POLITECNICO DI TORINO
Repository ISTITUZIONALE

Sensor network for museum environmental monitoring

*Original*
Sensor network for museum environmental monitoring / Lombardo, L., Corbellini, S., Elsayed, A.M., Angelini, E., Parvis, M., Grassini, S.. - ELETTRONICO. - 1:(2017), pp. 1-6. (4th IEEE International Workshop on Measurement and Networking, M and N 2017 San Giovanni University Complex, ita 2017) [10.1109/IWMN.2017.8078394].

*Availability:*
This version is available at: 11583/2701370 since: 2020-02-17T10:36:06Z

*Publisher:*
Institute of Electrical and Electronics Engineers Inc.

*Published*
DOI:10.1109/IWMN.2017.8078394

*Terms of use:*

This article is made available under terms and conditions as specified in the corresponding bibliographic description in the repository

*Publisher copyright*
IEEE postprint/Author's Accepted Manuscript

©2017 IEEE. Personal use of this material is permitted. Permission from IEEE must be obtained for all other uses, in any current or future media, including reprinting/republishing this material for advertising or promotional purposes, creating new collecting works, for resale or lists, or reuse of any copyrighted component of this work in other works.

(Article begins on next page)

08 September 2026

© 2017 IEEE. Personal use of this material is permitted. Permission from IEEE must be obtained for all other uses, in any current or future media, including reprinting/republishing this material for advertising or promotional purposes, creating new collective works, for resale or redistribution to servers or lists, or reuse of any copyrighted component of this work in other works.

*Title: Sensor network for museum environmental monitoring*

*Authors:*

*Luca Lombardo*
*Dept. of Electronics and Telecommunications, Politecnico di Torino, Torino, Italy*

*Simone Corbellini*
*Dept. of Electronics and Telecommunications, Politecnico di Torino, Torino, Italy*

*Ahmed Elsayed*
*Dipartimento di Scienza Applicata e Technologia, Politecnico di Torino, Torino, Italy*

*Emma Angelini*
*Dipartimento di Scienza Applicata e Technologia, Politecnico di Torino, Torino, Italy*

*Marco Parvis*
*Dept. of Electronics and Telecommunications, Politecnico di Torino, Torino, Italy*

*Sabrina Grassini*
*Dipartimento di Scienza Applicata e Technologia, Politecnico di Torino, Torino, Italy*

DOI: 10.1109/IWMN.2017.8078394

# Sensor Network for Museum Environmental Monitoring

Luca Lombardo, Simone Corbellini, Ahmed Elsayed, Emma Angelini,
Marco Parvis, *Fellow, IEEE,* Sabrina Grassini, *Member, IEEE*

***Abstract*—Museum environmental monitoring is an important issue for the artifact conservation. Many solutions have been proposed to tackle this problem, but the museum constraints prevent an easy application in several cases, especially if the monitoring has to be performed in museums where an environmental control system has been already installed. This paper describes a simple though powerful solution, which complies with most of the common constraints and which is based on small sensors implementing a BT-LE wireless protocol coupled with a receiving architecture. The sensing nodes have dimensions of few centimeters, do not require cabling and power supply, and can work unattended for several years. Data are collected by a receiving architecture, which can work either on-line, with immediate data delivery, or off-line when an Internet connection is not available. Users can browse the measurements by using their smart-phones from any place and can download the data on their personal computer. In addition they can browse locally the data also in the absence of any data connection, such as in the case of remote and or recessed sites. The proposed solution has been deployed in three museums, also in the basements, and in an ancient building proving its flexibility and capability to be adapted to the different conditions.**

***Index Terms*—Cloud measuring system, Environmental monitoring, Cultural Heritage, smart sensors**

## I. Introduction

Environment monitoring inside heritage buildings and museums requires specific precautions to allow measuring the different quantities of interest by means of accurate and totally not invasive systems, insuring this way the long-term conservation of the artifacts. Conservation of cultural heritage assets needs developing indoor environmental monitoring systems able to measure temperature and relative humidity, as well as to detect very low concentrations of different atmospheric pollutants [1], [2], which could induce and accelerate the artifact degradation. As a matter of facts, improper environmental conditions can severely affect the conservation state of many materials, as well as the presence of a large number of persons in closed rooms can modify the environmental conditions. Moreover, in closed environments, like exhibition rooms and showcases, temperature and relative humidity gradients create micro-climatic problems, which get worse if an air conditioning system is not correctly installed.

In this contest, the development of an easy-to-use, cheap and multi-point measurement network able to monitor the micro-environment very close to the artifacts and promptly highlight risky conditions without impacting on the daily activities as well as on the visitor fruition, could be an important challenge in the development of tailored preventive conservation strategies in the cultural heritage field.

Many different solutions feasible for various indoor environmental conditions, with rather different costs and measurement capabilities [3], [4], are actually available on the market. However, it has to be pointed out that working inside heritage buildings and museum rooms requires complying with several constraints mainly related to the sensor visibility and the difficulty to deploy the monitoring network with cabling and connections. Furthermore, to satisfy the requirements of restorers and curators, the monitoring system must be easy to expand, modify and use also by people who do not have any specific knowledge on the measurement issues.

The sensor network proposed in this paper tries to address all these aspects: it is based on small almost not visible measuring nodes (about 3 cm in diameter), whose color can be selected according to the surrounding environment; the nodes can be simply deployed in place and start measuring; the network architecture automatically could easily add new nodes; the collected data can be downloaded and managed either on users' phone or personal computer.

## II. The Proposed System Architecture

Different system architectures have been proposed in the literature for environmental monitoring in indoor environments [5], [6], [7], [8]. However, in most cases, these solutions are conceived for specific applications, such as telecommunications and energy power distributions. Therefore these systems are often not suitable for monitoring museum indoor environments, where power supply and Internet connection are not always available. To deal with both these situations a two fold application has been deployed. Fig. 1 shows a diagram of the main blocks composing the proposed sensor network and architecture:

- Several nodes, capable of sensing the quantities of interest are installed into the different sites to be monitored. These nodes are designed to have small dimension, to be powered by a small battery and to send the data through a wireless connection. This way the nodes can be easily installed and hidden in the monitored area without any aesthetic impact on the user fruition. Of course small measuring nodes require small batteries and therefore a wireless radio with limited power in order to have a long battery life. For these reasons, different compromises can

S. Grassini, A. Elsayed, and E. Angelini are with the Department of Applied Science and Technology, Politecnico di Torino, Italy,

S. Corbellini, L. Lombardo and M. Parvis are with Department of Electronics and Telecommunications, Politecnico di Torino, Italy.

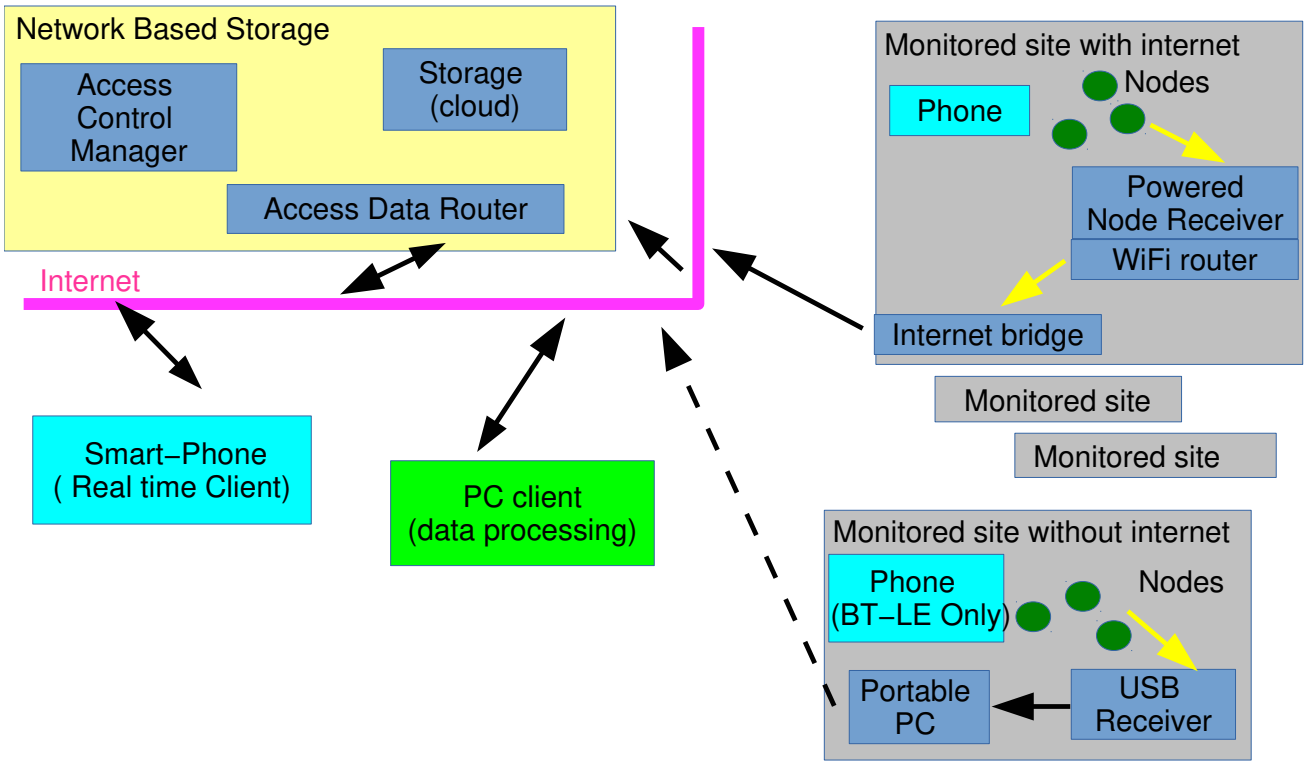


Fig. 1. Block diagram of the proposed measuring architecture.

be conceived; however connection distances of more than 10 m can be easily achieved still providing a node life of a few years without changing the battery. The nodes have a local memory so that the measurements are always permanently stored for quality assurance and in the case they cannot be delivered to the receiver for any reason.

- If the monitored site has the possibility to use electric power, it is possible to install powered receivers that can continuously receive measurements from the nodes in real time. A receiver can cover roughly a radius of 10 m so usually it can cover a space equivalent to a room and thanks to its small dimensions could be installed without impairing visitor fruition. The receiver can store locally all the measurements and can be connected to the Internet via cabling or, if cabling should be avoided, via a WiFi connection (Fig. 1). In both cases the measurements collected from the nodes can be immediately delivered through the Internet to a distributed storage where users can remotely access them. If, for any reason the Internet connection drops and/or if the power supply goes off for a limited period of time, the receiver can collect the measurements relying on a backup battery and deliver them when the connection is re-established. The receiver, therefore, represents a second buffer level suitable for reducing the data latency during the system measuring life.
- If the monitored site does not have power supply, such as in the case of some museum basements or unaccessible sites, it is possible to rely on the nodes' memory downloading their measurements only from time to time. In this case a USB receiver connected to a portable PC can be used. Once the PC is taken back to a place where Internet is available, the measurements can be delivered to the network storage and made available to the users. This configuration allows following the evolution of the environmental parameters even though not in real time.
- The network based storage represents the bridge between monitored sites and users. While the actual storage can be obtained anyway by using the cloud paradigm, a server has to be in charge to manage the data and to provide them to the authorized users. The Access Control Manager block takes care of this issue; from one side it accepts data from the registered receivers, and from the other side it delivers the measurements to the authorized users.
- Measurements are eventually made available to the users, which can look at them either via a smart-phone or on a PC. Unfortunately, developing applications for smart-phones can be a long and tedious operation, for this reasons the authors decided to take advantage of the $\mu Panel$ environment [9], [10], which permits a very fast and easy deployment of a measuring system. In this case data can be either viewed on a web browser or a simple program can be implemented to download and manage the measurements.
- Using the $\mu Panel$ environment also enables another interesting feature, which is related to the possibility of directly connecting to the powered receiver: in this case

users can directly monitor the local nodes to see what happens in the monitored rooms, even in the case of a missing Internet connection. The same can also be performed in un-powered sites, if the sensing nodes implement the BT-LE protocol as described in the following section.

## III. The Measurement Nodes

The measurement nodes are responsible for the metrological performance of the entire network and consequently they are the starting point in the system design. The nodes can be arranged to measure different quantities, even though battery constraints have to be taken into account to ensure a long operating life of the monitoring system.

The simple button architecture which has been specifically designed for indoor environmental monitoring in the cultural heritage field, is shown in Fig. 2.

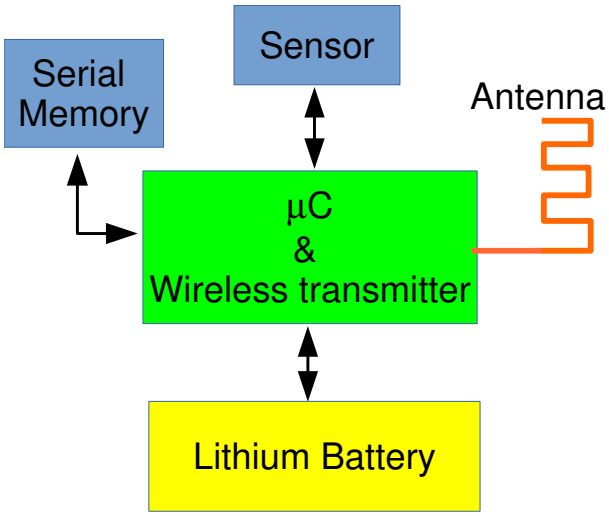


Fig. 2. Block diagram of the sensor node which can be arranged either to use a proprietary protocol or to rely on the BT-LE.

In particular, the figure shows:

- The node core that provides the wireless transmission and the local data management. Depending on the environment to be monitored, the node can be based on a CC2510, which is a compact System On Chip by *Texas Instruments* that employ a proprietary wireless protocol, or on a 32bit ARM NRF51822, a chip by *Nordic Semiconductor*, which provides a BT-LE wireless capability. Both chips contain an ADC, which can be used for analogue measurements, when required, and digital pins suitable for controlling the other components in the node. Moreover, the chips exhibit a low energy consumption and can be selectively put in sleep mode to further increase the battery life.
- The non volatile local serial memory, which is used to store all the measurements and to provide a complete measurement history for quality assurance. Different memory capacities can be used, all with low energy consumption. The current arrangements employ $0.5$ Mbytes chips that are enough for three year measurements collected every $15$ min.
- The sensor, which change according to the specific measurement requirements, and which represents the node front end.
- The lithium battery which powers the node and whose dimension dictates the node size.
- The antenna, connected to the core transmitter, which is used for data exchange with the measurement receiver.

Fig. 3 shows some node prototypes that employ a Sensirion STH21 sensor which is able to measure relative humidity and temperature. The STH21 has a digital output and can measure temperature with a nominal uncertainty of about $\pm 0.3°$ in the range of $5$ °C to $60$ °C and relative humidity with a nominal uncertainty of about $\pm 2\%$ in the range of $20\%RH$ to $80\%RH$; the sensor has a temperature resolution of $0.01°$, an RH resolution of $0.04\%RH$ and a supply current as low as $150$ nA in sleep mode.

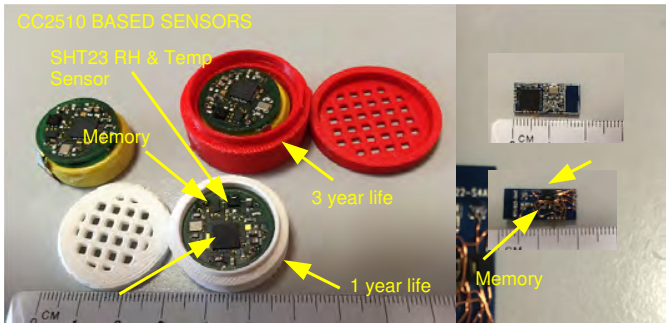


Fig. 3. Measuring node prototypes arranged with different technologies.

In particular, Fig. 3 shows, on the left, two prototypes based on the CC2510 $\mu C$. These nodes employ either a lithium battery CR2032, which provides $225$ mAh capacity, or a CR2477 battery which provides $1$ Ah capacity. The CC2510 is capable of generating a wireless signal of $0$ dBm at the frequency of $2.4$ GHz thus providing a connection range between $10$ m and $30$ m [11] depending on the surrounding environment. The nodes are contained inside a 3D printed ABS box whose diameter and dimension thickness are either $35$ mm $\times 20$ mm or $25$ mm $\times$ $15$ mm respectively when the higher and lower capacity battery are employed. The power consumption is obviously related to the measurement frequency and increases with it as described in section VI, anyway, the lithium batteries allow a sensor life from 1 to 3 years, by collecting and storing measurements every $30$ min. Fig. 3 shows on the right an example of node prototype based on the NRF51822, equipped with the same sensor and memory. This node prototype is arranged by using a commercial board and is capable of providing an access range of about $30$ m.

## IV. The Receivers

As shown in fig. 1, the proposed sensor network can work in two different modes depending on the availability

of power supply and Internet connection. When the power supply is present a receiver capable of receiving the data provided by the nodes in real time can be installed in the monitored environment. Fig. 4 shows a receiver prototype, which is designed for on-line monitoring when CC2510 based measuring nodes are deployed.

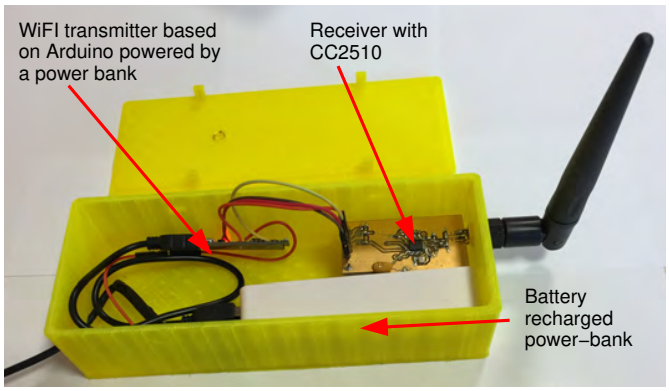


Fig. 4. Prototype of a CC2510 based receiver designed for on-line monitoring in the presence of power supply.

This device contains three main blocks:

- A simple board containing a CC2510 which listens for data coming from the measuring nodes using the CC2510 proprietary protocol. In the receiver the chip is powered and the radio always on so that it can react immediately each time one of the node sends data. Upon successful data receive the board sends back to the node an acknowledge so that each node knows which data have been successfully transmitted and does not send them again to the receiver. The CC2510 board is coupled to another board which connects to the WiFi network, as described below;
- A commercial Cactus Micro (Rev. 2) board which mixes into a single PCB an Arduino system and a low-cost ESP8266 WiFi chip for routing and connection. The ESP8266 firmware is based on $\mu Panel$ infrastructure, which is used to speed-up the receiver development. In addition, the $\mu Panel$ firmware is capable of using the ESP8266 memory to implement a local storage of about 16000 measurements. This permits to operate even thought the Internet connection goes off for a limited period, providing that the receiver remains powered to receive the data from the nodes. The $\mu Panel$ firmware is also capable of easily arranging the code suitable to activate a Virtual App on any smart-phone to observe the measured data locally;
- A power-bank for connecting it to the power supply and filtering the power spikes; it also provides energy to the receiver even thought the power supply is interrupted for few hours.

Fig. 5 shows two receiver prototypes designed to work in the absence of power supply and directly connected to a USB port of a personal computer. The yellow box is composed of two main blocks:

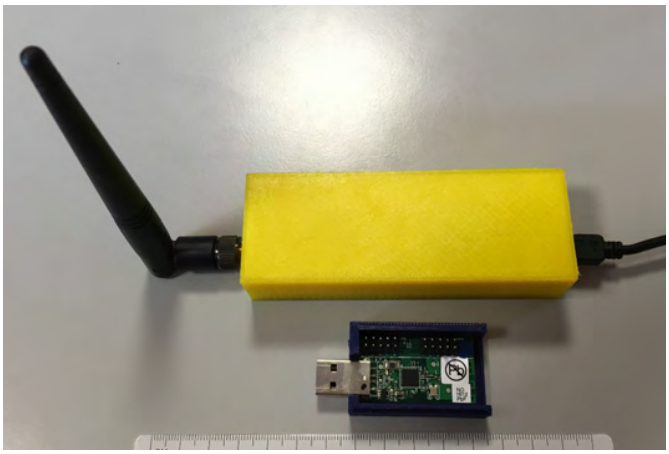

Fig. 5. Picture of two prototypes of receivers designed to be powered by the USB port of a PC.

- A CC2510 data receiver equal to the one already discussed in the previous picture which works the same way as the powered receiver and which takes the energy from the USB;
- A commercial Arduino USB 2 Serial micro board which provides the USB-PC interface and is connected to the receiver via its digital pins. In this case data are simply delivered to the PC. Once the PC is taken back to a place where Internet is available, such data are delivered to the storage system.

On the contrary, the blue box implements both the radio receiver and the USB interface with a reprogrammed dongle CC2511-EMK, which is provided by *Texas Instrument* as development board for these devices.

Of course, in order to use one of the off-line receivers, users are required to go to the monitored room with a portable PC and a receiver, to turn it on by connecting it to a PC USB and to wait until all nodes have delivered their data. Fortunately, the capability of the nodes to store locally all measurements for the entire measurement life, does not impose a timing for this operation, which can be performed at arbitrary time intervals at user convenience.

## V. The Clients

Two types of clients with different capabilities can be used in the proposed architecture: smart phones and personal computers.

Smart phones can take advantage of the $\mu Panel$ architecture in which a free App, downloadable on both iOS and Android based devices, permits both real-time monitoring and control of the receivers. This is obtained through the so called Virtual App, which consists of graphical panels described by the receiver and automatically transferred and displayed on the smart phone's screen when the communication between receiver and mobile device is established. Such a communication can occur through Internet (optionally via Cloud) or through a direct connection, in case the user is located close to the nodes in the monitored room. The $\mu Panel$ architecture can be employed also with micro-controllers with very limited

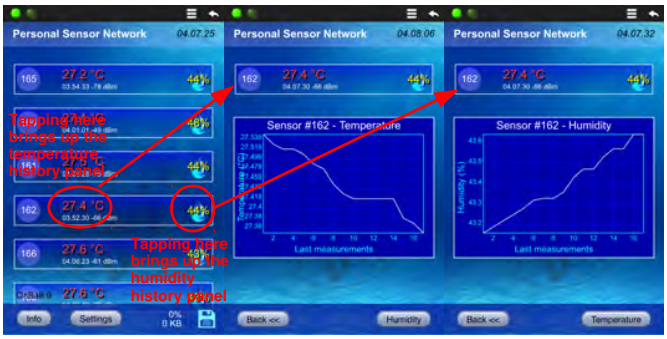


Fig. 6. Pictures of the virtual panel arranged on a smart-phone by using the $\mu Panel$ technology and which is generated by the on-line receiver

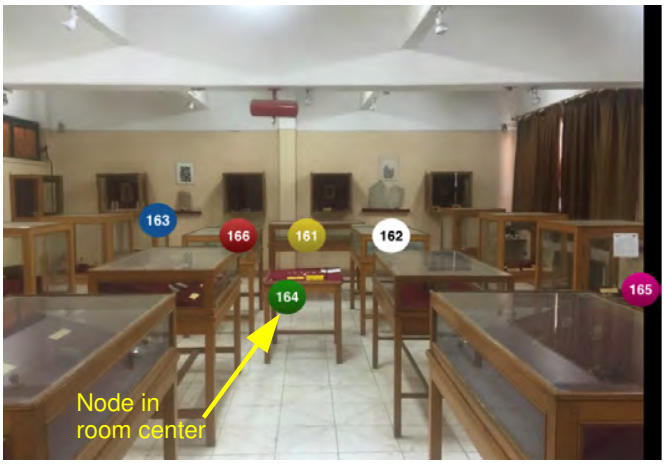


Fig. 7. Position of the nodes in the monitored room: five nodes are inside showcases, while one is located outside the showcases, in the room

resources in terms of memory and available power, such as in the case of the Arduino-based receivers, and potentially even in the case of low power BT-LE systems. The $\mu Panel$ system is based on a graphical and functional description of the Virtual App coded with a language called HCTML (Hyper Compact Text Markup Language), which originates from the HTML but, with respect to the latter, it can easily reach a compression ratio of 1:20, in terms of required memory.

Another great advantage of using the $\mu Panel$ infrastructure is that it also takes care of clients authorization and security issues, granting the access to the receivers only to users who have been previously authorized.

Fig. 6 shows three examples of screen-shots of graphical panels implementing the Virtual-App sent by a receiver through an HCTML string of only about 500 bytes. The first screen (on the left) consists of a box for each received sensors reporting its last measurement and state. If the user taps on the temperature or humidity values, the other panels appear (center and right) with the history of the last measurements. Each receiver can be easily reprogrammed with a different HCTML for generating others panels or graphics depending on the sensors to manage in its room.

Personal computer based clients can access the measurement database simply through a Web browser and a valid account on the Cloud. Specific web-pages permit the clients to display the measurements using different criteria, in particular it is possible to obtain all the data generated by specific sensors over a given time interval. Fig. 8 shows an example of a web page in which all the measurements collected in a museum room during almost one year are plotted.

## VI. Results

Table I reports the energy required by each element in the system: the sensor's battery life is dictated by the measurement interval and by battery auto discharge, while the duration of the receiver battery pack mainly depends on the sensor receiver power requirement. The WiFi receiver would consume far more than the sensor receiver, but the Arduino CPU has been programmed to shut the WiFi down as soon as the external power is unavailable. This choice does not impact on data fruibility since the Internet access point is usually unavailable as well when the main supply is off.

| Element and operating mode | mean consumption | life |
|---|---|---|
| Sensor stand-by | 1 $\mu$A | $>$ 3 years |
| Sensor measurement, tx and store | 2 mC | 400 K cycles |
| Receiver's radio | 20 mA | 4.5 days |
| Receiver's Arduino CPU | 2 mA | 45 days |
| Receiver's ESP WiFi | 90 mA | 24 hours |

TABLE I
MEASURED ENERGY REQUIRED BY EACH ELEMENT AND CORRESPONDING EXPECTED LIFE FOR A SENSOR BATTERY CAPACITY OF 220 mAh (E.G. CR2032) AND A RECEIVER POWER BANK OF 2.2 Ah .

The proposed system has been deployed in different museums both when power supply is available and in the absence of such power. Fig. 7 shows, as an example, the monitored node position in the Museum of the Faculty of Art of the Sohag University in Egypt where six monitoring nodes have been installed. The museum has power supply and Internet connectivity so that the on-line version of the proposed system can be used.

Fig. 8 displays temperature and relative humidity recorded by the six nodes located in five different showcases and in the room. The node located outside the showcases is #164, while the others are inside the showcases: it is easy to see the yearly temperature values which changes from a minimum of less than 15 °C during winter, to a maximum above 35 °C during the summer. In addition, it is also easy to observe how sensor #165, which is located in a showcases close to the wall, has a remarkable temperature change during the day, similar to the room, especially during the summer when a high daily excursion is expected. The humidity of course has a reversed behavior increasing during winter up to more than 50% and decreasing during summer. It is clear how the humidity in the room changes of up to 20% during the day, while in the showcases the change is much lower.

Overall the monitored location can be considered safe for metallic artifacts, while at least one of the showcases may apply a thermal stress to textiles which are displayed inside.

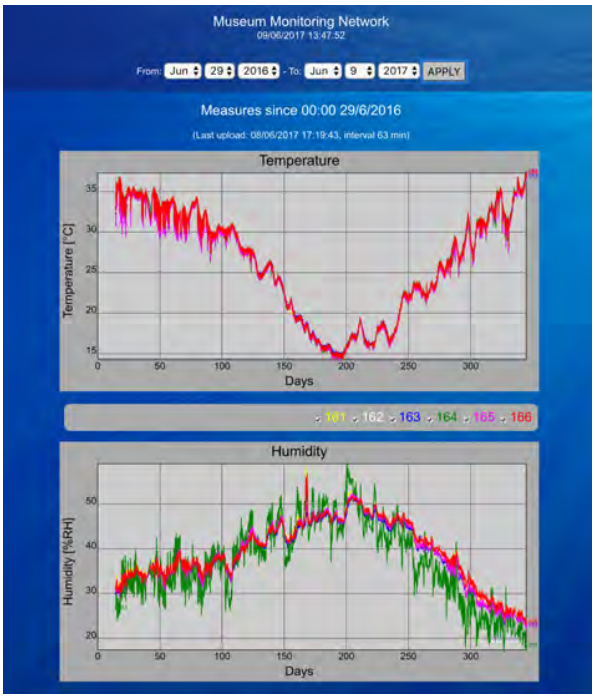


Fig. 8. Pictures of the virtual panel arranged on a smart-phone by using the $\mu Panel$ technology and which is generated by the on-line receiver

## VII. Conclusions

Monitoring museum environments can be extremely important to insure a log-term preservation of the displayed artifacts. A simple monitoring of the exposition rooms is not enough since both temperature and humidity can greatly change from point to point. Unfortunately the museum environment is not easy to monitor as the sensing points have not to interfere with the artifact fruition and often it is not possible to deploy wiring and to bring power supply to many different points in any room.

This paper describes a possible solution to these problems which is based on small nodes, powered by a battery and capable of wireless sending the measurements to a receiver. These nodes have an extremely long life, in excess of one year without the necessity of any manual intervention and have a dimension of about 3 cm.

All the measurements are sent to a receiver which if possible pushes them via WiFi to a remote cloud-based storage. Curators and authorized users can monitor in real time what is happening both via a PC or via their smart-phones by means of a simple and free App based on the $\mu Panel$ environment.

Despite the described system for the on-line monitoring is based on receivers which are capable of managing one museum room each, the architecture scalability for large museums is not an issue, since the receiver cost is very low and comparable to that of the sensors themselves.

In addition, multi-hop communication could be potentially used to reduce the number of required Internet access points. This is achievable thanks to the double interface feature of the ESP8266 chip, which permits the system to operate simultaneously as a WiFi client and as a WiFi access point. In addition, the $\mu Panel$ architecture provides also high level functions for the exchange of UDP packets to facilitate the implementation of this kind of multi-hop scenario.

Moreover, the proposed system can also be used in situations where either no energy or no Internet connections are available. In this case the real time monitoring cannot be achieved, but the memory inside the nodes insure the history the artifacts are subjected to can be downloaded at any time.

## References


[1] C. M. Grzywacz, "Monitoring for Gaseous Pollutants in Museum Environments", The Getty Conservation Institute, 2006, available at http://www.getty.edu/conservation/publications_resources/pdf_publications/pdf/monitoring.pdf, last checked 2015, Sept. 20.

[2] D. Camuffo et. al, "Environmental monitoring in four European museums", Atmospheric Environment, Vol.35, supp.1, 2001, pp. S127-S140

[3] National Park Service: "Comparing Temperature and Relative Humidity Dataloggers for Museum Monitoring" Conserve O Gram Series, N.3/3 Sept. 2011, avaliable at http://www.nps.gov/museum/publications/conserveogram/03-03.pdf, last checked 2015,Sept. 20

[4] Testo Saveris - Available at https://www.testo.com/en-US /Target-groups /Industry/Industry—Museums-and-Archives /c/target _groups_industry _museums _archives last checked 2016, Oct. 25

[5] G. Zhongwen, et al,"IMA: An Integrated Monitoring Architecture With Sensor Networks", IEEE Tr. on Instrumentation and Measurement, vol. 61, no.5 pp. 1287-1295, 2012

[6] J. Schmalzel; F. Figueroa; J. Morris; S. Mandayam; R. Polikar, "An architecture for intelligent systems based on smart sensors", IEEE Tr. on Instrumentation and Measurement, vol. 54, no. 4, pp. 1612-1616, 2005

[7] A. Carullo; S. Corbellini; F. Ferraris; M. Parvis; A. Vallan, "Integration of low computational power nodes in a GRID measurement architecture", IEEE Instrumentation and Measurement Technology Conference IMTC 2007, pp. 1-5, 2007

[8] B. Gedik; L. Liu, "A scalable peer-to-peer architecture for distributed information monitoring applications", IEEE Tr. on Computers, vol. 54, no. 6, pp. 767-782, 2005

[9] The $\mu Panel$ system. Available at http://www.miupanel.com, last checked 2016, July. 26.

[10] S. Corbellini, M. Parvis "Wireless Sensor Network Architecture for Remote Non-invasive Museum Monitoring", Proceedings of the 2016 International Symposium on System Engineering ISSE 2016, Edinburgh, UK, Oct. 3-5, 2016, pp. 34-40

[11] S. Corbellini; F. Ferraris; M. Parvis, "A system for monitoring workers' safety in an unhealthy environment by means of wearable sensors", IEEE Instrumentation and Measurement Technology Conference IMTC 2008, pp. 951-955, 2008

[12] S. Corbellini; M. Parvis; S. Grassini; L. Benussi; S. Bianco; S. Colafranceschi; D. Piccolo; "Modified POF sensor for gaseous hydrogen fluoride monitoring in the presence of ionizing radiations", IEEE Transactions on Instrumentation and Measurement, Vol. 61, Issue 5, pp. 1201-1208, 2012