WSNs for Structural Health Monitoring of Historical Buildings

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***Abstract*— Monitoring structural health of historical heritage buildings may be a daunting task for civil engineers due to the lack of a pre-existing model for the building stability, and to the presence of strict constraints on monitoring device deployment. This paper reports on the experience maturated during a project regarding the design and implementation of an innovative technological framework for monitoring critical structures in Sicily, Italy. The usage of Wireless Sensor Networks allows for a pervasive observation over the sites of interest in order to minimize the potential damages that natural phenomena may cause to architectural or engineering works. Moreover, the system provides real-time feedback to the civil engineer that may promptly steer the functioning of the monitoring network, also remotely accessing sensed data via web interfaces.**

I. Introduction

The present paper reports on the experience gained during the development of a project regarding an advanced sensory system for monitoring the stability of a building after restoration works were conducted. The focus of the project was the development of a system specifically targeted for structural engineers to help them study the dynamics of an unknown site, in order to monitor its current dynamics, and to plan future interventions.

Structural Health Monitoring (SHM) is a specific field in the context of Civil Engineering, that deals with such issues as damage detection, and stability and integrity monitoring of infrastructures [1]. Civil infrastructures, such as bridges or public buildings, are an essential part of our social life, and thus represent critical systems that need constant and careful monitoring. The assessment of the integrity of such structures is typically carried out manually by experts with specific domain knowledge, but this may easily lead to high costs, insufficient monitoring frequency, and to the possibility of errors due to imprecise positioning of the instrumentation or to mere mistakes during data collection; a great effort is also necessary in order to collect data from a significant amount of sensing spots. Data acquisition in a digital form also sometimes poses a problem, in that it traditionally requires wiring the site under observation, which may be impractical due to cost or architectural constraints.

We consider here the particular issue of monitoring the state of an ancient building after consolidation interventions, a change in the state of the building materials, or in the overall geometrical properties of the system that may adversely impact the performance of the restoration works. The monitoring process thus typically involves the observation of the structure for a prolonged time using a periodic sampling of dynamic response measurements, captured through sensors deployed on the site under observation; the goal of the civil engineer is the creation of a model of the behavior of the observed building, in terms of its reactions to external strains, and it typically involves performing some kind of statistical analysis on the sensed data, possibly followed by a feature extraction process; moreover, the model typically needs dynamic adjusting in the course of time in order to adapt to subsequent changes in the monitored structure. The availability of a reliable model is of great help not only in order to assess the integrity of the structure under normal conditions, but also to promptly react to sudden disruptive events, such as earthquakes.

The project described here specifically targets monitoring of historical heritage buildings; such structures require periodic interventions in order to preserve them from deterioration, and occasionally need more accurate restoration in order to fix damages caused by natural phenomena. Our project proposes a novel approach to SHM of such buildings that involves the use of an innovative framework based on Wireless Sensor Networks (WSNs) [2], [3] in order to provide a real-time, pervasive, non intrusive, low-cost, and highly flexible data collection and analysis infrastructure. Such networks are typically made of a potentially large number of autonomous units, equipped with different sensors in order to measure the required physical quantities; moreover, ad-hoc sensors may be devised for specialized tasks. While the primary purpose of a sensor node is data sensing and gathering toward a base station, through wireless communications, each of them also has limited processing capabilities that may be exploited in order to carry on preliminary operations on raw data. Despite the difficulty of collecting and managing huge amounts of measurements, meaningful information can be extracted by means of intelligent in-network processing and correlation of sensed data.

We have devised a comprehensive and flexible infrastructure for studying the stability of historical buildings, based on measurements acquired from a wireless sensor network; unlike traditional approaches, our proposal allows for pervasive and non intrusive monitoring, and provides explicit feedback in the form of high-level information rather than raw data to support civil engineers during the process of planning long-time restorations. The proposed framework is composed of a peripheral sensory system, with wireless sensor nodes cooperating with each other, a middleware for managing data acquisition, and a remote presentation infrastructure, for data and information visualization, and for feedback acquisition.

The remainder of the paper is organized as follows. Section II presents the considerations that motivated our work. The architecture of the whole system is described in Section III, and Section IV reports the design choices for the hardware, and some considerations about network optimization, and data gathering strategies. In Section V the actual deployment is described in detail, and finally Section VI reports our conclusion and gives some directions on the on-going work.

II. Project Scope and Goals

While several variants of traditional sensory system have already been widely discussed and employed in the context of SHM, the present paper describes an approach exploiting the innovative technology of wireless sensor networks in order to provide pervasive monitoring without imposing intolerable constraints, such as requiring wiring the sensing devices, or other heavy modifications to the site before deploying the sensory hardware. Although employing invasive hardware may be acceptable in specific scenarios, as in the case of structural monitoring of large civil infrastructures, e.g. bridges or motorways, sometimes the site under observation is also characterized by having specific constraints; for instance, historical buildings must typically take architectural requirements into account.

The goal of the project described here was to monitor the restoration works carried out on a historical building as a consequence of the damages suffered after a light earthquake. In particular, it was required both to analyze the response of the structure to vibrations on the fly, in order to promptly signal potential alarms, and to collect the corresponding measurements for further, more refined analysis. Indeed, mere monitoring is not the only action that structural engineers need to perform on a construction; on the contrary, they are usually required to predict the behavior of the structure in reaction to unforeseen stress, and in order to do this, pre-constructed or general purpose models usually cannot be applied.

Current solutions for an automated structural health monitoring of relevant buildings typically rely on wired sensors that often cause intolerable costs, pose limits on the extension of the area to be monitored, and to the spatial density for the sensor themselves, thus dimishing the quality and reliability of the outcome of the monitoring. Wireless sensor nodes appear to be a good alternative for this issue, in that they might provide punctual monitoring, reduced deployment costs, and more accurate sensing thanks to their processing capability.

WSNs have already been extensively used for SHM research projects; for instance [4] describes a project aimed at monitoring ambient vibration at the Golden Gate Bridge in San Francisco, while other approaches explicitly study the issue of dynamic model extraction from sensed data, via Gibbs sampler [5], model partitioning [6], or other iterative and decentralized process ([7], [8]).

The present project aims to exploit those aspects and to focus on embedding the user's knowledge into the entire process. The outcome of our project has been a prototypal system for supporting an expert user in conducting structural and dynamic stress analyses on a historical building by extracting higher-level information from raw sensed data regarding vibrations and accelerations in strategical points. Users may thus monitor the state of previous interventions, reason about the stability and integrity of the structure, identify potential risks, and plan reinforcement activities accordingly; in addition, they are able to interact with the system in order to tune the behavior of the monitoring network to some extent. Besides the specific scenario considered here, such a system may find application in several areas, as for instance in a museal scenario, or other historical building monitoring projects.

III. The System Architecture

Systems for SHM must typically include a sensory and data acquisition subsystem, some mechanism for data gathering and storage, and finally a data analysis subsystem, where the structural model is computed and update, and general structural conditions may be assessed at a higher level of abstraction.

Figure 1 shows a functional description of our system architecture through its composing blocks; in particular, two separate, and functionally different, sets of sensor nodes may be identified, as well as a collecting device where part of the low-level data processing is conducted, a temporary storage device, and a remote database, where also heavier data processing is performed.

According to the projects requirements, two main phenomena needed to be monitored, each imposing different functional requirements as reflected by the architectural schema. The set of sensor nodes labeled as **`HF-WSN`** will deal with high-frequency measurements, so nodes belonging to this set will need careful programming in order to optimize resource usage, especially in terms of energy consumption. On the other hand, the **`LF-WSN`** nodes will have less stringent requirements regarding sampling rates, so that simpler data collection algorithms might be employed there.

The former set of nodes have been equipped with accelerometers in order to monitor vibrations in critical points of the structure. As discussed later, such sensors are very energy-hungry and their continuous usage would soon deplete the node's battery; an independent energy source has thus been provided for them, but this does not relieve the node of the task of data transmission: if any of these nodes is to be used as an alarm trigger, quasi-continuos sensing must occur, and accurate data compression algorithms must be devised in oder to reduce the overall amount of transmitted data. Nodes belonging to the **`LF-WSN`** set have instead been equipped with strain gauges, among other sensors, and their sampling rate will be sensibly lower as compared to the former one.

Data collected by both kind of nodes will flow into the base station where further data compression and coarse-

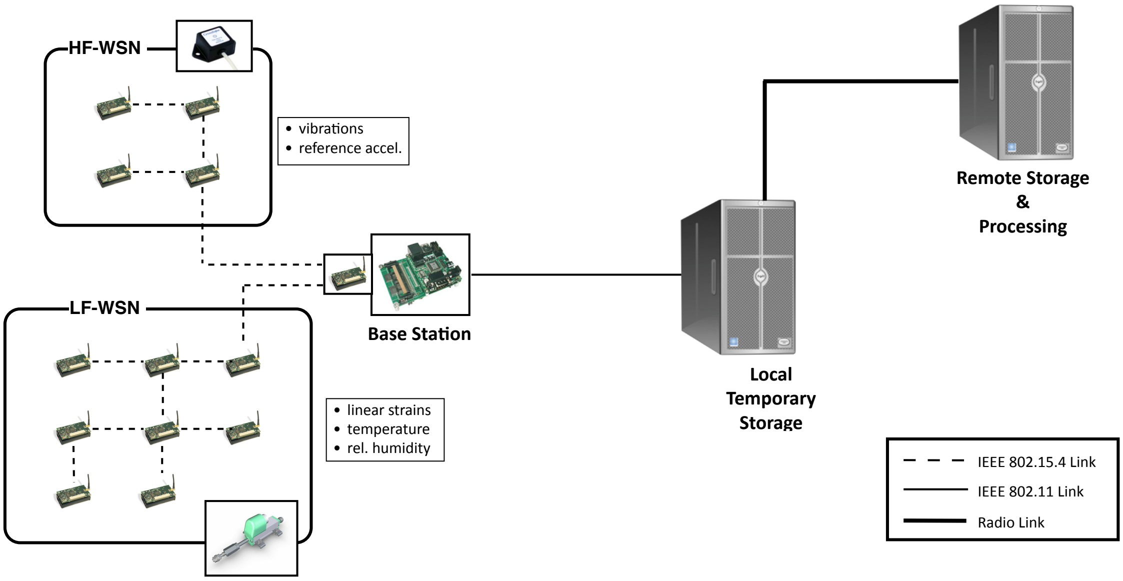

Fig. 1. A schematic description of the architecture of the proposed system.

grained analysis will be performed, before forwarding the partially-processed data toward a local storage device; this acts as a buffer before data is further transmitted to the final collector device. Communications will always happen through wireless links, albeit of different nature, in order to comply with the non-intrusivity requirement; in order to make information readily available to the remote user, connection to the Internet has been provided so that data may be transferred to the final remote storage device; this is depicted as a radio link in the picture, which was the choice in the particular scenario considered here. In general, in environments where a more stable connection may be guaranteed, this link may be substituted by a direct connection (e.g. an Ethernet link), thus making the local temporary storage redundant.

The final storage area is also where more refined processing is performed on the collected data in order to extract complex models for structural behavior in response to stress. The original data, together with higher-level information generated by such models, is made available to the end user through web-based GUIs that do not just provide a view on the DB of collected data, but also allow users to obtain more elaborated information, and to modify the system's behavior.

Among the functionalities provided by the system are the possibility of accessing several kinds of information, such as:

- information on the deployment settings (map of the monitored are, nodes locations, available sensors, etc.);
- information on the sensing parameters (sampling rate, thresholds);
- history of past monitoring activities;
- view of current monitoring (measurements ordered by sensor type, etc.);
- view of current and past events.

We also devised different tasks available to different classes of users; the most relevant ones are:

- **data analysis**: users may select different algorithms to apply to a selection of the collected data, chosen from a library of commonly available tools; results will also be stored in the system;
- **alarm setting**: users may select specific thresholds in order to signal potentially risky situations; an alarm will generate an event that will be handled as specified;
- **wsn tuning**: sampling rate, forwarding rate, and all others tunable parameters for low-level network behavior may be set by an expert user;
- **event management**: creation and deletion of events, defined as a combination of alarms (e.g. an accelerometer measurement beyond the predefined threshold will be seen as "high dynamic stress";
- **event handling**: the action to be taken in response to an event (visual alarm, email or sms sending).

IV. Design Choices

Sensor nodes employed in the project have been carefully programmed in order to comply with the diverse requirements relative to the different functionalities. Commercially available boards have been used in order to speed up the design process; however, they had to be customized for the presence of application-specific sensors.

At the earlier stage of the project, during the requirements elicitation phase, structural engineers had pointed out that one of the main areas to be monitored presented some damages that had been fixed in a previous intervention. In particular, one of the walls in the attic area presented a few cracks that needed to be monitored in order to detect potential deformations along the horizontal and vertical axes. Moreover some environmental quantities in the same area had to be monitored, namely temperature, and relative humidity, as those might influence the sensors readings. All the relative sensors require a low sampling rate, and generally do not pose a heavy communication burden on sensor nodes.

Furthermore, the topmost part of the front of the building had suffered heavy damages from an earthquake few years earlier; all safety hazards had been cleared thanks to past restoration works, but the experts needed to monitor the stability of some specific parts of the building, especially in response to sporadic events, such as vibrations caused by heavy street traffic. The project thus required that high-stability accelerometers be installed on the specified locations; moreover an accelerometer was installed in a separate area, supposedly not affected by unpredictable dynamic stress, in order to act as reference value. Since no thorough study had been conducted on the area under observation after restoration works had occurred, no dynamic model was available for the damaged front part of the building. Structural engineers thus required that the accelerometers acquired data at the highest possible rate in order to infer the pattern induced by vibrations on the structure; moreover, with no predicting model available in the earlier phases of monitoring, abnormal conditions can only be signaled by comparing measured values with preset thresholds, thus requiring a very high sensing rate in order to promptly trigger alarms.

Sensor nodes used for this project are characterized by a limited amount of storage, non-renewable energy source and the capability of communicating through a low-band, low-range wireless link. According to these considerations, nodes equipped with accelerometers must be programmed in order to implement data compression algorithms to increase the quantity of information carried by a reduced amount of transmitted data. This is a well-known problem, but unfortunately most of the traditional approaches are not appropriate for the WSN scenario, where memory and computational resources are very constrained. On the other hand, we have tested some more specialized techniques presented in literature. [9] contains an interesting survey on some of the more specific techniques that have been designed for WSNs; for instance, the *coding by ordering* data compression scheme, introduced in [10], relies on a hierarchical routing structure and reduces transmission on the hypothesis that the order in which the remaining data is sent may be used to convey the information contained in the "missing pieces". In [11], another interesting compression scheme is described that exploits the high correlation typically present between consecutive samples and, according to the principles of entropy compression, computes a compressed version of each value acquired on-the-fly.

Moreover, accurate but cheap synchronization among nodes must be provided. As already explained, in our case we adopted a simple scheme, where one of these nodes acts as a reference; its sensor will be triggered once an anomaly is detected by one of the other accelerometer nodes, and measurements collected by both kind of nodes will be correlated by a remote data analysis module.

On the other hand, nodes belonging to the **`LF-WSN`** set are characterized by lower sampling and transmission rates.

Data collected by both kind of nodes will be at first collected at a local base station, implemented on a higher-performance node that will further compress data before transmitting it to the local storage area; this node will also provide synchronization to the **`HF-WSN`** nodes. From the user's point of view, the base station node will be the one to receive user's commands and to dispatch them to the sensor nodes; as already mentioned such commands may be used for instance to start and stop sensing, to tune the network parameters, or to diffuse remotely computed data models to interested nodes in order to modify their behavior according to the user's expertise.

V. Experimental Scenario

The project described here regarded the use of wireless sensor networks on a cultural heritage building with a great historical and artistic interest, namely the church of St. Teresa in the Kalsa district in Palermo, Italy, a baroque building dating back to early 1700. In particular, the goal was to monitor a specific area of the building where consolidation works were being carried out in order to ensure safety for the whole structure. A view of the building, and details of the monitored areas are shown in Figure 2.

The topmost part of the front of the church was damaged as a consequence of the earthquake in 2002, and previous interventions regarded the pose of reinforcements in order to let the facade retain its static functionality, while keeping the external aspect intact. Such works have been judged as excessively invasive for the inner part of the building and are being substituted by less intrusive ones. The goal of the present project has been to monitor the overall state of the building, and the state of current restoration works; in particular, structural engineers needed support in planning more accurate countermeasures against exceptional events, such as strong meteorological or seismic activity, or dangerous vibrations provoked by street traffic. Measurements acquired via wireless sensors are to be processed in order to detect potential variations in the actual frequency response, to be interpreted as damage signals when compared to the frequency response obtained through abtsract mathematical models customized to describe the specific area under monitoring.

The experimental scenario described here regards a proof-of-concept prototype of the entire system. One sensor board equipped with an accelerometer was positioned on the base of the iron cross on the top of the building; this was one of the most heavily damaged areas and, also because of the peculiar conformation, needs specific and constant monitoring. A second accelerometer was positioned on a stable area inside the attic of the building, in line with the first one, in order to provide a comparison measurement. In the same area, also a few strain gauges were deployed in correspondance with two cracks in the walls. Each crack was monitored by two gauges, positioned along the horizontal and vertical axes. Figure 3 shows a schematic representation of the actual deployment.

Fig. 2. The deployment site for the project.

Table I shows the sensor nodes chosen for the present project. MicaZ nodes belongs to the *mote* family and are well suited for low-cost, resource-constrained applications; they may be equipped with off-the-shelf sensors, or, as in the present case, may be adapted to interact with ad-hoc sensors. The Intel's *Stargate* platform, on the other hand, is typically used for higher-performace tasks or for mote coordination.

The characteristics of the sensors used in the project are reported in Table II; it is worth noting that accelerometers are very energy-hungry sensors so, in order to preserve the sensor node's energy source for data processing and transmission, the accelerator on top of the roof was equipped with an independent energy source, represented by a rechargeable battery connected to solar panel. All the equipment was positioned on the back of the stone base in order to be hidden from view, for architectonic reasons.

The sensing accelerometer is constantly on; the corresponding node will at first just compress sensed data and forward them to the base station at a very high sampling rate (128 samples per second, on each axis); measurements are compared with preset thresholds and, in case an alarm is noticed, the second accelerometer is triggered so that comparison measurements may be collected as well. The Stargate node acting as base station will take care of sending the proper commands, and will also supervise time synchronization between nodes. Collected data is again preocessed and compressed at the base station, and forwarded to the local storage, and then to the remote processing unit via a radio link.

In the long term, users will be able to analyze data and to infer an accurate model for structural behavior in response to dynamic stress. The remote unit allows them to inject such models into the system, and to communicate them to the remote sensor nodes that will use them to tune their behavior; namely, only data not adhering to the model will be transmitted, thus saving energy, and more accurate alarms

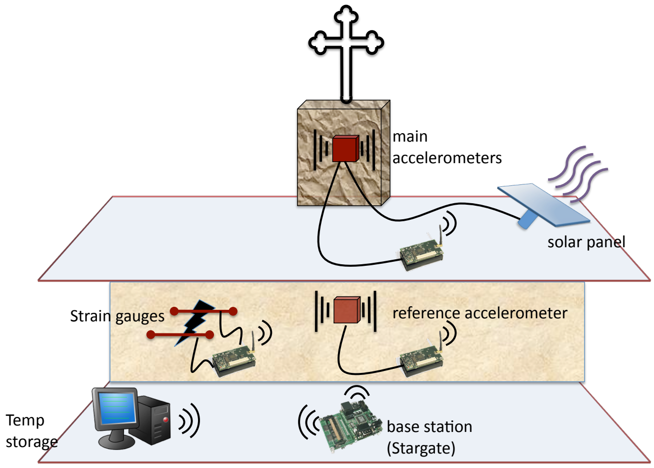

Fig. 3. A schema showing the deployment of sensor nodes in the building.

will be triggered.

As regards nodes equipped with strain gauges, their programming is more traditional, in that they implement a typical application of environmental monitoring. The sampling rate was set to one measurement every 15 minutes, where each measurements includes 10 readings, processed via a median filter. They also carry sensors for measuring temperature and relative humidity in the same environment.

All nodes are fully parameterized, and users my interfere with their behavior via the provided commands, as mentioned earlier.

VI. Conclusion and on-going work

This paper described the experience learned thanks to a project aimed at providing a structural health monitoring framework, specifically targeted to historical building preservation. The system expoits the peculiar charcteristics of Wireless Sensor Networks that are not just used as a pervasive sensory system, but also as a distributed computational entity. This allows users to interact with the system, not just to view the collected data, but also to modify its behavior in order to tune it to the specific, and dynamically changing, requirements.

The paper described a scenario where the system is employed in an actual project that required monitoring abaroque church after restoration works had been carried out to restore it after a minor earthquake; currently, experiments are being carried on in order to test the basic behavior of the deployed WSN, and to collect a sufficient amount of data to be used to extract more refined models for the dynamic response of the structure.

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TABLE I

CHARACTERISTICS OF THE DIFFERENT TYPES OF SENSOR BOARDS EMPLOYED IN THE PROJECT.

Sensor type	CPU			Memory	Radio		
	Description	Energy per computation	Sleep power		Description	Energy per bit	Idle power
MicaZ 	ATMega128 8 bit	4 nJ/instr 31 mJ/beamform	30 μW	128KB RAM 512KB Flash	CC2420 250Kbps IEEE 802.15.4/Zigbee	430 nJ/b	7 mA
Stargate 	Intel PXA255 32 bit	1.1 nJ/instr 1 mJ/beamform	20 mW	64MB SDRAM 32MB Flash	Orinoco Gold 11Mbps 802.11b	90 nJ/b	160 mA

TABLE II

THE SENSORS USED IN THE PROTOTYPAL SYSTEM AND THEIR MAIN CHARACTERISTICS.

Measure	Sensor	Characteristics
Temp. and rel. humidity	Sensirion SHT11	Temperature range: -40 °F to +254.9 °F Temp. accuracy: $\pm$0.5 °C Humidity range: 0-100% RH Abs. RH accuracy: $\pm$3.5% RH Low power cons. (typ 30 μW)
Linear strain	GEFRAN PY2	Precision: 10 μm Ind. linearity: up to $\pm$0.1% Linear range: 10-100 mm
3-axis acceleration	Crossbow CXL01LF3	Span: $\pm$1g Sensitivity: 2 V/g BW [Fc(Hz)=-3dB]: DC-50 Noise (mg rms): 0.5

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