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Application of a novel monitoring technology at "Minerva Medica Temple" archaeological site in Rome

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***Abstract* – Environmental parameters monitoring 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, NO2 and SO2). The aim of the project is to monitor 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 organization and management, and for interventions planning in terms of restoration, consolidation, and conservation.**

I. INTRODUCTION

The need for preventive maintenance and monitoring of the deterioration process of cultural heritage has been widely documented. Currently, air quality monitoring strategies consist on 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 form structures of interest, due to their dimensions [1]. 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 artefacts, as originally designed for assessing human exposure to atmospheric pollutants. 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 [2].

Furthermore, the European Air Quality Directives and reports [3], [4] describe the possibility to use not normed sensors as 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. [5], [6] discussed and validate the possibility to use commercial low-cost sensors according to Data Quality Objective (DQOs) of the just citied Directives.

We developed and tested a complete solution integrating sensors for tilt and vibration detection, sensors for environmental parameters (temperature and relative humidity) and electrochemical-cells for pollutant concentrations detection (SO_2 and NOx) [7].

The aim of the project is to monitor effects of different factors: (i) the seasonal thermal variations on the structure; (ii) the dynamic response of the structure to the "Roma-Giardinetti" tramway line along with the trains of the nearby Roma Termini railway station; and (iii) the contamination due by local traffic in terms of gaseous pollutant that affect Minerva Medica Temple in Rome.

In the present paper, we describe firstly the developed sensors hub and the experimental setup (section II). Result of the research are presented and discussed in section III. Finally, in the concluding section the major achievements are summarized.

II. MATERIAL AND METHODS

A. Hardware

Our solution is based on an *ad-hoc* designed PCB, to reduce costs and dimensions of device with respect to commercial development boards (Arduino UNO, UDOO, etc.), that require external shield for each adjunctive function (ex. SD card for data logging, Real Time function etc.). In addition, we could integrate different sensors without limitation imposed by producer (ex. Libelium).

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 development board; (ii) a BME280 Bosch Sensors development board; (iii) NO-A4, NO2- A43F and SO2-A4

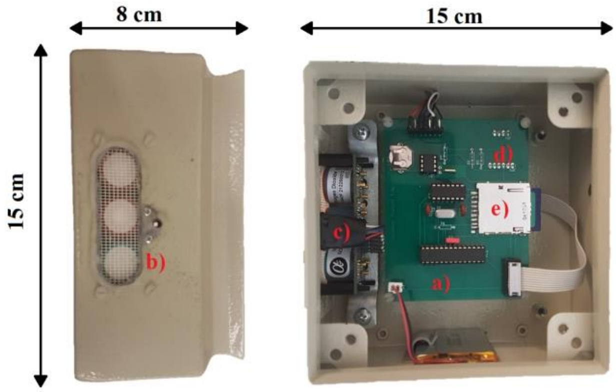

Fig. 1. The system with highlighted the components: a) microcontroller board, b) gas sensors, c) BME280, d) BMO055, e) RTC and storage SD card system and the dimension.

Alphasense sensors. In addition, a RTC ds1337 and a connector for memory card (SD) are added.

We have chosen the ATmega328p for his 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), low cost (1.98 € each one) and the easy programmability and interfacing, directly through the Arduino IDE. BNO055 is a low-cost MIMU 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 ranges; the cutoff frequency of low pass filter or the interrupt signal generation if a certain event occurs (a changing in linear or angular acceleration). The price of the development board is 35 € and has a power consumption of 0.2 mA at 3.7V.

BME280 is a low-cost MEMS that combines digital humidity, pressure, and temperature sensing elements. The price of the development board is 35 € and has a power consumption of 0.2 mA at 3.3V.

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, NO2 and SO2 gas concentrations. 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 programed the microcontroller to runs all the operation, recommended by Alphasense producer in the calibration certified, to calculate the concentration expressed in part per billion (ppb). The price for 810-0019-03 board model and the 3 sensors is 345 € with a power consumption of 2 mA at 3.7V.

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 day 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 2Ah, which guarantees forty days of functioning. The cost is 650 € for the entire system with a dimension of 15 cm (W), 15 cm (H), 8.0 cm (D).

B. Firmware

Fig. 2 shows the measurement firmware flowchart with highlighted the most important functions. In particular, it is based on two external interrupt, (i) one triggered by ds1337 RTC and (ii) one generated by BNO055 that are set in the *void setup()* function. In the *setup()* all sensors are also switched off.

The first interrupt (Alarm1) is set every minute. When entering the interrupt routine, the microcontroller firstly reads the Temperature (T in °C) value, Relative Humidity (RH in %) value and NO, NO_2, SO_2 (ppb) concentrations, and then stores all data into an external SD.

The second interrupt is used to acquire data provided by

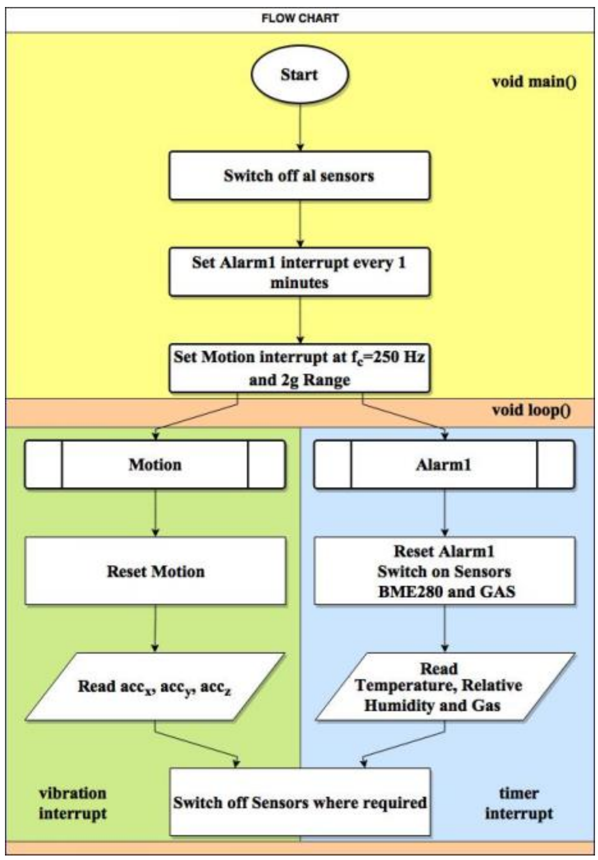

Fig. 2. Measurement Flow with highlighted the different states: the "void main()", the "void setup()" with the two internal interrupts: Motion and Alarm1.

the BNO055 when vibrations exceed a fixed threshold. The MIMU is set with a cut-off frequency at 250Hz and an acceleration range of ±2g with a threshold of 3.91 mg as LSB and 996 mg as MSB. The vale are chosen based on UNI 9916 recommendation [8] as motived in subsection C.

Both interrupts help to reduce the power consumption of battery power supply with respect to a polling routine, because after the reading, sensors are switched off or put in safe-mode, and the microcontroller enters the "sleep mode"

Acquired data in the Clock Interrupts Level have been post-processed by calculating the moving averages of the outputs, with a one-hour step and an 8-hours window (8h-Avarage).

C. Accuracy evaluation experimental Setup

The UNI 9916 recommendation describes variables and methods to measure the vibrations and their effects on a building, modern or ancient, identifying two key parameters: the *peak particles velocity* (p.p.v) and the *peak component particles velocity* (p.c.p.v). The p.p.v-value represents the maximum value of the magnitude of the vector speed measured at a given point while p.c.p.v-value is defined as the module of one of the three orthogonal components measured simultaneously at one point. In addition, both values could be directly measured or obtained by integration of acceleration data.

The relation between magnitude and frequency of the vibration signal is summarized in Table 1. In this work we focus our attention only on 0 to 30 Hz range, according to other studies in the field [9], [10].

Before the application of the instrumentation we have tested it in our laboratory to confirm the performance. In particular we focus our attention on the accuracy of MIMU

For this reason we adapted the procedure described in D'Alvia et Al. [7], applying cardinal sin (sinc) signal to a Vibration Exciter Type 4809 (Bruel&Kjaer).

The vibrometer was used to provide known inputs to the sensor. We compared the output of the filtered (at 250 Hz cut-off frequency) MIMU output with a reference signal provided by a certified mono-axial accelerometer (Bruel&Kejar 4371 model.) Both sensors have been placed on top of the Vibration Exciter as shown in Fig. 3.

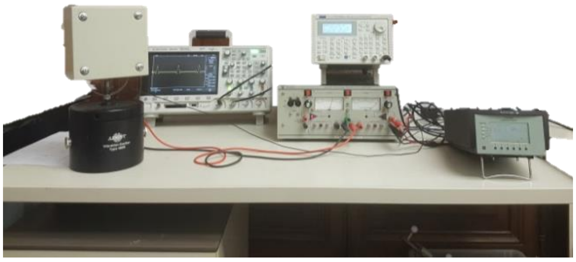

Fig. 3. The experimental setup.

A high accuracy waveform generator has imposed the cardinal sin motion, and the amplitude of the gain was set to produce a maximum velocity of 2 mm/s. The sinc signal is chosen because it is the function that better reproduce the vibration caused by the tram travel.

The test has been repeated for 3 different frequencies (5, 15, 25 Hz).

The described procedure has been repeated three times, by aligning each time a different MIMU axis with the motion axis. Accuracy has been evaluated by calculating the RMSE between test and reference signals, normalized to the peak-to-peak value of the reference sensor (nRMSE).

Table 1. Relation between magnitude and frequency for p.p.v and p.c.p.v values

At Ground Level			
Frequency (Hz)	< 30 Hz	30 – 60 Hz	>60 Hz
p.p.v (mm/s)	6	8	12
Frequency (Hz)	< 10 Hz	10 – 50 Hz	>50 Hz
p.c.p.v (mm/s)	3	3 to 8[a]	8 to 10[b]

[a] Grow-up linearly with the frequency.
[b] Grow-up linearly with the frequency, over 100 Hz 10 mm/s is used as reference value.

D. Application Point

Minerva Medica is an Ancient Roman temple, nowadays nestled between Roma Termini railway station and the "Roma-Giardinetti" tramway line.

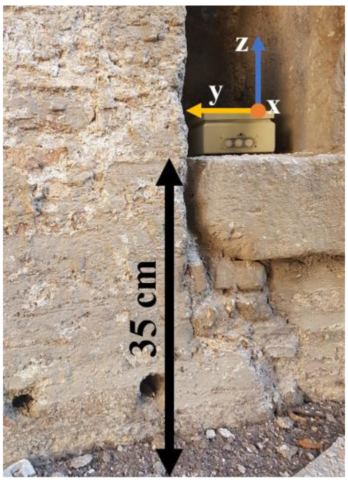

Fig. 4. Placing of the measurement system at the third niche of Minerva Medica Temple

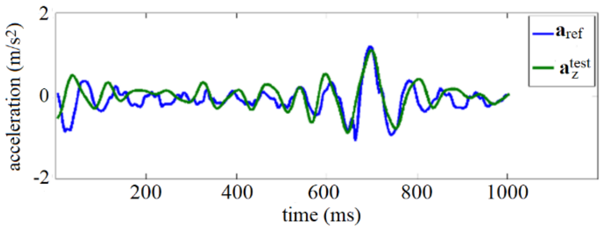

Fig. 5. The experimental result at 5 Hz

The structure presents a decagonal plant and nine niches around the structures. We chose the third from the entrance and moving right.

This niche was chosen due to its proximity to the tramway line for vibrations, the proximity to via Giolitti, for gas pollution and for the natural protection from rainwater. The system was placed at 35 cm to ground level, the direction of sensors axis is shown in Fig. 4.

III. RESULTS AND DISCUSSIONS

A. On-site vibrations

Fig. 5 shows the comparison between the reference acceleration $\boldsymbol{a_{ref}}$ and the test acceleration along z axis $\boldsymbol{a_z^{test}}$, in correspondence of an excitation frequency equal to 5 Hz. From the analysis of figure it clearly appears that phase shift between the acceleration measured through the MIMU and the one measured with the certified accelerometer is negligible, despite the difference in signal filtering. MIMU uses an internal second order low pass filter, with undeclared parameters, while to the certified accelerometer signal we applied a second order Butterworth digital filter, with a 250 Hz cut-off frequency.

The nRMSE value was similar for the three axes, with a mean value of 0.35 for the x and z axis, and of 0.36 for the y axis.

B. On-site vibrations

Fig. 6 reports an example of vibrations induced by the tramway. The maximum value of acceleration is 4.5 m/s^2

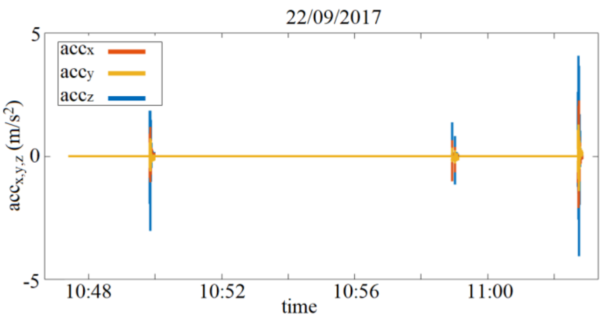

Fig. 6. Vibration results.

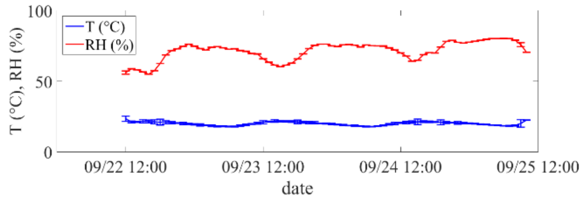

Fig. 7. Environmental result.

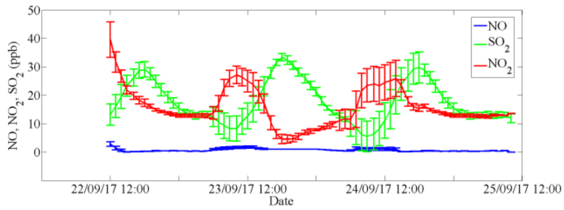

Fig. 8. Gas concentration.

along the z axis. This value is compatible with the safety recommendation, as the time-integrated signal presents a maximum speed value of 1.8 mm/s, which is lower than the 3 mm/s recommended threshold. The maximum amplitude for all axis was observed in correspondence to the train passing on the nearest track, (at 11:03) while the smaller signal peak corresponds to a train passing on the farther track from the sensors hub (at. 10:59).

C. On-site environmental data

Fig. 7 and Fig. 8 report environmental parameters (T and RH) and concentrations of pollutant gasses in ppb in three chosen days, from 12:00 AM of 22/09/17 to 12:00 AM of Sunday 25/09/17. In general, the pollutant gasses' concentration is lower during the night than during daytime. Values are compatible with the concentration values provided by the closest certified system and lower than the recommended day limits (140 ppb for SO_2, 100 ppb for NO_2 and NO). Maximum Standatd Deviation was 0.8 ppb for NO, 6.9 ppb for NO_2 and 6.5 ppb for SO_2

As expected, the sensor shows an evident decrease in relative humidity, in correspondence to an increase in temperature; maximum Standatd Deviation was 1.8 °C and 1.4 % respectively for T and RH

CONCLUSION

In the present work, we described a system for monitoring the effects of thermal variations, trolley vibrations, and traffic pollution on an ancient Roman structure. The proposed system has two main advantages (i) an integration of multiple and heterogeneous sensors on a single node and (ii) a lower cost respect to traditional instrumentation. Data acquired by the proposed system could be useful in the preservation of the Minerva Medica Temple archaeological site.

In particular the experimental setup for vibration detection demonstrated a stable behavior over the chosen frequency range (5-25 Hz), along the three different axes. Despite relative error on shock acceleration measurement is not negligible (nRMSE up to 35 %), it can be considered acceptable for the purpose of shock detection.

Gas concentration sensors showed results comparable to data from the ARPA system.

Future study will increase the number of probing points around the structure to better explore the dynamic of vibration's propagation, and to obtain a gradient of pollutant concertation and hydrothermal variable.

The future device will integrate other pollutant sensors, such as CO_2, to provide a complete description of the environmental parameters of interest in an archeological site.

IV. ACKNOWLEDGEMENT

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