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## Design of Wireless Sensor Nodes for Structural Health Monitoring applications

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### Abstract

Enabling low-cost distributed monitoring, wireless sensor networks represents an interesting solution for the implementation of structural health monitoring systems. This work deals with the design of wireless sensor networks for health monitoring of civil structures, specifically focusing on node design in relation to the requirements of different structural monitoring application classes. Design problems are analysed with specific reference to a large-scale experimental setup (the long-term structural monitoring of the Basilica S. Maria di Collemaggio, L'Aquila, Italy). Main limitations emerged are highlighted, and adopted solution strategies are outlined, both in the case of commercial sensing platform and of full custom solutions.

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### 1. Introduction

In recent years, structural health monitoring emerged as a useful tool for assessing the condition of civil structures and rapidly determining a safety level. Traditional monitoring systems are composed of grids of sensors distributed along the structure to be monitored and connected to a central acquisition and processing unit through cables [1]. Lately, the use of wireless sensor networks (WSN) as an alternative base infrastructure for structural monitoring systems has been explored [2].

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A wireless sensor network is usually a more flexible solution (in fact, it does not require any cable deployment if the nodes are battery powered) with minor costs associated (especially if the network is composed by low cost devices). Respect to a wired solution, new problems should however be considered: the optimization of energy consumption, the synchronization between sensor nodes and the selection of adequate low-cost sensors.

This work details the main results obtained in the context of the Basilica S. Maria di Collemaggio monitoring project, with specific attention to different monitoring application requirements and design choices. Commercial platform selection and custom nodes design are analysed. Possible further developments are also detailed.

## 2. Wireless Sensors for Structural Health Monitoring

Structural health monitoring (SHM) indicates a wide range of tools and techniques for unobtrusive test and assessment of structures. Different analysis techniques have specific requirements: for example, structural identification requires accurate and synchronized measurement of the dynamic response from different points of the structure, whereas analysis of slow varying phenomena (e.g. analysis of concrete fractures evolution) require very low frequency sampling over long periods. Specific application requirement may significantly influence the design of measurements apparatus. In the case of wireless sensor nodes, this directly reflects on node architectures, with different specification in terms of processing capabilities, memory availability, interfacing options, etc.

Various WSN solutions addressing different structural monitoring applications have been presented in literature, both based on commercial platforms and on custom solutions. Illinois Structural Health Monitoring Project (ISHMP) vibrational monitoring solution is based on MEMSIC Imote2 wireless communication platform [3] and on a custom SHM oriented sensor board (MEMSIC SHM-A). Chen et al. [4] presented a custom node with high computational capabilities supporting multi-modal sensing. Wu et al. [5] presented a custom low power wireless sensor node for structural monitoring applications which includes interfacing blocks for piezoelectric and strain gauge sensors.

## 3. A real-world case study: structural monitoring of the Basilica S. Maria di Collemaggio

After the earthquake that interested the city of L'Aquila (Italy) in 2009, a long-term monitoring project of one of the most important churches of the city, the Basilica S. Maria di Collemaggio (Fig. 1, a), strongly damaged by the main seismic shock [6], started [7].

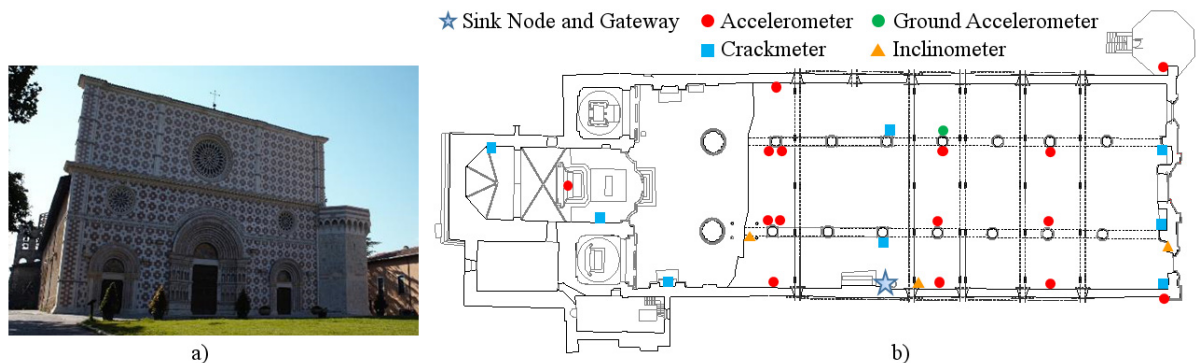


Fig. 1. Structural Monitoring of the Basilica S. Maria di Collemaggio a) front view of the Basilica, b) schematization of the installed system

Focus of the Collemaggio monitoring system is vibrational and seismic monitoring, with a vibration monitoring oriented WSN deployed within the church. An additional WSN for wall crack width and wall inclination measurement is also installed. Sensor data are collected and uploaded on a remote server on a daily basis.

A common requirement for both monitoring systems was long term operation, with a minimum operating lifetime of two years. Specific requirements of each monitoring system are detailed in the following paragraphs.

### 3.1. Acceleration monitoring for structural identification

Accurate, synchronized measurements of the acceleration response from different points of a structure are essential in order to proceed to the identification of its modal parameters. In order to use operational modal analysis techniques, sensor nodes must be able to record the structural response to environmental excitation (modeled as white noise). In this regard, it is recommended to use high-performance acceleration sensors (class B sensors, in reference to the USGS classification [8]). Each sensor node must record the structural response over a significant time interval, in order to ensure the correctness of the analysis. The synchronization error should be  $\varepsilon_s \leq 10 \mu\text{s}$  in order not to compromise the accuracy of the structural analysis and avoid phase errors in identified mode shapes [9].

For the Basilica S. Maria di Collemaggio sixteen different point have been selected for tri-axial acceleration measurement (Fig. 1, b) with a sampling frequency  $f = 100 \text{ Hz}$  [7].

### 3.2. Long-term monitoring of slowly-varying phenomena

A frequent need in the context of structural monitoring is the need to track the evolution of slowly varying phenomena. For example, it is possible to mention the monitoring of fractures evolution. This action has less stringent requirements with respect to vibration monitoring: a sensor node must only transmit a single measurement to a sink node on a periodic base. It is important to obtain accurate measurements ensuring the longest operating lifetime for nodes. A precise synchronization between different measurement points is not strictly required.

In the case of the Basilica S. Maria di Collemaggio, periodic crack width and wall inclination measurement were required, respectively with a resolution of  $10 \mu\text{m}$  and  $0.002^\circ$ . Minimum time interval between measurements was fifteen minutes.

## 4. Design choices analysis

In the context of the Basilica S. Maria di Collemaggio monitoring project, various technological solutions, both based on commercial and on full custom solutions, have been adopted.

MEMSIC Imote2 sensor nodes have been selected for the implementation of a vibration monitoring system. Main motivation behind this choice has been the notable processing and storage capabilities of the node, with an Intel PXA271 XScale CPU, 256 KB of SRAM, 32 MB of DRAM and 32 MB of Flash memory. Moreover, a sensor board specifically designed for vibration monitoring (MEMSIC SHM-A, equipped with 1 mg resolution tri-axial ST Microelectronics LIS344ALH accelerometer) and an open-source management software (ISHMP Toolsuite, developed by the University of Illinois) natively including structural monitoring oriented tools were already available for the node. This allowed the rapid installation of a state of the art, cost-effective monitoring system in the immediate aftermath of the structural retrofitting. In order to avoid possible problem related to battery replacement (nodes are installed at relevant heights in a heavily damaged structure [7]), it has been chosen to adopt mains power supply for all devices composing the monitoring system.

The vibration monitoring network installed inside the Basilica is organized in two distinct node subgroups, in order to obtain a continuous monitoring of the structure over alternating subgroups. Two main software components from ISHMP Toolsuite have been used: Automatic On-demand Distance Vector (AODV) routing and Time Synchronization Service. The routing protocol supports multi-hop communication between nodes. The synchronization service includes a network-level synchronization mechanism based on Flooding Time Synchronization Protocol (FTSP), coupled with a post-processing algorithm for the correction of data synchronization errors. The use of these software components allowed to meet coverage and synchronization requirements.

Limited performance of ST Microelectronics LIS344ALH accelerometer complicated the identification of the structure's modal parameters. However, continuous operation (guaranteed from node mains-powering and automatic management of measurement operations) allowed the recording of the structural response to major seismic events occurred in recent years (Table 1) even at significant distances from the monitored site.

Table 1. Recorded response of the Basilica S. Maria di Collemaggio for significant seismic events.

Date	Time (UTC)	Location	Latitude	Longitude	Magnitude (Mw)	Peak Acceleration Response [g]
05/05/2012	2:03 AM	Finale Emilia	44.896	11.264	5.8	0.0054
05/05/2012	1:18 PM	Finale Emilia	44.814	11.441	4.9	0.0018
06/06/2012	4:08 AM	Ravenna	44.40	12.322	4.5	0.0014
14/10/2012	4:32 AM	L'Aquila	42.395	13.243	2.8	0.0072
30/10/2012	1:52 AM	L'Aquila	42.396	13.272	3.3	0.0073
16/11/2012	3:37 AM	L'Aquila	42.411	13.37	3.2	0.0082
14/02/2014	8:51 PM	L'Aquila	42.409	13.278	2.9	0.0026

The analysis of seismic recordings led to important considerations on structural integrity and safety, and allowed preliminary identification of the main modal parameters of the structure [7].

In order to handle long-period measurements from crack width and wall inclination sensors, a custom wireless node able to operate for a prolonged period has been developed [10]. The node (WESTmote, developed in collaboration with WEST Aquila S.r.l.) is based on Atmel ZigBit 900 module (ATZB-900-B0) and includes an advanced analog front-end for data acquisition. The selection of low-power components and the careful design of system's blocks allowed the satisfaction of application requirements for a battery-powered setup. Implemented node is able to run with an average current consumption of 20  $\mu$ A in standby mode and of 21 mA for data transmission [10], meeting required performance even in the case of notable sensor consumptions (up to 20 mA of drawn current).

## 5. Conclusions and future developments

The Basilica S. Maria di Collemaggio experimental setup allowed the evaluation of wireless sensor networks in a real-world post-disaster structural monitoring application. Choices for the design and deployment of the monitoring system have been reviewed, both in the case of commercial platform selection and in the case of custom platform development, for different classes of structural monitoring applications. The development of a flexible sensor node, able to fully meet different requirements of structural monitoring will be considered in the next future.

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