GolfSense: A Golf Course WSN Monitoring Application

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Abstract— This paper proposes an environmental monitoring application based on the concept of Wireless Sensor Networks (WSNs). The goal of this application is to enable, through the measurement of relevant parameters, the constant evaluation of the state of the grass in the different zones of a golf course. The environmental monitoring systems currently installed on most golf courses make use of a single weather station. This weather station only gives general data about the weather conditions of the region where the course is located and doesn't allow greenkeepers to distinguish the irrigation needs of the different zones of a golf course. By continuously monitoring the soil condition in real time on all the zones of a golf course it is possible to obtain a more detailed vision of the grasses water needs and of the hydrological behaviour of each soil, thus improving irrigation efficiency.

I. INTRODUCTION

The technological developments on the fields of microelectronics and wireless communications allowed the creation of a new type of devices called sensing nodes (some times also referred to as motes or smart dust). Each one of these sensing nodes generally consists of a microprocessor, memory, sensors and/or actuators and a wireless transceiver that allows it to communicate with other similar nodes forming an intelligent wireless network (WSN), as described in [1].

There are many areas were the concept of WSN is being applied. From the monitoring of buildings and structures (e.g. bridges and tunnels) to the scientific study of natural events like seismic activity or the behavior of ecosystems, every phenomenon that might be useful to supervise can be monitored using a WSN. The use of WSNs offers advantages over traditional monitoring systems: lower installation and maintenance costs, greater flexibility and the possibility of mobility. These advantages can help make the traditional monitoring applications more efficient or even create opportunities for the creation of entirely new applications.

The monitoring of environmental parameters as a support for the agricultural management is one of the areas where de concept of WSN can be applied with more success. The worldwide problem of agricultural sustainability makes the adoption of solutions that help increase productivity mandatory. The concept of "precision agriculture" appeared with the aim to optimize agricultural productivity by increasing crop production and/or lowering its costs. To meet this objective it is essential to manage irrigation in order to maximize its efficiency. Because water is an increasingly scarce resource, and agriculture is its biggest consumer, irrigation management is gaining importance as a means to minimize the environmental impact of agricultural productions. Apart from irrigation also the application of fertilizers, pesticides and other agricultural supplies could be greatly reduced if they were used only when strictly necessary.

The concept of precision agriculture requires a detailed knowledge of the conditions of each culture. Currently the measurements needed to assess the status of each plantation are carried out manually and sporadically. The use of a WSN to monitor a plantation could dramatically alter this scenario. A WSN would significantly reduce the costs associated with each measurement, enabling the monitoring of a greater number of sites per culture and a much higher measurement frequency. The more precise and exact knowledge of the soil and weather conditions could be used to create more accurate agronomic models that would enable a better management of all agricultural activity and thus increase the profitability of each hectare of cultivated soil.

The Portuguese region of Algarve is simultaneously one of the areas with the highest desertification risk in Europe (due to the pressure that has been put on its hydrologic capacity over the years) and the region of the country with the greatest number of golf courses. These golf courses are one of the main attractions for foreign tourists visiting our country. The great importance of tourism on the Portuguese economy will force Portugal to find solutions to maintain the golf courses operating in a sustainable manner and in harmony with the surrounding environment.

In this context the optimization of water consumption on golf courses will be of vital importance. The objective of this project is to create an environmental monitoring solution based on the concept of WSN that can be used as an aid to the irrigation management of a golf course. The characteristics of a golf course, where specialists do all the irrigation management, make this an ideal place to develop and test solutions of this type. Besides, the economic capacity of these sports fields may cause them to be early adopters of this technology. A solution for monitoring environmental parameters using WSNs that can operate successfully on a golf course may be adapted later to other types of agricultural crops.

II. RELATED WORK

There are several projects in the area of environmental monitoring that make use of WSNs to aid on the management of crops or that are used for strictly scientific purposes. The specific objectives of each project determine which parameters should be monitored. The most common measured parameters are moisture, air temperature, atmospheric pressure, soil moisture, soil temperature, brightness and seismic vibrations.

The general WSN architecture used in these projects is represent on Figure 1. The remote nodes are installed in the areas where the parameters should be monitored. The number of nodes, the density with which they are installed and the WSN topology to be used (e.g. star, tree, mesh, single-hop, multi-hop) depend on the application requirements. Each remote node can control one or more sensors that can measure various parameters or the same parameter in different areas or at different depths.

As can be seen in Figure 1, the communication between remote nodes and between these nodes and the sink is always performed using wireless communication protocols. The type of communication used between the sink nodes and the final processing node depends on the characteristics of each project and can be done using cables or a wireless technology with grater range (e.g. GPRS or 802.11). An overview of the projects considered most relevant in the area of WSNs applied to the monitoring of environmental parameters will be presented on the following sections.

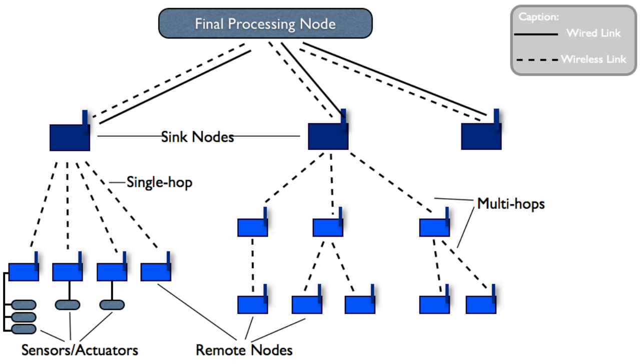


Fig. 1. Generic WSN Architecture

A. Vineyard Computing

The project Vineyard Computing: Sensor Networks in Agricultural Production, described in [2], started with an analysis of the needs and priorities of all the stakeholders present on the wine production value chain in order to answer the following questions:

- What information should be collected and how often?
- What level of treatment and interpretation should be applied to the data collected?
- What is the best way to present information to the user?
- When should the system operate automatically and when should it wait for orders from the user?

The answers to these questions, in addition to being dependent on the equipment capabilities and environmental conditions of the site to be studied, are closely related to the needs of future users of the developed system. This initial study identified the best ways to apply the concept of WSN to the management of an agricultural production.

The proposed architecture (see Figure 2) uses mobile nodes that collect the information stored on the remote nodes installed in the vineyards and transports this information to the final processing system located at the farms headquarters. The mobile nodes can be installed in different objects, people or animals that usually make journeys between the wine regions where data is collected and the location of the final processing system. This type of configuration has the advantage of allowing a more spaced installation of the nodes at the vine because there is no need for neighbor nodes to communicate. The fact that the remote static nodes have to be constantly with their radios on (listening the channel) in order to detect the passage of mobile nodes is a disadvantage of this type of architecture which as consequences in terms of the energy consumption of each node.

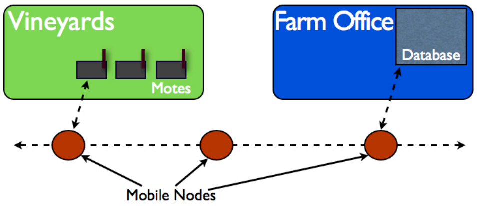


Fig. 2. Vineyard Computing Architecture

B. Life Under Your Feet

The project Life Under your Feet, described in [3], consists in the application of a WSN to the study of soil ecology. It is a joint effort of three departments of the Johns Hopkins University (Earth and Planetary Sciences, Physics and Computer Science) and Microsoft Research and is designed to understand the effects of environmental conditions in the soil ecosystem. This project has the concern to cause the least disturbance to the monitored area.

The architecture of the developed system is shown in Figure 3. It consists of a data collection subsystem (motes + base station) and a database. Each mote is connected to four sensors. The acquisition board from Crossbow (MTS101) includes ambient light and temperature sensors and ports to connect external sensors. To these ports are connected a soil moisture sensor and a soil temperature sensor. The data collected by the sensors is supplemented with information obtained from external sources such as online repositories in

CSV format. This information includes temperature, precipitation, humidity, atmospheric pressure and weather events (e.g. rain, snow, lightning).

Data collected in this project will be used by biologists to predict where and when microbial or soil invertebrate organisms activity will occur. This activity is closely related to the process of soil respiration, which is an important, but little-studied component of the carbon cycle. The continuous monitoring of the soil ecosystem will help to understand the contribution of these processes in the large-scale carbon cycle.

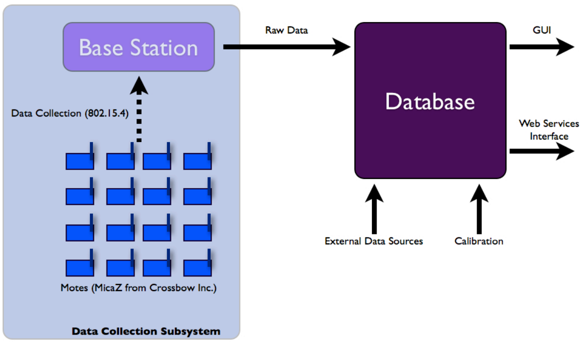


Fig. 3. Life Under Your Feet Architecture

C. Wireless Sensor Network for Variable Rate Irrigation in Citrus

The project Wireless Sensor Network for Variable Rate Irrigation in Citrus, described in [4], uses a network of sensors and actuators to irrigate citrus plantations in the Brazilian state of Sao Paulo. This state has one of the largest citrus production areas in the world. Currently most of this area has no irrigation system, but climate change and the emergence of new diseases will require a change of scenery. The scarce water resources of the region make it essential to develop and implement methods of water conservation.

The proposed system uses a network of fixed sensors and actuators that communicate through wireless connections to manage the whole process of irrigation. The remote nodes use capacitive sensors to measure soil moisture, while the actuators are connected to electro-valves that allow the control of the irrigation system.

Each Field Station has a coverage of about 100 hectares, which means it can control 400 remote nodes separated by a distance of 50 meters. Given the average size of farms in this region of Brazil, it's estimated that on average each farm will need 10 Field Stations. Each Field Station consists of a CPU, a mini weather station, an 802.11b WLAN interface, and a proprietary communications device that allows the communication with the remote nodes. Two 55Ah batteries recharged by a 70 watts photovoltaic solar panel power all these devices.

The Base Station consists of a personal computer and an 802.11b WLAN access point that performs all communication with the Field Stations. From the Base Station the user can access all the collected information, manage the system and control the actuators.

D. PermaSense

The project PermaSense: Investigating Permafrost with a WSN in the Swiss Alps, described in [5], uses a WSN to measure physical parameters of frozen soil in order to understand their behavior during climatic changes. Permafrost is defined as soil that remains at temperatures below 0° throughout the year. Its occurrence is common in colder regions of the planet (near to the poles or at high altitudes). Global warming has led to some areas formed by this type of soil to reach higher temperatures than usual. In mountainous areas, such as the Swiss Alps, the temperature rise makes the soil less consistent and thus can cause the release of rocky material causing damage to infrastructures such as hotels, roads or railway lines.

The architecture used in this project is represented in Figure 4. One or several GSM/GPRS nodes are used to connect the WSN to the Internet. Each remote node measures in "almost" real time four temperatures and four conductivities, which allow accessing the moisture content and physical condition of the soil. A multi-hop topology to route data to the node that contains the GPRS module (Siemens Wireless Module TC65) is used. The data gathered by the sensors is sent to a database that runs on a Linux server. This server contains a Web interface that lets the user generate reports and graphs from the collected data.

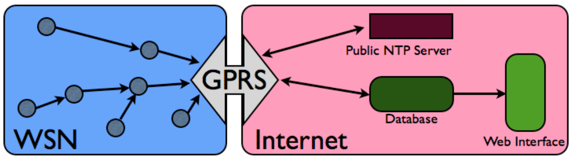


Fig. 4. PermaSense Architecture

E. Wireless Underground Sensor Networks (WUSN)

The project Wireless Underground Sensor Networks, described in [6], differs from the others in that it proposes that the sensing nodes (and their antennas) to be completely buried. Wireless communication is therefore carried through the soil rather than using the traditional air channel. On the projects that monitor soil parameters, described previously, sensors are underground but the antennas are installed on top of the surface, where wireless communications is typically performed. This type of configuration requires the different components of a remote node (sensors, mote and antenna) to be connected through cables, which makes its installation complex.

The solution presented in this project makes it possible to create devices that contain all the components that a remote node needs to function (sensors, memory, processor, radio, antenna and power source). The fact that each node is contained in a single device facilitates the installation by a non-specialist person. The installation process consists only in putting the device in the place to be monitored and ensure that it is at a distance from the other nodes that enables communication.

The installation of all equipment on the sub-soil ensures that it's protected from damage caused by the weather, animals or farm equipment like tractors or lawn mowers. The invisibility granted by this solution has the additional advantage of allowing its use in gardens or sports fields (e.g. football, golf) since there is no equipment above ground to interfere with the practice of sports or the aesthetics of these sites. In public places this invisibility is also beneficial since it makes the equipment less susceptible to theft or vandalism.

Despite all the advantages described above there are some problems that must be addressed to make the application of Wireless Underground Sensor Networks (WUSNs) feasible in the real world. Wireless communication underground is far more complex and less studied than the wireless communication through the air. This fact, combined with the difficulty to change or recharge the batteries because the nodes are underground, requires the revision of the architectures and protocols currently used in WSNs.

Due to the poor results obtained using electromagnetic waves for underground communications some alternatives like the use of magnetic induction or seismic waves are proposed. Because the magnetic permeability of soil is similar to that of air, and thus the decay rate of the magnetic field is approximately the same in both media, magnetic induction is presented as an alternative solution. However, the magnetic field strength decreases as a function of $1/R^3$, where R is the distance to the transmitter, compared with $1/R$ or $1/R^2$ for EM waves. Another alternative, the communication using seismic waves, requires amounts of energy incompatible with battery-powered nodes.

This chapter presents a description of the current state of the art of applying WSN to the monitoring of environmental parameters. With this presentation we can conclude that each project takes different solutions to similar problems. The unique features of the concept of WSN make even small variations in the requirements of each project require the development of quite different solutions. In an embryonic stage of technological development there are few universal solutions that can be used successfully in all WSNs applications. For this reason, one of the biggest challenges to the development of applications in this area lies in the choice of the solutions that best fit the requirements of each application.

III. DESIGN AND IMPLEMENTATION

A. Requirements and Goals

The first step in identifying the requirements that this project should meet was to study the operation of a real golf course and its irrigation system. The golf course *Oeiras Golf & Residence* served as a case study for this purpose. The contribution of those responsible for maintaining the lawns of this golf course was instrumental in the characterization of its current operation and identifying what are the requirements that an application for aiding the irrigation management should meet.

A brief description of how the irrigation system of a typical golf course works and what are the mechanisms used to adjust the amount of water used in its irrigation follows. Afterwards the functional requirements identified are listed.

1) Current Situation

The irrigation system of the studied golf course consists of four components: water pumps, control satellites, sprinklers and pipes.

The water pumps are used to extract ground water and to give pressure to the irrigation system. The control satellites are small base stations installed throughout the golf course that allow controlling the operation of the sprinklers. In the studied course there are 15 satellites - about one per green. It's possible to control how long each zone of the golf course remains in irrigation through these satellites. The control satellites are constantly fed with 220V AC while 24V DC power the sprinklers only when they are on. The person responsible for the maintenance of the grass, referred to as a greenkeeper, relies only on the data provided by a weather station and on its own experience to adjust the amount of water used on the irrigation of the course.

2) Functional Requirements

- Measure soil moisture at different depths.
- Measure temperature at the ground level.
- Measure the voltage of the batteries that power the remote nodes.
- Measure the above mentioned parameters at regular intervals.
- Transmit the data collected by the remote nodes to the final processing node at regular intervals.
- Each remote node must be in one of two states: Normal Mode or Irrigation Mode.
- The energy consumption of the remote nodes must be optimized.
- The installed equipment should not interfere with the practice of the game or the aesthetics of the golf course.

B. System Architecture

The general architecture of the monitoring system proposed in this project is represented in Figure 5. The WSN is divided into cells in order to adapt the network architecture to the geographical distribution of the sites that must be monitored. Each of these cells is composed of four remote sensing nodes. Three of which must be installed on the green (the most relevant place to monitor) while a fourth node should be used to monitor the area of the fairway. Each of these remote sensing nodes consists of a MicaZ mote, depicted in Figure 6, a sensory board, shown in Figure 7, and soil moisture sensors. Each of these components is described in further detail on the next section.

All cells also have a sink node responsible for ensuring communication between remote nodes and the final processing node (FPN). The FPN gathers all the information collected by the WSN providing it to the end user, which may be a human or an application that uses the data collected to directly control the irrigation system.

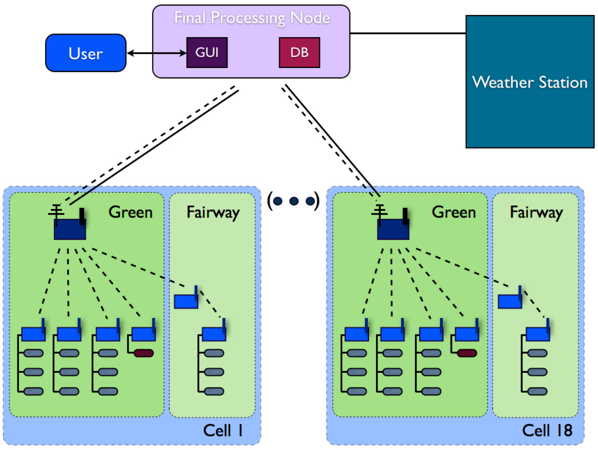


Fig. 5. System Architecture

1) *System Components*

- **MicaZ Mote**

The MicaZ mote from Crossbow [7] is a module composed of an AVR 8-bit Atmel ATMEGA128 microcontroller and an IEEE 802.15.4 compliant transceiver operating in the 2.4GHz frequency: the Chipconn CC2420. This mote has a 51-pin Hirose connector that allows the connection of different types of sensor boards. These boards can have passive sensors that are measured directly using the ADC ports of the ATMEGA128 processor or they can have their own microprocessor that communicates with the MicaZ mote using SPI or I^2C.

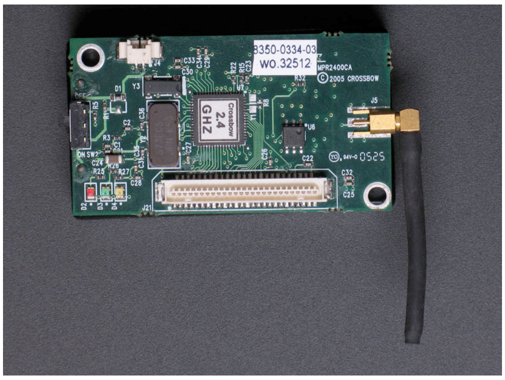


Fig. 6. MicaZ Mote

- **Sensor Board with Co-Processor**

A sensor board, which connects to the MicaZ mote through the 51-pin Hirose, was developed for this project. This board uses a PIC24FJ64GA002 processor to control the operation of a set of sensors, perform calculations and communicate with the mote MicaZ ATMEGA128 processor.

The developed board is shown on Figure 7.

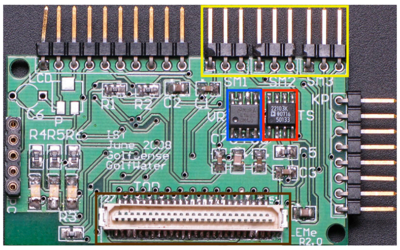


Fig. 7. Sensor Board with Co-Processor

The PIC microprocessor has a set of ADCs that allow it to be used to read analog sensors. This board uses three types of sensors in order to measure soil moisture, temperature and the voltage of the batteries that power the remote node.

The EC-5 soil moisture sensors, described in more detail on the following section, can be connected to this board using three-pin connectors, highlighted by a yellow rectangle on figure 7. This connector allows connecting the EC-5 sensor excitation to an output port of the PIC, the output of the EC-5 sensor to an ADC of the PIC and the grounds of both devices. The three connectors that allow connecting soil moisture sensors to this board are highlighted by a yellow rectangle in Figure 7.

A temperature sensor, highlighted with a red rectangle on Figure 7, was added to the sensor board. The sensor chosen was the AD22103 from Analog Devices. This sensor was considered to be a good compromise between accuracy (maximum error 2.5%) and price. Its small size (SOIC-8 package with about 19mm^2 of area) was also essential to produce a sensor board with the same dimensions as the MicaZ mote. The equation used to obtain the temperature from the output voltage of the AD22103 sensor was the following:

$$Temp = ((((Vout\ .\ 3{,}3) / Vin) - 0{,}25) / 0{,}028)$$

Where Vout is the output voltage of the temperature sensor and Vin is the input voltage of this sensor and it’s the same as the voltage that powers the remote node.

In order to determine the voltage of the batteries that power the remote node a reference voltage had to be added to the sensor board. This reference voltage is highlighted by a blue rectangle in Figure 7. The reference voltage chosen was the LM4140CCM from National Semiconductor. This model can receive an input voltage between 1.8V and 5.5V and has a fixed output voltage of 1.024V. Because the voltage of the batteries that power the remote node is used by the PIC as the maximum value in the conversion of analog to digital values it is possible to calculate its value using one of these ADCs to measure a voltage previously known. The reference voltage LM4140CCM provides a precise known voltage. Using the following equation we can get the voltage of the batteries that power the remote node:

$$Vbat = (ADC\_Max\ .\ Vref) / ADC\_Res$$

Where Vbat is the battery voltage, ADC_Max is the maximum value of the ADC (for the PIC24 ADC_Max is equal to 1023), Vref is the voltage output of the reference voltage LM4140CCM (1.024 V) and ADC_Res is the output given by the ADC when used to measure Vref. Replacing the previously known values we get:

$$\text{Vbat} = (1023 \,.\, 1{,}024) / \text{ADC\_Res}$$

- **Soil Moisture Sensors**

The EC-5 soil moisture sensor (described and tested in [8]) is represented in Figure 8.

Fig. 8. EC-5 Capacitive Soil Moisture Sensor

These capacitive sensors use the soil as part of the dielectric of a capacitor. The equivalent circuit of the EC-5 sensor is represented in Figure 9, where Vin and Vout are the input voltage and output voltage respectively, R is the resistance, C is the capacity of the environment, Cs is the parasitic capacity and G represents the energy lost due to ionic conductivity. The circuit includes an electronic oscillator that produces a rectangular wave with a frequency of 70MHz. The total capacity of the sensor is equal to the sum of the capacity of the medium (C) plus the parasite capacity (Cs). To transform the alternating current (AC) into direct current (DC) an RMS converter is used at the end of the circuit.

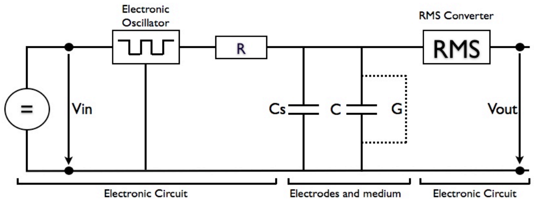


Fig. 9. Equivalent circuit of a capacitive sensor

This circuit is designed to measure the permittivity of the medium (soil) in which it is inserted. This permittivity may be determined by measuring the charging time (t) from an initial voltage (Vi) to a defined voltage (V) with an applied voltage (Vf) of a capacitor that uses the soil as a dielectric. The charging time of the capacitor (t) is related to the capacity by the following equation, considering that resistance R and voltages Vf and Vi are constant:

$$t = -RC.\ln((V-Vf+Vi) / (Vi-Vf))$$

The capacity is a function of the dielectric permittivity of the medium (ε) and of a geometric factor (g) that is associated with the shape of the electromagnetic field that penetrates the medium:

$$C = g\, \varepsilon$$

The dielectric permittivity of the medium (ε) can then be calculated using the following equation:

$$1/\varepsilon = (1/t) \,.\, (Rg.\ln((V-Vf+Vi) / (Vi-Vf)))$$

Figure 10 can help to understand the operation of this type of sensors. The time it takes the capacitor to recharge depends on the dielectric permittivity of the medium and hence of the percentage of water in the soil.

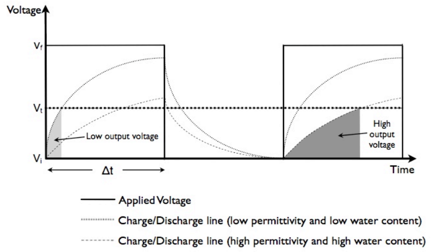


Fig. 10. Permittivity Charge/discharge curves of two different soils

In a soil with a large percentage of water the capacitor will charge more slowly and therefore the load curve is more linear than in a soil with a low percentage of water. This implies that on a wet ground the capacitor will reach a certain threshold voltage (Vt) later than in dry soil.

The output voltage of the sensor is directly related to the average voltage during the period Δt. Thus a soil with high water content will result in a higher output voltage while a soil with low water content will result in a low output voltage.

C. Measurement and Actuation Algorithm

In order to obtain the data collected by the WSN and control its operation a distributed measurement and actuation algorithm was developed and implemented. The development of this algorithm aimed to answer the following 5 fundamental requirements:

- Measure soil moisture, temperature and battery voltage at regular intervals.
- Send the measurements collected by the WSN to the final processing node at regular intervals.
- Allow the user of the system to control the state (Irrigation Mode or Normal Mode) in which each node is at each time.
- Allow the user to configure in run-time the following configuration parameters of the WSN: the frequency with which the data collected by the WSN is sent to the final processing node and the number of samples collected in each period.
- Reduce the time that the remote nodes have to stay with their radios turned on to a minimum.

This is a distributed algorithm that runs on the following three platforms:

- Sensor board with co-processor described on section III.B.1.
- MicaZ mote from Crossbow with an Atmega128 processor described on section III.B.1.
- Final Processing Node (PC)

The activity diagram of the GolfSense application that runs on the final processing node is represented on Figure 11. When this application receives a packet with measurements from a remote node of the WSN it sends the received data to the GolfWater application and writes that data to a locally stored file. Then it checks if there is a pending irrigation order for the remote node that sent the packet of measurements. If there is no pending order a packet containing only the configuration parameters of the WSN is sent to the remote node. If, on the contrary, there is a pending irrigation order the start and stop times of the irrigation period are calculated and sent to the remote node. If, for example, an irrigation order has been entered into the system 5 minutes (300 seconds) ago with the following parameters:

- StartTime = 15 minutes (900 seconds).
- Duration = 30 minutes (1800 seconds).

The order of irrigation sent to the remote node will have a start time equal to 600 seconds (900 seconds - 300 seconds) and an end time equal to 1500 seconds (1800 seconds - 300 seconds). In other words, the time that passed since the order was placed until it is actually sent to the remote node is subtracted from the start and stop times of the irrigation order. Thus it is guaranteed that the remote node will enter into irrigation mode during the period that the user entered into the system. Finally it is sent to the remote node a packet containing the configuration parameters of the WSN and the irrigation order.

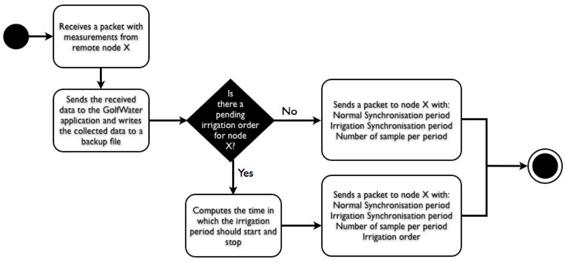


Fig. 11. FPN Activity Diagram

An activity diagram that contains the set of events that occur on the remote node (MicaZ) when the synchronization timer is triggered is represented on Figure 12. In this case, the first action taken by the program that runs on the remote node is to obtain the average of the parameters (soil moisture, temperature and battery voltage) calculated by the sensor board described in III.B.1. This transfer of information between the sensor board and the MicaZ mote is performed using the Inter-Integrated Circuit (I^2C) protocol. After obtaining this information the remote node activates its radio interface and sends the data collected to the final processing node. After this, the remote node listens to the channel until it receives a message from the FPN or a time-out occurs. If the remote node receives a message from the FPN the message is analyzed to see if there was any change in the settings of the WSN or if there is a new irrigation order. In the end the MicaZ radio interface is turned off again.

Through this mechanism the radio interface is turned on only for a short period during which the remote node sends the data collected to the FPN and waits (a limited time) for a configuration message from that node. Some latency is thus introduced in the control system of the WSN as the FPN can only send to the remote node configuration messages during the period following the sending of a data message from the remote node to the FPN. Allowing the remote nodes to keep their radio interfaces off during most of the time and thus saving energy offsets this latency.

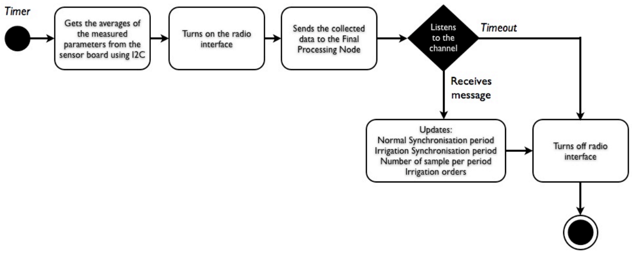


Fig. 12. Remote Node (MicaZ) Activity Diagram

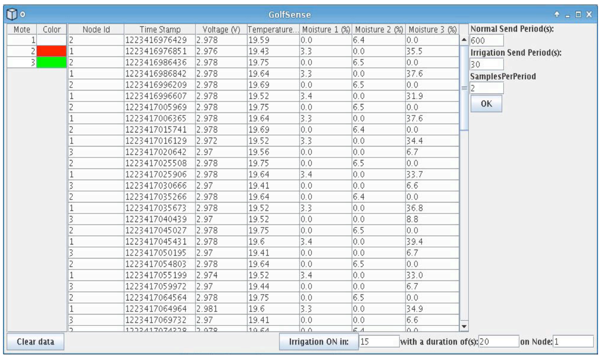
The events described in Figure 12 are triggered by the synchronization timer that runs periodically with a period equal to the "Synchronization period in Normal mode" or to the "Synchronization period in Irrigation Mode" depending on the state of the remote node. There are two timers that control the state in which the remote node is (beggin_irrigation_timer and end_irrigation_timer) that are created when a new irrigation order arrives to the remote node.

When the beggin_irrigation_timer is triggered the synchronization period is changed to the irrigation mode period and the MicaZ mote sends to the sensor board (using I^2C) a new measurement period. When the end_irrigation_timer is triggered the synchronization period is reset to the "Synchronization period in Normal mode" and the sensor board is once again informed of the new measurement period.

The program that runs on the PIC of the sensor board has the following functions:

- Receive from the MicaZ mote the measurement period.
- Take measurements (soil moisture, temperature and battery voltage) using a set of ADCs.
- Perform the calculations necessary to transform the measures of the ADCs in the actual values of voltage, temperature and soil moisture.
- Add the calculated values to a table of averages that is periodically reed (and reset) by the MicaZ mote using I^2C.

Due to the fact that it was impossible to develop and test the GolfSense and GolfWater applications simultaneously a graphical user interface was developed using the Java development platform *Java Swing* that allowed testing the functionalities of the GolfSense application separately. This graphical user interface is shown in Figure 13. On the left there's a list of the active nodes in the WSN. At the center is a table with the data collected by the WSN (which contains the same information sent to the GolfWater application). And on the right there are a set of fields and buttons that let the user change the configuration of the WSN and generate irrigation orders. By observing in real time the reception of the data collected by the WSN this graphical interface facilitated the testing and correction of the features described above.



Mote	Color
1	
2	🟥
3	🟩

Node Id	Time Stamp	Voltage (V)	Temperature...	Moisture 1 (%)	Moisture 2 (%)	Moisture 3 (%)
2	1223416976429	2.978	19.59	0.0	6.4	0.0
1	1223416976851	2.976	19.43	3.3	0.0	35.5
2	1223416986436	2.978	19.75	0.0	6.5	0.0
1	1223416986842	2.978	19.64	3.3	0.0	37.6
2	1223416996209	2.978	19.69	0.0	6.5	0.0
1	1223416996607	2.978	19.52	3.4	0.0	31.9
2	1223417005969	2.978	19.75	0.0	6.5	0.0
1	1223417006365	2.978	19.64	3.3	0.0	37.6
2	1223417015741	2.978	19.69	0.0	6.4	0.0
1	1223417016129	2.972	19.52	3.3	0.0	34.4
3	1223417020642	2.97	19.56	0.0	0.0	6.7
2	1223417025508	2.978	19.75	0.0	6.5	0.0
1	1223417025906	2.978	19.64	3.4	0.0	33.7
3	1223417030666	2.97	19.41	0.0	0.0	6.6
2	1223417035266	2.978	19.64	0.0	6.4	0.0
1	1223417035673	2.978	19.52	3.3	0.0	36.8
3	1223417040439	2.97	19.52	0.0	0.0	8.8
2	1223417045027	2.978	19.75	0.0	6.5	0.0
1	1223417045431	2.978	19.6	3.4	0.0	39.4
3	1223417050195	2.97	19.41	0.0	0.0	6.7
2	1223417054803	2.978	19.64	0.0	6.5	0.0
1	1223417055199	2.974	19.52	3.4	0.0	33.0
3	1223417059972	2.97	19.44	0.0	0.0	6.7
2	1223417064564	2.978	19.75	0.0	6.5	0.0
1	1223417064964	2.981	19.6	3.3	0.0	34.9
3	1223417069732	2.97	19.41	0.0	0.0	6.6

Normal Send Period(s): 600
Irrigation Send Period(s): 30
SamplesPerPeriod 2

Irrigation ON in: 15 with a duration of(s): 20 on Node: 1

Fig. 13. GolfSense Graphical User Interface

IV. TESTS AND RESULTS

This section describes several tests that have the purpose of validating the proper functioning of the developed features and evaluating the performance of the system. The architecture used to perform these tests is shown in Figure 14. Three MicaZ motes that have been connected to sensor boards, described in III.B.1, were used. Each of these boards, besides measuring the voltage of the batteries that power the remote node and the ambient temperature, allow the connection of three soil moisture sensors. Since that at the time of these tests there were only three soil moisture sensors available only one sensor was connected to each remote node. To accomplish communication between the remote nodes and the FPN a MIB600 that communicates with the MicaZ motes through 802.15.4 and the FPN through an Ethernet cable was used. The FPN used was an ACER 1300XC laptop with the following characteristics: Athlon XP 1400+ processor, 512MB of RAM and Xubuntu 7.04 (Feisty) OS. It was on this test bed, installed in the courtyards of the Instituto Superior Técnico - Taguspark, that the tests described below were performed.

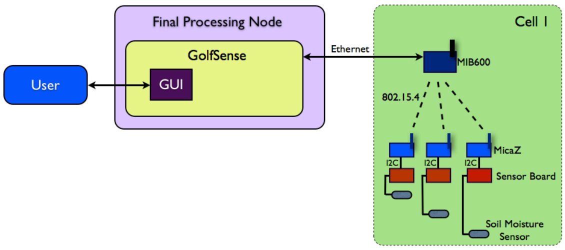


Fig. 14. Testing Architecture

A. Measure of Soil Moisture during irrigation periods

The purpose of this first test was to determine the capacity that the system has to accurately measure soil moisture at various depths and transmit the measured values to a FPN. The aim was also to check that the system was able, through the measurements performed by the soil moisture sensors, to quickly detect the beginning (and end) of rain or irrigation periods.

On this test the system performed soil moisture measurements before, during and after periods of irrigation. The total duration of the test was of about four hours during which the irrigation system was activated three times. The first time the irrigation system was turned on was between minute 25 and minute 35 of the test. Later the system was activated for two minutes more, between minutes 39 and 41 and again for another 10 minutes, between minutes 42 and 52. After this last irrigation period the system continued to carry out measurements for approximately 170 minutes.

These constant changes between watering times and periods during which the system was disabled, had the purpose to evaluate the system's ability to detect periods of irrigation (or rain).

The system was configured to send the data collected with the frequency of 1 minute during which 4 soil moisture measurements should be collected.

The values of soil moisture measured by the 3 sensors placed at 3 different depths are showed on Figure 15. Sensor 1 was located at a depth of 2 cm, sensor 2 at a depth of 5 cm and sensor 3 at a depth of 10 cm. The blue vertical bars represent the periods during which the irrigation was turned on.

By observing this graph we can conclude that this monitoring system is effective to detect watering times since about 1 minute after the irrigation system has been activated there was a sharp increase in the values of soil moisture measured by sensor 1. As expected, the soil moisture measured by sensors 2 and 3 only began to increase after a few minutes due to the time it takes for water to seep into the soil and reach the depth at which these sensors were.

It is also possible to conclude that the two sensors that are closer to the surface are much more sensitive to the fact that the irrigation is active or not than sensor 3, which is at a greater depth. In fact, the measurements made by the two sensors that are closest to the surface almost immediately reflect the change of the state in which the irrigation system is (active or inactive).

It is also interesting to compare the values of soil moisture reported by the 3 sensors at the beginning and at the end of this test. Both times the sensor that measures higher soil moisture is the one that is installed deeper, followed by the one that is in the middle and finally the sensor closest to the surface is the one that reports the lowest soil moisture. This can be explained by the fact that the surface soils retain less water due to evaporation and infiltration effects.

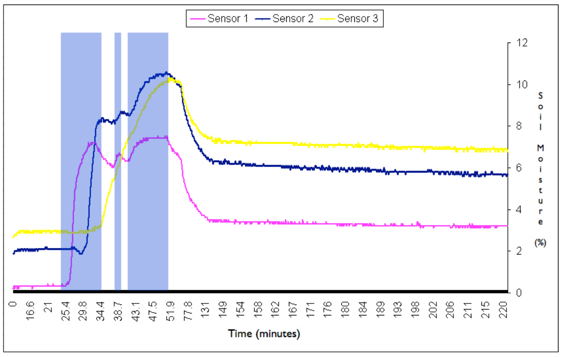


Fig. 15. Soil moisture variation at 3 different depths

B. Measure of Battery Voltage

The purpose of this test was to verify the quality of the battery voltage measurements done by the sensor board developed. To fulfill that objective two multimeters (Univolt DT-64 and Langoir UT71C) were used. Measurements made by the sensor board were compared with the measurements made by these two multimeters. The precision with which the remote node measures the voltage of the batteries that feed it is important, not only to inform the user of the system that it is time to replace the batteries, but also because the temperature and soil moisture calculations use the battery voltage as a parameter. For this reason the accuracy of the temperature and soil moisture reported by the sensor board depend directly on the precision with which it measures the battery voltage.

Ten measurements were performed for ten different sets of two AA alkaline batteries with voltages ranging between approximately 2.2V and 3.2V. The differences between the voltages measured by the multimeters and the sensor board ranged from 0.001V to 0.036V. That is, the maximum difference observed was of 0.036V. The average difference between the voltage values measured by the sensor board and the two multimeters was of 0.0104V, value that can be considered quite acceptable and would not significantly affect the calculation of the remaining measurements (soil moisture and temperature) made by the sensor board.

C. Long Term Test on an Outdoor Garden

The test described in this section was intended to evaluate the behavior of the developed system in an environment as close to the reality for which it was designed as possible. In order to test the system's behavior in an outdoor environment an installation similar to that of Figure 14 was done on an outdoor garden. The soil moisture sensors were placed at a depth of 3 cm. Each remote node was installed in a location with specific characteristics in order to determine how these characteristics influence the measurements taken. Follows a description of each location where the remote nodes were installed:

Location 1: Near the irrigation system sprinkler in a flat area.

Location 2: Near the irrigation system sprinkler in a flat area under the influence (shadow) of a tree.

Location 3: At the edge of the sprinkler range in a sloping area.

Each day an irrigation period with an extent of 5 minutes beginning at 17:30 was defined. The chart of Figure 16 shows the temperatures and soil moistures measured by the 3 remote nodes during 3 days. The blue vertical bars show the periods during which the irrigation system was turned on.

As shown on this chart, during the nights the measured temperatures were quite low (around 12.7º) while during the day the temperature achieved values of around 46.1º. Another interesting information is that the temperature of remote node 2 never reaches values as high as those measured by the other nodes. The maximum temperature measured by remote node 2 was of 36.7°. This behavior can be explained by the fact that remote node 2 was installed near a tree which caused it to be in the shade during the hottest periods.

As it was expected, the rate at which soil moisture decreases after an irrigation period is directly related to the temperature measured at the time. Looking at the chart of Figure 16 it can be concluded that the higher the temperature the faster the soil moisture decreases. During the night periods, when the temperature was lower and the air moisture was presumably higher, the soil moisture hardly diminished and even increased slightly on the 3rd day probably due to the infiltration of water from the irrigation.

Since the irrigation periods should ideally be performed at a time when the area to be irrigated is no longer under direct sunlight exposure, the temperature information collected by the system can be very useful in determining when to irrigate each zone.

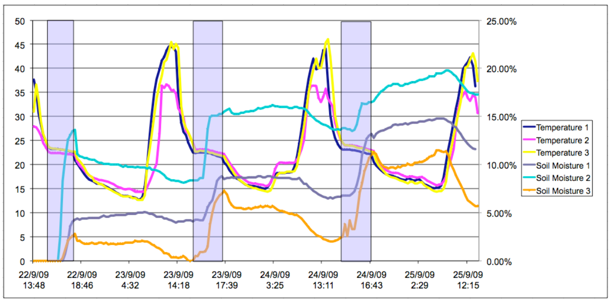


Fig. 16. Temperature (ºC) and Soil Moisture (%) Variation

D. Energetic Performance

The purpose of this test was to evaluate the energetic performance of the algorithm described in III.C. A major objective of this measurement and actuation algorithm is to optimize the energy consumption of the remote nodes maximizing its useful life. To achieve this objective this algorithm creates opportunities to turn off the radio interface of the MicaZ motes and to put the Atmega128 processor in idle mode.

In this test we used two remote nodes consisting of MicaZ motes and sensor boards (described in III.B). Both remote nodes were programmed to synchronize with the Final Processing Node, sending the data gathered by its sensors and receiving configuration parameters each 10 minutes (600 seconds).

The first remote node (node 1) was programmed to take advantage of the opportunities created by the algorithm described in III.C. Thus this remote node only turns its radio interface on and enables the Atmega128 processor when it needs to communicate with the FPN (each 10 minutes). The maximum time during which the radio interface and the processor of mote MicaZ are active is of 2 seconds for each period of synchronization. The duty cycle of the node 1 radio is thus of 2/600 or 1/300.

The second remote node (node 2) keeps its radio permanently active and does not use any energy saving features offered by the Atmega128 processor (e.g. idle mode).

In Figure 17 it's possible to compare how the battery voltage of both nodes varies over time. Through the analysis of this graph it's possible to conclude that the battery voltage of node 2 decreased much faster than the battery voltage of node 1. Node 2 has reached its minimum voltage (2.126V) after approximately 77.5 hours. After this time the FPN stopped receiving packets from this remote node. Node 1 remained in operation for approximately 318.8 hours after which it reached the voltage of 2.128V and failed to communicate with the FPN.

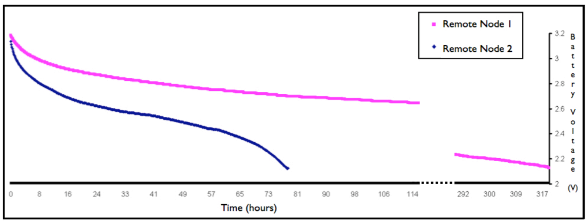


Fig. 17. Battery voltage evolution

It is possible to verify that the use of the algorithm described in section III.C enabled to multiply by 4 the battery life of a remote node. This can be explained by the huge impact that the radio has on the energy consumption of the MicaZ remote node even when it is not transmitting but only listening to the channel. Because the algorithm proposed in this project allows the remote nodes to know exactly when to expect transmissions from the FPN it enables them to keep their radios turned off during most of the time, thus significantly improving their energy performance.

V. CONCLUSIONS

The work proposed in this paper sought to apply the concept of WSNs to the monitoring of environmental parameters in order to optimize agricultural productivity and thus be beneficial from an economic point of view. The studies developed within this dissertation, including the requirements analysis conducted with the help of agronomy experts and greenkeepers, can serve as a demonstration of the feasibility of applying the concept of WSNs in agricultural management.

Golf courses were chosen as the setting for this first approach to the optimization of farm management using the concept of WSN due to the fact that these facilities consume very high quantities of water but at the same time have sufficient financial resources to invest in systems that optimize irrigation. For these reasons, golf courses should be the first places where the installation of such a system will be economically feasible. Later, if the expected increase in the use of WSNs leads to the decrease of equipment costs, the monitoring system proposed in this paper can be easily adapted to assist in the management of other agricultural explorations.

The development of a reference implementation, based on a more general conception of an application for environmental monitoring, allowed validating the concept by putting it to the test in real scenarios. The set of tests made on this prototype leads to the conclusion that it is effective in measuring both soil moisture and temperature, and that these measurements can be very useful to aid in the irrigation management. The periods of irrigation (or rain) are quickly detected by the monitoring system and the temperature gradients measured are extremely useful to determine the best times to irrigate each area of a golf course. Also, the measurement and actuation algorithm proved to be effective to control the operating parameters of the sensor network (synchronization period, number of samples per period and irrigation orders) and to optimize the power consumption of the remote nodes.

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