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A Low Power City-Scale Wireless Sensor Network for the Monitoring of Monumental Structures

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***Abstract* – In this paper the authors describe the architecture of a Wide Area Wireless Sensor Network (WSN) to be employed for the monitoring of large scale monumental structures. The proposed Sensor Network is composed by low power sensor nodes, provided with LoRa connectivity, able to measure displacements of structural cracks in buildings with a ten-micrometer degree of accuracy. Description is provided about the functioning of the displacement sensor, the structure of the sensor network node and the overall network architecture.**

The whole infrastructure has been designed for the monitoring of the medieval city walls in the town of Siena, where two prototypical sensor nodes have been installed and have acquired data for about one year. The proposed architecture can be applied to any context where a city scale monitoring is required. Test results are provided about the data collection and network coverage for the test site.

I. INTRODUCTION

The wide diffusion of low cost wireless monitoring solutions has radically changed the approach to the preservation of Cultural Heritage. The availability of cheap devices characterized by very small dimensions has allowed the realization of wireless sensing infrastructures that are currently employed in several different sectors, from environmental monitoring [1,2] to industrial monitoring [3] and agriculture [4]. The sector of Cultural Heritage preservation is among the ones that has exploited the technical advances in Wireless Sensor Network technology [5,6,7]. Monitoring architectures for ancient buildings have been tested and developed: nevertheless, these applications still suffer from severe limitations.

First of all, the question of energy consumption cannot be disregarded: the most part the monitoring infrastructures developed to be deployed on historical buildings are expected to be positioned in sites where no power grid connection and wired data transmission is available. This means that currently the most part of Wireless Sensor Nodes is provided with ZigBee, GSM or WiFi connectivity. These communication technologies can be optimised to reduce energy consumption: nevertheless, the majority of the Sensor Nodes is not able to operate autonomously for long time without the use of an energy harvesting solution. A second limitation comes from the scale of the site to be monitored: when monitoring a single building, a Wireless Sensor Network based for example on IEEE 802.15.4 data transmission can be deployed. Conversely, such a solution cannot be applied in the case the monitoring of an infrastructure like for example large castles or city walls. In these contexts, these communication technologies are not able to provide the required data transmission range, and the choice to provide each sensor node with GSM connectivity is not feasible due to high power requirements.

To address the previously underlined problems, in this work the authors propose Sensor Network architectures and Sensor Nodes characterized by low power consumption and wide range communication, suitable to define a monitoring infrastructure deployed at a city scale. In particular, the proposed solution has been designed to monitor the structural stability of the City Walls surrounding the town of Siena, in Tuscany, Italy, by analysing with a high degree of accuracy (in the order of tens of micrometres) the possible displacements of structural cracks that can be found in several sections of the walls.

This paper is structured as follows: in section II the test site is briefly described. Section III is devoted to the description of the displacement sensor while in section IV the architecture of the sensor network node is presented. Section V focuses on the network architecture while in section VI the results of the tests in terms of connection coverage and data acquisition are discussed. Finally, in section VII conclusions and possible future work are presented.

II. THE CITY WALLS OF SIENA

The proposed Wide Area Wireless Sensor Network (WSN) has been designed to be installed on the Ancient

City Walls that still almost totally surround the town of Siena, in Tuscany, Italy (See Fig. 1). This architecture was built in several centuries: the oldest sections date back at the XII century while the newest ones were erected in the XV century. Even if the base structure is original, several sections have been restored in the XIX and in the XX century, with partial reconstructions of the top sections and of the external masonry.

The perimeter of the whole structure is around 7km long and it encloses an area of around 1,8 km^2: it is interrupted only by 8 monumental gates and three passages created in the nineteenth century to allow the passing of vehicles. Siena is built on three hills: this means the walls height ranges from 290m a.s.l. to 340m a.s.l., a feature that notably affects the data transmission reliability. The height of the structure varies considerably, reaching in some points a 15 m peak, while the averages thickness is around 2 meters.

Even if the general conditions of the structure are mostly good, some sections are characterized by structural cracks whose origins are centuries back dated. Some of them are probably steady while in other cases they could be newer and slightly moving. This means that perspective structural failures like the ones that hit the walls of the towns of Volterra and Magliano, in Tuscany, Italy, in 2014 due to meteorological events are currently unlikely to happen, but cannot be totally excluded.

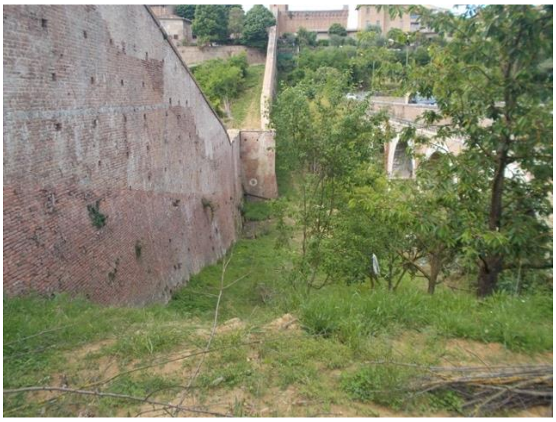

Figure 1: a section of the City Walls of Siena

III. THE DISPLACEMENT SENSOR

The structural crack monitoring has been achieved using for each network node a low-cost prototypical displacement sensor based on a permanent neodymium magnet, a Hall-effect sensor (A1302 by Allegro Microsystems) and a temperature sensor (LMT86 by Texas Instruments). The permanent magnet was a commercial neodymium (NdFeB) magnetic cylinder with dimensions 8mm (height) x 10 mm (diameter) and magnetization grade N45, suitable to operate up to a temperature of 80°C degrees. The sensors and the conditioning electronics were housed in a 3D-printed ABS holder made of two sliding parts (Fig. 2), which allows fixing the magnet and the Hall sensor to the two sides of the crack respectively, maintaining the alignment (Figures 2 and 3). As discussed in [8,9], the information provided by the temperature sensor allows compensating the effects of the temperature on the displacement measurement accuracy, due to both the gain error of the Hall-effect sensor and the thermal expansion affecting the length of each ABS part composing the holder. As a result, the obtained measurement accuracy was experimentally measured to be in the order of tens of microns, on a full-scale range of 2 mm. The design full scale range was set considering that the holder can be mechanically adjusted during the installation phase, such to tune the reference initial distance to match the mid-range, corresponding to the ‘medium-field’ region of the Hall-effect sensor. Moreover, it was assumed that for displacements growing beyond this limit a maintenance intervention should be required. The voltage signals provided by the sensors were conditioned with low-noise electronic circuitry [9] to properly fit the input range of the A/D conversion stages (5V, 10bit), whereas guaranteeing the target measurement sensitivity.

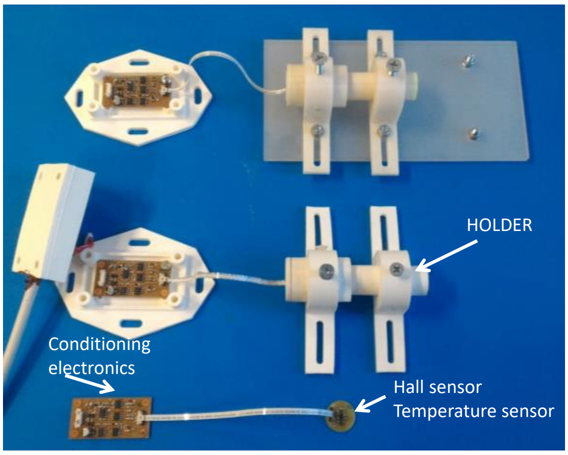

Figure 2: the prototypical displacement sensor

IV. THE SENSOR NETWORK NODE

The developed sensor network node comes from a first prototype, shown in Fig. 3 composed by the following components:

- An Arduino Uno board for local data processing;
- An IEEE 802.15.4 XBee local area communication module based on the ZigBee protocol for data transmission to a local gateway. The module is integrated on the Arduino board with the use of an XBee Arduino shield;
- An energy harvesting solution based on the use of a solar cell;
- A GSM/GPRS module for remote data transmission (only on the gateway node).

Figure 3: the first sensor node prototype installed on site

While the first prototype was able to collect data sets about the crack displacement every minute, transmitting them every 10 minutes, several problems emerged, requiring the project and development of a totally new typology of sensor node. The following are the major drawbacks that emerged during the test phase:

- The GSM module requires too much energy to be powered with the used 10W solar cell (the used module requires around 500mAh for data transmission but this value can grow up to 2Ah in case of low GPRS coverage). This means that to allow the continuous functioning of this device a more powerful solar cell would be required. Moreover, in case of no GPRS coverage this solution cannot be employed;
- Regarding the ZigBee Local Area Network in charge of transmitting the data to the gateway, this solution requires the ZigBee Routers to be always powered. This poses a limit for the reduction of energy consumption, forcing to employ a solar cell for each sensor node;
- The use of the solar energy harvesting solution (that includes the solar cell itself, a 12V battery and a charge regulator) is in conflict with the need for a small device to keep low the visual impact on the monument. Moreover, the solar cell suffers for lack of energy in case of bad weather and presence of clouds. The choice of higher quality solar cell would increase the overall cost of the node to an unsustainable level.

All these open questions required the development of a new sensor node characterized by a more basic architecture in terms of components to be employed (removal of the solar energy harvesting system and of the GSM module) and with a simpler network topology. The current version of the sensor node has then been designed to fulfil the following requirements:

- Wide data transmission range (2-3km in order to transmit the collected data directly to a central data acquisition gateway, avoiding power hungry Router nodes and possibly the use of the GSM module);
- Low consumption levels and long life time, to allow autonomous functioning without the need to frequently change the batteries and to avoid the use of solar energy harvesting solutions;
- Limited impact on the monumental structure.

The new version of the sensor node is based on the use of the following components:

- An Atmega328 microcontroller provided with the bootloader;
- A crystal oscillator;
- An SX1272 LoRa communication module;

- A HEF4060 binary counter;
- A MOSFET acting as switch;
- A D24V22F5 Pololu 5V Step-Down voltage regulator;
- Additional electronic components like resistors or capacitors.

The use of the Atmega328 microcontroller, together with the crystal oscillator, two 22pF capacitors and one 10kΩ resistor allows to emulate the basic functions of the Arduino board, avoiding the consumptions deriving from additional components like the LED whose presence is not necessary for the functioning of the Sensor Node: such a configuration allows to reduce the overall consumption of the node since the energy consumption is roughly the half of the one of the Arduino board.

The SX1272 communication module is based on the LoRa transmission technology: this modulation technology operates in the licence-free Sub-GHz radio frequency bands of 433MHz in Asia, 868MHz in Europe and 915MHz in America. LoRa belongs to the family of the LPWAN (Low-Power Wide-Area Network) technologies and operates according to the LoRaWAN MAC layer protocol. This technology is provided with two features that make it ideal to be employed in the proposed scenario: it is provided with very low energy consumptions and it is characterized by a transmission range that can reach 3km in urban areas and up to 20km in open space. Regarding the other modules, the HEF4060 binary counter is used to drive the interrupts that are used to wake up the Atmega328 when it is put in Sleep mode, the MOSFET is used to switch on the LoRa module when the data transmission is required, while the Step-Down Voltage Regulator is used to stabilize the power supply of the Atmega328 and the LoRa module.

The architecture of the node foresees the use of a 12V battery to power both the sensor and the node. The battery is connected to the Step-Down Voltage Regulator: who powers all the components. The HEF4060 is connected to the Atmega328 driving is wake up. The Atmega328 is then connected to the LoRa radio module whose powering is controlled by the MOSFET and to the sensor in order to retrieve the data.

With such a kind of structure a rough consumption analysis can be performed. When the Atmega328 is put in Sleep mode the average absorption of the whole node is around 0.755mAh: when the Atmega328 is awaken, absorption grows up to 15.3mAh, reaching 50mAh when the LoRa module is transmitting. Assuming one transmission per hour, that requires the Atmega328 to be awaken for 5 seconds, and a transmission time of around 2 seconds, the hourly absorption of the circuit is:

$$\frac{0.755 * 3593 + 15.3 * 5 + 50 * 2}{3600} = 0.8mA$$

Using a 1200mAh battery the average life time of the node is:

$$\frac{1200}{0.8} = 1500h$$

This value allows the ideal functioning of the Sensor Node for around 62 days. The life time could be notably increased by employing more a set of batteries put in parallel, employing batteries provided with a higher capacity (for example using a 4500mAh battery the ideal life time grows up to 234 days) or optimizing voltage regulation. Nevertheless, this value still allows to remove the solar energy harvesting solution together with the battery charge regulator, thus notably limiting the visual impact of the node on the structure.

Such a solution also allows to reduce the overall cost of the Sensor Node since the total number of components to be integrated is notably lower than the one used to realize the first prototype.

V. THE NETWORK ARCHITECTURE

The use of the LoRa communication technology allows to set up a new network architecture based on a star topology.

The Siena City walls stretch for 1.5km from East to West and 2km from North to South. These distances still fall in the transmission distance of LoRa communication technology in urban areas. This means that theoretically, depending on the total number of Sensor Nodes, with a single LoRa Gateway node it is possible to cover the whole circle of the City Walls. In the proposed context, the final number of Sensor Nodes to be deployed is lower than 100: in particular, cracks can be found on average every 100 meters while very close cracks (in a 5m range) can be connected to a single Sensor Node provided with more than one sensor.

Following the previous suggestions, the proposed architecture is based on a single Gateway: this device is expected to be positioned in a central location in order to reduce its distance from each Sensor Node. In particular, the final location of the Gateway node is planned to be the tower of former astronomical observatory in the building of the rectorate of the University of Siena. This building is located right in the centre of Siena, with a maximum 1.15km distance from the city walls, and the tower allows the positioning of the Gateway in a high position, thus optimizing the communication with all the Sensor Nodes.

The Gateway is realized using an SX1272 LoRa communication module to an Arduino Leonardo board: this board has been chosen due to the presence on board of an Ethernet port. While this device can be connected to the power grid, no consumption optimization like the one studied for the sensor nodes has been carried out. The Ethernet connection allows the Gateway to be connected to the Internet: this feature allows it to transfer each received data packet directly to a remote Glassfish server. Indeed, on this server a Java Web Application is deployed, providing a set of Web Services that allow to store each data packet on a MySQL database and to retrieve, visualize and export them for further analysis.

VI. THE TEST RESULTS

A set of tests about network coverage have been carried out in order to prove the full network coverage of the City Walls and thus the possible realization of a City-Scale Wireless Sensor Network. These tests have been carried out by positioning the Gateway node directly on the astronomical observatory tower and then checking the actual data packet reception by moving a Sensor Node is different sites all along the City Walls.

In particular, data reception has been tested at each of the 8 gates that interrupt the walls: here the transmission of a set of packet has been performed and the actual reception has been verified at the Gateway by connecting a laptop to it. Then, moving counterclockwise by car from one gate to the adjacent one, data transmission has also been tested during the trip: in this case a 10 seconds sampling rate has been defined. In addition to this test, data transmission and reception has been checked moving farther from the city walls to analyse the coverage of some of the city suburbs. While this test is not interesting for the City Walls monitoring network, it was carried to prove the effective City-Scale of the network.

The results can be summarized as follows:

- Data reception was achieved for each transmission from the eight gates;
- For the trip between one gate and the other some packet loss occurred (with a rate lower than 10%): this fact mainly depends on the travel speed of the car since all the packet losses were noticed when the car was moving faster than 30km/h.
- A second factor that affects the packet losses is the height difference between the Gateway position and the transmission position. A relevant number of packet losses occurred when being at the foot of the hills. In this case, no line-of-site was available.

Fig. 6 shows the area that was analysed, i.e. the central section of Siena together with some suburbs (in particular the areas of the hospital and of the train station): the star shows the position of the Gateway while the red shadow encompasses the area where the presence of LoRa connection was proven.

In parallel with the test about network coverage two nodes were installed in two test sites, in the southern part of the city, close to two of the monumental gates, namely Porta Romana and Porta Ovile. These two nodes were placed with the purpose to test the reliability and accuracy of the sensor and the data acquisition and elaboration structure.

The Porta Ovile node was the first one to be installed: data by this node have been acquired for around one year, and the node is still positioned on-site. In order to test the accuracy of the node samplings were collected every minute, using a support battery: data analysis proved the 10-micrometre precision of the sensor, that was able to survey the processes of expansion and contraction due to thermal variations between night and day: the measured value, on average 35μm, is in accordance with the value calculated theoretically by the architects in charge of the walls preservation. Fig. 4 shows the elaboration of one week data set.

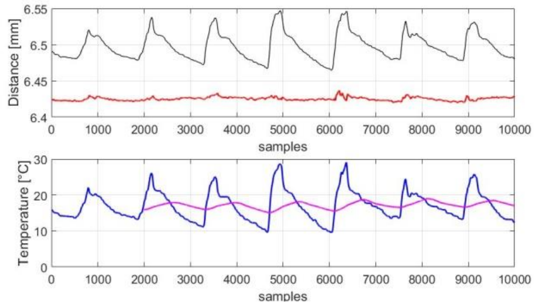

Figure 4: one week data acquisition example

The Porta Romana node was placed around 6 months after the Porta Ovile node and is shown in Fig. 5: this sensor node too is still on site and operating. This node included two sensors: one placed directly on the wall and one positioned on a crystal plate characterized by a very low thermal expansion coefficient. This node was useful to prove the actual detection of the expansion and contraction processes of the wall structure.

Figure 5: the Porta Romana Node

All the data sets collected during the test period were stored on the Glassfish server and van be currently consulted through the use of a common Web browser.

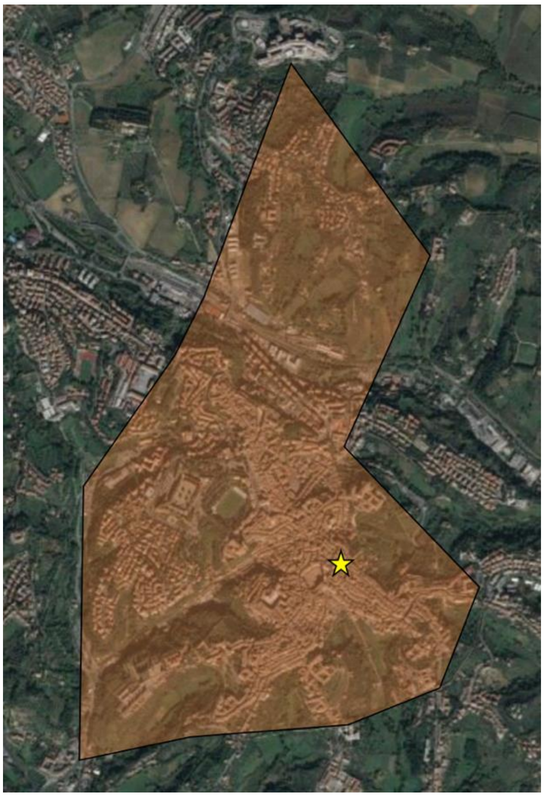

Figure 6: the Centre of Siena with the area covered by LoRa connectivity. The star shows the position of the Gateway

VI. CONCLUSION

In this paper the architecture of a Wireless Sensor Network to be employed for the monitoring of large monumental structures has been described. The developed system has proven its effectiveness in collecting data about possible crack displacements in the described scenario, thus allowing the development of an alert system to avoid possible structural collapses.

The described infrastructure is suggested to be employed in a specific city scale scenario: nevertheless, its features make it a general-purpose framework that could be employed in each Smart City application where the deployment of a large quantity of low cost sensor nodes is required. Moreover, the proposed architecture is open and predisposed to be expanded modularly. The independence of the Gateway from each network node allows the straight connection to the network of both monitoring systems for more than one and structure and new typologies of node, in charge of collecting different typologies of data.

While the results about the network coverage are mainly focused on the city of Siena, the dimensions of its centre and its morphological peculiarities suggest that a network with similar features could be deployed in almost any urban centre with a similar scale.

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