An Integrating Platform for Environmental Monitoring in Museums Based on Wireless Sensor Networks

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Abstract **– Monitoring the museum's environment for preventive conservation of art purposes is one major concern to all museums. In order to properly conserve the artwork it is critical to continuously measure some parameters, such as temperature, relative humidity, light and, also, pollutants, either in storage or exhibition rooms. The deployment of a Wireless Sensor Network in a museum can help implementing these measurements in real-time, continuously, and in a much easier and cheap way. In this paper, we present the first testbed deployed in an Contemporary Art Museum, located in Madeira Island, Portugal, and the preliminary results of these experiments. On the other hand, we propose a new wireless sensor node that offers some advantages when compared with several commercially available solutions. Furthermore, we present a system that automatically controls the dehumidifying devices, maintaining the humidity at more constant levels.**

Keywords – Art preventive conservation, Awareness tool, Environmental monitoring, Wireless Sensor Networks.

I. INTRODUCTION

Today's museum managers are faced with the constant demanding of gaining greater control of the indoor environment, under increasing budgetary constraints. Those in charge of historic buildings have the added complexity of preserving not only the existing artwork but also the building's historic structure. In this type of environments, it is very important to minimize the visual impact caused by monitoring systems for esthetical reasons. So, both kinds of protections must be accomplished with minimal intrusion from the new system being installed.

The conservation of artwork in museums is a very well known problem, either in exhibition rooms or in archival collections. Monitoring the museum's environment is one of the most important tasks and concerns of all museums. In order to properly conserve the artwork it is critical to continuously measure and control some parameters, such as temperature, relative humidity, light and, also, pollutants (such as: carbon dioxide, several types of acids, dust particulates, etc.).

It is also crucial to consider that the desired values of these parameters depend on the type of material or on the group of materials (typical in contemporary art) that constitute the artwork. So, depending on the type of works that are in exhibition or in storage rooms, different rooms may have different requirements regarding environmental conditions. The main goal of preventive conservation is to maintain the artworks under basically constant levels of, above all, humidity and temperature. However, in the case of rare objects and artefacts, it is required an extremely precise control of temperature and humidity levels.

The deployment of a Wireless Sensor Network (WSN), which is composed by wireless sensor nodes, in a museum can help implementing these measurements continuously, and in a much easier and cheap way. It causes almost no visual impact due to the small size of sensor nodes and to the absence of cables, what is extremely important in a museum. Also, it eliminates the problems inherent to traditional measuring equipments, such as mechanical hygrothermographs, psychometers and hygrometers; there are no moving parts to break and it stays in calibration.

A WSN typically consists of a large number of tiny wireless sensor nodes (often referred to as nodes or motes) that are densely deployed [2]. Nodes measure some ambient conditions in the environment surrounding them. These measurements are, then, transformed into signals that can be processed to reveal some characteristics about the phenomenon. The data collected is routed to special nodes, called sink nodes (or Base Station, BS), typically in a multi-hop basis. Then, the sink node sends data to the user. Depending on the distance between the user and the network, a gateway may be needed in order to bridge both, either through the Internet or satellite.

A sensor node typically consists in five components: sensing, memory, processor, transceiver (transmitter and receiver) and battery. Nowadays, nodes are intended to be small and cheap. Consequently, their resources are limited (typically, limited battery, reduced memory and processing capabilities). Moreover, due to short transmission range (caused by restrained transmission power), nodes can only communicate locally, with a certain number of local neighbours [2]. So, nodes have to collaborate in order to accomplish their tasks: sensing, signal processing, computing, routing, localization, security, etc. Consequently, WSNs are, by their nature, collaborative networks [3].

Taking advantage of wireless communications, WSNs allow for a wide range of applications: environmental monitoring, catastrophe monitoring, health, surveillance, traffic monitoring, structural monitoring, security, military, industry, agriculture, home, etc.

In this paper, which is an extension version of paper [1], we describe the experimental deployment of a small WSN carried out in a contemporary art museum called Fortaleza São Tiago, in Madeira Island. This WSN aims at monitoring the environment of the museum, for artwork and for building conservation purposes. We highlight all the problems identified at the initial phase, which influenced the final deployment of the complete WSN. We also present a new wireless sensor node that we have developed specifically to environmental monitoring applications, but considering the specific requirements of the museum, for example, reduced size and cost. This is one of the main contributions of our work.

This work was developed in the context of the WISE-MUSE project (Environmental Monitoring based on Wireless Sensor Networks for conservation of artwork and historical archives project).

This paper is organized as follows. In section II, we describe the related work in the area of WSNs applied to the monitoring of museums or historical buildings. Section III presents the problem of environmental monitoring of museums and the use of WSNs as a cheap and suitable solution. Still in the same section, a practical testbed deployed in a museum is described, as well as all the problems identified. The results of these experiments are, also, described. Section IV presents the proposed WISE-MUSE sensor node and Section V presents the humidity control device. Finally, Section VI provides some conclusions and some perspectives of future work.

II. Related Work

There are some works that are related to the deployment of WSNs in museums. However, the most common applications are, usually, to use WSNs for security reasons [4, 6]; or to monitor the number and distribution of visitors in the museum [5]; or for the creation of interactive museums [5, 7, 8].

There are also some wireless equipments that measure humidity and temperature commercially available (Omega, 2007 [9], 2DI 2007 [10]), however they have bigger dimensions and they are more expensive than wireless sensor nodes.

Spinwave Systems offer a solution for preserving a building's architecture using WSNs [11]. Spinwave provide precise control and monitoring of environmental variables, such as temperature and humidity, in buildings where wired sensors are not feasible or are prohibitively expensive. However, they do not monitor light or pollutants. Besides, the nodes are expensive. They claim to ensure minimal disruption to building occupants and improved indoor climate. But, nodes are quite big for being applied in an environment where the visual impact is of extreme importance.

Lee et *al.* [12] present a scenario of applying WSNs to monitor the environment of art galleries, but focusing in measuring only humidity and temperature. However, the paper focus on a different problem, i.e., on evaluating the efficiency of the ALOHA protocol without retransmission, when transmitting from sensor nodes to a base station. Del Curto & Raimondi [13] present a work where WSNs have been used for preserving historic buildings. Crossbow manufacturers [14] present two systems to be applied in museums and archives: a system that monitors humidity and temperature, the CLIMUS, and a system that controls the air conditioning unit, the REAQUIS. However, they do not use WSNs; sensors used are wired are much bigger than wireless sensor nodes commercially available.

Our goal is to create a WSN for monitoring not only humidity and temperature, but also light and pollutants, in a museum. We are also using smaller and cheaper wireless sensor nodes than the ones used by [11]. These factors are the basis that makes our solution more suitable to the environmental monitoring of museums or historical building.

III. Applying WSNs in Museums Environmental Monitoring

Today's museum managers are faced with the constant demanding of gaining greater control of the indoor environment for preventive conservation of art purposes, under increasing budgetary constraints. In the particular case of Fortaleza São Tiago, in Madeira Island, Portugal, environmental measurements are performed in a very rudimental way, using traditional and very expensive measuring equipments, such as mechanical hygrothermographs, psychometers and hygrometers. These measurements take too long to be performed in the all museum and require a specialized person for this purpose. These equipments require calibration and caused visual impact on visitors and on exhibition rooms. And, so far, these measurements haven't been performed as often as it should. The administration choices regarding a more flexible and practical solution are limited by severe budgetary constraints.

The deployment of a WSN in a museum can help implementing these critical measurements automatically, continuously, and in a much easier and cheap way. It causes almost no visual impact due to the small size of sensor nodes and to the absence of cables, what is extremely important in a museum. Also, it eliminates the problems inherent to traditional measuring equipments; there are no moving parts to break and it stays in calibration.

Our goal is to create a WSN for monitoring not only humidity and temperature, but also light and some pollutants, in a museum, for art conservation purposes. This work was developed in the context of an ongoing project named WISE-MUSE, which aims to applying WSNs to museum environmental and structural monitoring and automatic control.

Our initial deployment at the museum of contemporary art, Fortaleza São Tiago, has served as a proof-of-concept and consisted of a small group of wireless nodes capturing environmental data continuously. Data collected by sensor nodes is sent wirelessly to a database, through the sink node that is connected to a PC. Data can be visualized, in real time, through a web page, in different ways: tables, graphics, colour gradients, etc.

As Fig. 1 illustrates, we have defined, essentially, five phases involved in the environmental monitoring of a museum. The first phase regards the monitoring of temperature, humidity, light and pollutants; then, collected data is sent to a data repository; after that, this data can be visualized in different formats (graphics, tables, colour gradients, etc.); afterwards, data is analyzed to verify its compliance with the art conservation rules; finally, as a last phase, the environment conditions are automatically optimized accordingly to the analysis results.

A. Field Deployment

With this first experimental testbed, we aimed at testing the behaviour of the wireless sensor nodes and at identifying some problems regarding both the nodes and the application scenario. This way, we were able to choose the sensor nodes that best suit to this specific application.

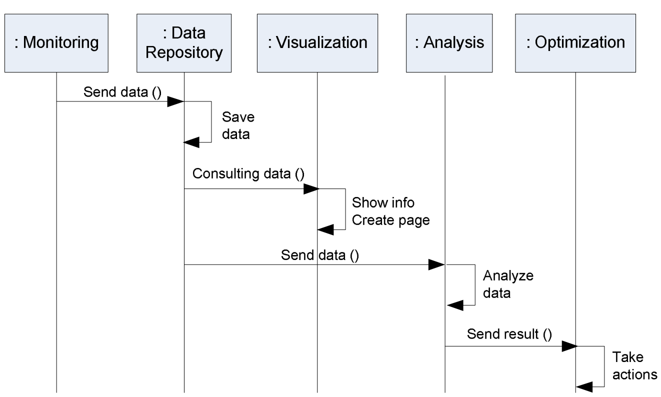


Fig. 1. Phases involved in a museum's environmental monitoring.

As this was an experimental testbed, we have only deployed three wireless sensor nodes and one sink node (or base station), as Fig. 2 illustrates. So, we decided to install three Crossbow [14] mica2 motes, equipped with an MTS400CA data acquisition board and a mote equipped with a mib520 board, functioning as the base station. The radio transceiver of these nodes operates at the 868,919 MHz ISI band and they communicate using the ZigBee [19] communication protocol.

The MTS400CA data acquisition board measures: ambient light, relative humidity, temperature, 2-axis accelerometer, and barometric pressure. This board has a common humidity and temperature sensor, the Sensirion SHT11, which can measure a temperature range from -10 to +60°C and a humidity range from 0 to 90% RH. The ambient light sensor is a TAOS TSL2550D, which has a spectral response similar to human eye [14]. In our future experiments, we intend to replace the humidity and temperature sensor by the Sensirion SHT15, because it has a higher accuracy than the Sensirion SHT11.

Mica2 nodes are smaller than Spinwave [11] nodes, with 58 x 32 x 7mm (excluding the battery pack) opposed to 121 x 70 x 25 mm, respectively. Nevertheless, our WISE-MUSE sensor node implemented in this project is smaller and cheaper than Mica2 node, which will be described next. Fig. 3 shows mica2 motes equipped with the battery pack.

Currently, this WSN measures the most important parameters, which are temperature, humidity and light; however, internal voltage is also monitored so that the user is aware of the state of the nodes' batteries. The sensor nodes are programmed to measure and send data each 60 seconds.

B. Preliminary Results

As explained before, all collected data is centralized in a PC, connected to the Internet. Fig. 4 shows some screenshots of the web interface created for the specific application of museums' environmental monitoring. In this figure we present the 24 hours' graphics of temperature, humidity, light and internal voltage.

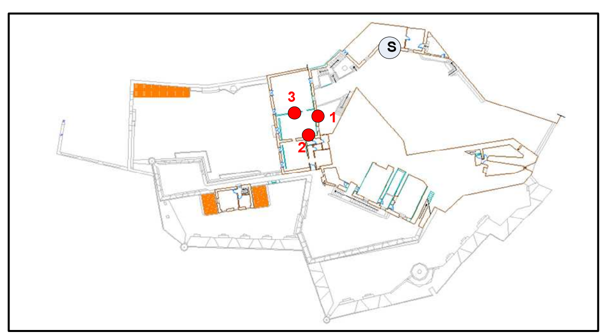


Fig. 2. Experimental WSN deployment in Museum Fortaleza São Tiago.

Fig. 3. Crossbow Mica2 mote.

After analysing this data, it was possible to achieve some conclusions about the behaviour and the type of variations of temperature and humidity throughout the day and night, in a single room of the museum. Considering the graphics of each node, we verified that temperature varies about 2ºC whereas humidity varies about 6% RH (see Fig. 4 a) and b)). According to the museums' managers, these variations are typical during the winter, in this museum; however, these parameters usually vary a lot more in summer. Fig. 4 c) shows that light varies, essentially, accordingly to the day and night periods, or when the lights are turned on or off (corresponds to the variations at the end of the graphic).

So, we verified that these parameters are not as constant as they ideally should be. Therefore, it is very important that the WSN is connected to the air conditioning and dehumidifying systems in order to automatically control, above all, the temperature and the humidity of these rooms.

As mentioned before, the sensor nodes are programmed to measure and send data each 60 seconds. Fig. 4 d) illustrates the decrease of batteries level during a 24 hours' period.

To evaluate the duration of batteries, we changed this value by programming the nodes to perform one measurement and transmission each 10 seconds. Comparing the internal voltage parameter obtained in both cases, we concluded that the duration of the batteries is proportional to the energy consumption. In this specific experiment, the batteries lasted about 6 times less than in the first case.

Fig. 4. Initial Web interface created to the museum' environmental monitoring application, showing the 24 hours' graphics of temperature (a), humidity (b), light (c) and internal voltage (d) measurements.

C. Problems Identified

Several problems were identified during this experimental phase. These problems are related, essentially, with the type of building where the WSN was deployed and, also, with the hardware characteristics and resource limitations of the wireless sensor nodes.

Type of building - Fortaleza São Tiago was built in the 17^{th} century as a military fortress. Therefore, the width of the walls is very large (from 0,5 to 1m, with 1m being the predominant width). The building has double doors and windows. It has an irregular shape and its rooms and terraces are distributed among three floors, as shown in Fig. 5. All these factors influence and difficult the signal propagation and, consequently, the transmission range of sensor nodes.

Location of the sensor nodes - Sensor nodes must not be placed near to the visitors' passageways, in order to avoid the risk of being stolen or damaged. This will also help to minimize the visual impact caused by the nodes. As can be seen in Fig. 6, nodes were located in rather discrete places. (Fig. 6 shows nodes 1 and 2; node 3 is located on the opposite side of the exposition room, also above an electricity socket, like node 2).

Batteries - The batteries of sensor nodes do not last more than some days and their transmission range is not as good as described in the manufacturer's datasheets, even in line-of-sight conditions. In order to increase the transmission range of sensor nodes, we had to set their transmitting power to its maximum value (5dBm). This obviously affects the energy consumption, which is a typical problem of WSNs. To minimize this problem we have decreased the number of measurements and transmissions per time period (one each 60 seconds). The program can still be changed so that the nodes perform even less measurements and transmissions in order to save more energy. Decreasing the transmission power, by increasing the total number of nodes or using a more efficient antenna, or equipping the nodes with a better radio device will also decrease the energy consumption.

Type of antenna – Nodes are equipped with omnidirectional antennas. Thus, the location of the nodes near the walls can cause signal reflections. Changing the type of antenna to a more efficient one (directional) will improve the signal propagation characteristics and, consequently increase the duration of batteries.

Offset adjustment – Even though the sensors used on the nodes do not have to be calibrated, an offset adjustment has to be made. This way, more reliable measurements are ensured.

Temperature and humidity sensor – This sensor should be placed away from the main circuit board, to avoid that the chip's temperature affects the readings.

Fig. 5. Museum Fortaleza São Tiago and correspondent floor plants.

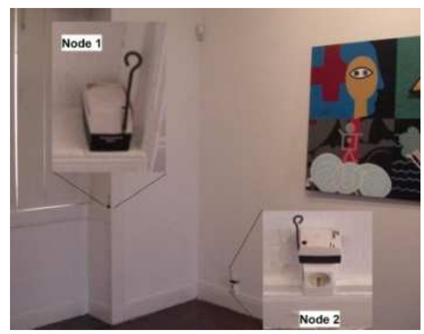


Fig. 6. Wireless Sensor Network deployment in an exposition room of Fortaleza São Tiago

D. Awareness tool for WSNs visualization

Opposing to traditional networks, WSNs are only useful if sensor nodes are aware of the environment surrounding them. This means that the great potential of WSNs lies in its ability to correlate collected data in time and in space [17, 18].

This is one of the reasons why we are developing a 3D web-based awareness tool for WSNs visualization, which will be applied to the specific case of a museum's environmental monitoring. This tool is based in the CWSN (Collaborative Wireless Sensor Networks) model, published in [16].

CWSN is a formal model of collaborative work created specifically to the case of WSNs. It is, essentially, a graph-based model; but, it also includes other objects in order to make the modelling of all the entities of a WSN (presented in Table I) possible, which is fundamental to completely represent a WSN. The network hierarchy (from the collected data to the user) can be visualized, as well. Moreover, it is a generic model because it can be applied to heterogeneous networks (any type of nodes, any size, any hardware characteristics, any types of signals, etc.). According to the WSNSCW model definitions, the specific case of this small WSN deployed in the museum will be represented as deployed in Fig. 7. Due to the reduced number of sensor nodes available, data collected by nodes 1, 2 and 3 is sent to the sink node on an one-hop basis. Accordingly, nodes 2 and 3 send data to node 1, which, in turn, sends data to the sink node. The obstacle existent between nodes 2 and 3 is shown in Fig. 8.

Regarding the awareness tool, one of its most important properties is the 3D representation of the network. This is very important so the user can have a more realistic view of the network, becoming more aware of the surrounding environment (different types of terrains, different types of rooms, which obstacles might interfere with the collaboration established between nodes, etc.).

This tool will allow for the visualization of different granularities: fine-grain (sensor nodes), middle-grain (clusters) and coarser (sessions) modelling level. Also, it will allow for an interactive navigation in the map of the network.

We will apply this awareness tool to the specific case of a museum's environmental monitoring. So, data visualization will be enhanced by integrating it in a 3D representation of the museum, giving the user a much more realistic view of the network.

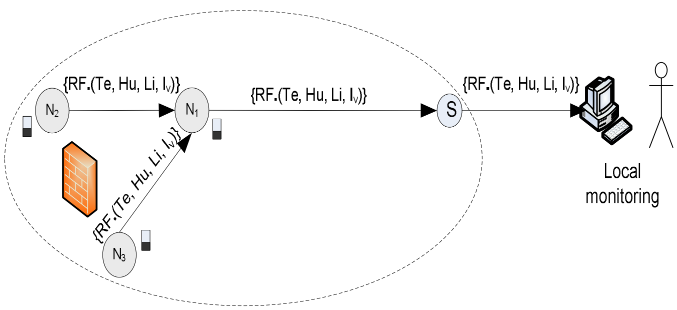


Fig. 7. Representation of the WSN created in Fortaleza São Tiago, using the entities and notations defined in the CWSN Model [16].

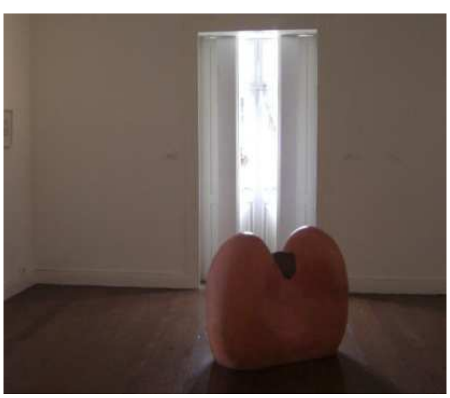


Fig. 8. Artwork that obstructs the line-of-sight between nodes 2 and 3, impeding communication.

IV. The WISE-MUSE Sensor Node

We have developed a new wireless sensor node, which is shown in Figure 9. It is designed specifically for environmental monitoring applications, but also considering the specific requirements of the museum, for example, reduced size and cost. This device emerges as the element that collects the environmental parameters, such as temperature, humidity and light. In addition to these three parameters, it is possible to send the battery status (internal voltage) and the RSSI signal. The sensor node transmits the captured data to the base station, via radio frequency (RF).

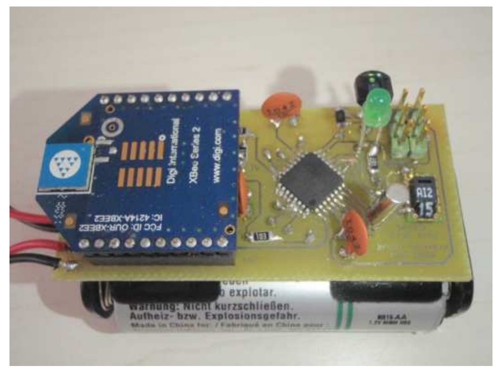


Fig.9. New Wise-Muse sensor node.

The radio module used is the XBee or the XBee PRO, from the Digi manufacturer [20], which operate according to the ZigBee protocol [19], i.e., it is designed according to the IEEE 802.15.4 standard and to support the specific requirements of WSNs (above all, low cost and low power). The ZigBee protocol allows the creation of Personal Area Networks (PAN) networks, supporting several network topologies, namely star, mesh and cluster-tree.

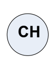
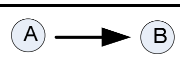
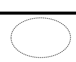
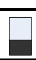
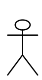
To meet the requirements of the museum in terms of the physical location of the rooms that needed to be covered by the WSN and, consequently, in terms of transmission range, we had to employ a cluster-tree topology. As a result, the type of nodes we needed to deploy were some end devices, some routers and one coordinator. The end devices and the routers were developed by us, whereas the coordinator was acquired to DIGI manufacturer. Nevertheless, the router created can also act as an end device whenever needed; in our experiments, it was used as both a router and as an end device. The differences between the end devices and the routers, at the hardware level, reside in the power supply module since it has to be connected to an electricity socket; the router can never be turned off or go into the sleep mode. At the software level, there are also some differences since it has to be programmed as a ZigBee router, i.e., it has to receive data from the end devices that are wirelessly connected to it (i.e., end devices that are not under the range of the coordinator), and forward this data to the coordinator (sink node).

The WISE-MUSE sensor node, which corresponds to the ZigBee end device, was designed and built from scratch, with a set of components to meet the proposed requirements. This is a node of small dimensions, which causes minimum impact in the Museum. Its low cost is one of the strengths of this sensor node (less than 70€). Another advantage is its low energy consumption.

To be more precise, the WISE-MUSE sensor node has four main blocks:

- The power unit, which is composed of two AA batteries and a step-up circuit that allows to guarantee the supply of a constant power (3.3V) to the microcontroller Xbee and to the sensors;
- The microcontroller that is the "brain" of the node. It receives data from multiple individual sensors, processes it and, then, sends it through an Xbee radio frequency card;
- Two specific sensors: a light sensor that measures the brightness in the rooms of the Museum, and a sensor that measures both temperature and humidity;
- The transceiver module that transmits the collected data.

TABLE I
ENTITIES OF THE CWSN MODEL

Symbol	Concept	Description
	Sensor node	Wireless sensor nodes, typically with limited resources. These nodes can be either stationary or mobile. Also, they can be in one of two possible states: active or inactive (sleep mode) in order to save energy.
	Sink node/ Base Station	Node to which data collected by ordinary nodes is sent; being responsible to send data to the gateway.
	Anchor node	Node with known localization.
	Cluster	Group of nodes, created according to: geographical area, type of sensor, type of phenomenon, task, etc.
	Cluster Head	Sensor node to whom all sensor nodes in the cluster send the collected data; it is responsible for sending the received data to the Sink node.
	Relationship	The arrow represents a relationship between nodes A and B. It also represents and adjacency relation between nodes A and B (see section 3.2); nodes A and B are neighbours. A relationship can be established based on: localization, phenomenon, type of sensor node, etc.
	Data flow	This label identifies both the type of signal being used (radio frequency, ultrasound, acoustical or light) and the type of data being transmitted between nodes (temperature, humidity, light, sound, video, internal voltage, etc.).
	Gateway	Device responsible to send the data to the user, through the Internet.
	Obstacle	An object (building, tree, rock, etc.), which obstructs line-of-sight between two or more nodes, not allowing for direct communication between them.
	Session	In a certain moment, there may be several collaborative sessions in a WSN. A session can be established based on the objective (type of phenomenon to monitor, geographical area to monitor, etc.) of the WSN.
	Battery	It represents the percentage of the sensor node's remaining battery.
	User	Person that interacts with the WSN, querying the network, visualizing data, etc. The user customizes the work of the sensor nodes; the data collected by sensor nodes is used by the users' application.

As just mentioned, the microcontroller is the sensor's core. To guarantee an easy programming of this component, it was designed to be easily connected to a programmer, using the AVR-ISP500 protocol (AVR-ISP500 is USB low cost in-system programmer for AVR microcontrollers; it implements the STK500v2 protocol as defined by Atmel. ISP stands for In-System Programmable). Using this connection, the code can be easily updated whenever necessary. The chosen microcontroller is the Atmega 168 (Atmel, 2009), since it presents a set of characteristics that fits almost perfectly all our purposes; its low cost, low consumption and high performance are the main reasons for this choice.

The sensor elements chosen are the SHT15 humidity and the temperature sensor, from the Sensirion Company [21], and the S1087 photocell, from the Hamamatsu Company [22]. The photocell captures the sunlight and returns a value of voltage to the microcontroller, which is then converted to the intensity of sunlight (LUX) unit values. The SHT15 sensor calculates the relative humidity and the temperature values. This is a CMOS industrial device, totally calibrated, that allow for good stability at low cost. Its accuracy is much appropriated considering the requirements of the project (+/-2% for humidity and +/-0.3Cº for temperature).

In order to meet the power autonomy requirements of a sensor node, each node is powered by two AA batteries (1.5V each) that feed the microcontroller, the Xbee module and the sensor STH15. These batteries have a capacity of 2450mAh and an output voltage of 1.5V. Their technology is the Nickel Metal hydride and they weight only 28g.

Finally, we describe the modules for radio transmission frequency (Xbee or Xbee-PRO from Digi manufacturer). These modules were chosen because they require minimal power and because they provide a real and consistent delivery of information between devices, operating at the 2.4GHz ISM frequency band. Although there are other brands for radio transmission modules with lower power consumption, the popularity and the characteristics of Xbee modules determined our choice.

Table II presents a comparison of sensor nodes that could be used in the environmental monitoring of museums. We have considered the nodes' characteristics, as described in the manufacturers' datasheets. It is important to highlight that, in the current market, there are several RF modules separated from the sensing modules. Therefore, we attempt to look beyond the prototype created in the project, by analysing other solutions that perform the collection and transmission of data in these indoor environments.

Analysing Table II, there are several advantages and disadvantages of each solution proposed for monitoring environmental parameters. At the sensing module level, the sensors presented are quite similar. Most of the modules use the SHT15 or STH11 sensors, by Sensirion, and their accuracy does not vary much, about +/-0.3ºC for temperature and about +/-3% for relative humidity.

Almost all sensor nodes collect light, temperature and humidity, with the exception of the Mica2 Sensor Board MTS101CA that can't measure the humidity. The Mica Z reads other kind of data, but this is not necessary in the specific case of the Museum. Besides, Mica Z has the disadvantage of a higher cost.

Regarding the microcontroller there are some considerable differences. Most microcontrollers are manufactured by Atmel, with the exception to the Tmote Sky sensor, which is manufactured by Sentilla [23]. Atmega devices have many features in common with our prototype; The WISE-MUSE prototype presents a smaller flash memory; however, this factor should not be seen as a disadvantage since it conducts to a reduction on the amount of code programmed into the microcontroller. Consequently, the microcontroller has to process less amount of code what leads to a lower power consumption of the node. Therefore, it is not necessary a bigger flash memory. We verified that the energy consumption of our prototype can be reduced when operating at a frequency of 1MHz. In these conditions, its consumption can be decreased to 0.3mA, a value smaller than for the other devices.

The Mica motes [14] must be programmed through a base station, which involves an additional cost. The Tmote Sky and the WISE-MUSE nodes offer an advantage over the others; they are more easily programmed. The Tmote is programmed using USB, while the Wise-Muse prototype is programmed using the Olimex programmer that uses the AVR-ISP500 protocol.

In relation to the transceivers of each sensor node, all of them use the IEEE.802.15.4 protocol, which is the most appropriate protocol for WSNs. The Mica 2 operates in the 868/916Mhhz, 433MHz or 315MHz ranges, while the others use the 2.4GHz range.

We believe that the Xbee module used in the WISE-MUSE prototype is well ranked due to its higher power transmission. Using the Xbee-PRO, which allows an even higher transmission range what is one advantage when comparing to the other nodes. Its disadvantage regards the energy consumption; however, the Xbee is designed to enter in the sleep mode, waking up only in pre-defined intervals to send data; in this way, the problem of energy consumption is minimized.

Figure 10 shows the battery status of the two AA batteries that are used on the WISE-MUSE prototype. We have collected samples during several days to get an estimated battery lifetime. Analysing the graph, we can observe that the batteries' level follows a typical behaviour: in the first 10 days, the battery level dropped from 2.8 to 2.6 volts; however, from that point on, the battery level only dropped 0.1V during the next 30 days, which represents lower battery consumption. Therefore, after 40 days, the sensor node remains operational.

TABLE II
COMPARISON BETWEEN THE WISE-MUSE MOTE AND OTHER COMMERCIALLY AVAILABLE MOTES.

SENSOR NODES					
Characteristics		***WISE-MUSE***	***Mica 2 (MPR400CB) + Sensor Board (MTS101CA) [14]***	***Mica Z (MPR2400CA) + Sensor Board (MTS400CB) [14]***	***Tmote Sky [19]***
Produced by:		The authors at the UMa	Crossbow	Crossbow	Moteiv Corporation
Sensors	*Ambient parameters*	Light, relative humidity, temperature and battery level.	Light, temperature, and prototyping area	Light, relative humidity, temperature, 2-axis accelerometer, and barometric pressure	Humidity, temperature, and light
	Temperature and humidity sensors	SHT15	Termistor	SHT11	SHT11 or SHT15
	Accuracy	Temp: +/- 0.3Cº Hum: +/- 2%	Temp: 0.2 Cº	Temp: +/- 0.2ºC Hum: +/- 3.5%	Temp: +/- 0.2ºC or +/- 0.3Cº Hum: +/- 3.5% or +/- 2%
	Light Sensors	S1087 by Hamamatsu	CdSe photocell	TLS2550, by TAOS	S1087, by Hamamatsu
Transceiver	*Module*	Xbee or Xbee PRO, both by Digi	Chipcon Wireless Transceiver	TI CC2420 802.15.4/ZigBee compliant radio	Chipcon Wireless Transceiver
	Frequency	2.4GH	868/916 MHz, 433 MHz or 315MHz	2.4Gh	2.4GHz
	Standard	IEEE.802.15.4/ Zigbee	IEEE.802.15.4/ ZigBee	IEEE.802.15.4/ ZigBee	IEEE.802.15.4/ ZigBee
	RF Power	0dBm to 18dBm (PRO)	-20 to 5dBm	-24 to 0dBm	0dBm
	Outdoor range[1]	100mt to 1200m (PRO)	150mt	75 to 100mt	50 to 125mt
	Current Draw (Tx)	35mA @ 0dBm[2]	27mA @5dBm	17,4mA @ 0dBm	17,4mA @ 0dBm
Processor	*MCU*	Atmel, Atmega 168	Atmel, ATmega128L.	Atmel, ATmega128	Texas Instruments MSP430 microcontroller
	Current Draw (in Active mode)	0.3mA @1MHz 1.9mA @4MHz 6.8mA @8MHz	5mA @4MHz 17mA @8MHz	5mA @4MHz 17mA @8MHz	2.4mA @ 8MHz
	Flash Memory	16Kb	128kb	128kb	48kb
	Programming access	ISP	Base station	Base station	USB
	Serial Communication	UART	UART	UART	UART
	Physical dimensions (mm) (Excluding battery pack)	(58x28x12)	(58x32x10)	(58x28x10)	(65x32x22)
Sensor Node Price		70€	352€	[3]	82€

[1] Considering an outdoor environment without obstacles.
[2] The consumption of the Xbee´s module regarding the RF transmission is certainly a little below 35mA, because this value is not totally spent with the RF transmission, but it also includes some processing activities.
[3] No information has been obtained so far on this feature, however as the sensing module of the Mica Z is superior than the Mica 2, the total cost of the module will be higher.

Even though the decrease of the battery level does not follow a linear function, we think that the battery level will remain stable for some more days. Further tests will continue to be carried out, nevertheless, the WISE-MUSE prototype is supposed to have at least 1 month of autonomy, although its batteries can last 2 months. These tests were performed on one node only, but in the future all the nodes should be tested.

Looking to the sensor nodes as a whole, they all have similar dimensions, and the WISE-MUSE mote presents a very low cost when compared to the Mica motes.

In conclusion, it is important to note that the module created was designed and built for the specific indoor environment monitoring at the Museum, presenting a number of advantages that may be attractive for this monitoring application, where its skills are within the requirements of the final client. Moreover, this new sensor node brings some advantages when compared to other commercially available solutions, such as low cost, small size, low power consumption, and higher transmission range.

V. HUMIDITY CONTROL DEVICE

The humidity control device has been developed in the WISE-MUSE project to carry out the automatic control of dehumidifiers in order to regulate relative humidity levels inside the rooms where the WSN is implemented.

Figure 11 shows the developed device. It is essentially composed of one Xbee module, one relay, and one AC-DC converter, integrated in a box that allows the device to be plugged into an electrical outlet and at the same time to the dehumidifier.

When the humidity values reach an unacceptable limit (this limit were specified by the Museum), the base station sends a control message by radio frequency to the control device (more precisely to the XBee module, activating one of its pins). It receives the control message and analyzes it. As a consequence, it activates the relay. If humidity level is above the maximum limit then it turns on the dehumidifier. In opposite, if humidity level is below the minimum limit then it turns off the dehumidifier.

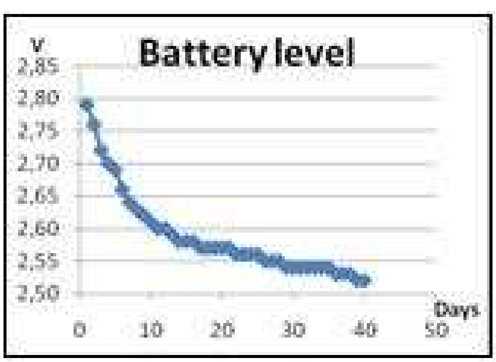


Figure 10. Average battery level

Figure 11. Humidity control device.

VI. CONCLUSION AND FUTURE WORK

In this paper, the first experimental WSN for automatically and continuously monitoring the environment of a museum was presented. This solution was compared with related solutions, being outlined its advantages.

Besides being a simpler solution, the use of WSNs for environmental monitoring of a museum is, indeed, a more reliable solution. It is also less expensive than manual data collection or than a wired central monitoring system. Several problems were identified during the experiments, but they can be classified in two types. The problems related with the type of building where the WSN is being deployed, because it affects the signal propagation; and the problems related with the hardware characteristics and resource limitations of the sensor nodes, with the battery being the most limited resource. Equipping the nodes with a more efficient antenna and using a higher number of nodes will lead to the need of a lower transmission power, increasing the duration of the batteries. Also, changing the node’s program so that they perform less frequent measurements and transmissions will allow for high energy savings.

We also analyzed the graphics of collected data, what allowed us to understand the behaviour and the type of variations of temperature, humidity and light, throughout the day and night.

One of the main contributions of our work is the development of a new sensor node created for environmental monitoring applications, which is still a prototype since it is currently being tested. Nevertheless, even at this stage, we have already demonstrated that it brings some advantages when comparing to other commercially available solutions.

Furthermore, in order to increase the efficiency of this environmental monitoring system, we have implemented a system that automatically controls the dehumidifying devices, maintaining the humidity at more constant levels.

Regarding the visualization of data, data is available in different formats (tables, graphics, colour gradients, etc.), in a real-time basis. Additionally, an historic of collected data is kept for future consults in Microsoft excel and word format.

As for future work, we have several tasks to accomplish. After understanding the environment variations in Fortaleza São Tiago and after identifying all the existent problems, we have to carefully plan the deployment of a complete WSN that coverage all the exhibition rooms, archives and library. At the moment, only the Museum´s storage rooms are being monitored and controlled by the WISE-MUSE platform. We also have to extend the WSN to monitor some pollutants, in particular the carbon dioxide (CO_2).

We are developing a 3D awareness tool, based in the WSNSCW model, and that will be validated applying it to this specific application. So, data visualization will be enhanced by integrating it in a 3D representation of the museum, giving the user a much more realistic view of the network.

We also intend to carry out an analysis of the battery performance of other existing sensor nodes, in order to proof the effectiveness of the WISE-MUSE prototype.

Finally, we intend to connect the WSN to the air conditioning and dehumidifying systems in order to automatically control the temperature and the humidity of the exhibition and storage rooms.

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