Low Power Wireless Sensor Network for Structural Health Monitoring of Buildings using MEMS Strain Sensors and Accelerometers

T. Torfs[1], T. Sterken[1], S. Brebels[1], J. Santana[2], R. van den Hoven[2],
N. Saillen[3], N. Bertsch[4], D. Trapani[5], D. Zonta[5]

[1] IMEC, Kapeldreef 75, 3001 Leuven, Belgium
[2] IMEC / Holst Centre, High Tech Campus 31 5656 AE Eindhoven, The Netherlands
[3] ThermoFisher Scientific, Colosseum 20, 7521PT Enschede, The Netherlands
[4] MEMSCAP, ZI Bernin, 38 926 Crolles, France
[5] University of Trento, Via Mesiano 77, 38123 Trento, Italy

---

Abstract

Within the MEMSCON project, a wireless sensor network was developed for structural health monitoring of buildings to assess earthquake damage. The sensor modules use custom-developed capacitive MEMS strain and 3D acceleration sensors and a low power readout application-specific integrated circuit (ASIC). A low power network architecture was implemented on top of an 802.15.4 media access control (MAC) layer in the 900MHz band. A custom patch antenna was designed in this frequency for optimal integration into the sensor modules. The strain sensor modules measure periodically or on-demand from the base station and obtain a battery lifetime of 12 years. The accelerometer modules record during an earthquake event, which is detected using a combination of the local acceleration data and remote triggering from the base station, based on the acceleration data from multiple sensors across the building. They obtain a battery lifetime of 2 years. The MEMS strain sensor and its readout ASIC were packaged in a custom package suitable for mounting onto a reinforcing bar inside the concrete and without constraining the moving parts of the MEMS strain sensor. The wireless modules, including battery and antenna, were packaged in a robust housing compatible with mounting in a building and accessible for maintenance such as battery replacement.

Keywords: structural health monitoring, wireless sensor network, MEMS sensors

---

1. Motivation

The goal of the MEMSCON project is to create a structural health monitoring system to monitor buildings for damage that can accumulate during their operational lifetime, due to seismic events , unforeseen foundation settlement, material aging, design error, etc, in order to allow rationally planning the maintenance needed to guarantee an adequate level of safety and serviceability.

However, in order for the installation of a permanently installed sensing system in buildings to be economically viable[1], the following conditions must be fulfilled:

- The sensor modules must be wireless to reduce installation costs by eliminating the need for installation of large amounts of cabling.
- The sensors must require low amount of maintenance, which implies that they must operate for a long time without battery replacement, and therefore have low power consumption.
- The sensors must be low cost, which can be accomplished by sensors that can be mass produced such as MEMS sensors.

The capability of MEMS and wireless networking for monitoring civil structures is well documented [2][3][4].

The sensor system realized in the MEMSCON project as described in this paper addresses all of the above requirements.

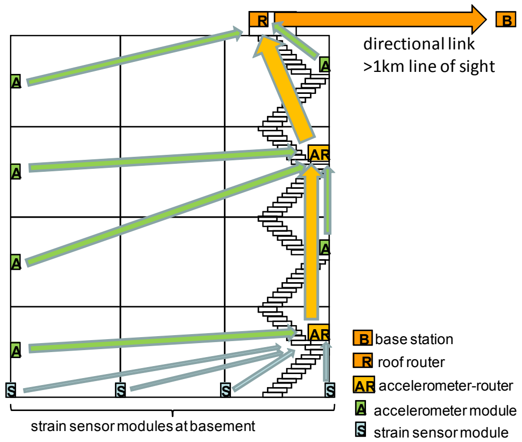


Fig 1. Network architecture

2. Architecture of the monitoring system

2.1 Network architecture

The network architecture is shown in Fig. 1. The monitoring system consists of two types of sensor modules: strain sensing modules and acceleration sensing modules. The strain sensor modules are mounted at the baseof the building, to estimate the vertical column loads and to measure the settlement and plastic hinge activation of the building after an earthquake. The accelerometers are mounted at every floor of the building to measure the seismic response of the building during an earthquake by measuring horizontal acceleration at each level during an earthquake. This allows the analysis of the seismic response of the whole structure. A typical 7-story, 24-column building requires approx. 72 strain sensors (3 per column) and 14 accelerometer modules (2 per floor).

The data obtained by the sensor system is wirelessly transmitted to a nearby base station using a line of sight link with a range of >1km. The line of sight link uses directional antennas to improve the link budget. The directionality is kept limited to avoid the need for alignment, which could pose a problem during seismic events. The receiver base station can store and process the data or forward them, immediately or later, using classical wide area network connection technology. In this way, provided all modules as well as the receiver base station have battery back-up power, the data acquired during seismic events can be properly recorded even in case of outages of the electric power and/or communication networks.

In order to form a robust wireless link from all modules, including the strain sensor modules at the basement of the building, towards the receiver base station, a multi-hop network architecture is used as shown in Fig. 1. On the roof of the building a dedicated router module (without sensor) is placed to forward the data between the sensor network and the receiver base station. Some accelerometer modules on intermediate floors can be configured as additional intermediate routers when required to obtain a robust link from all sensor modules in the building towards the roof router module. As shown on Fig. 1, it is recommended to place the router modules in or close to the stairwell for improved vertical floor-to-floor propagation through the building.

For lowest power consumption in the sensor modules, the network is implemented using a custom protocol that implements indirect data transfer using polling on top of a standard 802.15.4 MAC. In this way, the end nodes' radio is powered down most of the time. Only the routers and base station have their receivers constantly on. To avoid rapid battery depletion, the modules with router functionality are mains-powered through an AC/DC adapter, with the battery serving only for back-up power in case mains power is interrupted. The end nodes are powered exclusively by their battery.

2.2 Measurement scenarios

2.2.1 Accelerometer measurement scenarios

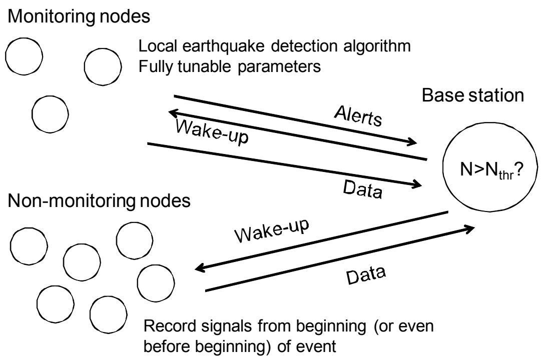


Fig. 2: Network earthquake wakeup procedure

The main trigger for the recording of an acceleration measurement is the detection of the start of an earthquake. The detection and wake-up procedure is shown in Fig. 2. When the output of the built-in accelerometer in a selected number of monitoring nodes exceeds a certain minimum threshold, during a certain minimum time, these monitoring nodes provide alerts to the base station. The base station software will decide based on the number of monitoring nodes providing alerts whether to wake up the entire network of acceleration sensing nodes over the radio The monitoring nodes are selected based on their location and amount of environmental noise. Ground-level nodes may be suitable candidates, provided they are sufficiently far removed from disturbance sources such as heavy traffic. The selection of monitoring nodes can be done dynamically from the base station. This allows for example to disable the monitoring function on nodes that report unusually high numbers of false alarms. To that purpose, the hardware and software of the monitoring nodes are identical to that of the non-monitoring nodes. The monitoring function is an optional function which can be enabled or disabled during operation by the base station. After the nodes have been woken up the recorded data is read out by the base station which sequentially requests the data of each sensor module.

To support this scenario the wake-up of (most of) the acceleration sensing nodes to initiate measurement has to be done over the radio link. This also implies that it is possible to wake up the nodes via the base station over the radio link at any chosen time independent of the presence of an earthquake, which is a desired functionality for testability and monitoring of the system. It also means that all modules in the network will be woken up during a detected event, even if the accelerations locally at some modules have not (yet) reached a value exceeding the trigger threshold.

It is required to be able to record the early onset of an earthquake event, even before and certainly no later than 1 ms after it reaches a pre-set trigger threshold. In order to do this, the accelerometer is constantly running at 3 x 200Hz sample rate with the measurements recorded in a 54-second loop buffer., This requires an ultra low power sensor and readout. The power consumption of the 3D accelerometer and 3-channel readout operating continuously is 125 µA at 3V.

The node must be woken up within 54 seconds after the start of the recording of interest to avoid the loop buffer overflowing which would lead to data loss. To respond timely to an event triggered from the base station, the radio polling interval of the accelerometer modules is set to 15 seconds. Once the event trigger is reached the loop buffer contents are preserved and once the buffer is full recording will continue in a secondary 54-second buffer until the next event trigger.

2.2.2 Strain sensor measurement scenarios

The main measurement scenario for the strain sensor is a periodic readout. Samples are taken at a configurable sample rate between 2 seconds and 18 hours. The strain sensor modules use a radio polling interval of 60 seconds. This also allows manual wake-up functionality from the base station, again useful for monitoring and testability reasons. Unlike for the accelerometers, in the case of the strain sensors the sensor and read-out ASIC can be entirely shut down between measurements. This results in a lower power consumption and longer battery life. Since a typical building requires many more strain sensors than accelerometer modules, it is useful for the strain sensors to have the longest battery service life.

3. Architecture of the sensor modules

3.1 MEMS sensors

The accelerometer consists of 2 transverse comb finger structures for the X and Y axis and a pendulating one for the Z axis and was fabricated with a surface micro-machined process from a 85µm thick SOI wafer. It has 78 fingers with a total sensitivity of 2.02pF/g. The Z sensor has an area of 2.17mm2 per plate. Innovative cap through connections were used. The main tradeoff in the design of the accelerometer is the sensitivity-bandwidth-linearity in all three axes, a challenge for the design given the different used structures. The XY and Z accelerometers are packaged together with the readout ASIC into a system-in-a-package and then mounted onto the printed circuit board as can be seen on Fig. 3.

The MEMS strain sensor is a longitudinal comb finger capacitor. The strain sensor fabrication procedure starts with a SOI wafer with a 500µm thick handle, 50µm thick fingers and 2µm thick oxide layer with 400 fingers in the sensor and it has a sensitivity of 0.133fF/µe. Two anchors were etched-out of the surface to create the necessary clamps to attach the sensor to the rebar of a pillar. The fingers are protected with a borosilicate class cap.

The use of custom-developed MEMS sensors and read-out ASIC allows to meet the specific requirements of the building monitoring application and differentiates the presented system from the earlier prototype system presented in [6], [7] and [8].

3.2 Embedded strain-sensing module

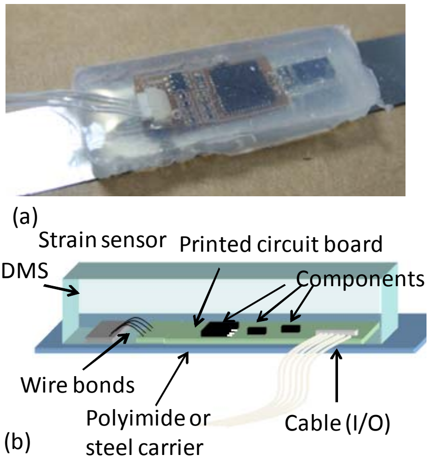


Fig. 3: Embedded strain sensor front-end module

The MEMS strain sensor is packaged together with the readout ASIC into a special front-end strain sensing module (Fig. 3) which is to be embedded inside the reinforced concrete onto the reinforcing bar, preferably prior to the pouring of the concrete. The sensor is mounted on a polyimide or steel carrier which in turn is glued (or in case of steel, could also be welded) onto the reinforcing bar. The module is molded in PDMS silicone to protect the components from the environment during installation and pouring of concrete, while remaining a mechanically compliant package to avoid distorting the strain sensor measurement.This front-end strain sensing module is connected to the rest of the module with a small 4-wire cable with a maximum length of 1.5m.

3.3 Wireless & accelerometer module

The block diagram of the sensor modules is shown in Fig. 4. Both the accelerometer and strain sensing variants of the module use the same core components. For installation into the building these components are placed into a standard off-the-shelf plastic casing that can be conveniently mounted on the floor, wall or

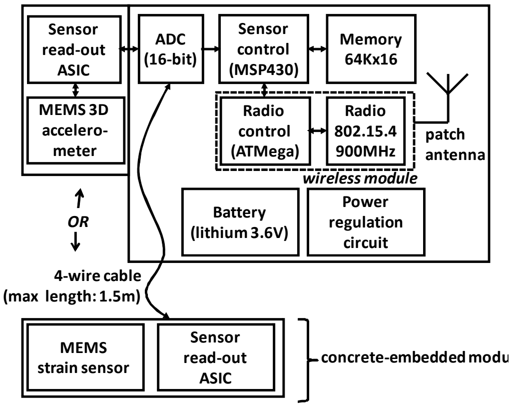


Fig. 4: Sensor module block diagram

Fig. 5: Wireless sensor module inside opened housing

ceiling using screws, and offering access for sporadic battery replacement if needed. The core components are:

1) A custom-developed low power capacitive sensor read-out ASIC [5]. This ASIC can be matched to either MEMS-based comb finger capacitive accelerometers or strain sensors in a half-bridge configuration. Its gain can be set by a number of integration pulses N, optimizing signal-to-noise ratio and bandwidth with power. In addition, the architecture suppresses residual motion artifacts. In combination with the MEMS strain sensor, it can measure a range of ± 20,000µε with a resolution of 10µε and non-linearity <0.6%. In combination with the MEMS accelerometer it can measure an acceleration range of ±2.5g with a resolution of 80dB (13-bit) for vibrations between 10-100Hz and a non-linearity <1%.

2) A low power 16-bit successive-approximation analog-to-digital converter (Analog Devices AD7683).

3) A low power microcontroller (TI MSP430) to control the sensor data acquisition and temporarily store the data in a 64Kx16bit SRAM memory (Cypress CY62126) .

4) A low power wireless IEEE 802.15.4-compatible module (Atmel ATZB-900) operating in the 900MHz band. This frequency band was chosen in preference to the more common 2.4GHz band because it offers a larger propagation range for the wireless communication. The wireless module includes a radio chip (Atmel AT86RF212) and a baseband microcontroller (Atmel AVR) which needs to be active only during wireless communication events.

5) A custom patch antenna was designed for the modules. The patch antenna is tuned for 868MHz operation with an efficiency of 51% using standard FR4 material as the substrate. Its size is 5 x 5 x 1.3 cm3. Its shape and radiation pattern is optimized for wall-, floor- and ceiling-mounting in the building.

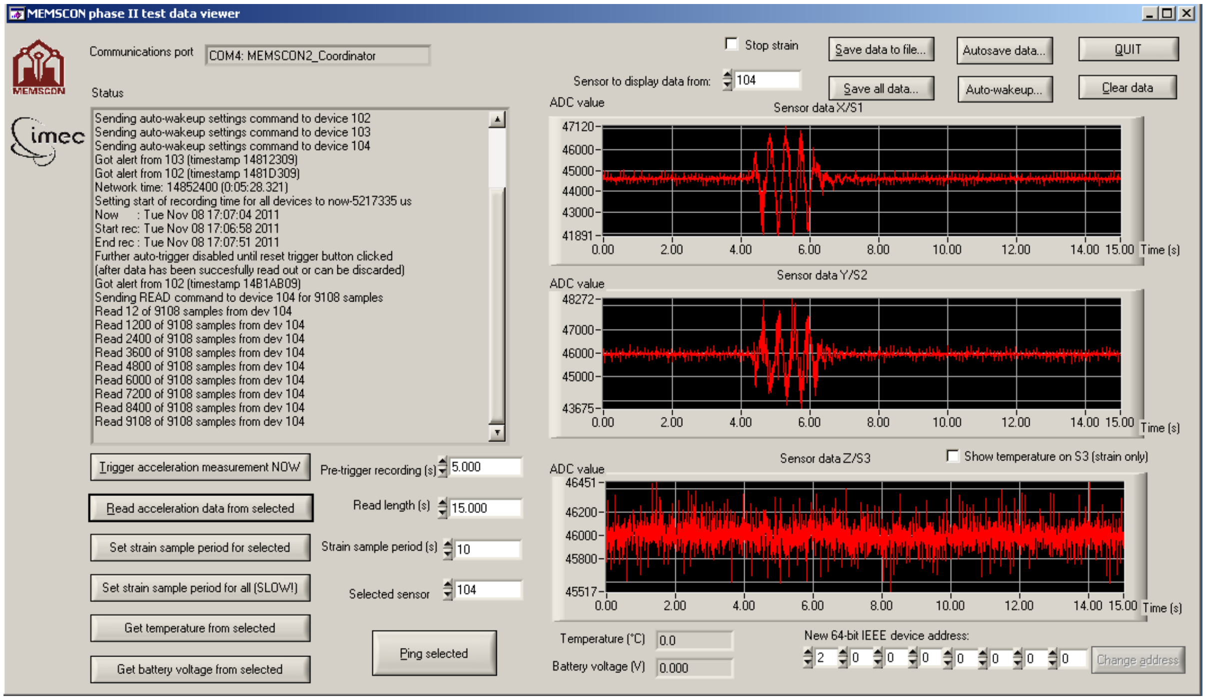
6) The modules are powered by a an 8.5Ah C-cell long operating life primary Lithium Thionyl Chloride battery (Tadiran SL-2770), suitable for 10 to 25 years of operation.

A picture of a realized wireless sensor module inside its opened housing is shown in Fig. 5.

4. User interface

A user interface was developed that runs on the base station and allows to control the network and read out the sensor data. A screenshot is shown in Fig. 6, which includes an example of wirelessly read out accelerometer signals, where the recording event is triggered by a manually applied stimulus on the X and Y axes.

Fig.7 shows the user interface window that allows configuring the earthquake detection wake-up parameters. This consists of local detection parameters, whereby each node can be optionally



Communications port: COM4: MEMSCON2_Coordinator

```
Sending auto-wakeup settings command to device 102
Sending auto-wakeup settings command to device 103
Sending auto-wakeup settings command to device 104
Got alert from 103 (timestamp 14812309)
Got alert from 102 (timestamp 1481D309)
Network time: 14852400 (0:05:28.321)
Setting start of recording time for all devices to now-5217335 us
Now      : Tue Nov 08 17:07:04 2011
Start rec: Tue Nov 08 17:06:58 2011
End rec : Tue Nov 08 17:07:51 2011
Further auto-trigger disabled until reset trigger button clicked
(after data has been succesfully read out or can be discarded)
Got alert from 102 (timestamp 14B1AB09)
Sending READ command to device 104 for 9108 samples
Read 12 of 9108 samples from dev 104
Read 1200 of 9108 samples from dev 104
Read 2400 of 9108 samples from dev 104
Read 3600 of 9108 samples from dev 104
Read 4800 of 9108 samples from dev 104
Read 6000 of 9108 samples from dev 104
Read 7200 of 9108 samples from dev 104
Read 8400 of 9108 samples from dev 104
Read 9108 of 9108 samples from dev 104
```

☐ Stop strain

Sensor to display data from: 104

Pre-trigger recording (s): 5.000

Read length (s): 15.000

Strain sample period (s): 10

Selected sensor: 104

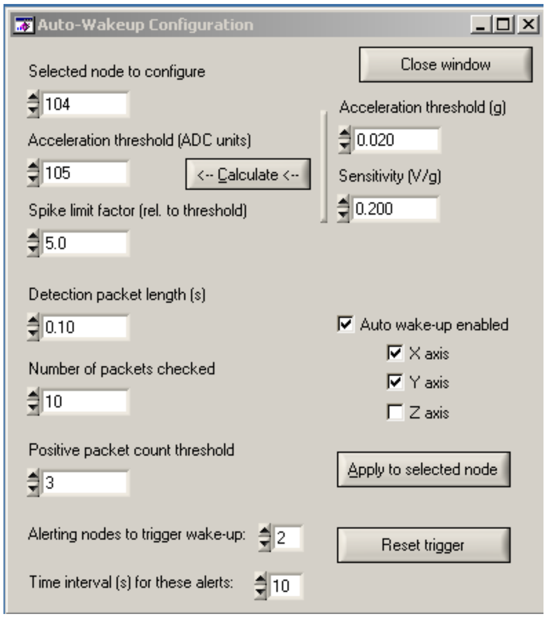
☐ Show temperature on S3 (strain only)

Temperature (°C): 0.0

Battery voltage (V): 0.000

New 64-bit IEEE device address: 2 0 0 0 0 0 0 0

Fig. 6: Screenshot of user interface



Selected node to configure: 104

Acceleration threshold (ADC units): 105

Spike limit factor (rel. to threshold): 5.0

Detection packet length (s): 0.10

Number of packets checked: 10

Positive packet count threshold: 3

Alerting nodes to trigger wake-up: 2

Time interval (s) for these alerts: 10

Acceleration threshold (g): 0.020

Sensitivity (V/g): 0.200

☑ Auto wake-up enabled
☑ X axis
☑ Y axis
☐ Z axis

Fig. 7: Earthquake detection wake-up configuration

configured as monitoring node by enabling its auto-wakeup functionality based on an event on one or more of the accelerometer axes. The amplitude and timing parameters for the detection are fully configurable for each node separately. There are also the global parameters that configure how many monitoring nodes must raise an alert and in which time interval in order to trigger a global wake-up across the network.

5. Results

5.1 Power consumption

The use of low power sensors and electronics combined with a custom low-power network protocol allows to achieve a low overall power consumption and therefore a long battery life.

Fig. 8 shows the breakdown of the power consumption in the sensor modules for strain sensor and accelerometer modules. The total average power consumption is 0.274mW for the strain sensor modules and 1.73mW for the accelerometer modules. With the abovementioned C-cell size battery this implies a battery life of 12 years for the strain sensor modules and 2 years for the accelerometer modules.

5.2 Laboratory validation of accelerometer modules

The wireless accelerometer modules were first validated in the lab on a scale model (see Fig. 10) of the building used to validate the accelerometer modules. For this first test, the final housing and custom patch antenna was not yet used. The result shows a very good correlation between the reference accelerometers and the new wireless modules. Afterwards the final wireless accelerometer modules were validated on a full-scale model of a building together with reference accelerometers during an experiment simulating earthquake conditions. Further details on this full-scale lab experiment are presented in [10].

5.3 Laboratory validation of strain sensor modules

The strain sensor modules were preliminarily validated in a calibration setup and show sensitivities between 10 and 20 µε/mV, varying from sensor to sensor. They were also included inside the full-scale model of the building described in [10], but did not produce stable data in this experiment. It is hypothesized that the strain sensors were damaged during concrete pouring or ultrasonic vibration while setting up the experiment. After this experiment, free sensors (no strain applied) have been monitored over time together with the temperature output of the strain sensor module. The results shown in Fig. 9 show that (after smoothing to reduce noise) the strain signal follows the same curve as the temperature, as expected. Also a temperature-compensated signal is shown on Fig. 9 where the residual strain signal change after compensation for temperature is stable with very small remaining variation (below 1mV), which indicates that the sensor modules produce a stable output signal in these conditions.

6. Conclusion

In the MEMSCON project a wireless system for building monitoring was succesfully developed which takes advantage of the unique features of custom-developed MEMS sensors and read-out ASIC combined with an optimized network and module architecture, to realize a solution which offers long

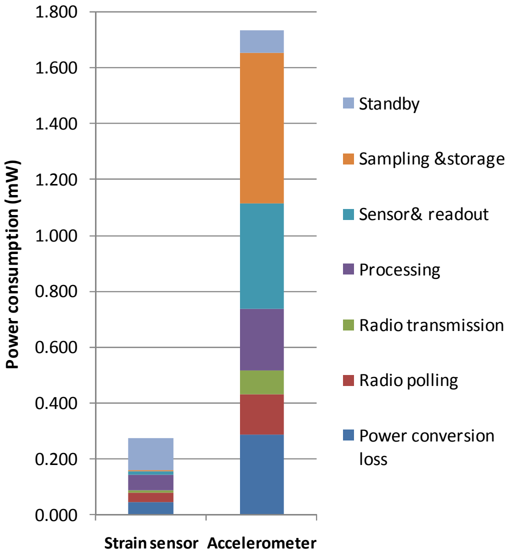


Fig. 8: Power consumption breakdown

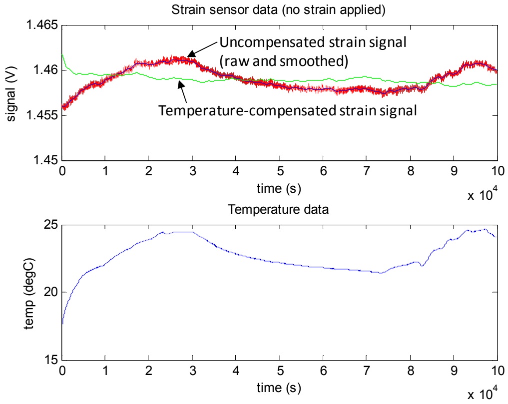


Fig. 9: Strain sensor and temperature output signal

battery lifetime and potentially low cost in manufacturing, installation and maintenance. The sensor modules' output signals have been successfully validated in a laboratory environment in a calibration setup and against reference sensors.

7. Acknowledgements

This work was performed in the MEMSCON project, funded by the European Commission (FP7, contract number 036887).

8. References

[1] Pozzi M., D. Zonta, W. Wang and G. Chen. 2010. "A framework for evaluating the impact of structural health monitoring on bridge management". Proc. 5th International Conf. on Bridge Maintenance, Safety and Management (IABMAS2010), Philadelphia, 11-15 Jul 2010.

[2] Lynch, J.P. and K.J. Loh. 2006. "A summary review of wireless sensors and sensor networks for structural health monitoring," The shock and vibration digest, 38(2):91-128.

[3] Zonta, D., M. Pozzi, and P. Zanon. 2008. "Managing the Historical Heritage Using Distributed Technologies," International Journal of Architectural Heritage, 2:200-225.

[4] Kruger, M., C.U. Grosse and P.J. Marron, 2005. "Wireless Structural Health Monitoring Using MEMS", Key Engineering Materials 293-294: 625-634.

[5] J. Santana,R. van den Hoven,C. van Liempd, M. Colin, N. Saillen, C. Van Hoof, "A 3-axis accelerometer and strain sensor system for building integrity monitoring", Proc. 16th International Conference on Solid-State Sensors, Actuators, Microsystems, Beijing, June 5-9, 2011.

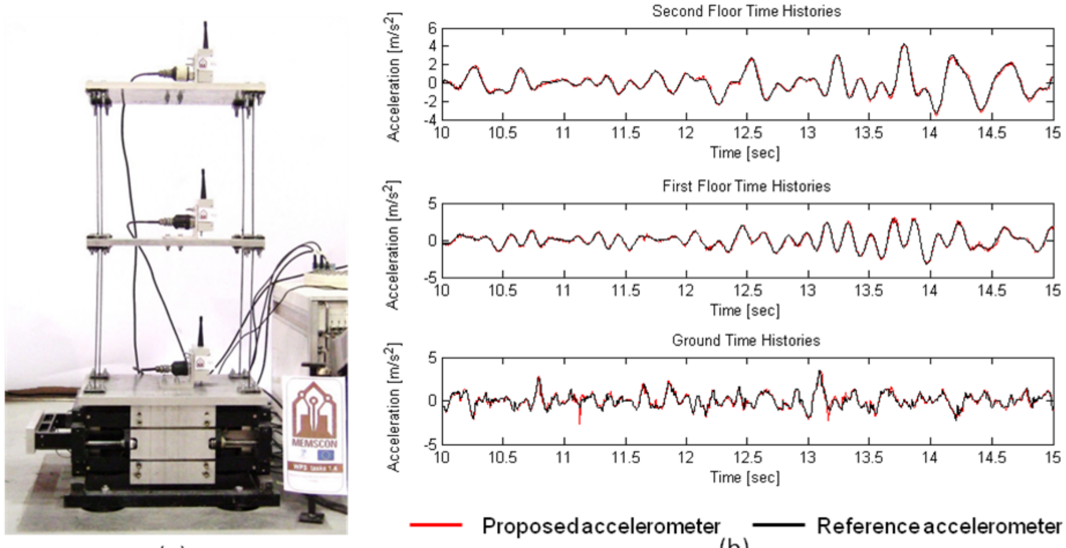
[6] A. Amditis, Y. Stratakos, D. Bairaktaris, M. Bimpas, S. Camarinopolos, S. Frondistou-Yannas, et al., "An overview of MEMSCON project: an intelligent wireless sensor network for after-earthquake evaluation of concrete buildings", Proc. "14th European Conference on Earthquake Engineering (14ECEE)", Ohrid, FYROM, 30 Aug - 03 Sep, 2010.

[7] A. Amditis, Y. Stratakos, D. Bairaktaris, M. Bimpas, S. Camarinopolos, S. Frondistou-Yannas, et al. "Wireless sensor network for seismic evaluation of concrete buildings", Proc. 5th European Workshop on Structural Health Monitoring (EWSHM 2010), Sorrento, Italy, 29 Jun - 02 Jul, 2010.

[8] A. Amditis, Y. Stratakos, D. Bairaktaris, M. Bimpas, S. Camarinopolos, S. Frondistou-Yannas, et al. "Wireless sensor network for seismic evaluation of concrete buildings", Proc. 5th European Workshop on Structural Health Monitoring (EWSHM 2010), Sorrento, Italy, 29 Jun - 02 Jul, 2010.

[9] Torfs, T.; Sterken, T.; Brebels, S.; Santana-Corte, J.; van den Hoven, R.; Van Hoof, C.; Saillen, N.; Bertsch, N.; Trapani, D.; Zonta, D.; Marmaras, P.; Bimpas, M. , "Low Power Wireless Sensor Network for Building Monitoring ", Proc. 10th IEEE Conference on Sensors (SENSORS 2011), Limerick, Ireland, 28-31 October, 2011

[10] D. Zonta et al., "Laboratory Evaluation of MEMS-Based Sensors for Post-Earthquake Assessment of Reinforced Concrete Buildings", Proc. MEMSCON Workshop 2012, Athens, Greece, March 29, 2012



(a) (b)

Fig. 10: Laboratory validation of accelerometer modules on a building scale model