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Validation and application of a novel solution for environmental monitoring: A three months study at “Minerva Medica” archaeological site in Rome

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ABSTRACT

Monitoring of environmental parameters is necessary to preserve materials, identify causes of degradation, and quantify their effects, as a function of time. In this research, we propose a measuring unit and present an example of collected data. The unit is based on an ATmega328P microcontroller, gathering signals from: a 9-axis MIMU; a sensor for temperature and relative humidity; and three gas detection miniature boards (NO, NO_2 and SO_2). The aim of the project is to monitor the effects of different factors: (i) seasonal thermal variations; (ii) dynamic response of the structure and (iii) gaseous pollutant concentration. The developed system allows for a prioritization of intervention both for management and interventions planning, in terms of restoration, consolidation, and conservation. The experimental setup used to evaluate the accuracy of MIMU system highlighted a relative error on shock acceleration measurement, in term of percent root mean square error, lower than 0.36 for the sinusoidal input, and 0.49 for cardinal sin input, with an average accuracy in the principal peak reconstruction lower than 2% in the chosen frequency range (5 Hz to 50 Hz). Data collected *in situ* showed a maximum frequency of vibration, at ground level, equal to 40 Hz with a peak of 8 mm/s. The gas detection and temperature/humidity boards showed data comparable with the closest certified ARPA system device.

1. Introduction

In the last decade, increasing attention has been paid to novel technologies and methodologies for the real-time monitoring for maintenance of archeological sites and conservation of cultural heritage and artworks [1–3]. Although the necessity for preventive maintenance and monitoring has been widely documented, is still difficult to find a standard approach in the state of the art, due to the intrinsic heterogeneity of problems related to each monument or artifacts [4–7].

Literature of the field permits to identify and classify the most important degrading effects of manufactures in cultural heritage as morphological, physical-mechanical, physical-chemical, and optical alterations [8,9]. Morphological alterations can involve: dimensional strain (e.g. expansion, torsion), loss of material and continuity (holes and cracks) [10]. Physical-mechanical alterations determine a decrease of cohesion, adhesion, and elasticity, etc. [11]. Physical-chemical alterations cause a variation of porosity, hydrophilic and hydrophobic characteristic. Finally, an optical alteration influences visual parameters, such as color or luminosity. [12]. The previously mentioned effects are mostly driven in both indoor/outdoor conservation by: (i) relative humidity and temperature [13,14]; (ii) gaseous pollutants (O_3, SO_x, NO_x, CO_x, etc.) [15,16] and particulate matter [17,18]; (iii) light intensity [19,20]; (iv) air velocity and direction [21,22]; and, finally, (v) vibrations [23,24].

Currently, air quality monitoring strategies consist of sparse stations, holding dedicated units for capturing and/or processing and displaying data about macro- e micro-pollutants. Stations are instrumented with expensive air quality sensors, which provide accurate data but only in a few pre-defined locations, usually far from structures of interest, due to their dimensions [25,26]. The expensiveness of commercial solutions, in terms of purchasing, running, and maintaining costs, actually limits the number of installations. On the other hand, those devices are cumbersome, bulky, and unaesthetic when placed next to artifacts, as originally designed for assessing human exposure to atmospheric pollutants.

De La Fuente et al. [27] used the national “Air Pollutants Database of the Council Service for Environmental Information” of Madrid to develop a model to calculate dose response and the risk for mobile and immovable cultural heritage in Madrid. This model, used by several authors [4,28], allows for evaluation of a global environmental impact

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in a certain region but does not provide any local information about the monuments under investigation.

In this scenario, the deployment of a wireless sensors network (WSN) monitoring system presents valuable pros, such as: architecture scalability, capability to integrate multiple and heterogeneous sensors on a single small node, and possibility to distribute a high number of wireless and low-cost measurement points in the exhibition areas or at Historic sites [29–31]. Furthermore, the European Air Quality Directives and reports [32,33] describe the possibility to use not normed sensors to obtain indicative measurements or in support of "objective estimation" for air quality assessment, as long as they comply with the quality objectives set for each pollutant. Moreover, Spinelle et al. [34,35] discussed and validate the possibility to use commercial low-cost sensors according to data quality objective (DQOs) of the citied directives.

Recent studies showed how new instrumentations are developed to quantify the risk for cultural heritage in terms of pollution. The authors of this paper developed and tested a complete solution, integrating sensors for environmental parameters (temperature and relative humidity), electrochemical-cells for pollutant concentrations detection (SO_2 and NO_x) and sensors for tilt and vibration detection [36]. The device is expected to fuse benefits of different non-integrated solutions recently proposed. Leccese et al., in fact, realized a new device able to detect the particle matter using a low-cost microprocessor boar ad a CMOS sensor camera [37,38]. Mead et al., instead, proposed a WSN able to detect only gas pollutant using low-cost electrochemical sensor [39]. Osmancikli et al. investigated the dynamic characteristics of the structures [40].

The aim of this work is monitoring effects of different factors affecting the "Minerva Medica Temple", an archeological site in Rome. In particular, we focus on: (i) the seasonal thermal variations on the structure; (ii) the contamination due by local traffic in terms of gaseous pollutant and (ii) the dynamic response of the structure to the "Roma-Giardinetti" tramway line.

The remainder of the paper is organized as follows. In Section 2, we describe the proposed system both in terms of hardware and software. In Section 3, we present and discuss the results obtained during lab sessions of validation and onsite application. Conclusions and major achievements are summarized in Section 4.

2. Materials and methods

2.1. Hardware

The device, presented in Fig. 1 is composed by a computational unit based on a RISC Microcontroller AVR ATmega328P. The solution embeds: (i) BNO05 Bosh sensors MIMU development board [41]; (ii) a BME280 Bosch Sensors THP (Temperature, Relative humidity, and Pressure) development board [42]; (iii) NO-A4, NO2-A43F and SO2-A4 Alphasense sensors [43–46]. An RTC ds1337 and a connector for memory card (SD) are added.

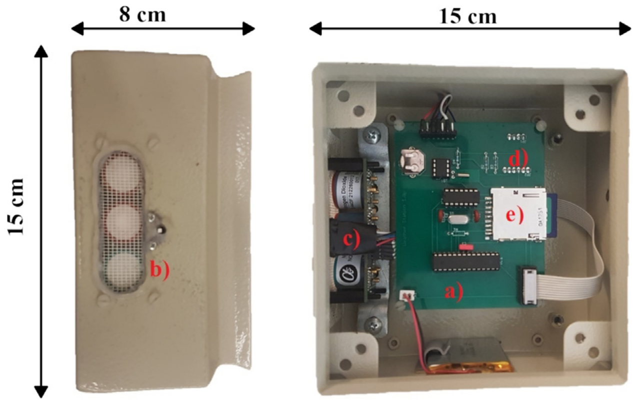

Fig. 1. The system with highlighted the components: (a) microcontroller board, (b) gas sensors, (c) BME280, (d) BMO055, (e) RTC and storage SD card system and the dimension.

We choose the ATmega328p for low power consumption (0.2 mA in Active Mode, 0.10 µA in Power-Down Mode and 0.75 µA in Power-Save Mode at 3.7 V), and low cost. In particular, we choose this microcontroller due to the simplicity of *bootloading* and the availability of libraries in the creative common right for the chosen sensors.

BNO055 is a low-cost MIMU (Magnetic Inertial Measurement Unit) System on Package (SoP) that combines a 3-axis accelerometer, a 3-axis gyro and a 3-axis geomagnetic sensor and a 32-bit M0 + Cortex microcontroller that runs the data fusion firmware. In addition, the SoP gives the possibility to set-up different parameters as the acceleration range; the cut-off frequency of low pass filter, or the interrupt signal generation if a certain event occurs (a changing in linear or angular acceleration). The power consumption of the MIMU is of 0.2 mA at 3.7 V. BME280 is a low-cost MEMS that combines digital humidity, pressure, and temperature sensing elements. Power consumption is 0.2 mA at 3.3 V.

Alphasense 810-0019-03 model is a three-input analogic front-end sensor board mounting NO-A4, NO2-A43F and SO2-A4 electrochemical cell for NO, NO_2 and SO_2 gas concentrations. In particular, the NO-A4 and the NO2-A43F present respectively a sensitivity of 0.342 mV/ppb and 0.197 mV/ppb in the range of 0 to 20 ppm while the SO2-A4 a sensitivity of 0.372 mV/ppb in the range of 0 to 50 ppm. The system is calibrated and certified by the producer to provide the user with information needed to compensate both zero and sensitivity drift for each sensor. The board is connected to the principal microcontroller (ATmega328p) through an analog-to-I2C converter based on a low power microcontroller ATtiny84 programmed for this application. Furthermore, we programmed the microcontroller to run all the operation recommended by Alphasense producer in the calibration certificate, to calculate the concentration levels expressed in part per billion (ppb). The power consumption of 810-0019-03 board model and the 3 sensors is 2 mA at 3.3 V.

The real-time clock ds1337 is a System on Chip (SoC) with a calendar in different output format: only dates (years, mounts and days), only times (hours, minutes and seconds), or complete. It has two different time alarms: Alarm1 in the rage seconds to days and Alarm2 minutes to days. The chip has a dedicated power supply (CRC1220 3.3 V Li-ion battery) to guarantee a no time reset when not powered.

The entire system is powered by a Li-ion battery with a capacity of 2 Ah, which guarantees forty days of functioning. Dimensions of the entire system are 15 cm (W), 15 cm (H), 8.0 cm (D). All sensors have been chosen according to the values present in literature as shown in Table1.

2.2. Firmware

Fig. 2 shows the measurement firmware flowchart with highlighted the most important functions. In particular, it is based on two external interrupts, one triggered by ds1337 RTC and one generated by BNO055.

The first interrupt (Alarm1) is set every minute. When entering the interrupt routine, the microcontroller firstly reads the Temperature (T

Table 1
Parameters, Measurement Units, Range of Tolerance.

Parameters	Unit	Rang of tolerance
Temperature[a]	˚C	Depends on the material
Relative Humidity[a]	%	Depends on the material
SO_2[b]	µg/m3	500 µg/m3
NO_x[b]	µg/m3	200 µg/m3
COx[b]	µg/m3	100 µg/m3

[a] [47].

[b] [48,49].