MEMSCON Newsletter

March 27, 2012

Issue 6

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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Inside this issue:

Editorial: Welcome to the 6th Memscon Newsletter!

This is the final issue of the Memscon newsletter after a series of 6-month newsletters over the past three years. In this newsletter we present the consolidated project results, with the concluding results from the Trento laboratory of the Memscon Monitoring and Decision Support System. More details of the final Memscon workshop are in the following pages. Last but not least, Memscon exploitation strategy is briefly presented by our project exploitation manager.

Towards the end of the project, we have organized the final EC review and Memscon workshop. This workshop (*'Towards Intelligent Civil Infrastructure'*) will be on 29th March 2012 in Greece. The workshop will be at the Athenian Capitol Mall Conference Centre of the Charagionis Foundation in Athens. The workshop will describe the state-of-the-art as to research, technology and commercialization activity in structural monitoring systems and software for status-dependent structural maintenance and repair.

More details of the workshop are on the Memscon website: www.memscon.com . It will be our pleasure and honour to see you there and share your experience in Structural Health Monitoring applications as well as new technologies and methods!

We expect the very significant research performed in this project will have a big impact on structural monitoring. Our research will continue, on the basis set by Memscon, and will extend applications, scopes and results.

With kind regards

The Coordinator of Memscon project

Angelos Amditis

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Theme 4 - NMP-Nanosciences, Nanotechnologies, Materials and new Production Technologies

SEVENTH FRAMEWORK PROGRAMME

Laboratory results

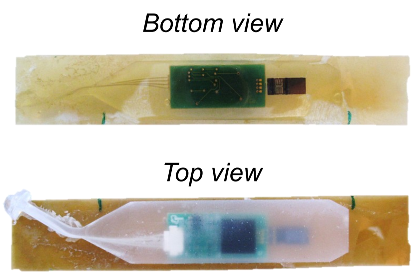

Fig.1. Memscon strain sensor: bottom and top views.

Fig.2. Memscon accelerometer

In our previous Memscon Newsletters we presented the laboratory validation of Phase 1 and Phase II.1 sensor prototypes, done with various types of test on small scale specimens. In this Newsletter we present the conclusive experimental laboratory campaign on a full scale three-dimensional concrete frame of size 3.15x3.15x3.90 m, built in the laboratory and instrumented with Memscon accelerometers and strain sensors. The aim was to validate the whole Memscon system, from sensors to Decision Support System, which provides the owner with data on his structure after a severe earthquake or in normal service. For this, strain measurements at the interface between columns and foundations were recorded during frame construction. The response of the Memscon device was compared with a reference system based on commercial metal foil strain gauges. The concrete frame was also subjected to a simulated and increasingly intense earthquake. This allowed comparison of the Memscon sensor performance with that of piezoelectric wired reference devices, fitted back-to-back; and also validated the damage recognition module, part of the Decision Support System.

The test campaign reproduced under laboratory conditions the behaviour of a prototype building in a seismic zone. The concrete frame, designed to European rules, was built in the laboratory. It has four 350x700 mm orthogonal post-tensioned beams as foundations, four 300x300 mm columns 2.80m height, two 300x500 mm longitudinal beams and two 300x400 mm transversal beams at the top and a 120 mm concrete slab. All the elements were designed to form plastic hinges at the interface between foundation and column and to keep in the elastic range all the elements except the columns at the bottom.

The columns were instrumented using Memscon strain sensors and commercial metal foil strain gauges as reference. All the sensors were bonded to the column rebars using cyanoacrylate glue. Three sensors were installed on each bar, two as reference and one Memscon. One reference sensor was placed on the opposite side to the Memscon sensor, while the other was on the same side and 50 mm above. Both the Memscon system and the reference system were turned on the day after the slab casting, to monitor the column strain due to gravity loads, temperature effects and concrete shrinkage and creep. System operation was controlled continuously during the entire monitoring period.

The dynamic tests reproduced in the laboratory the response to an earthquake of increasing amplitude of a prototype concrete building. The loading system consisted of a vertical actuator to simulate gravity load,

Fig. 3. Memscon 3-dimensional frame during laboratory validation.

Laboratory results

held constant during the tests; and a horizontal actuator that induced at the top of the frame the expected response of the building. We chose to reproduce in the laboratory the response of a two-storey concrete building to a spectrum compatible earthquake (Chenoua earthquake, 1989). The response of the building, characterized by a 1.5 Hz first frequency of vibration and a 5% damping ratio, was estimated using the typical expressions for structure dynamics. The actuators were driven in real time and inducing displacement in the frame slab. This response was scaled in the different tests, in order to reproduce various damage scenarios of the prototype building, including cracking (1.5 mm horizontal displacement), steel reinforcement yield (17 mm horizontal displacement) and different levels of ductility demand (up to 100 mm horizontal displacement).

During dynamic tests, the acceleration at the top of the concrete frame was recorded using both Memscon and reference piezoelectric wired accelerometers, mounted back-to-back, fastening the instruments directly to the concrete slab. Dynamic tests conducted at different amplitudes highlighted that Memscon accelerometers can monitor a real concrete structure during a seismic event, with RMS discrepancies against the wired accelerometers of less than 20 mg. Acceleration data were also used to estimate the displacement time history at the top of the frame, by double time integrating the acceleration. This estimate was compared with the time history of displacements as produced by the horizontal actuator. The comparison showed that the error in estimating displacement using double acceleration integration as recorded by the Memscon accelerometers is of the order of 0.5mm.

The displacement recorded using linear voltage displacement transducers show that plastic hinges developed at the base of the column at a displacement of about 17 mm, as expected. Progressive damage is seen at the top of the columns too, up to formation of a plastic hinge at the interface between column and beam.

The DSS was validated using data recorded during dynamic tests, taking the three-dimensional frame as a case study. First the data provided by the strain sensors were imported to the Long Term module. The Memscon layout includes a separate specimen with a strain sensor attached, where shrinkage strain and temperature effects can be measured. Data recorded during vertical load application by reference strain gauges were used to assess the reliability of the strain module, comparing the force estimated by the software with the values estimated by a SAP 2000 analysis. The accelerometer data are processed using an appropriate high pass filter. The filtered results are integrated to velocities and then to displacements. The high pass filter is applied after each integration sequence. The calculated displacements are filtered again using a custom algorithm within the DSS, in order to derive the extreme displacements which are imported as imposed displacements to the 3D model in ETABS/SAP2000 analysis. The results of the calculation correspond to the real condition of the structural members. The results show that the correspondence of the recorded real results of the 3D frame test and the DSS damage index is reliable. Therefore, the data derived from the accelerometers and the reference sensors, combined with the methodology implemented in the DSS provide a solution that meets all requirements.

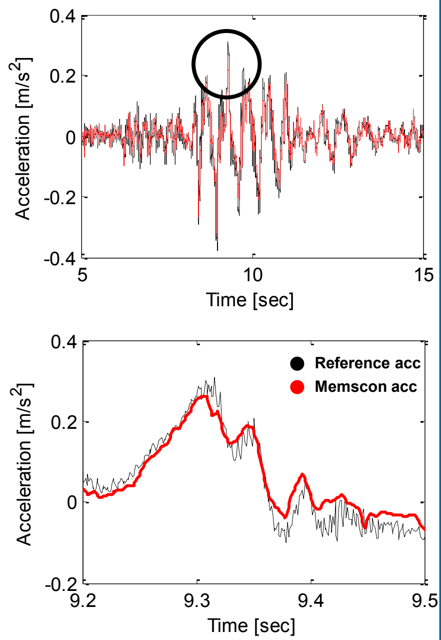

Fig. 4. Comparison between Memscon and reference accelerometer signals.

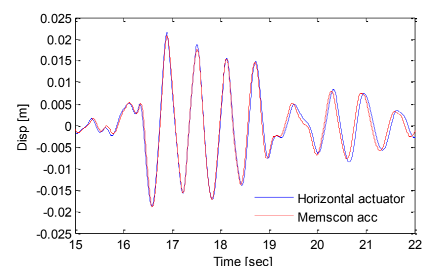

Fig. 5. Comparison between the displacement time history as estimated by double integration of acceleration data and that produced by the horizontal actuator.

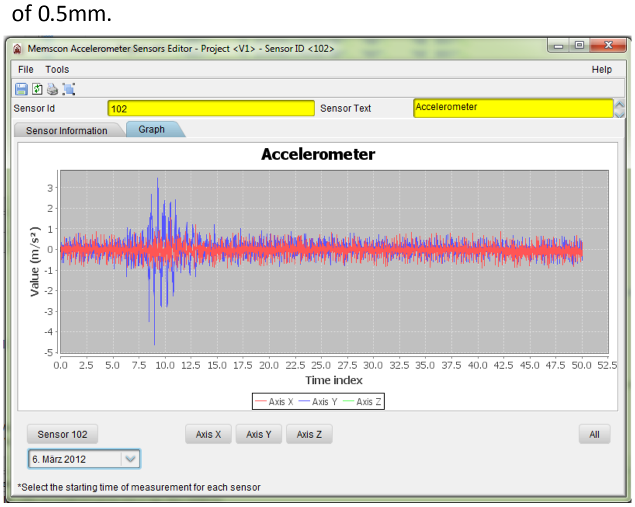

Fig. 6. Accelerometer data imported in the DSS

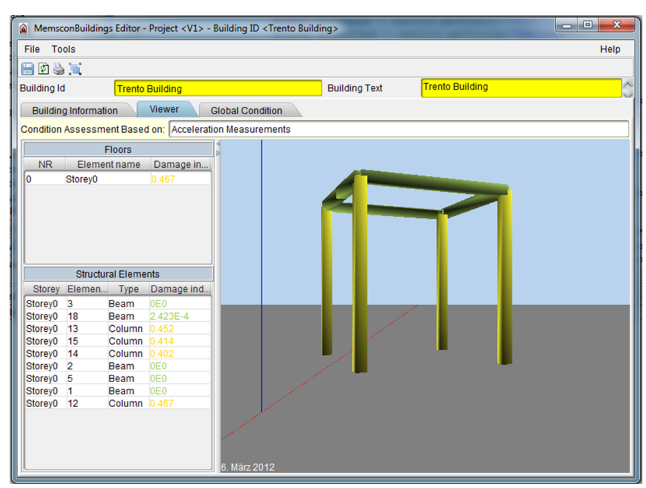

Fig. 8. Example of the DSS output.

'Towards Intelligent Civil Infrastructure' Memscon Final Workshop

Civil engineering structures are generally the most expensive assets in any country and are currently deteriorating at a frightening rate. These structures have a very long service life while assessment of their on-going structural condition practically does not exist.

Introduction of monitoring systems, an evolving technology, can provide objective measurements of their structural condition and aid in timely and cost-effective maintenance.

Of special importance is the monitoring of civil infrastructure during an earthquake. During such an event structures may exceed their functional or structural limits and this can be visible. On the other hand, they can also suffer enormous damage to their capacity without producing any apparent visible signs. Such damage can result in life threatening conditions evolving in the structure long after the earthquake has happened. Such damage can also render the structure incapable of surviving consecutive aftershocks. These aftershocks take place within few hours of the earthquake and can have an intensity of up to 90% of the earthquake intensity.

Monitoring systems can provide a quick and accurate estimate of the level of seismic damage that can be used to indicate loss of function and a quick and reliable assessment of the capacity of the structure to survive expected aftershocks.

The goal of the Memscon final workshop 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, which is organized by the partners of the EC funded project Memscon, will bring together the Structural Health Monitoring community, European construction companies, owners of constructed facilities, insurance companies, policy makers and sector experts.

The workshop will be held at the Conference Centre 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.

Workshop Sessions:

- Advanced Sensing Technologies for Civil Engineering Structures
- Wireless Sensors for Remote, Real-Time Structural Evaluation of Civil Engineering Structures
- Monitoring-Based Assessment of Structural Condition and Maintenance/Repair Management in Construction
- Field Applications: Structural Monitoring and Assessment of Buildings and Bridges

Workshop details and registration can be found at the Memscon website: www.Memscon.com

Keynote speeches

Memscon workshop will bring together the major research groups, industries and end users, involved in the health monitoring of civil structures from 13 different countries. The keynote speakers of the Workshop are:

Prof. James Brownjohn, University of Sheffield, UK

Prof. Spilios Fassois, University of Patras, Greece

Prof. Branko Glisic, Princeton University, USA

Prof. Christian Grosse, TU Munich, Germany

Prof. Jerome P. Lynch University of Michigan, USA

Prof. Kenichi Soga, University of Cambridge, UK

James Brownjohn,
University of Sheffield, UK

"Simple but effective SHM: The sceptic-practitioner view of what works well, what doesn't and where we should direct our efforts"

Applications of SHM in the real world of civil infrastructure are still relatively few because of the difficulty of the difficulty in making a convincing case that it will provide a cost effective and reliable solution to a stakeholder requirement. That requirement may be evaluating the need for and subsequent effectiveness of a retrofit, assuring operational safety of a structure during extreme loading, diagnosing (vibration) serviceability problems and generally proving a structure is fit for purpose and operating within the design performance 'envelope'. In civil structures it is hard to find anyone who will admit their structure has been saved from disaster by SHM, but the technology certainly does have the capability to identify anomalous performance, signalling and assisting with further structural investigation. The technology for effective SHM as defined above is available and is not necessarily dependent on complex arrays of hundreds of sensors. What works well is often simple and inexpensive if deployed appropriately; some examples will be shown. Some technologies that have not worked quite so well (for the author at least) are mentioned, along with suggestions for future research, which should perhaps focus rather more on software than hardware.

Prof. Spilios Fassois,
University of Patras, Greece

"Non-Stationary Random Vibration Parametric Modelling and Identification: methods and applications"

Non-stationary random vibration signals exhibit time-dependent characteristics and require proper models and corresponding identification methods. The focus is on parametric models and identification methods, which are classified according to the type of model parameter temporal evolution postulated: unstructured, stochastic and deterministic. The relative model characteristics and the primary identification methods within each class are discussed, along with model analysis issues. Three application case studies are then briefly considered: (i) Output-only identification of the non-stationary dynamics of a laboratory bridge-like structure with moving mass, (ii) non-stationary modelling of the El Centro earthquake ground motion signal, and (iii) output-only identification of non-stationary wind turbine dynamics under normal operating conditions.

Prof. Branko Glisic,
Princeton University, USA

"Monitoring Civil Structures using Fiber Optic Sensors"

Sustainable preservation of existing infrastructure and sustainable construction of new infrastructure represent goals that are essential for future vitality of economy and prosperity of any society. Structural health monitoring (SHM) emerged in the last two decades as a novel multi-disciplinary branch of engineering, with promising potential to help reaching the above goals. Several SHM methods based on application of various sensing technologies combined with specific data analysis algorithms have been researched, developed and with more or less success applied to real structures. Fiber optic sensing (FOS) technologies have signifi-

Keynote speeches

cantly evolved and have reached their market maturity during the last decade. The main widely recognized advantages of these technologies are high precision, long-term stability, and durability. But in addition to these advantageous performances, FOS technologies provided with long-gauge and truly distributed strain sensors, which led to the development of new transformative SHM methods based on these types of sensors. Using these methods it is possible to affordably instrument large areas of structure, enabling global, large-scale monitoring based on long-gauge sensors, or integrity monitoring based on distributed sensors. These two approaches are presented in details along with enabling FOS technologies, and illustrated with applications on building, bridge, and pipeline.

Prof. Christian Grosse,
TU Munich, Germany

"Wireless monitoring of historic structures using sensor networks – an overview about several recent implementations"

Structural health monitoring of historic structures using autonomous wireless sensor nodes becomes more and more important for conservators and restorers. In regard to the monitoring devices and data processing techniques several boundary conditions are special for the field of cultural heritage compared to other (wired or wireless) applications. These boundary conditions are summarized and several case studies are presented including indoor and outdoor measurements. Since a single monitoring technique among the actually existing might not cover all requirements this overview paper illuminates a selection of four different European monitoring systems along with demonstrations of their performance at field applications.

Prof. Jerome P. Lynch
University of Michigan, USA

"Partitioned Computing of a Markov Parameter System Identification Method in a Heterogeneous Wireless Sensor Network Comprised of iMotes and Narada"

The efficient extraction of information from wireless sensor networks (WSN) can be carried out using algorithms embedded in the network itself. These embedded programs allow the network to harness the computational resources of the individual wireless sensor nodes to create a distributed computing network. To execute more sophisticated data processing algorithms, it is often desirable to add additional computational resources to the existing network. However, additional computing resources come at the cost of increased energy consumption. This can be problematic as wireless sensor networks are often limited to the energy that can be scavenged from the surrounding environment or from battery packs coupled with the nodes. Thus, it is desirable to create a network that can provide additional computing power while minimizing the increase in energy consumption. To this end, a heterogeneous wireless sensor network consisting of wireless units optimized for low power sensing interspersed with units optimized for low power computing can create a more computationally efficient network than is currently available when working with a homogeneous network. As a proof of this concept, a hybrid WSN was created consisting of the Narada wireless sensing units (WSU) to provide low power sensing node and iMote2 units serving as efficient computational engines. In order to demonstrate the efficiency of such a configuration, a network was created to extract modal parameters based on Markov parameters. The resulting network was then tested in the lab.

Prof. Kenichi Soga,
University of Cambridge, UK

"Innovative monitoring technologies for underground infrastructure"

One of the greatest challenges facing civil engineers in the 21st century is the stewardship of civil engineering infrastructure. Nowhere is this more apparent than in underground structures in the major cities around the world. Advances in the development of fibre optics, computer vision, miniature micro-electro-mechanical sensors (MEMS) and wireless sensor network (WSN) offer intriguing possibilities that can radically alter the paradigms underlying existing methods of condition assessment and monitoring of such infrastructure. This paper discusses potentials of these technologies for monitoring underground infrastructure.

Memscon: next? An exploitation prospective

Building Code legislation and regulation is bound to become more pervasive in the future; and will require monitoring systems on all types of new public and private buildings as well as on bridges and the other infrastructure. The ideal implementation of the code requirements will be 3-axis monitoring platforms in multiple locations within the structure. Current building codes provisions in most cities in seismic zones 3 and 4 already require accelerographs in new high rise buildings.

We note here that most buildings in the European Union in general, and more specifically in the earthquake prone South, are built of reinforced concrete. We note too that most of the building stock is several decades old, has suffered lack of maintenance and now needs significant maintenance.

Today, available structural monitoring systems use wiring to connect sensors to their central processing units. This system has high installation costs and is vulnerable to signal noise; and these factors have impeded wide application. Moreover, the size and complexity of a large structure leads to large numbers of sensors. The sensor size too is an obstacle to their use when many sensors would be needed. Their high cost is also a difficulty, leading to a high overall system cost. Consequently their use is limited to expensive and critical structures in civil engineering, such as important bridges and buildings.

The Memscon consortium has overcome these limits; using proprietary state-of-the-art modelling know-how for reinforced concrete structures, innovative decision support algorithms and breakthrough low power wireless sensor networks including accelerometers and strain sensors, the consortium has developed a complete, cost effective monitoring system for building and structural monitoring, also offering assessment of damage and settlement. With the sole exception of inaccessible areas in existing RC buildings, the Memscon integrated package will be useful for both existing and future buildings, in seismic areas.

The Memscon monitoring system can be used to monitor strain and acceleration in existing and future RC, steel and other structures subject to static and dynamic loading at frequencies up to 20 Hz. The system specifically covers seismic action.

The strain monitoring system also contains a module for 'Condition Assessment Based on Strain Measurements' for structures subject to operational loads. This module provides a structural integrity assessment of the construction, and is of use in both existing and future structures and buildings in all areas. The core value proposition of the Memscon monitoring system addresses the demands of above market segments in many ways:

- the system needs a limited number of low cost sensors to monitor the structure
- power demand is very low, ensuring low maintenance of the sensor network
- easy network installation and communication (wireless)
- innovative structure modelling requires a limited number of sensors to assess structure integrity or repair needs
- the decision support system allows rational action to be decided on quickly, without expensive inspection of all structures involved in a seismic event by highly qualified personnel.

Existing monitoring systems in civil engineering are wire based. Important limitations are their high initial cost due to cable installation and also high maintenance costs. The Memscon monitoring system uses wireless communications for data transfer between wireless sensing units and drastically reduces the cost of system installation and maintenance.

An added advantage is that a wireless system can withstand an earthquake better than a wired system: in an earthquake telecom cables often fail. Clearly for a wireless system to operate, the GSM network must be available. This cannot be assured in case of a disaster but experience shows that the probability of the GSM network remaining operative in such a case by far exceeds the probability of normal telephone cables being in service.

The number of sensors needed in the Memscon system is also low. Instead of trying to directly assess the internal forces in each member, we measure some critical global parameters of the overall stress condition. Then, the forces in each member as well as their structural adequacy are assessed by finite element algorithms that use as inputs the measured values of the said critical parameters.

The analysis uses commercially available finite element software in a central processing unit. The unit memory stores models of all building elements together with their initial design values. Since the reinforcement and the order of magnitude of the internal forces are known, stage II stiffness data for each member are input to the model, enabling a far lower number of sensors in each building.

Based on these competitive advantages of the Memscon monitoring system over currently available solutions, the main customer types that Memscon can address are in two main groups: the first includes system integrators in the area of structural monitoring in the construction field, while the second group will be of building monitoring and security systems providers.

In future development, we expect the proposed package will be extended to cover additional services in the same markets, other construction materials and sectors such as bridge building.

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