



MEMSCON Newsletter

July 13, 2011

Issue 5

Radio Frequency Identification Tags Linked to on Board Micro-Electro-Mechanical Systems in a Wireless, Remote and Intelligent Monitoring and Assessment System for the Maintenance of CONstructed Facilities

MEMSCON Facts:

- Contract No: 036887
- Project total cost: 4.632.430 €
EC contribution: 3.814.816 €
- Project Start Date: 1/10/2008
Duration: 36 Months
- Coordinator:
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Editorial: New MEMSCON sensors

The most relative properties for structural analysis are movement (acceleration and displacement) and forces. The corresponding sensors that produce these measurements are accelerometers and strain sensors (stresses and forces can be deduced from strain measurements).

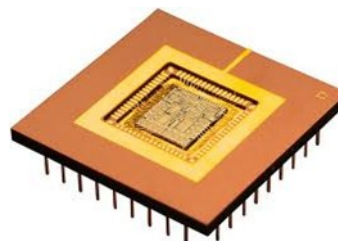
The sensor node of the MEMSCON system is based on the integration of MEMS-based sensors and an RFID tag in a single package of small size that is attached to reinforced concrete (r.c.) buildings. For structural health assessment, acceleration in 3 dimensions and strain in 1 dimension are transmitted to a remote base station using a wireless interface.

MEMSCON partners have chosen to use MEMS technology to realise the sensors.

Accelerometers and strain sensors are both based on Silicon On Insulator technology and on capacitive detection principle, thus enabling the use of a common ASIC for signal exploitation of both devices.

The strain sensor, which is fixed on the rebars of the r.c. building, consist of three distinct areas: an anchor area used to attach the device, the sensor area which provides with an electrical signal upon strain experience, and a flexible area which transmits the strain that the device is experiencing to the flexible area. The design of the strain sensor is performed in such way that the devices does not break and actually provides low signal in case of inappropriate alignment of the sensors along the main axis of the rebar.

The MEMS accelerometers are built using three mechanically independent proof masses to measure the acceleration in the 3 directions. Each basic element sensor element will form a differential capacitor. For the in plane accelerations (x and y direction) the sensor is using an interdigitated comb structure. Two of these structures rotated by 90 degree's are placed on the die. For the measurement of out of plane accelerations (z axis) a pendulum with asymmetric mass distribution is used, which is forming the movable part of a differential capacitor. The fixed part is realized by counter electrode on top of the mechanical element. Although the basic structure of the x,y sensor and the z-sensor is different, an appropriated design allows the achievement of similar sensor parameters which can then be exploited by the same ASIC.



Both the strain sensor and the accelerometers are then packaged together with their ASIC to provide protection against the environmental stresses and particles. They can then be easily fixed on the building and connected to the RFID tag which interacts with the network and decision support software of the system.



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MEMSCON Accelerometers

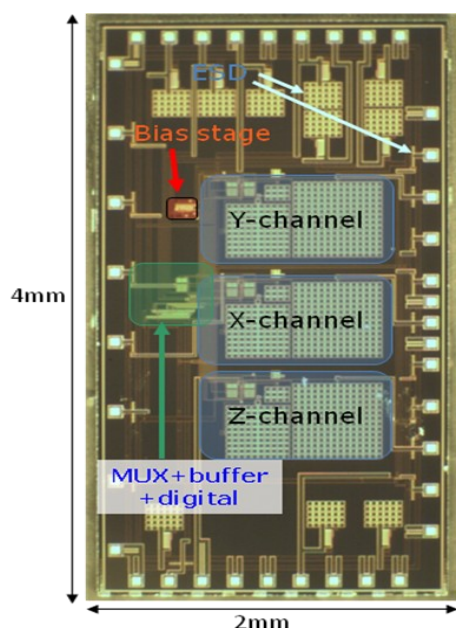


Fig.1. Fabricated ASIC readout

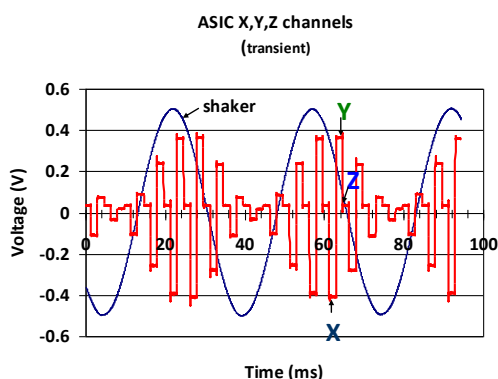


Fig.2. Accelerometer measurements

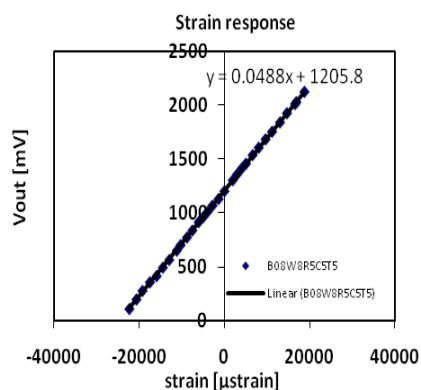


Fig. 3. Strain sensor measurements

Long life battery operated systems represent one of the most challenging areas of circuit design. When applied to monitoring applications, such as those for the construction and maintenance industry, ultra-low-power systems are a must. Versatility is also a characteristic of such systems. They must be able to monitor several parameters or signal at any one time in order to produce relevant information that is later processed and analysed. Critical decisions about the integrity of a building, bridge or a house can then be taken.

Right after the sensor, either an accelerometer or a strain sensor, is the readout electronics. This stage shapes and amplifies the signals from the sensors according to the desired levels of gain, Signal-to-Noise ratio, resolution, time constraints and power dissipation, among others. Low power ensures a long battery lifetime but, trade-offs have to be done in order to comply with the required specifications and the time the system can operate without changing the batteries. The readout stage is usually power-consuming; the system must be operational at all times in order to detect an earthquake, for example. Duty cycling is not always the best solution, therefore new topologies and clever electronics have to be designed in order to provide state-of-the-art functionality while keeping battery life as long as required.

Developed ASIC readout

IMEC-NL has developed a versatile low-power solution to be used as readout for accelerometers and strain sensors. Developed on standard CMOS 0.25µm technology the ASIC readout can process signals from MEMS-based comb-finger accelerometers and strain sensors (Fig. 1). Its uniqueness lies in the fact that the same ASIC can be used for both types of sensors, therefore making the system simple, cost-effective and versatile. Integration of the ASIC readout with either accelerometers or strain sensors, as described above, is optional for the end user. The 3-channel system

can be used for a 3-axis accelerometer system or 2-axis accelerometer in combination with 1-channel strain sensor or any combination of them. DC signals, as those from a strain sensor, are easily sensed and amplified. The dynamic input range of the ASIC readout has been tuned for optimum usage of both the accelerometers and strain sensors used in the project. The user can connect either of the two sensors to the readout and, a maximum output range of the two sensed signals, namely ± 2 g or $\pm 30,000$ micro-strains appear at the output (Figs. 2 and 3). No extra trimming or tuning is required.

Performance targets

The whole system including biasing stages, excitation of the MEMS sensors and a strong output buffer to drive several pF, draws only 120 micro amps (on a 3.0V supply), thus making it comparable to the most advanced commercial devices available in the market. Its multiplexed analogue output allows the end user to readout 3 signals at 200Hz each, in a sequence with a minimum of overhead. The linearity of the ASIC readout plus sensors gives a deviation of less than 1%. The resolution target of 1mg is according to expectations and more measurements are under way to find out the ultimate working conditions of the readout.

Digital control and interfaces

Two extra synchronization signals make the reading of the analogue signals easy for subsequent stages such as a micro-processor. Moreover, the analogue signals are already sampled and held, thus helping to reduce power consumption when used for example, in combination with an Analogue-to-Digital converter. The digital control of the ASIC was custom made so to minimize glitches that may cause noise into the device, therefore making the architecture optimum for the application.

MEMSCON Accelerometers

Innovation

Additional to the previous characteristics the architecture of the ASIC readout allows the user to set the required gain via timing control (optional), which in standard devices is not an option, external components or a device with a different sensitivity has to be used. This is a highly innovative characteristic of the developed ASIC readout. Its architecture also allows for minimization of MEMS-devices artefacts, such as residual motion. The system's sinc function response filters-out harmonics that usually increases distortion, such feature is not common in commercial devices. Therefore the fabricated device represents an optimum solution for monitoring systems intended for long-life periods with a state-of-the-art performance.

In the 90's, Deep Reactive Ion Etching (DRIE) revolutionized the world of inertial MEMS. This technique, initially developed by Bosch, allows to anisotropically etch structures with a very high aspect ratio (up to 70), and smooth side walls. Combined with Silicon On Insulator (SOI) wafers with thick device layer (from 15 to 100 microns), DRIE allows MEMS manufacturers to increase the size of the seismic mass compared to thin Silicon available so far (a few microns), and dramatically increases the nominal capacitance of the devices.

That new technology opens the path to capacitive sensors with reasonable capacitance values in the range of 10pF and enables the hybrid integration of these sensors with the ASIC. The advantage of hybrid integration over monolithic integration is the decoupling of the MEMS fabrication from the ASIC process. MEMS and IC processes can be chosen independently, and both parts of the sensor can be optimized. Development costs are lower, and the adaptation to different application areas is simpler.

Surface micro machined accelerometer for in plane accelerations are typically built as interdigitated differential capacitive accelerometer as shown in Fig. 4. A movable proof mass is building the movable plate of a differential capacitor. Fixed fingers are building the fixed plate of the capacitor. In case of an

in plane acceleration along the longitudinal axis of the structure the mass hence the movable capacitor plate is forced to move. The resulting change of the two capacitors is a measure for the deflection, which is proportional to the acceleration. The size of the mass and the supporting spring allows the adaptation of the acceleration to be measured.

Mechanical elements are more or less always sensitive to accelerations in all directions. For a 1D sensor, the design goal is to reduce this cross sensitivities to a minimum by making the mechanical element very rigid in all directions except the desired one. But it is also possible to use this effect to get a 3D accelerometer. The biggest disadvantage of this approach is the large cross sensitivity between the different axes.

For surface micromachining technologies, the use of two structures shown in Fig. 4 rotated by 90degree allows the realization of a 2D accelerometer. For the third axis for the out of plane accelerations, different designs are possible. One design consists in a pendulum that is supported via two torsion bars and which is building the movable plate of the capacitor, and the fixed counter electrodes are located underneath the pendulum on the substrate. The advantage of this approach is the fact, that the cross sensitivities can be very small as each element can be designed very stiff in all undesired directions.

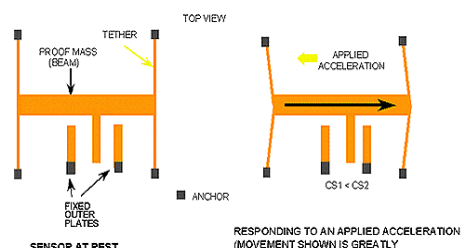


Fig. 4. Functional principle of an interdigitated capacitive accelerometer

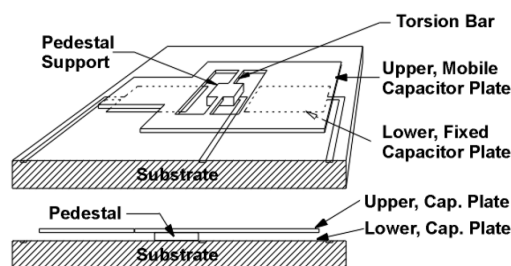


Fig. 5. Pendulum type z-axis accelerometer

MEMSCON Accelerometers

Description of the selected sensor concept

A capacitive sensing principle with mechanical elements realized in a surface micromachining technology has been selected for the MEMSCON accelerometer. The sensor is using independent mechanical elements for each axis. For the in plane sensing, interdigitated comb structures as shown in Fig. 4 and for the out of plane sensing a pendulum as shown in Fig. 5 have been realized. The fabrication technology for the three elements is identical; therefore the three elements can be placed on one die as shown in Fig. 6. We have also chosen a hybrid integration of the MEMS and its ASIC within a hermetically sealed ceramic package (see Fig. 7).

Wafer level packaging

Under normal environmental pressure conditions, the MEMS would run into an over-damped regime. In that case the functionality of the accelerometer could not be guaranteed especially regarding the linearity in the bandwidth. Therefore, some level of vacuum is needed within the micro-cavity. It appears from simulation that the pressure level must be controlled in the vicinity of the moveable elements and that it should be about 1Torr. This has been experimentally confirmed. The wafer level packaging (WLP) technique consists in bonding a cap wafer onto the MEMS wafer once the moveable structures are released. This technique offers several advantages compared to traditional packaging techniques. First, it allows the protection of the fragile MEMS structures from the early stages of the manufacturing process and eases the problematic step of the singulation of the MEMS dies. Furthermore, since the bonding step can easily be performed under controlled pressure, the vacuum inside the MEMS accelerometer is set at the desired value. And finally, WLP takes full advantage of the parallel manufacturing to drastically reduce the cost associated to the packaging. With traditional packaging techniques the cost of the packaging can be as high as 50% of the final sensor manufacturing cost and is down to 25%

with our WLP approach. In addition, WLP simplifies the implementation of the out-of-plane acceleration sensor since the counter electrode can be integrated into this cap layer. Therefore, the WLP technique is used for the realization of these accelerometers.

Fabrication process

As previously explained, the proposed concept uses three separate mechanical elements, one for each axis. For the in plane accelerations (x and y directions) the sensor is using interdigitated comb structures, which form a differential capacitor. The fixed plates of the differential capacitor are formed by fingers attached to the substrate, whereas the movable part is a mass with fingers attached. Two of these structures rotated by 90 degree's are placed on the die. For the measurement of out of plane accelerations (z axis) a pendulum with asymmetric mass distribution is used, which is forming the movable part of a differential capacitor (Fig. 6). The fixed part is realized by counter electrode on top of the mechanical element (Fig. 8). Although the basic structure of the x- and y-sensors and the z-sensor is different, an appropriated design allows the achievement of similar sensor parameters. A sensor SOI wafer is used for the MEMS sensors. The device layer is 85mm thick, the buried oxide 2mm and the handle silicon 635mm. The mechanical structures are defined by a combination of DRIE etching and sacrificial layer etching. The cap is formed by two silicon wafers bonded together. The top wafer of the cap stack is etched with KOH to allow the electrical contact to the cap bottom wafer thanks to Through Silicon Vias optimised for low electrical parasitics. For the bottom part of the cap, deep trenches are etched all around the different areas to ensure the electrical isolation. For the top part, the isolation is guaranteed by a thick surface oxidation (1-2µm) of the silicon wafer (green area in Fig. 8). The cap itself is mounted to the MEMS wafer by using a metal-silicon eutectic bonding process. The metal for the sealing ring is also used to realize the electrical connections between the cap and the MEMS wafer.

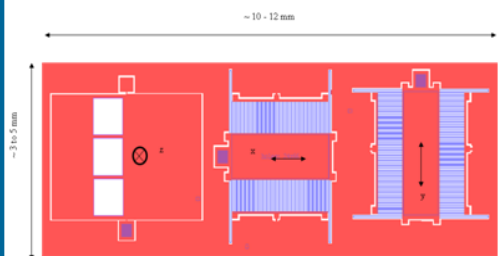


Fig. 6. Concept for the 3D accelerometer

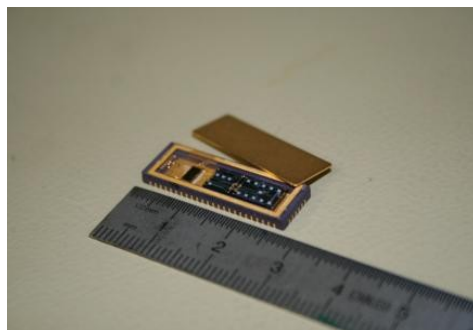


Fig. 7. First accelerometer prototype with MEMS and ASIC dies in a ceramic leadless carrier

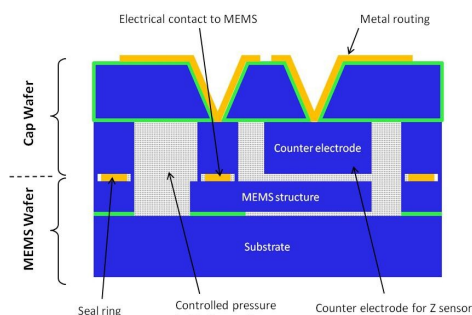


Fig. 8. Schematic sensor cross section

MEMSCON Strain Sensors

The MEMS Strain Sensor chip was designed using a capacitive sensing principle. Hence a strain in the rebars of the building under study has to be transfer to a change of capacitance in the sensing part of the sensor. In our case, this is done by a relative displacement of the fingers of a capacitive comb drive structure. The design of the sensor is based on the inputs of the end users, and is designed to measure strain over a $\pm 30'000\mu\epsilon$ range with a resolution of $10\mu\epsilon$. It has a size of $3600 \times 8400 \times 1050\mu\text{m}$.

The MEMS sensor is fabricated using a SOI (Silicon on Insulator) wafer as substrate. SOI wafer consist of a Device layer, a BOX layer and a Handle. Both the Handle and the Device layer are made out of doped Silicon (for the MEMSCON Strain Sensor) and the BOX layer out of Silicon Oxide (glass). The purpose of using such a type of wafer is that it simplifies the production of the moving capacitor (in the Device layer). With such wafers, the desired structure can be patterned in the device layer and released by selectively etching the oxide layer under it.

The layout of the structure is such that 2 differential capacitors are created and each of those capacitors consists of 4 comb drives in parallel. Each comb drives consist of 50 fingers. The dimension of the combdrive is shown hereafter.

The capacitance of a comb drive can be simply calculated from the parallel plate equation. Adapted for the geometry of a comb drive, this equation becomes:

$$C = nC \cdot 2 \cdot n \cdot \frac{\epsilon \cdot l \cdot t}{g} = 5.31 \text{ pF}$$

with ϵ being the permittivity of the medium ($\epsilon_0 \epsilon_r$)

Two anchors are located on the back side of the MEMS Sensor. They define the position where the strain will be transfer from the rebar to the sensor. The distance between the 2 anchor points define the relation between strain in the structure and displacement in the comb

drives. In our case, the distance between the anchors (center to center) is 3mm, which means that the strain of $30'000\mu\epsilon$ in the rebar produces a displacement of $90\mu\text{m}$ in the comb drives.

A challenge was in designing the large stiff spring that holds the moving parts together. An optimum needed to be found between having enough stiffness so that the offset due to packaging and assembly stays within the allowed limit ($20\mu\text{m}$), not to stiff to limit creep in the glue during operation and finally the stress at full elongation/compression shall not exceed the yields strength of the silicon.

The theoretical yield strength of monocrystalline silicon is around 7GPa, however, due to defect in the crystal the actual yield strength is closer to 3.5GPa. For the design of the spring, we want to stay in a region of 700MPa-1GPa (5-3.5 time lower that the actual yield strength) in order to have a sufficient security margin. The design was modeled with a 3D CAD drawing software (IronCAD) and simulations were performed with a Finite Element Model Analysis software (ALGOR) to check that the design doesn't exceed the maximum stress and have enough stiffness.

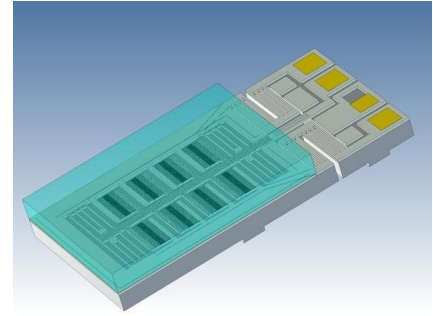


Fig. 9. General 3D representation of the MEMSCON MEMS Strain Sensor

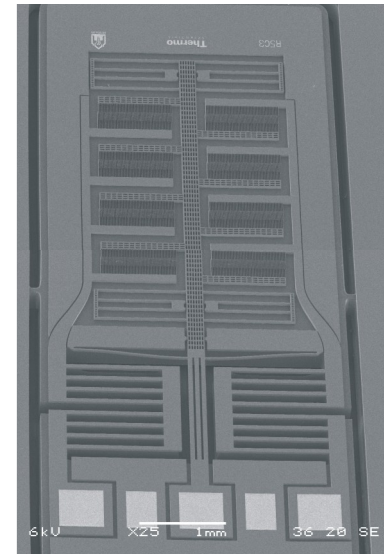


Fig. 10. SEM picture of the final chip (without the glass cap)

Parameter	Short name	Value	Unit
Number of comb drives	nC	4	n.a.
Number of fingers per comb drives	n	50	n.a.
Length of the comb drive	L	240	μm
Overlap between fingers	l	120	μm
Width of the fingers	w	5	μm
Height of the fingers	t	50	μm
Gaps between fingers	g	4	μm

System Integration

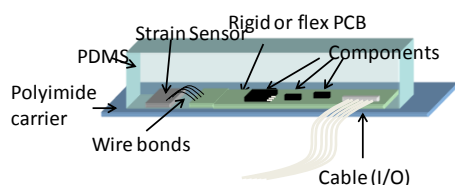


Fig. 11. Strain sensor package

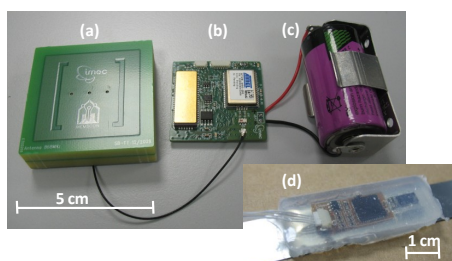


Fig. 12. Picture of the components of the wireless sensor module: (a) antenna, (b) electronics, (c) battery, (d) strain sensor front-end (here on metal rather than polyimide carrier).

The MEMS sensors are integrated into wireless sensor modules to form a monitoring system which communicates the measurement data to and is controlled by a remote base station. The accelerometers are integrated using standard printed circuit board technology and assembled into a rigid protective housing that allows fixation to the building. The strain sensor modules consist of two parts. The wireless communication and processing part is implemented in a similar rigid housing and remains accessible for potential battery replacement. The front-end sensing module combining the MEMS strain sensor, read-out ASIC and supporting oscillator circuitry and passives, is embedded inside the concrete structure, applied to the metal reinforcing bars. It uses a special package (Fig. 10) using PDMS silicone molding and a polyimide carrier in order to allow the sensor to be glued onto the metal bar similarly to a traditional strain gage while efficiently transferring the strain from the metal bar to the MEMS sensor.

For the wireless communication an IEEE 802.15.4 radio module in the 900MHz band is used in combination with a custom-designed patch antenna, in order to obtain robust links in real-world conditions inside a building. The wireless sensor modules are powered by an 8.5Ah C-cell long operating life primary lithium battery (Fig. 11). The modules (Fig. 12) also include a low power processor and a 64Kx16 bit RAM memory to record earthquake events or strain data.

A low power network architecture was implemented on top of an 802.15.4 MAC using indirect data transfers which allows

the sensor modules' radios to remain powered down most of the time except during brief polling moments and during periodic or even-triggered transmission of recorded data. The strain sensor modules measure periodically and use a radio polling interval of 60 seconds. The 3D accelerometer is constantly running at 3 x 200Hz sample rate with the measurements recorded in a 54-second loop buffer. This is required to be able to record the early onset of an earthquake event, even before it reaches a trigger threshold, and requires an ultra low power sensor and readout as we have developed in the MEMSCON project. It also enables the triggering to be done remotely by the base station based on the combined information from several monitoring nodes across the network. In that way data can be obtained from all accelerometers in the network during an earthquake or other global event, even if locally at some sensor nodes the chosen earthquake threshold was not exceeded. It also allows the wake-up monitoring function to be enabled only on a select amount of sensor modules which do not give many false alarms, e.g. due to street traffic or other local interfering signals. To respond timely without data loss to an event triggered from the base station, the radio polling interval of the accelerometer modules is limited to 15 seconds.

The strain sensor modules show an average power consumption of 0.274mW, which results in a operational time of 12 years before the batteries need to be replaced. The accelerometer modules consume 1.73mW, resulting in 2 years of battery life.

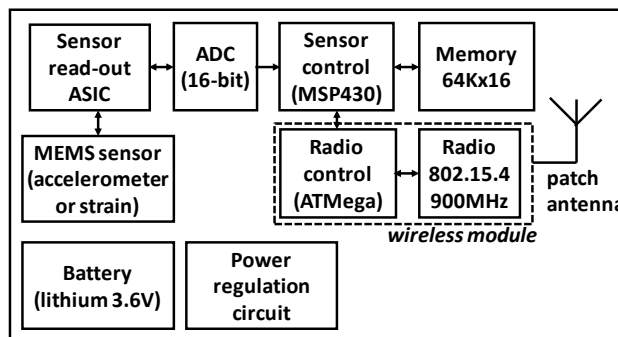


Fig. 13. Block diagram of the wireless sensor module

Laboratory Validation

To test the new accelerometers performance, three wireless nodes were mounted on a shaking table, back to back with wired reference accelerometers model 393B12 (1000 mV/g sensitivity, 0.5g measurement range). The nodes underwent several vibration tests, with excitation of various shape, frequency and amplitude, on the shaking table driven by a function generator connected to an amplifier. The aim of the test 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. In calibration tests, with the nodes mounted in parallel on the shaker, each axis was tested with harmonic excitation at frequencies in the range of relevance for seismic monitoring (1-20Hz). Calibration coefficients were calculated directly comparing reference and wireless measurements, minimizing the RMS value of the difference between each acceleration time history. To simulate operative conditions during an earthquake, the wireless sensors were mounted on a two-story metal frame, again back to back with the wired instruments, as shown in Figure 13. Tests revealed that the sensitivity of the devices differs among the 3 axes, and particularly between axes X and Y on the

one hand, with MEMS finger comb technology, and the Z-axis (with asymmetric pendulum technology) on the other. Resolution is anyway between 1 and 4 mg, therefore better than system requirements. Developed technologies, in particular the Pendulum one, appear to be the more reliable, with accuracy up to 10 mg. Phase II.1 sensors fulfil therefore the project requirements in terms of both resolution and sampling frequency.

The validation carried out on strain sensors included tensile and compressive tests, performed on steel bare bars and reinforced concrete cylinders adopting various load protocols, all consisting of load-unload cycles with increasing intensity, up to the failure of either the specimen or the sensor. The sensors performances were assessed directly comparing the devices with commercially available reference strain gauges (HBM LY41-3/700). Tests verified that most part of the sensors survive the installation procedure and the concrete hardening. In terms of performances, we assessed very high resolution (1 mm/m) measurements of strain up to 2%, with a precision higher than the one required by the project specification (10 mm/m).

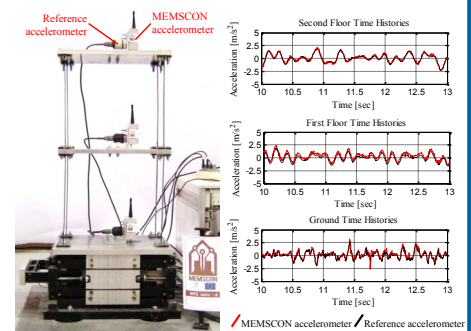


Fig. 13. Overview of test setup for MEMSCON Phase II.1 accelerometers during seismic simulation test and typical response compared with that of reference sensors.

Are you interested? Join us to the Final Event of MEMSCON

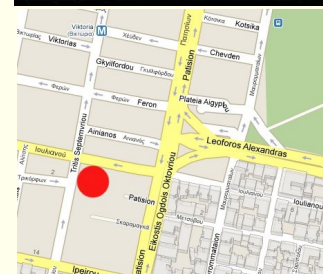
The goal of this workshop in Athens titled 'Towards Intelligent Civil Infrastructure' is to provide a state-of-the-art report on recent research activities, technological utilisation and commercialisation activities in structural monitoring systems and software for the status-dependent maintenance and repair of constructed facilities. This event will bring together the Structural Health Monitoring community, European construction companies, owners of constructed facilities, insurance companies, policy makers and sector experts.

When: Thursday, March 29, 2012

Venue: Athenian Capitol Mall, Ioulou and Triti Septemvriou Corner, Athens, Greece

The workshop will be held at the Conference Center of the Athenian Capitol Mall of the Charagionis Foundation in the city of Athens, Greece. The Athenian Capitol Mall also contains a 3D cinema, some 30 shops, and 10 restaurants and cafes and Greece's first Motor Museum. This museum, part of the Foundation, hosts 110 antique and top-of-the-line vehicles, with the oldest on display being a 1895 Hungarian-made fire engine and the newest a 1980 Ferrari 308 GTS.

For more information: www.memscon.com





Radio Frequency Identification Tags Linked to on Board Micro-Electro Mechanical Systems in a Wireless, Remote and Intelligent Monitoring and Assessment System for the Maintenance of CONstructed Facilities

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	Concept to Volume BV (C2V)		Acropole Charagionis S.A. (ACH)
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