A wireless sensor network implementation for an industrial environment

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***Abstract*— This paper reports the design and implementation of a system based on a wireless sensor network for measuring the temperature and pH in a tannery barrel. The prototype consists of a base node and two battery-powered remote sensor nodes. These sensor nodes are responsible for performing the measurements and transmit them via multi-hop radio links to a PC-connected base station. The system includes a user application running on a PC that can store and display data, and monitor and configure the system. The analysis of experimental data obtained in tests in the industrial plant shows that the system is capable of measuring pH in the range of 2 to 8 with an uncertainty of 0.1 pH, and temperature in the range of 10°C to 70°C with an uncertainty of 0.5°C. The main contribution of this work consists in adapting a system based on a wireless sensor network to an industrial environment.**

I. Introduction

Measurement of temperature and pH are very important in a wide range of industrial processes. This is particularly true in the leather processing within a tannery barrel. A tannery barrel is a cylindrical enclosure (about 3 meters in diameter and 3.5 meters in length) as shown in Figure 1.

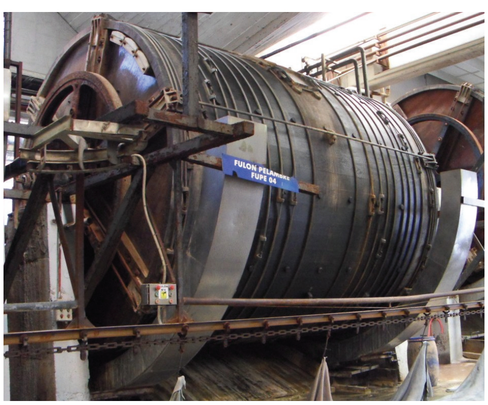


Fig. 1. Tannery barrel hosting the sensor

Throughout these processes, the barrel rotates with a speed of 4 rpm to achieve the proper homogenization. Traditionally, in order to measure temperature and pH, the operator needs to stop the process, open a side door, and take a sample of the inside substance. This way of collecting the measurements not only has the disadvantage of being manual and stopping the process but also the operator is exposed to vapors that may be harmful to his health. Another method consists of using data loggers with temperature sensors placed inside the barrel. These devices gather the information during the process, afterwards it is removed from the barrel and the data is analyzed in a PC. This process avoids the problems of the previous method, since neither is manual nor stops the process. On the other hand, it is not performed in real time and therefore cannot control the process.

The choice posed by this work is to develop a system based on a wireless sensor network. This alternative allows real time measurements without interrupting the process, eliminates the possibility of human error in the measurement and minimizes health risks to the operator. Likewise, the solution is scalable and the maintenance cost is low. In contrast, the use of this technology in this application is hampered both by the turning of barrels and the propagation of radio waves in an industrial environment.

The choice posed by this work is to develop a system based on a wireless sensor network. This alternative allows measurements without interrupting the process, eliminates the possibility of human error in the measurement and minimizes health risks to the operator. Unlike the data logger option, real time measurements are obtained, giving important information to take actions during the industrial process. Likewise, the solution is scalable and the maintenance cost is low. In contrast, the use of this technology in this application is hampered both by the turning of barrels and the propagation of radio waves in an industrial environment.

Wireless sensor networks have been successfully applied to monitoring environmental conditions [1] [2] [3]. The quality of outdoors links is good, but indoors, the reflections and refractions of waves on the walls and objects create disruptions that decrease the range and quality of communication. In [4] different configurations of sensor networks are analyzed by simulating an industrial environment by generating interference. In [5] different sensor network architectures for industrial applications of preventive maintenance are compared concluding that the investment cost is low compared with the obtained results. The development achieved by the latest standards [6] improves the communication through the use of Spread Spectrum and by means of combining 802.15.4 with 802.11 mesh type [7].

This paper presents a system for measuring temperature and pH, based on a IEEE 802.15.4 tree-like network, capable of operating in an industrial environment. Laboratory tests were conducted with three nodes: the base station and two sensor nodes, one measuring temperature and pH, and the other measuring only temperature. The system was validated in the industrial plant of a tannery. A special container was manufactured for the temperature sensor, allowing to place it in the barrel and measure temperature during the tanning process. The node with the pH and temperature sensor was not attached to the barrel, it was tested by making measurements of samples taken from the barrel within the industrial plant. Finally, we validated the pH sensor calibration procedure.

II. Design and implementation

A. Overview

The system (Figure 2) consists of a PC-connected base node and sensor nodes that are installed on the barrels.

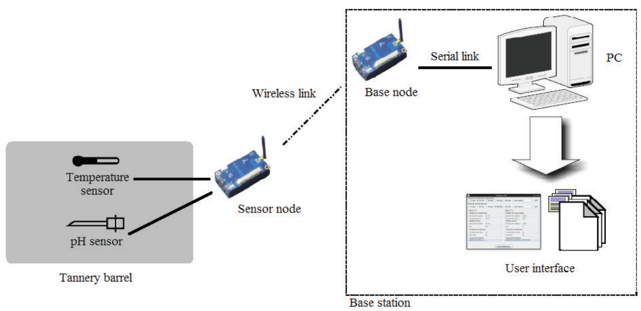


Fig. 2. System outline

The user application, running on the PC, stores the collected data and allows the operator to modify configuration parameters as well as enables data analysis and real-time monitoring of the remote nodes.

The IRIS platform from Crossbow [8] was used to deploy the sensor nodes and the base station, whose modules (called Motes) are basically a microcontroller and a radio. The Motes can receive information through their interfaces, process and transmit it wirelessly to another node or to a PC. The main features of the hardware platform are shown in Table I.

The system is scalable up to a maximum of 255 sensor nodes. The sensor nodes work properly up to a distance between them around 50 meters (indoors) or 500 meters (outdoors).

The sensor nodes are powered by two AA batteries whose estimated duration is more than one year for a star topology. This work focused on the optimization of the sensors power consumption, the power consumption of the communications was out of its scope. At this level, the system uses the LPL (Low Power Listening) protocol implemented in TinyOS. [9]

The pH and temperature measurement circuits were designed and manufactured. The system allows a minimum sampling period of 1 minute and is capable of measuring temperatures from 10°C and 70°C with an uncertainty of ±0.5°C and a resolution of 0.1°C. On the other hand, it is capable of measuring pH between pH 2 and 8 with an uncertainty of ±0.1 pH and a resolution of 0.1 pH.

TABLE I
Details of the Iris platform

Feature	Value
Program memory (flash)	128 kB
RAM	8 kB
Microcontroller frequency	7.37 MHz
A/D converter	10 bits
Others interfaces	Digital I/O, I2C
External flash memory	512 kB
RF frequency band	2.4 GHz
RF transmission rate	250 kbps
Power supply: 2 AA batteries	3V

B. Embedded software platform

The embedded software that runs in the sensor nodes and the base station was implemented on TinyOS 2.1. This is an open source operating system specific for low-power networks developed by the University of Berkeley. [9]

The communication between the sensor nodes and the base station was programmed using the TinyOS protocols called ”Collection” and ”Dissemination”. LPL protocol was also used for radio management.

Collection [9] is the multi-hop and best-effort protocol used by the sensor nodes to send the collected data. The network topology is a tree, where the leaves are the sensor nodes and the node connected to the PC is the root of the tree.

Dissemination [9] is the protocol used to send parameter changes from the base station to the sensor nodes. In this protocol all network nodes end up taking the same value in all variables. The protocol does not ensure a maximum wait time for all nodes to reflect the change, but the algorithm tends to quickly unify the value.

LPL is an asynchronous MAC layer protocol and provides energy savings by reducing the time that the radio is turned on by means of setting a radio duty cycle.

C. Temperature sensor

Temperature was measured with Maxim’s DS620. This integrated circuit measures the ambient temperature and transmits this data through an I2C serial interface. It has very low power consumption in idle mode and can operate with a 1.7 V supply (see details in Table II). Figure 3 shows a picture of the manufactured temperature measurement circuit.

D. pH sensor

The pH measurement circuit design was based on a pH glass electrode due to its low cost and its wide industrial development. The operation of this electrode is modeled by a galvanic cell. The electrode develops an electrical potential responding to the Nernst equation, which is a function of pH and temperature of the measured solution. This electrode

TABLE II
DS620 CHARACTERISTICS

Feature	Value
Supply voltage range	1.7 ... 3.5 V
Operating range	-55 ... 125°C
Accuracy	±0.5 °C @ 0 ... 70°C
Resolution	11 bits (0.25°C)
Conversion speed	50 ms
Interface	Serial I2C
Idle mode consumption	2 μA
Consumption during conversion	800 μA

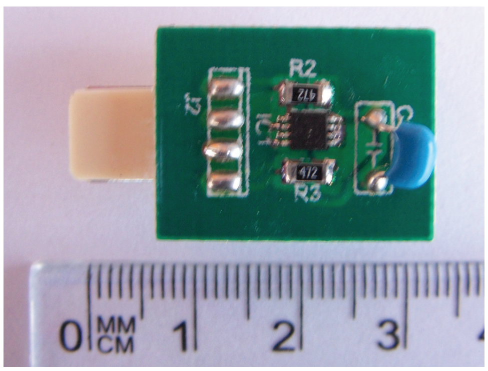


Fig. 3. Temperature measurement pcb

does not present power consumption, has a very high output resistance (hundreds of mega ohms) and pH-voltage characteristic has a temporal drift that must be corrected by periodic calibration.

The pH sensor circuit must respect the following requirements: an asymmetrical power source between 0 and VDD (VDD between 2 V and 3 V to take account of the voltage fall suffered by the batteries), low power and the ability to work with pH signals that may vary between 2 pH and 8 pH.

The designed electronic circuit (see Figure 4) was based on a previous development [10]. The main contribution of the new design is that it incorporates a method for automatically compensate the drift of the pH glass electrode and thus increases electrode lifetime.

The circuit has five main components. An analog switch (Texas Instruments' TS3A4741) is used to turn the circuit on only during the measuring time, so as to optimize power consumption. In order to maximize the resolution of the A/D converter, an instrumentation amplifier (Texas Instruments' INA333) presenting very high input resistance is used. A low pass filter is placed on the circuit output in order to reduce electromagnetic noise. A voltage reference (Maxim's MAX6018) is used to obtain a constant potential independent of battery voltage. A digital potentiometer (Microchip's MCP4652) is used to add a constant to the voltage of the pH glass electrode. The constant is established from the micro-controller through the I2C serial interface and makes

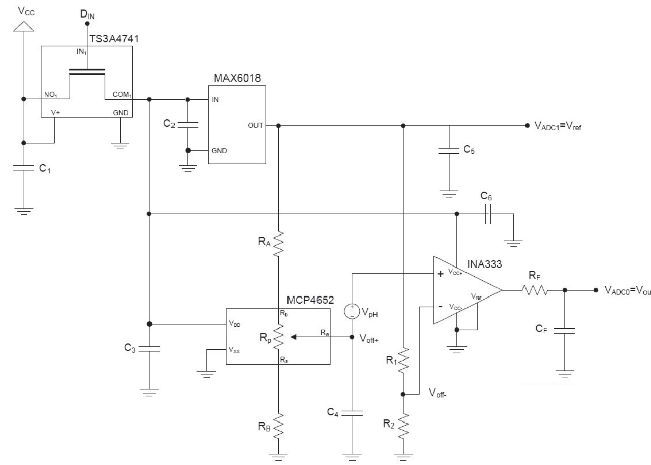


Fig. 4. Schematic diagram of the pH measurement circuit

it possible to compensate the pH glass electrode drift. Figure 5 shows a photo of the manufactured PCB.

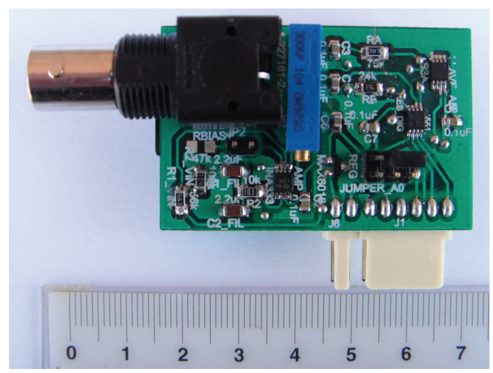


Fig. 5. pH measurement circuit

E. User Interface

The user application running on the PC was developed in Java. The main program window is divided into three sections (Figure 6). In the top section, the operator can select the temperature and pH sampling period at the sensor nodes. In the central section, there are panels for each barrel. In the lower section, there is a button to start the calibration of the pH sensors in a remote node.

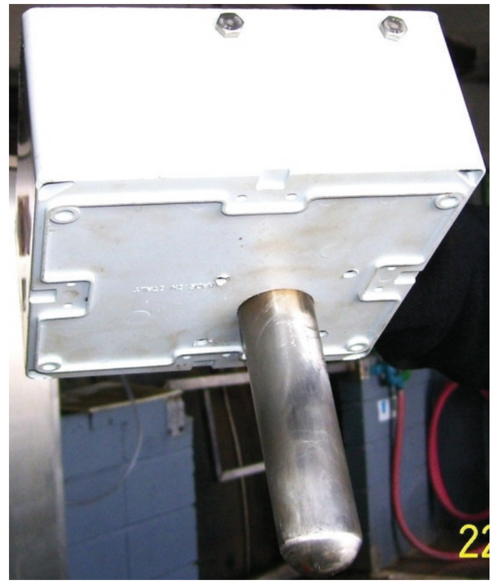
F. Mounting

The container of the sensor node was manufactured with a standard IP66, 15cm x 15cm box, with a screw-fastened lid (Figure 7).

The container has the robustness needed for an industrial environment and is particularly suitable to withstand the corrosive vapors that come out from inside the barrel. It also provides an easy mechanism to replace the batteries and calibrate the pH sensor. Finally, the internal components fit inside the container and are adequately protected.

The metal sheath (Figure 7(b)) that protects the temperature measurement circuit was designed taking into account three

(a) Interior view of the sensor node container



(b) Exterior view of the sensor node container detailing the metal sheath that contains the temperature measurement circuit

Fig. 7. Installation of sensor node

Fig. 6. User application main window

main requirements. In the first place, it should withstand the highly corrosive substances that would be found inside the barrel. In the second place, it should give a properly thermal transfer between the temperature measuring chip and the substance to be measured. Finally, it should be sized to accommodate the temperature measurement circuit.

III. Results

A. Power supply

In order to determine the minimum supply voltage at which the sensor node is capable of working, the following test was performed: the sensor node was left on continuously measuring temperature and pH and sending data to the base node. This test revealed that the sensor node is capable of operating at down to 1.9 V and that the Mote is the first component to work improperly.

B. Power consumption

The power consumption was measured by placing a one ohm resistor in series with the power source. Several measurements were taken considering the different activities that the Mote performs. This corroborated the low power consumption of the sensors circuits (less than 30 μA) and showed the high power consumption of the Mote operation (1.3 mA). This power consumption is mainly produced by the radio (transmission and reception) and the microcontroller.

C. Validation of the pH sensor

We surveyed and compared measurements obtained both from a commercial pH sensor (YSI EcoSense PH100) and from the developed pH sensor (with an InLab 413 glass electrode of Mettler Toledo). Figure 8 displays the measurements along with their corresponding confidence intervals showing that both sensors are consistent.

D. Measurements in an industrial environment

Several trials were conducted in a large industrial plant. This tannery has 30 barrels distributed over 15000 m^2 and is capable of processing between 5000 and 6000 pieces of leather per day (each one sizing on average more than 4 m^2). All tests were performed using a sensor node mounted on a barrel and a base station connected to a PC at a 30 meters distance.

The longest experiment lasted 108 hours, taking temperature measurements every 2 minutes, getting a packet loss rate of 13%.

Temperature measurements taken over 42 hours of are presented in Figure 9. The first 10 hours of the graph correspond to the end of the liming process (it consists of placing a skin within a barrel and dissolve hair using lime and sodium

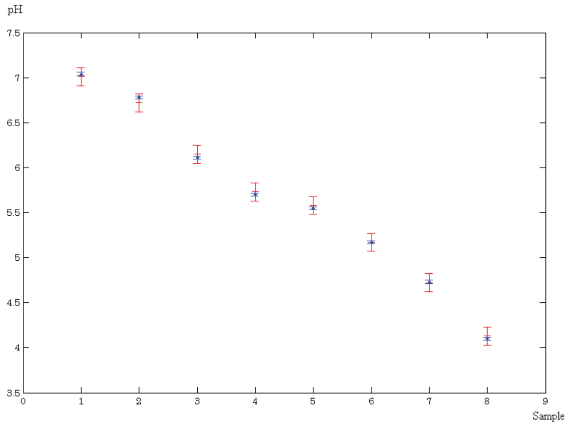


Fig. 8. Graphical comparison of pH measures

sulphide.). Then, the barrel was cooled at ambient temperature for approximately 20 hours. The last part shows the beginning of a new process when ice is added to quickly lower the temperature. The results were validated by expert operators.

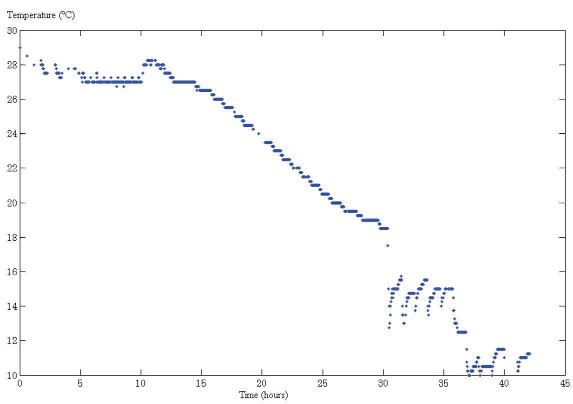


Fig. 9. Graph of temperature measurements at the plant

IV. Discussion

The chosen tree-network and dissemination protocol, which did not allow us to lower the radio duty cycle, significantly reduced our initial estimation of power consumption. This parameter and the packet loss rate can be improved using other protocols. Indeed, there are protocols for environmental monitoring, which allow battery lifetimes of several years [11] [12], but porting them to our platform was not an objective of this phase. Finally, the multiplicity of paths through a mesh network can reduce the packet losses, but in our case, being a first prototype, only three nodes were used.

V. Conclusion

A wireless sensor network based system to measure temperature and pH in an industrial environment was implemented, fulfilling the application requirements. The system is very easy to install not requiring any wiring. It provides real time information of important variables, improving the monitor and control capabilities for the different processes. Finally, it introduces substantial improvements compared to the current measurement method as the process does not need to be stopped, potential errors in operation and data registration are minimized, and it is safer for the operator's health.

We measured a 13% packet loss rate in the communication between the sensor node and the base station and we estimate that the battery life of the sensor node will not exceed three months.

Future work has to deepen on the power consumption, working on the radio and micro-controller, as well as on the sensors to drastically reduce the power consumption. In addition, an integrated full version could be proposed in the future.

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