A LOW COST DISTRIBUTED MEASUREMENT SYSTEMS BASED ON HALL EFFECT SENSORS FOR STRUCTURAL CRACK MONITORING IN MONUMENTAL ARCHITECTURE

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Abstract: In this paper the authors discuss a low-cost distributed monitoring system for structural crack monitoring in monumental architectures. The proposed solution is suitable to monitor widely extended areas like the Siena's ancient city walls. The prototype sensing system, based on Hall sensor technology, has been designed to reach a displacement resolution in the order of tens of micrometers. The distributed measures are transmitted using a wireless communication network, based on a mesh topology, to a server receiving, collecting, post-processing and storing the data in a database.

Keywords: Hall Effect Sensors, Monumental Monitoring, Wireless Sensor Network.

1. INTRODUCTION

Monumental architecture preservation and monitoring is a research field that is under continuous development due to the possibility to merge traditional approaches with emerging and more sophisticated monitoring techniques [1-6].

Monumental architecture monitoring presents different crucial points and constraints. Huge buildings or structures like palaces or ancient city walls require a wide range and distributed sensing network for their monitoring, depending on their size, accessibility and state. By applying the proper measurement techniques and by choosing the best sensing solutions it is possible to retrieve additional information about the condition of the monitored structure, with advantages for its conservation, its stability and for public safety.

Nowadays structural crack monitoring is generally achieved by means of LVDT sensors or potentiometric devices which provide the required accuracy but are quite expensive.[7-9]

When considering a wide distributed network of sensors, different aspects have to be taken into account for its design, influencing each other, e.g., the network architecture, the budget, the measurement accuracies, the environmental scenario, the energy budget, the physical dimensions of network nodes, the system durability and the extent of the area to be monitored.

In this paper the authors discuss a low-cost measurement sensor network to be used for structural crack monitoring in monumental architecture, suitable to monitor widely extended areas like the Siena's ancient city walls.

Our goal is to have network nodes providing accurate information about the crack width whereas exploiting a low cost technology and requiring a reduced energy budget. To this aim, the network architecture is based on a mesh topology based on local multi-hop transmissions, being the power supply based on local energy harvesting. Moreover, the nodes can measure different physical quantities related to the spot being monitored such as the local temperature and the humidity. This approach allows for the correlation analysis of acquired data, to compensate, e.g., the temperature influence on the crack width measurement.

The circuit for the crack width measurement exploits a displacement sensor based on a permanent magnet and an IC Hall-effect sensor [10] mounted in a special holder, obtained by 3D printing in PLA. This low-cost solution is characterized by a large sensitivity, low power consumption and a low-complexity conditioning electronics, i.e., suitable for being embedded in devices that have to be remotely managed and accessed through a wireless network.

The paper is organized as follows: in Section 2 we present the network architecture, and a proof of concept node architecture. In section 3 we discuss the crack width sensing system composed by the sensor and the conditioning circuit. Finally, we present the sensor characterization with experimental results.

2. NETWORK ARCHITECTURE

The Siena's ancient city walls have an extension of approximately 7km, with an irregular shape around the medieval city. The density of nodes that should be used for this monumental structure can reach an average of 50 nodes per km, involving an overall estimated large number of sensors, in the order of one thousands, considering different types of sensors per node.

In order to reduce costs, the number of long-range transmitters has to be minimized, and an ad-hoc Wireless Sensor Network Architecture has been designed (see Fig. 1). The proposed network foresees the use for each node of a XBee Series 2 transmission modules, able to transmit data in a range over 100m. These modules implement the ZigBee protocol that allows multi-hopping and the setup of a network based on a mesh topology [11-12]. In the considered scenario, due to the geometry of the structure to be monitored, a star or a tree network topology cannot be applied: indeed, city walls are developed in length, and each sensor node should transmit only to the closest adjacent nodes.

ZigBee protocol allows three typologies of network nodes: the Coordinator, the Router and the End Device. If a node is set up as a Router, it is able to route to the Coordinator all the packets transmitted by other nodes that are not in line-of-sight with it. In our case each node is set up as a Router, while only one node is set up as a Coordinator. The routers are provided only with local (ZigBee) connection, while only the coordinator is equipped with a GSM module in charge of transmitting all the data collected by the Network to a remote data management center. To reduce the number of nodes linked in a same network, depending also on the amount of information to be collected and transmitted, the city walls can be divided in distinct sectors, each one with its own network.

3. NODE ARCHITECTURE: PROOF OF CONCEPT

In this paper, as a proof of concept, we present a hardware implementation of the network node based on an Arduino Uno development board, equipped with a GSM shield, for the data transmission. The DA converter of the Arduino board has been used to acquire the output voltage of the measurement circuit discussed in the next section.

It is worth remarking that this solution has been chosen only for testing, with a special focus, in this developing phase, on the design of the data management center, the data receiving system and the evaluation of the prototypical measurement circuit based on the Hall-Effect sensor. It is clear that, when no data processing is required on the node, the measurement analog data, expressed as voltages, can be directly connected to the AD inputs of a Xbee module implementing the local node functionalities, discussed in the previous section, whereas using a GSM module only for the Network Coordinator.
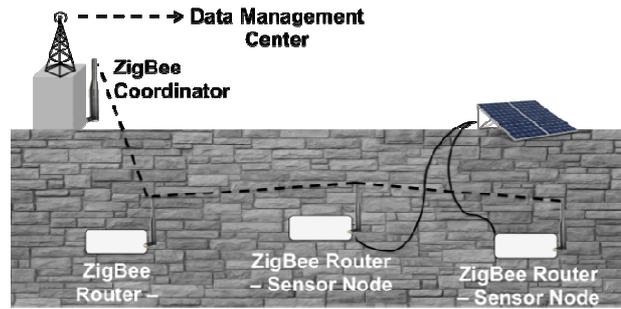

Figure 1:Wireless Sensor Network Architecture.

In the developed proof of concept the Sensor Node operates as follows: the output of the sensing system is received by the Arduino Uno Board through the Analog 0 channel with a sampling rate of 1 sample per second. Each data is stored in a 60 value vector. When the vector is full, the average of all the values is calculated. It is converted in a voltage value and then integrated into a GSM data packet that is sent to a remote server by the GPRS connection through the use of a GET method. Data is then received by a Glassfish server that is able to store it in a MySQL database. A Web Application based on JSP programming language has been developed, providing the following services:

1) The data receiving and storage in the database. Every received data is stored in a table composed by three records. The first record holds an auto-increment ID, the second one the actual data and the third one a time stamp;
2) The data visualization through the Internet.

The energy harvesting solution is based on a 12W solar panel, a 10A, 12/24V solar charge controller and a 12V lead acid battery. The solar panel is connected to the solar charge controller that is then connected to the battery. The solar charge controller manages the work of both the panel and the battery: it protects the structure against overloading, short-circuit, reverse discharging, reverse polarity, under-voltage and over-charging. Proper voltage regulators have been used to provide the power supply to the involved equipment.

4. DESIGN AND CHARACTERIZATION OF THEMEASUREMENT CIRCUIT

In this Section we present the sensing circuit providing the measurement to the transmitting module.

Sensor structure

As already said in the introduction the crack width is monitored with a displacement sensor based on a permanent magnet and a Hall sensor. The required sensitivity is 10 μm whereas the measurement range is approximately 2 mm, because if the crack grows beyond this limit an intervention is required. The measurement range has to be considered
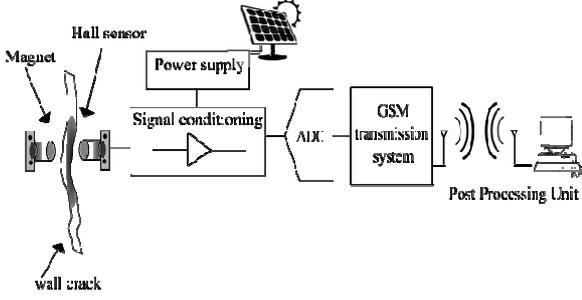
Figure 2:Schematic diagram of the measurement system.
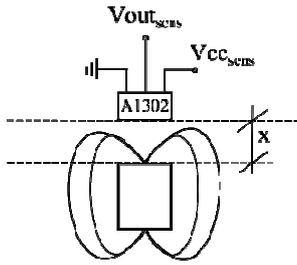

Figure 3: Structure of the displacement sensor for crack monitoring

extended to 4 mm in order to account for possible offset due to the mechanical mounting. The measurement system and the sensor structure is shown in Figs. 2 and 3.

Fig. 3 shows a permanent magnet on one side of the crack,generating a magnetic flux density field which, on its axis, is approximately:

$$B_x = 2\mu_0 \frac{\mu}{4\pi x^3} \qquad (1)$$

Where x is the distance, μ is the magnetic field moment and μ_0 is the magnetic permeability of vacuum. A Hall sensor mounted on the opposite side of the crack provides the measurement of the Hall voltage, $V_{out_{sens}}$ which is linearly related to the magnetic flux density field, B, as follows:

$$V_{out_{sens}} = K_H\, I\, B_x, \qquad (2)$$

Where K_H is the Hall constant, I is the current in the sensor and B_x is the value of the magnetic flux density field component perpendicular to current flowing in the sensor (sensor surface).

The overall displacement sensors provides a voltage output which is non-linearly related to the distance x from the magnet to the sensor surface. Being the device highly non-linear, a careful selection of the working point has to be performed according to the target sensitivity and the metrological characteristics of the developed sensor in the selected measurement range.
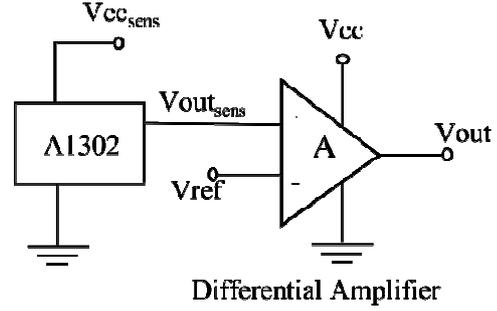

Figure 4:The linear circuit to adapt the sensor output voltage range to the input full scale of the ADC in Fig. 2.

The Hall voltage is amplified with a linear conditioning system (Fig. 4) providing the voltage

$$V_{out} = (V_H - V_{ref})A_0 \qquad (3)$$

Where A_0 is the overall gain and V_{ref} is an offset voltage. The ADC resolution sets the basic constraint to the overall design given the required sensitivity of 10 μm, whereas the voltage full-scale sets a limit to the distance range (x_{MIN}, x_{MAX}). In formula, referring to (1), we have:

$$\frac{V_{LSB}}{10\mu m} < A\, K_H\, I\, \frac{dB_z}{dx} = A\, \mu_0 \frac{K_H\, I}{6\pi} \frac{\mu}{x_{MIN}^4}, \qquad (4)$$

$$|V_{MAX-}V_{MIN}| = A\, \mu_0 \frac{K_H\, I}{2\pi} \mu \left| \frac{1}{x_{MIN}^3} - \frac{1}{x_{MAX}^3} \right|, \qquad (5)$$

As discussed in the following, due to the working range required by the application, we decided to operate in the 'medium field' region. Indeed, if close to the magnet, a large variation of the sensitivity is obtained, while in the 'far field' the sensitivity is heavily reduced. On the other hand, we had to obtain the required worst case resolution avoiding the sensor output saturation.

Measurement system design and characterization

In the proposed proof of concept system the measurement system in Fig. 2 has been obtained using the Hall-effect sensor A1302 by Allegro Microsystems and a neodymium magnetic disk (NdFeB) with dimensions 8mm (height) and 10mm (diameter), and magnetization grade N45, suitable to operate up to a temperature of 80°C degrees. The B field on the surface is approximately 0.4 T.

The Hall sensor is a three-terminal device (supply voltage ground and output) internally equipped with a linear amplifier and a CMOS Class A output structure. In the absence of magnetic field, the device presents a nominal quiescent output voltage equal to 50% of the supply voltage, the nominal magnetic sensitivity is 13mV/mT and full scale is $B_{max} \approx 0.02$ T with power supply voltage 5V.
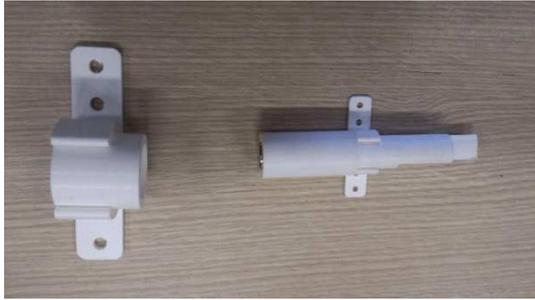
Figure 5: Printed PLA holder for the magnet and the Hall-effect sensor.
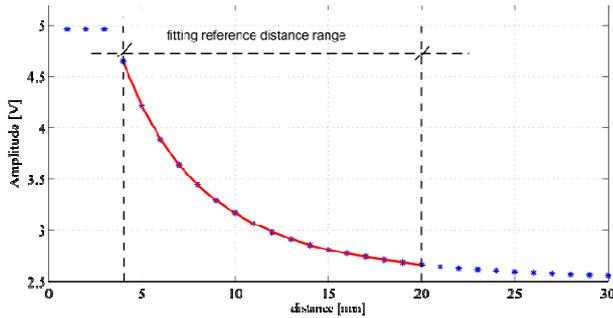

Figure 6:The 5th degree polynomial (solid line) used to fit the output sensor voltage measured at different distances (dots).
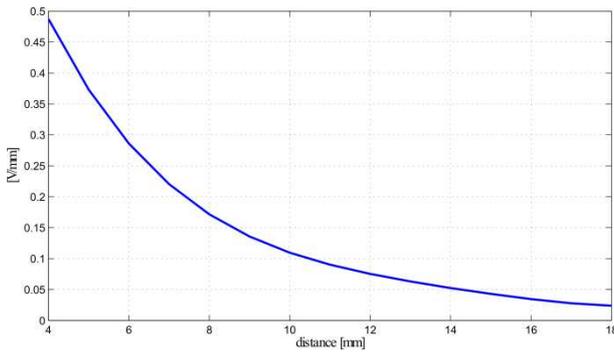

Figure 7: Estimated sensor sensitivity.

Figure 8:The output voltage of the measurement system and its second order fitting polynomial.

Figure9:The noise present a the output voltage of the measurement system. The measurement was obtained for x = 5mm, using a sampling frequency of 2Hz.

Figure 10:The distribution of the noise shown in Fig. 8.

The output voltage range of the sensor has been properly adapted to the input full scale 0 – 5V range of a 10-bit ADC converter, using the linear circuit shown in Fig. 4.

The Hall sensor and the magnet are coupled by a 3D printed PLA holder (Fig. 5), which allows for fixing the magnet and the Hall sensor to the two sides of the crack respectively, maintaining the alignment and housing also a temperature sensor. The developed displacement sensor was characterized varying the distance x in Fig. 3 within the range 0 – 30mm and measuring the output voltage $Vout_{sens}$. The experimental results in terms of sensor output and sensitivity are shown in Fig. 6 and 7 within the distance range 4 – 20mm.

For the considered application, given the reference requirements in eqs. (4-5), i.e., referring to the measurement range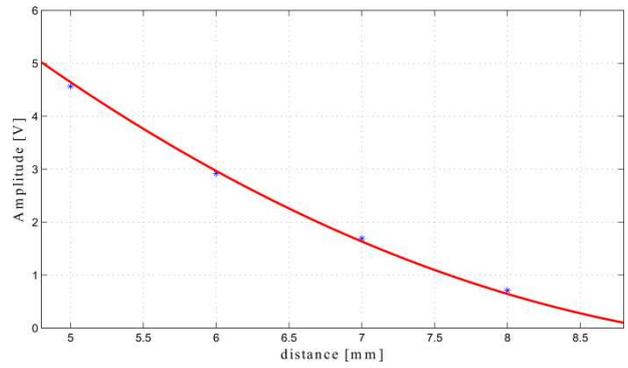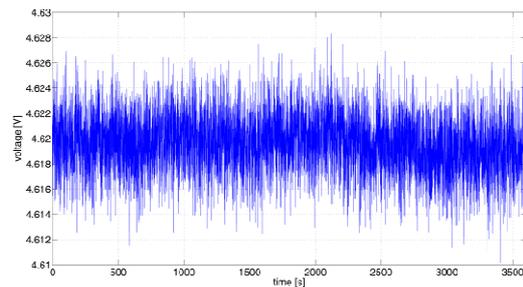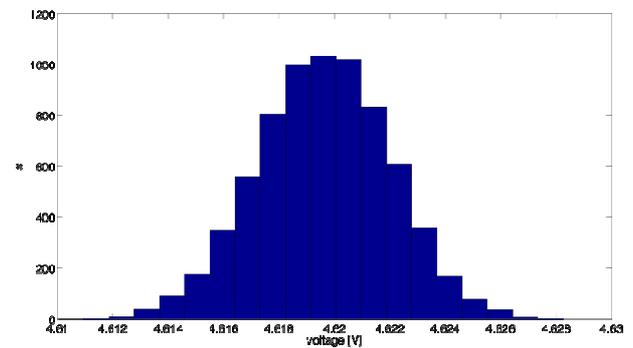 $\Delta x = x_{MAX}-x_{MIN}$ of 4mm, and worst-case sensing resolution of 10µm, considering a safety margin with respect to the sensor output saturation, the values of the gain of the front–end circuit A and of V_{ref} were chosen referring to a working distance range of 4.8 – 8.8mm, corresponding to a nominal voltage range at the sensor output approximately equal to 4.3 – 3.3V and a $\Delta V_{out} \approx 1V$. Accordingly, to adapt the dynamics to the input full scale range of the ADC (0V – 5V) the values of the gain A and the voltage reference V_{ref} was set to 5V and 3.3V, respectively. For the implementation of the circuit in Fig. 4, the authors used a differential amplifier AD627 and a low-noise reference voltage REF196 by Analog Device.

As shown in Fig. 9 and 10 the output of the measurement circuit exhibits the typical presence of a Gaussian noise with 3σ approximately equal to 8mV. The amplitude of this noise can be transformed in the distance domain, taking into

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account the worst case system sensitivity (x = 8.8mm), referring to the introduced fitting models. As a result, a 3σ uncertainty of 8mV at the measurement system output voltage corresponds to a 3σ uncertainty in the distance domain of about 11.5μm. The effect of the noise can be mitigated to negligible values, performing the average of the collected samples.

5. CONCLUSIONS

In this paper the authors discuss a low-cost distributed monitoring system for structural crack monitoring in monumental architectures. The proposed solution is suitable to monitor widely extended areas like the Siena's ancient city walls. The prototype sensing system, based on Hall sensor technology, has been designed to reach a displacement resolution in the order of tens of micrometers. The distributed measures are transmitted using a wireless communication network based on a mesh topology to a server receiving, collecting, post-processing and storing the data in a database. The proposed system is the first prototype which will be used to develop the definitive solution.

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