

COVER SHEET

Title: *Wireless sensor networks for seismic evaluation of concrete buildings*

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ABSTRACT

Rapid advances in computation, sensing and data transmission techniques, such as RFID technology, Micro-Electro-Mechanical Systems (MEMS) and low power wireless networking, offer hope of a new generation of small and inexpensive networked sensors. These can be distributed in buildings and structures to provide accurate quantitative information on the physical state of the structure while in service. The EU-funded MEMSCON project aims to develop MEMS-based sensors for structural monitoring and to integrate these sensors with a Decision Support System that will use the information from the sensors to evaluate reinforced concrete buildings. This both before and after earthquakes, to aid decisions on improvement and repair. Although today the appraisal of seismic damage is almost exclusively based on visual inspection, measuring quantitatively the response of buildings during and after an earthquake, in terms of acceleration and strain, is an easy task. However structure owners are somehow reluctant to install permanent sensing systems, due both to their high costs and to the difficulty of interpreting the data. To overcome these limitations, the MEMCON project aims to produce a small size sensing node, integrating MEMS-based sensors and an RFID tag in a single package. Such nodes can then be attached to reinforced concrete buildings for life-cycle measurements of acceleration and strain, with data transmitted to a remote base station using a wireless interface. These nodes will allow economically sustainable industrial deployment of structural monitoring systems. This paper presents the development of the first prototypes of strain and acceleration sensors, and their validation in the laboratory.

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INTRODUCTION

Structures that are subject to the effects of material aging (crack propagation and reinforcement corrosion), design error, overloading, unforeseen foundation settlement or seismic events, can progressively accumulate damage during their operative life. Periodical structure assessment is therefore a key step in rationally planning the maintenance needed to guarantee an adequate level of safety and serviceability.

Nonetheless the economic convenience of installing permanent sensing systems is not easy to demonstrate [1]: the only way to provide economic sustainability is to make use of robust sensors, industrially produced, which can be easily installed during building construction and can furnish highly relevant information to reliability assessment. Modern buildings tend to be overcrowded with electric wiring for power and signals, and the structural monitoring network should not interfere with these: nodes must be small and links wireless. Radio Frequency Identification (RFID) and Micro-Electro-Mechanical-System (MEMS) technologies offer a set of promising tools to develop a cost-effective wireless system able to fulfill these requirements. The capability of MEMS and wireless networking for monitoring civil structures is well documented [2,3,4].

The MEMSCON Project (www.memskon.com), co-funded by the European Community in the 7th Framework Programme, started in October 2008 and will last 3 years, involving partners from 7 countries. With this background, the project is devoted to development of a reliable and cost-efficient monitoring system to be integrated in new Reinforced Concrete (RC) buildings for their protection against seismic events and settlement. The system includes a wireless network within the building and a base station linking the building to a remote center for data interpretation. As outlined in Figure 1, the network includes sensing nodes measuring strain and acceleration. Strain measurements are collected at the lowest level of the building, to estimate the vertical column loads and any variation due to settlement; horizontal acceleration is measured by dedicated nodes at each level during an earthquake, allowing analysis of the seismic response of the whole structure.

The project has two main tasks: (i) development of the sensing network and (ii) development of software for remote data processing, structure condition assessment and for maintenance planning. The products will be validated both in the laboratory and in on-site applications. Task (i) includes creation of new dedicated instruments for strain and acceleration measurement. Both these devices will be based on RFID in MEMS [5], in small-size packages and with ultra-low power consumption. These nodes have been designed to improve their sensing performance with respect to that of existing technology [6].

Production of the definitive nodes is scheduled for end-2010; prototypes have been assembled from components available on the market, with the necessary design, packaging and programming. These devices do not now fulfill the target requirements of the project, but they let us investigate the relevant features of the system. The prototypes were tested in the laboratory and this paper reports on the current stage of the project.

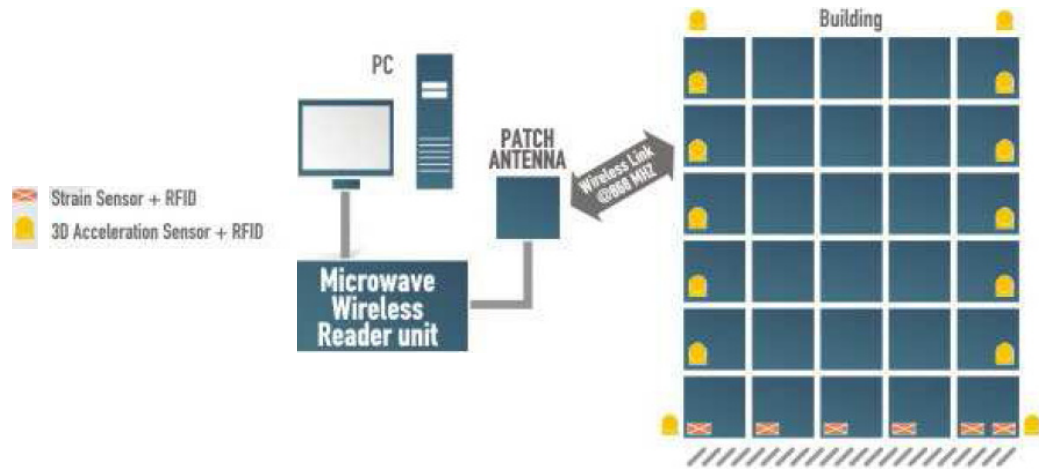


Figure 1: Scheme of the monitoring system proposed in the MEMSCON project.

STRAIN SENSOR WIRELESS NETWORK

Development of the hardware

At this phase of the MEMSCON project, the strain sensors employed are foil gauges available off-the-shelf, produced by HBM GmbH, to be attached to a reinforcement bar. Since the gauge is the only component permanently buried in the concrete, the external electronic interrogation node is connected via a 2-wire cable with an appropriate connector. This battery operated device was designed to partially fulfill the basic MEMSCON specifications: Ultra Low Power Consumption (no battery replacement ideally for the 10-year product life), accurate measurement of strain (20 $\mu\epsilon$ resolution), transmission of measurements via a wireless network to the base station.

With these specifications in mind, the hardware developed for the node includes an analog input management subsystem, with a strain gauge bridge, a programmable amplifier with digital offset and gain adjustments and a low pass filter. The data transmission makes use of a Zigbee Wireless Rx/Tx module, and the node also has a microprocessor for global device control, conversion of analog strain measurements to digital format and a clock that operates continuously for current date and time with 1 sec resolution [7].

Special firmware was developed that allows the device to wake from sleep-mode at specified time intervals, connect to the RF network, take strain measurements and transmit them to the interrogator; then returning to sleep-mode. The time interval is expected to be 2-4 months, to keep battery power consumption at very low levels. In sleep-mode, the device consumes only 54 μ W, while when active the demand is 100mW. The electronic system, battery and input connector are all in a plastic box size 11x8x4cm, with an antenna, as shown in Figure 2.

The base station assigns addresses to the sensing nodes, continuously waits and gives network access to any sensor that asks to transmit data. The acquired data then passes to the host PC using a 4-element patch antenna array offering a reliable link at up to 1 km distance for line-of-sight transmission.

Laboratory validation

The validating campaign for the strain-gauge nodes aims at reproducing in the laboratory the operative conditions of an RC element inside a building, up to an extreme scenario. During settlement and, more often, during an earthquake, the columns of a building can undergo extensive damage including concrete cracks, cover spalling, crushing and reinforcement yield. As we use the wireless network to estimate the damage level during or after these events, we must investigate the network performance and efficiency under the same conditions.

The gauges were attached to ordinary reinforcing bars (steel B450C, 20mm diameter), with a standard cyanoacrylate adhesive and a silicone protective coating. The installation procedure follows the instructions by HBM, and so the time required to fasten a gauge is about 30 minutes. In the first laboratory campaign completed so far, gauge performance was investigated in small specimens, tested in tensile and compressive load cycles. The bars and the complete specimens were also instrumented with additional strain gauges wired to a high-precision interrogation unit, to compare in real-time the data flow deriving from the wireless network with reference values. To investigate various aspects of network performance, three types of specimen were produced: (i) instrumented bare reinforcing bars, tensile tested; and reinforcing bars embedded in a concrete cylinder for testing (ii) in tension and (iii) in compression.

Figure 2 shows the outcome of a test on a type (i) specimen: the strains recorded by the wireless (red line) and by the wired (blue line) system are plotted *vs* time. The agreement between the two signals is very good, and can be quantified in $20\mu\epsilon$, of the same order as the resolution of the wireless system. Note that, independently of the acquisition mode (wired or wireless), the gauges become inactive at a strain of about $2200\mu\epsilon$, which is a predictable value for the fatigue life of a glued sensor.

The network was validated with two nodes working simultaneously and the base station connected to an ordinary PC via USB. When the nodes are activated and the corresponding software launched on the PC, the strain data, with timestamp and sensor identification tag, are stored in a database, for post-processing. Over the entire campaign, the network had no problem in data acquisition or transmission.

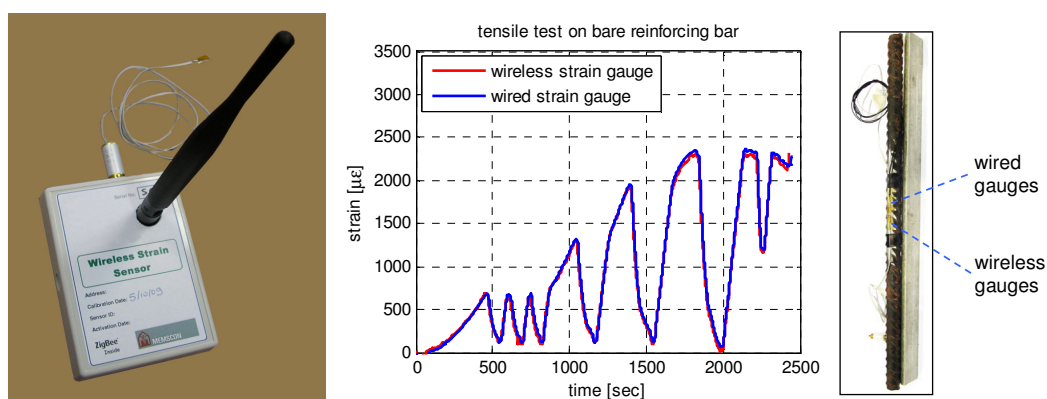


Figure 2: Strain Sensor Node (left). Test outcome on a bare bar (right)

THE ACCELEROMETER WIRELESS NETWORK

Development of the hardware

Each accelerometer node measures, records and transmits over the RF network, 3-axis acceleration data, using a MEMS-based sensor commercially available from Analog Devices Inc. [8]. This is a completely digital output device that communicates with the system through an SPI interface having a serial EPROM memory and a micro vibration sensor. The firmware developed allows device wake-up upon activation of the micro vibration sensor, fast setup of the node (accelerometer and Zigbee transceiver) from the microprocessor, and data recording in the EPROM. The power consumption of the unit is similar to the strain sensor unit. Special algorithms were developed to minimize unit activation by false alarms (vibration caused by events other than earthquakes).

Laboratory validation

To test the performance of the network, three wireless nodes were mounted on a shaking table, back to back with high precision wired piezoelectric seismic accelerometers. The nodes underwent several vibration tests, with excitation of various shape, frequency and amplitude. The aim of the campaign was to investigate the accuracy and reliability of the wireless sensing system under conditions similar to those experienced in the field during a seismic event.

Two types of tests were performed: in the “calibration tests”, the nodes were mounted in parallel on the table, and each axis was tested with harmonic excitation at frequencies in the range 1-20Hz. Then, to better simulate operative conditions, the wireless sensors were mounted on a two-storey metal frame, again back to back with the wired instruments, as shown in Figure 3. The same figure shows the comparison between the vibration recorded by the wired and the wireless systems, on each floor, during a sweep. Agreement is very good, of the same order as the resolution of the wireless system, which is equal to 18mg ($=0.18\text{m/s}^2$).

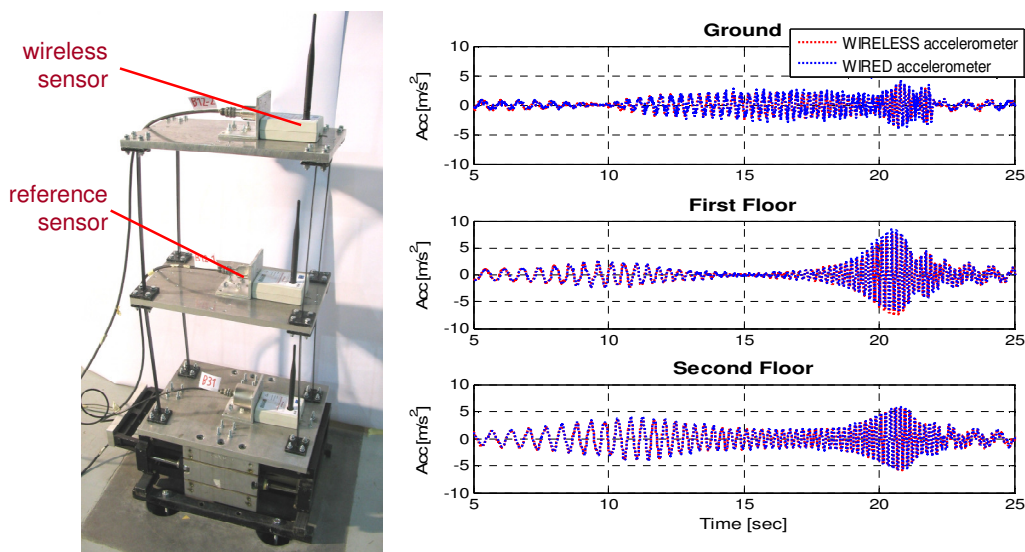


Figure 3: instrumented metal frame on the shaking table (left). Example of a test outcome (right)

CONCLUSIONS AND FUTURE STEPS

Both the strain gauge and the accelerometer networks proved to be reliable in the operative conditions to be expected in an in-field application. The performance in strain measurement allowed us to follow the onset of yield in the reinforcing steel, which is usually a limitation for sensors applied to civil structures. This is suitable for assessment of settlement. In the next few months, additional tests will be done on full-scale column specimens, to investigate the behavior of a larger wireless network in a more complex environment and in a seismic scenario.

The accelerometer network proved to be reliable in the frequency range relevant to seismic analysis, with sufficient accuracy, and several tri-axial nodes can be employed simultaneously. Data acquisition is triggered automatically when a vibration threshold is exceeded, and this allows long-term monitoring, recording all the relevant seismic events.

The final products of the MEMSCON project, expected by the end of 2010, will try to improve on this performance. In particular, the next steps in development of the sensing nodes will reduce the packaging size, improve the measurement range and reduce power consumption. Further development of the accelerometer nodes will be related to resolution improvement, to real-time synchronization of the nodes to allow acquisition of a reliable time-stamp years after installation, and adoption of a more sophisticated algorithm to reduce the number of false alarms.

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