchronously between the agents of the wireless monitoring system using unicast or broadcast inter-agent communication.

Representing a pivotal component of the monitoring system, the on-site computer is primarily assigned the responsibility for persistently storing the measurement data received from the wireless senor nodes. The data sets taken from the soil are stored in a MySQL database that is remotely accessible to authorized human individuals. As can be seen from the database extract depicted in Figure 3, soil moisture (i.e. the volumetric water content) and temperature measurements are recorded, sent to the on-site computer, and written into the database. Instead of submitting all collected field measurements to the on-site computer, the controller agents installed on the wireless sensor nodes, after analyzing the measurements locally, are sending averaged values to the on-site computer, which sufficiently represent the actual situation in the field. The averaged values are calculated directly on the nodes from multiple measurements, resulting in a significant reduction of wirelessly communicated data. In addition to the field measurements, weather data is requested from external resources, and automatically integrated into the monitoring database. In the prototype implementation, the probability of precipitation within the next 24 hours is remotely obtained from an external weather data service. For that purpose, an URL connection to a WWW resource, a dynamic weather website, is created on demand, the website is parsed, and the weather data of interest, here the probability of precipitation (PoP), is stored in the monitoring database.



Time	WaterContentAvg1	WaterContentAvg2	Temperature1	Temperature2	PoP
2011-10-21 15:00:00	0.095	0.093	22	22.25	0
2011-10-21 16:00:00	0.094	0.092	22.25	22.25	0
2011-10-21 17:00:00	0.094	0.092	22.25	22.5	0

Fig. 3. Monitoring database (extract).

III. FIELD VALIDATION TESTS

Serving as a proof of concept of the newly proposed agent-based monitoring approach, field validation tests are devised. The validation tests are also intended to study the real-time capabilities and the reliability of the mobile agents.

A. System calibration and test setup

To achieve a high accuracy of the wireless monitoring system, the soil moisture sensors, while being attached to the wireless sensor nodes, are calibrated soil-specifically. In a calibration routine conducted prior to the field validation tests in the laboratory, different soil samples have been taken from the area to be monitored. The soil samples have been dried and weighted, and defined amounts of water have been added. Exemplarily, the calibration curves constructed for two soil moisture sensors ($S_{2.1}$ and $S_{2.2}$) are shown in Figure 4. These curves are used during the validation tests by the mobile software agents to automatically convert the raw sensor readings (i.e. sensor output voltage) into corresponding estimates of volumetric water content.

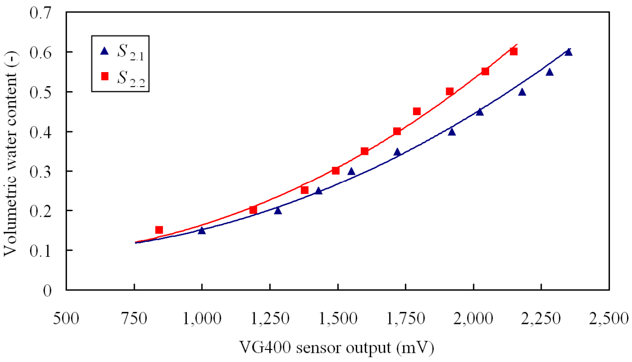


Fig. 4. Calibration curves constructed for soil moisture sensor $S_{2.1}$ and $S_{2.2}$ when being attached to sensor node S_2.

After calibration, the prototype system is installed in the field to monitor a 5.0 m × 2.5 m test area primarily to test the capabilities of the embedded mobile agents with respect to performing cooperative real-time diagnoses of the soil moisture conditions and reacting appropriately on changing site conditions. The area, as shown in Figure 5, is divided into two monitoring regions. In each region, one wireless sensor node is installed, hosting the mobile agents as described earlier. The wireless sensor nodes (labeled S_1 and S_2) are connected to the on-site computer, a laptop computer located next to the test area, through the base station. Each wireless sensor node is interfaced to two soil moisture sensors and includes one temperature sensor. The soil moisture sensors are placed at a soil depth of 30 cm representing a typical root zone of crop. Modified impact sprinklers (I_1 and I_2) are installed in the middle of each region.

B. Autonomous soil moisture monitoring

A relatively simple but efficient test procedure is applied to validate the capability of the mobile agents to cooperatively assess varying soil moisture distributions and to timely react on it. The test procedure is carried out in region 2 of the observed area. First, the range of ideal volumetric water content in the root zone of region 2 is pre-defined as $0.1 \le \theta_{R2} \le 0.5$. These threshold values are stored in the monitoring system. As soon as the wireless sensor nodes and the mobile agents are launched, the controller agent of wireless sensor node S_2 starts analyzing the actual volumetric water content of region 2. To this end, the controller agent requests measurements from the soil moisture sensor agent responsible for the soil moisture sensors $S_{2.1}$ and $S_{2.2}$. Averaging the measurements of $S_{2.1}$ and $S_{2.2}$, a volumetric water content of $\theta = 0.09$ is determined in region 2, which is slightly below the defined threshold value. The averaged values are periodically sent by the controller agent to the on-site computer, where all data sets are stored being remotely available to authorized human individuals.

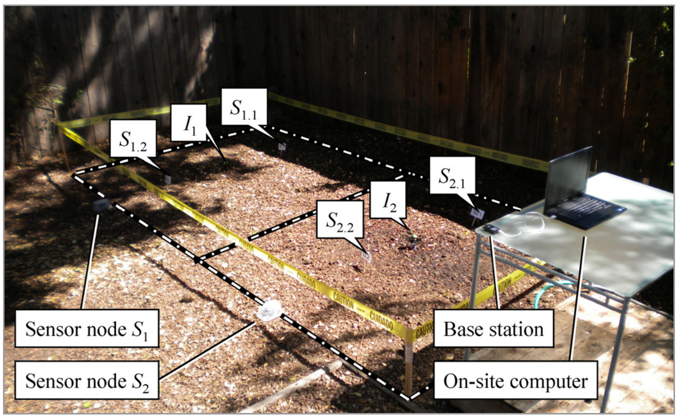


Fig. 5. Field validation tests of the autonomous monitoring system.

As a direct reaction to the dry soil, the controller agent sends a message to the on-site computer indicating that irrigation of region 2 is required. The irrigation event is executed through the impact sprinkler I_2 using a flow rate of 240 l/h. As shown in Figure 6, the irrigation event is initiated about 150 seconds after starting the monitoring system. The controller agent of sensor node S_2, continuously analyzing the volumetric water content, again sends a message to the on-site computer after about 1,300 seconds indicating that the average soil moisture in region 2 has reached the desired level, and irrigation is no longer needed.

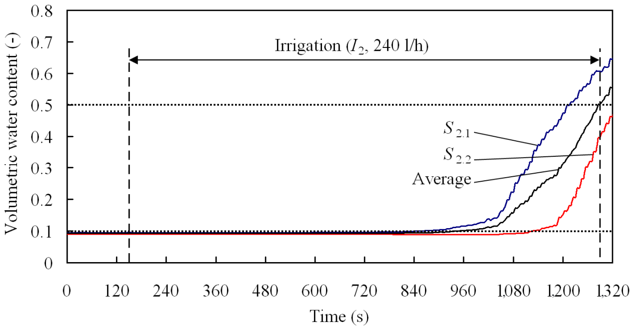


Fig. 6. Average volumetric water content of region 2.

In total, the test procedure shows that the monitoring system has captured the spatial and temporal variability of the soil moisture in real time. Moreover, the mobile agents have reacted appropriately to changes in the soil timely and, as a result of the collaborative real-time diagnoses, messages have been sent to the on-site computer to be used for triggering the irrigation event. Finally, due to the flexible, autonomous on-board data processing, the amount of wirelessly transmitted measurement data has significantly been reduced.

IV. SUMMARY AND CONCLUSIONS

In this paper, preliminary results have been presented illustrating the design, the implementation and the validation of a low-cost wireless monitoring system for agricultural ecosystems. The prototype monitoring system consists of a number of intelligent wireless sensor nodes, which are connected to an Internet-enabled computer system installed on site to store and disseminate relevant soil information and to provide remote access to the monitoring system. Specifically, intelligent software programs ("mobile software agents") have been embedded into the wireless sensor nodes enabling (i) autonomous communications among the sensor nodes, (ii) cooperative decision making for scheduling irrigation events in real time, (iii) dynamic adaptations to changing environmental conditions, and (iv) remote access to relevant soil information.

Field validation tests have corroborated that the concept of embedding mobile software agents into wireless sensor nodes can largely enhance the efficiency and the reliability of monitoring systems deployed in agriculture. Focusing on soil moisture monitoring, it has been shown that the mobile agents, performing data acquisition, data analysis, data aggregation and decision making directly on the nodes, are able to respond in a timely manner to changes in the soil and to precisely schedule irrigation events, which results in a reduction of freshwater consumption and lowered irrigation costs.

Nevertheless, the monitoring system can be further improved in some respects. For example, additional field tests may be devised to further investigate the water reducing potential of the implemented approach and to better understand the soil moisture processes in agricultural environments. Future work may also include interfacing the current monitoring system with an irrigation system comprising automatic valves (actuators) in order to achieve fully autonomous irrigation control. Last but not least, additional sensors, such as rain sensors, may be integrated into the monitoring system to further reduce the freshwater consumption and the irrigation costs.

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