IMEKO International Conference on
Metrology for Archaeology and Cultural Heritage
Torino, Italy, October19-21, 2016

Development of Wireless Sensor Network for Museum Environmental Monitoring

Livio D'Alvia[1], Eduardo Palermo[1], Stefano Rossi[2], Paolo Cappa[1,3,†]

[1] *Department of Mechanical and Aerospace Engineering, 'Sapienza' University of Rome, via Eudossiana, 18, Roma 00184, Italy.*
[2] *Department of Economics and Management, Industrial Engineering, University of Tuscia, Viterbo, Italy.*
[3] *Department of Mechanical and Aerospace Engineering, New York University Tandon School of Engineering, Brooklyn, NY11201, US.*

Abstract – Wireless Sensor Network (WSN) has been adopted in many contests, such as healthcare or industrial. In museum scenario, WSN has been introduced for environmental monitoring, to control temperature and relative humidity. Nowadays, the development of low-cost micro-scale sensing units, opened to new possibilities for WSN development, including other environmental measurements of interest, such as: gaseous pollutant, relative humidity, temperature, light intensity, air flow, vibration.

The present work is part of the overarching goal of the development of a low-cost and minimally invasive WSN designed for a museum scenario. The here proposed WSN node, based on a ZigBee-IEEE802.15.4 standard, gathers signals provided by: a 9-axis MIMU, a sensor for temperature and relative humidity, and a lux-meter. In this paper, we present performances of the WSN node in detecting structure tilt that can be due to structure deformations and/or seismic vibrations.

I. INTRODUCTION

In cultural heritage, the degrading effects of manufactures can be classified in: morphological, physical-mechanical, physical-chemical, and optical alterations. Morphological alterations can involve: dimensional variation (i.e. expansion, torsion, etc.), loss of material and continuity (holes and cracks). Physical-mechanical alterations determine a decrease of cohesion, adhesion and elasticity. Physical-chemical alterations cause a variation of porosity, hydrophilic and hydrophobic characteristic, etc. Optical alterations influence visual parameters, such as color, luminosity, etc. In indoor conservation, all these degrading effects are mostly driven by: (i) relative humidity and temperature; (ii) gaseous pollutants (O_3, SO_x, NO_x, CO_x, H_2S, NH_3, HCl, etc.) and particulate matter; (iii) light intensity; (iv) air velocity and direction; (v) sound pressure and vibration; and, finally, (vi) anthropic impact [1]–[3].

Environmental parameters monitoring is needed to preserve materials, to identify causes of degradation, and to quantify their effects, as a function of time [4], [5]. However, the development of a fully inclusive and compact solution to precisely and punctually identify the effects induced by environmental and anthropic related factors is still an open challenge [6]. Commercial solutions and wireless devices are cumbersome, bulky, not-esthetic when placed next to artifacts, and expensive.

Currently Wireless Sensor Networks (WSN) have been employed in several application fields as in indoor/outdoor environmental monitoring or gas detection, both in healthcare and industrial contest [7]–[9].

Application of WSN in a museum scenario has been so far restricted to the monitoring of temperature and relative humidity [10], [11]. The deployment of a WSN monitoring system presents valuable pros, such as: architecture scalability, the capability to integrate multiple and heterogeneous sensors on a single small node, the possibility to distribute a high number of wireless and low-cost measurement points in the exhibition areas.

We decided to develop a MEMS-based novel, low-cost, wireless, scalable system capable to control environmental parameters, as well as vibrations and deformation, and light intensity, in a multi-stage research project. At the present stage, we developed and validated the system for detection of tilt and shock detection.

In the present paper, we describe firstly the state of art of heritage monitoring and wireless network applied in this context (paragraph II), secondly the architecture of our developed WSN based on the IEEE 802.15.04 (paragraph III), and finally the experimental tests performed to validate the system (paragraph IV).

II. STATE OF ART

Despite internal museum environmental parameters play an important role in the conservation, the monitoring activity has not benefited substantially of technological

[†]Deceased 26 August 2016

developments so far [12], [13]. Several studies proposed limited solutions to evaluate the quality of expositive habitat, focusing especially on temperature and humidity measurements, and, sometimes, on gaseous pollutant, through passive/diffusive traditional sampler.

Some authors [14]–[20] highlighted the importance of investigating the fluctuation of air temperature (T) and relative humidity (%RH), identifying these parameters as determinant in the deterioration of collected artefacts. At the same time, they pointed out the difficulty to install sparse measurement stations preserving artworks appearance. As a matter of fact, many museums, art galleries and historical buildings in general are themselves masterpieces, making inappropriate the installation of bulky monitoring devices.

In addition to temperature and relative humidity, several works [16], [21]–[26] presented methodologies to sample the Inorganic and Volatile Organic Compounds (NO_x, O_3, SO_x, VOC) and particulate matter. The first quantities are sampled through chemisorbing cartridges that require a subsequent analysis with UV-VIS spectrophotometry or ion chromatography. For particulate matter, controlled flow ratio samplers with filters that permit a detailed analysis of elemental concentrations whit SEM microscopy are used.

All these analyses cannot be used in ordinary survey due to excessive costs in terms of equipment and post-process analysis. Moreover, only the thermo-hygrometric analysis can be associated to a remote wireless network, while the other techniques require the intervention of specialized technicians/analysts.

Saraga *et al.* [25] discussed the application of measurement units for external environmental monitoring, including: (i) ultraviolet photometry automatic analyzers for O_3 (EN 14625:05); (ii) ultraviolet fluorescence for SO_2 (EN 14212:05); (iii) chemiluminescence for NO_x (EN 14211:05), and (iv) gravimetric measurement for PM10 (EN 12341:99) and PM2.5 (EN 14907:05). The proposed instrumentation has a dimension of 42.5 cm (W), 157.5 cm (H), 58.5 cm (D), occupying a volume that could be incompatible with museum applications.

We are developing an indoor low-cost small scale solution, similar to Mead *et Al.* [27] for external monitoring. In their research they propose to integrate in a single board: (i) an environmental parameter sensor (temperature, relative humidity and barometric pressure) (ii) an electrochemical cell to monitoring gas pollutant; (iii) an optical particles counter (OPC) to control the total particle matter; and (iv) an anemometer to analyze the wind direction and intensity, showing the real benefits related to low-cost sensing

Differently from [10], [11] where an Original Equipment Manufacturer (OEM)-WSN has been proposed, to monitor only temperature and humidity into a museum environment, we propose and study a wireless sensor network that integrates small and cheaper sensor devices.

In particular in this research we seek to integrate in a single board three MEMS sensors for vibrations and displacement, environmental parameter (temperature, relative humidity and barometric pressure), and light radiation.

III. PROPOSED WIRELESS SENSOR NETWORK

The α-prototype of the WSN is composed by a transmitting/receiving ZigBee unit, a computational unit based on a RISC Microcontroller AVR ATmega328P, three development-board with MEMS sensor units that are: (i) a Bosh BMO055 nine-axis MIMU (Magnetic Inertial Measurement Unit), (ii) a Bosh BNE280 humidity, pressure and temperature sensors, and (iii) a Silicon Lab Si1445 lux-meter as schematized in Fig. 1.

At this stage, due to intrinsic modularity of the system, we validate the wireless communication and stability of the only BMO055 sensor.

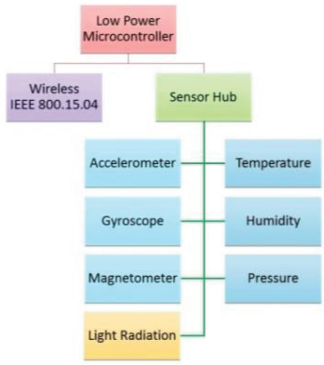

Fig. 1. Architecture of the proposed WSN

Fig. 2 shows the schematic of prototype with highlight the constituent block: (a) Control Unit, (b) Power Supply, (c) Radio Modules and (d) Sensor Unit.

A. Control Unit

The proposed wireless node is based on a Microcontroller ATmega328P. It is a low power microcontroller with two SPI serial interface, one programmable serial USART used to interface the µC with an external PC for programming and other serial devices (ex. Radio device) and a TWI serial used to communicate with MEMS Sensor Board.

B. Power Supply

The Radio Modules and Sensor Board required a stable 3.3 V source and µC unit a 5 V source. An LT7805 regulates input voltage (5-38 V) to 5 V output whit a SD lower than 35 mV and an LD33 tension regulator converts 5 V to 3.3 V.

C. Radio Device

Radio modules is a transmitting/receiving ZigBee unit IEEE 802.15.4 in 2.4GHz band with +3dB output power and 250kbit/s transmission. It is used in AT commands directly connected to USART of ATmega328P

D. MEMS Sensor Board

BNO055 is a low-cost MEMS SiP (System in Package) that integrates a 3-axis 14-bit accelerometer, 16-bit gyro, geomagnetic sensor and a 32-bit cortex M0+ microcontroller for the data sensor fusion (Quaternion and Euler angles) [28]. In particular the possibility for the experimenter to set-up the acceleration ranges and the low-pass filter bandwidths, permits to adapt the sensor to museum application (vibration induced by visitors, HAVC system etc.).

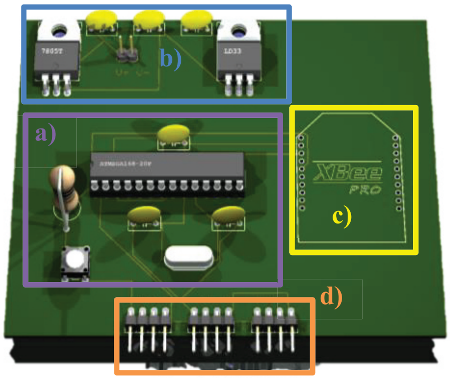

Fig. 2. α-prototype PCB board

IV. SYSTEM VALIDATION AND RESULTS

We performed the validation of the MIMU sensor for two monitoring activities: (a) possible tilt detection of wall due to fracture and/or deformation and (b) shock vibrations. In order to assess performance of MIMU in these two applications two experimental setup are designed: (i) a rotating plate and (ii) an electro-dynamic shaker.

A. Tilt detection

A servomotor controlled in closed loop by means of an angular encoder (Sanmotion rs1a03aa) has been used to estimate the accuracy and the stability of the embedded accelerometers. Specifically, the MIMU was mounted on a vertical plate connected to the servomotor through a belt as shown in Fig. 3.

The BNO055 has been programmed by setting the internal low-pass second order filter to 250 Hz and the measurement range to ±16 g. A LabVIEW program has been developed to rotate the plate around the horizontal axis from 0° to 90° with a step of 1° every 15 minutes, simulating tilt rotations induced by structural deformations. We acquired tilt angles measured by encoder ($\theta_{ref.}$), roll angle calculated directly by three acceleration components (θ_{raw}) and roll angle provided by the data fusion algorithm of the sensor (θ_{fusion}).

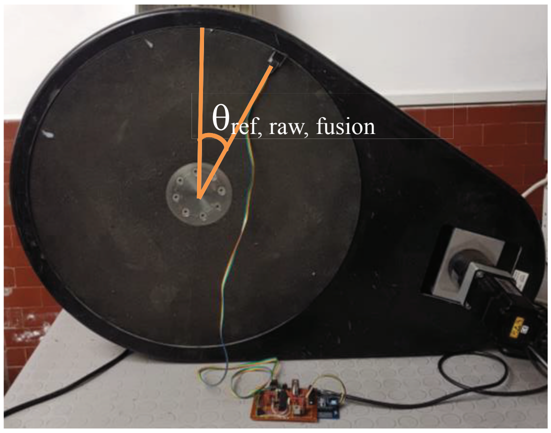

Fig. 3. Plate with highlighted the theta angles

Accuracy of accelerometers was estimated by means of the Root Mean Square Error (RMSE) between the average values of the measurement signals (θ_{raw}, θ_{fusion}) in the 15 minutes window, and each reference angle (θ_{ref}), gathered each 15 minutes. The standard deviation of θ_{raw} was evaluated to estimate the stability of the accelerometers, an important parameter to avoid deformation misdetection, due to long-term functioning of the sensor.

Fig. 4. shows the relation between $\theta_{ref.}$ and θ_{raw}. The accuracy of MIMU (RMSE) was equal to 0.3° and the stability range (SD) was always lower than 0.4° in the 0°-90° tilt range.

The RMSE between $\theta_{fusion.}$ and θ_{ref} was equal to 0.16° and the stability range (SD) was always lower than 0.18° in the 0°-90° tilt range.

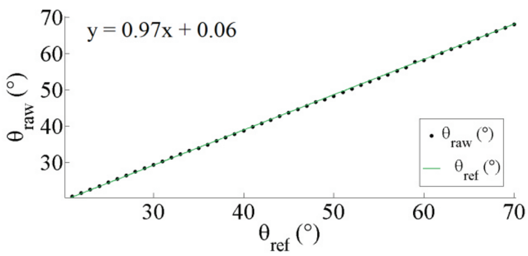

Fig. 4. Relation between θ_{raw} and θ_{ref}

Fig. 5 shows the comparison between the roll angle calculated θ_{raw} from the three measured accelerations $\mathbf{a_x}$, $\mathbf{a_y}$, $\mathbf{a_z}$, and the roll angle θ_{fusion} provided by the embedded sensor fusion algorithm (range 0°-3° is shown). Fig. 5, in particular, highlights how the fusion algorithm output is less sensible to noise and, consequently, more stable in the time, with a maximum SD of 0.18°. Embedded data fusion algorithm, based on Kalman filter, is able to filter noise. However, for the slow dynamics of the phenomenon, the increased stability is not payed in terms of sensitivity, how demonstrated by RMSE.

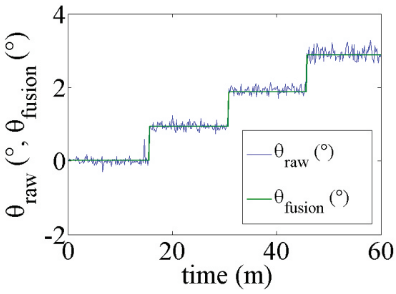

Fig. 5. Relation between θ_{raw} and θ_{fusion}

B. Shock detection

A Vibration Exciter Type 4809 (Bruel&Kejar) has been used to provide known inputs to the sensor. We compared the output of the MIMU with a reference signal provided by a certified mono-axial accelerometer (Bruel&Kejar 4371 model.) Both has been placed on the top of Vibration Exciter as show in Fig. 6 below.

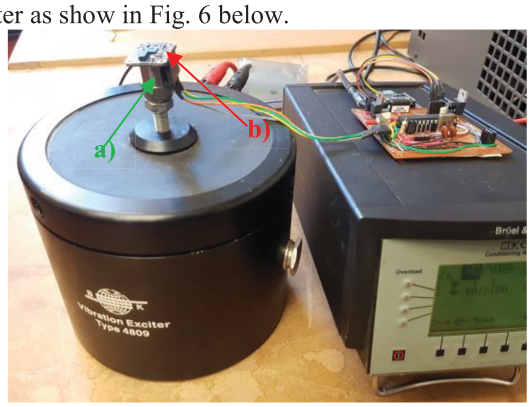

Fig. 6 Vibration Exciter whit reference sensor (a) and MIMU (b)

The test has been repeated for 8 different oscillation frequencies in the range 10-50 Hz with a 5 Hz step. This range of frequencies has been chosen to respect the Nyquist condition, as the maximum sampling frequency in this prototype is limited by the USART transmission time of 9 ms for sample. However, the selected range is compatible with other studies in the field [29]–[31]

The sinusoidal motion has been given by a high accuracy waveform generator, regulated to generate a fixed peak-to-peak displacement amplitude (0.5 mm) for all frequencies. All the described procedure has been repeated three times, by aligning each time a different MIMU axis with the motion axis.

Fig. 7 show, for example, the relation between $\boldsymbol{a}_{ref}$ and $\boldsymbol{a}_y^{test}$ at 20 Hz. Fig. 8 highlights the RMSE for the three axes for all frequency range. From both figures is clear how despite the use of two different filters there is not relevant phase shift between the acceleration of MIMU device and certified accelerometer. In particular, MIMU uses an internal second order Butterworth compensated with a Kalman filter with unknown patented parameter, while with the certified accelerometer is used a software second order Butterworth.

The higher RMSE, observable at frequencies above 30 Hz, can be due to a higher phase shift between the two signals, induced by the jitter of the USART communication time. With the increase of the oscillation frequency, the error induced by the jitter becomes more noticeable.

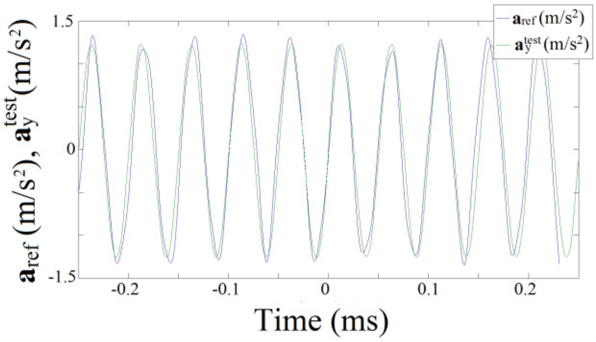

Fig. 7. Example of acceleration signals acquired via the two systems

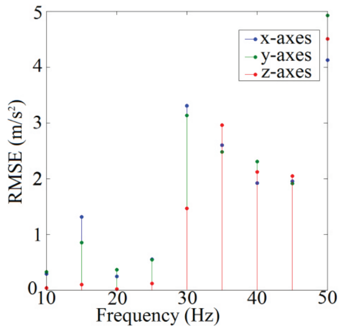

Fig. 8. RMSE as a function of the oscillation frequency for the three axes.

V. CONCLUSION

In this work we presented a low cost wireless sensor network for the environmental monitoring of cultural heritage. At this stage of development, we focused on the assessment of the accuracy and stability of tilt angle measured by the MIMU embedded in the developed WSN, and of accuracy in the detection of shock vibrations in the 10-50 Hz frequency range.

Tilt measurement demonstrated a good accuracy for the targeted application. The evaluated stability resulted more than acceptable, demonstrating the robustness of the solution as a function of time. Embedded data fusion algorithm demonstrated a good capability to filter noise without losing sensitivity in this application.

Shock vibration detection resulted more accurate for low frequency values (below 30 Hz), with an accuracy error about double at high frequencies (above 30 Hz). Accuracy error resulted lower than the other two for frequencies up to 30 Hz. Above such a frequency, no difference was observable along the three different axes.

In the β-prototype of WSN, temperature, relative humidity, atmospheric pressure and light sensors will be integrated to produce a complete description of the environment parameters to monitor a museum scenario. In addition, a finest firmware will be implemented on the device, including a data buffer to overcome the communication timing jitter.

REFERNCE

[1] G. Pavlogeorgatos, "Environmental parameters in museums," *Build. Environ.*, vol. 38, no. 12, pp. 1457–1462, Dec. 2003.

[2] P. Brimblecombe, "The composition of museum atmospheres," *Atmos. Environ. Part B. Urban Atmos.*, vol. 24, no. 1, pp. 1–8, Jan. 1990.

[3] R. Hamilton and H. Crabbe, "Environment, Pollution and Effects," in *The Effects of Air Pollution on Cultural Heritage*, 1st ed., R. Hamilton, V. Kucera, J. Tidblad, and J. Watt, Eds. Boston, MA: Springer US, 2009, pp. 1–27.

[4] F. J. García-Diego and M. Zarzo, "Microclimate monitoring by multivariate statistical control: The renaissance frescoes of the Cathedral of Valencia (Spain)," *J. Cult. Herit.*, vol. 11, no. 3, pp. 339–344, 2010.

[5] M. F. Mecklenburg and C. S. Tumosa, "Temperature and Relative Humidity Effects on the Mechanical and Chemical Stability of Collections," *Ashrae*, vol. 41, no. 4, pp. 69–74, 1999.

[6] N. S. Baer and P. N. Banks, "Indoor air pollution: Effects on cultural and historic materials," *Museum Manag. Curatorsh.*, vol. 4, no. 1, pp. 9–20, Mar. 1985.

[7] V. Jelicic, M. Magno, G. Paci, D. Brunelli, and L. Benini, "Design, characterization and management of a wireless sensor network for smart gas monitoring," in *2011 4th IEEE International Workshop on Advances in Sensors and Interfaces (IWASI)*, 2011, vol. 4, pp. 115–120.

[8] K. K. Khedo, R. Perseedoss, and A. Mungur, "A Wireless Sensor Network Air Pollution Monitoring System," *Int. J. Wirel. Mob. Networks*, vol. 2, no. 2, pp. 31–45, May 2010.

[9] A. Somov, A. Baranov, D. Spirjakin, A. Spirjakin, V. Sleptsov, and R. Passerone, "Deployment and evaluation of a wireless sensor network for methane leak detection," *Sensors Actuators, A Phys.*, vol. 202, pp. 217–225, 2013.

[10] F. Viani, F. Robol, E. Giarola, A. Polo, A. Massa, and A. Toscano, "Wireless monitoring of heterogeneous parameters in complex museum scenario," in *2014 IEEE Conference on Antenna Measurements & Applications (CAMA)*, 2014, pp. 1–3.

[11] G. Menduni, F. Viani, F. Robol, E. Giarola, A. Polo, G. Oliveri, P. Rocca, and A. Massa, "A WSN-based architecture for the E-Museum - the experience at 'Sala dei 500' in Palazzo Vecchio (Florence)," in *2013 IEEE Antennas and Propagation Society International Symposium (APSURSI)*, 2013, pp. 1114–1115.

[12] D. Camuffo, *Microclimate for Cultural Heritage*, Second. 2014.

[13] J. Ferdyn-Grygierek, "Monitoring of indoor air parameters in large museum exhibition halls with and without air-conditioning systems," *Build. Environ.*, vol. 107, pp. 113–126, 2016.

[14] F. Sciurpi, C. Carletti, G. Cellai, and L. Pierangioli, "Environmental monitoring and microclimatic control strategies in 'la Specola' museum of Florence," *Energy Build.*, vol. 95, pp. 190–201, 2015.

[15] J. Ferdyn-Grygierek, "Indoor environment quality in the museum building and its effect on heating and cooling demand," *Energy Build.*, vol. 85, pp. 32–44, 2014.

[16] D. Camuffo, "Environmental monitoring in four European museums," *Atmos. Environ.*, vol. 35, no. 1, pp. 127–140, 2001.

[17] D. Camuffo, A. Bernardi, G. Sturaro, and A. Valentino, "The microclimate inside the Pollaiolo and Botticelli rooms in the Uffizi Gallery, Florence," *J. Cult. Herit.*, vol. 3, no. 2, pp. 155–161, 2002.

[18] M. La Gennusa, G. Rizzo, G. Scaccianoce, and F. Nicoletti, "Control of indoor environments in heritage buildings: experimental measurements in an old Italian museum and proposal of a methodology," *J. Cult. Herit.*, vol. 6, no. 2, pp. 147–155, Apr. 2005.

[19] F. Becherini, A. Bernardi, and E. Frassoldati, "Microclimate inside a semi-confined environment: Valuation of suitability for the conservation of heritage materials," *J. Cult. Herit.*, vol. 11, no. 4, pp. 471–476, 2010.

[20] H. Janssen and J. E. Christensen, "Hygrothermal optimisation of museum storage spaces," *Energy Build.*, vol. 56, pp. 169–178, 2013.

[21] B. Krupinska, A. Worobiec, G. Gatto Rotondo, V. Novaković, V. Kontozova, C.-U. Ro, R. Van Grieken, and K. De Wael, "Assessment of the air quality (NO2, SO2, O3 and particulate matter) in the Plantin-Moretus Museum/Print Room in Antwerp, Belgium, in different seasons of the year," *Microchem. J.*, vol. 102, no. 2, pp. 49–53, 2012.

[22] B. Krupinska, R. Van Grieken, and K. De Wael, "Air quality monitoring in a museum for preventive conservation: Results of a three-year study in the Plantin-Moretus Museum in Antwerp, Belgium," *Microchem. J.*, vol. 110, pp. 350–360,

2013.

[23] R. H. M. Godoi, B. H. B. Carneiro, S. L. Paralovo, V. P. Campos, T. M. Tavares, H. Evangelista, R. Van Grieken, and A. F. L. Godoi, "Indoor air quality of a museum in a subtropical climate: The Oscar Niemeyer museum in Curitiba, Brazil," *Sci. Total Environ.*, vol. 452–453, pp. 314–320, 2013.

[24] F. Lamonaca, G. Pizzuti, N. Arcuri, A. M. Palermo, and R. Morello, "Monitoring of environmental parameters and pollution by fungal spores in the National Gallery of Cosenza: A case of study," *Meas. J. Int. Meas. Confed.*, vol. 47, no. 1, pp. 1001–1007, 2014.

[25] D. Saraga, S. Pateraki, A. Papadopoulos, C. Vasilakos, and T. Maggos, "Studying the indoor air quality in three non-residential environments of different use: A museum, a printery industry and an office," *Build. Environ.*, vol. 46, no. 11, pp. 2333–2341, Nov. 2011.

[26] A. Worobiec, L. Samek, A. Krata, K. Van Meel, B. Krupinska, E. Anna Stefaniak, P. Karaszkiewicz, and R. Van Grieken, "Transport and deposition of airborne pollutants in exhibition areas located in historical buildings-study in Wawel Castle Museum in Cracow, Poland," *J. Cult. Herit.*, vol. 11, no. 3, pp. 354–359, 2010.

[27] E. Esposito, S. De Vito, M. Salvato, V. Bright, R. L. Jones, and O. A. M. Popoola, "Dynamic neural network architectures for on field stochastic calibration of indicative low cost air quality sensing systems," *Sensors Actuators B Chem.*, vol. 231, pp. 701–713, Aug. 2016.

[28] B. Sensortec, "Intelligent 9-axis absolute orientation sensor." pp. 1–106, 2016.

[29] G. D'Emilia, A. Gaspari, and E. Natale, "Evaluation of aspects affecting measurement of three-axis accelerometers," *Meas. J. Int. Meas. Confed.*, vol. 77, pp. 95–104, 2016.

[30] M.-G. Masciotta, J. C. A. Roque, L. F. Ramos, and P. B. Lourenço, "A multidisciplinary approach to assess the health state of heritage structures: The case study of the Church of Monastery of Jerónimos in Lisbon," *Constr. Build. Mater.*, vol. 116, pp. 169–187, Jul. 2016.

[31] P. Pachón, V. Compán, E. Rodríguez-Mayorga, and A. Sáez, "Control of structural intervention in the area of the Roman Theatre of Cadiz (Spain) by using non-destructive techniques," *Constr. Build. Mater.*, vol. 101, pp. 572–583, Dec. 2015.