2008 Report

NEXUS

Expert Workshops in Microsystems for Structural Health Monitoring

Editors: S. Neylon, A Richardson & H. Van Heeren

FP6 NEXUS plus

Foreword

On behalf of the NEXUS association we would like to thank the 37 participants of the Lancaster & Eindhoven workshops for providing their knowledge, experience and recommendations that form the core of this report. We would also like to thank the European Commission for providing the brief and funding through the NEXUSplus project for running these workshops and producing this report.

The two workshops organised by NEXUS aimed to address the barriers to commercialisation around the deployment of Microsystems within the Structural Health Monitoring market. The first meeting focused on current and emerging market needs and systems applications. The results of this workshop were presented in an earlier report and have been attached here as an appendix.
The second workshop identified specific drivers and barriers, the results of which are also provided as an appendix to this report.

This report summarizes the findings of both workshops and provides specific recommendations based on the discussions between participating experts. We hope you and your organisations will find this information of value to your future business and projects and welcolme your continuing interaction with NEXUS over the coming years.

Sean Neylon
Chair: Nexus Association
Email: office@nexus-mems.com

Workshop Facilitators

Andrew Richardson
University of Lancaster
Email: a.richardson@lancaster.ac.uk

Henne van Heeren
enablingMNT
Email: henne@enablingM3.com

Contents

Objectives

The goal of these workshops were to identify barriers to and opportunities for the implementation of Structural Health Monitoring and to table potential solutions for overcoming these barriers. This will be used by the European Commission as input for future calls in the Framework 7 Program.

Scope of the Workshops

The first workshop held at Lancaster on April 17th 2008 focused on Markets, Applications & Business Opportunities although it also identified some technical challenges as input to the 2nd workshop held in Eindhoven on June 9th 2008. The second workshop specifically focussed on where progress is needed to realise technical solutions to accelerate opening up the markets identified and systems applications.

Contributors

Attendees 1st Workshop held in Lancaster University UK April 24th 2008
Facilitators: Sean Neylon (Colibrys CH), Andrew Richardson (Lancaster University UK), Henne van Heeren (Enabling3M, NL)
21 Attendees: 8 Industrialists from 6 different businesses / 13 Academics from 8 different academic centers
8 Countries: UK, France, Germany, Switzerland, Holland, Finland, Austria, Belgium;
Full Supply Chain representation.

Summary and Feedback: well facilitated, animated. Meeting size viewed as conducive to interactive discussion. Mix of industrial and academics welcomed.

Attendees 2nd Workshop held in Holst Centre, Nijmegen Holland June 8th 2008
Facilitators: Sean Neylon (Colibrys CH), Andrew Richardson (Lancaster University UK), Henne van Heeren (Enabling3M, NL)
25 Attendees; 12 industrialists, 13 academics
8 Countries
Full Supply Chain representation + Lloyds Register

Summary and Feedback: well facilitated, interest from participants to arrange follow-on meetings (twice yearly maybe).

Summary:
A total of ten businesses were represented from across the supply chain and Europe.
Five of these businesses were represented at both workshops to ensure continuity.
Some 13 different Academic bodies were represented from across Europe including standardization and test centers. Six of these bodies were represented at both workshops.

Other Contributors

Patric Salomon	enablingMNT
Marcel Verhoef	Chess
GertJan Heeres	TNO
Mark Begbie	iSLI
Gilles Hovhanessian	Advitam Group

Executive Summary

In essence Structural Health Monitoring (SHM) - a subset of the much larger Health Usage Monitoring (HUMS) application sector specifically focuses on providing diagnostic and potentially prognostic information on the structural integrity of large structures, thereby minimising the public safety risk associated with these structures, maximising uptime and enabling safe and cost effective operation. As such SHM must generate information that can increase confidence in structural integrity, minimise the risks associated with using the structure or minimise downtime. Whatever solution is proposed, it should include the whole applications trajectory from sensor development to the generation of meaningful information on which reliable decisions can be made.

The scope of the work debated by the expert group included the whole span of the integrated systems supply chain, from sensor development, interconnectivity, data acquisition, data interpretation and application training and support.

Market Drivers

All of the leading G8 governments today have made high level pronouncements on their commitments to assuring and improving public safety in all its forms. In parallel the worlds leading insurance companies are seeking to reduce the costs of their policies by demanding improved systems to validate the structural integrity of the expansive but ageing infrastructure installed over the past fifty years whether that be road networks, bridges, ships, buildings, dams, power plants, civil aircraft etc. This in turn is demanding a move from often older purely subjective inspection methods towards proven measurable but reliable diagnostic systems and most recently a move further towards predictive prognostic systems.

Markets

Several markets are significantly impacted today by SHM applications but the major areas of focus within the two NEXUS workshops were Aeronautics, Transportation, Civil Engineering / Construction and Energy.

Market structure is characteristically fragmented, conservative, with few standard platforms, diverse applications and market specific drivers. Quantification of market size is difficult.

The architechture of a SHM sensor network will depend on the application but will typically include a range of sensors including temperature, strain, vibration, corrosion and wind velocity sensors. Some systems will monitor the structure at a macro level, some a micro level, some the load on the structure and others the effect of the load. Structures with varying loads are particularly challenging in the context of modelling the system. For these appliations cost effective SHM solutions will likely be through adapting standardised units or through monitoring parameters that are indirectly affected by incorrect system behaviour.

For many practical applications today, damage detection is sufficient. The challenge for the future is to detect evolving damage at an early stage without generating false alarms and effectively isolating effects resulting from damage from those originating from changes in external environmental conditions. To extend the understanding of the level of damage, models are needed that are able to describe the effect of damage (by means of parameters such as crack length, extent of delamination or decrease in stiffness etc.) on the dynamic behavior. The highest level of SHM and the most sophisticated is the generation of prognostics for the remaining lifetime. This requires the combination of the global structural models with local continuum damage or fracture mechanics models that can reliably describe the evolution of damage or fatigue crack growth.

Inspection, maintenance and insurance are three cost factors that could be lowered in the short term through the use of SHM, assuming there is confidence in the validity of the information generated and the prediction models.

Market size

Quantitative estimates of the market size for microsystems were deemed too difficult to be accurately estimated although there seemed to be a market today for some tens of thousands of new sensor systems annually with an average value of $5K/system, amounting to a relatively small niche market of around $50M/yr. The importance and benefits of improving public safety is therefore largely disconnected from the market size and value at the sensor & system level. Investment for new technology development will not be easily found from the private sector alone.

Systems Applications

Geoscience (prediction of earthquakes and volcano eruptions) is predominantly government driven and is more or less an established market. Although there are several needs to be met, by nature of the market and investments already made it is not the area where we can expect a drive for breakthrough developments.

Aerospace is one of the first markets to adopt structural health monitoring for aircraft wings, engines and airframes. It is expected to continue to lead the market with a wide portfolio of existing funded activities when it comes to core technology research and specific sensor developments for harsh environments. The market is primarily seeking how to establish reliable dynamic (in-flight) 'prognostic' systems.

Civil engineering has two sub-sectors: 'geotechnical' (subsurface analysis) and geostructural (above surface). Both have exhaustive demands for improved SHM systems based on an increased aging infrastructure (dams, levees, roads, bridges, nuclear plants, high rise buildings and limited government funds for repair and maintenance). Many standards are imposed regionally and national and pan-European interests are not uniform. This sector could well become a driving force for SHM based on self-sustaining sensor networks. Faster, more accurate systems offering fully integrated data analysis are seen as key to opening up this market in the future.

In the world of transportation, track monitoring and maintenance for high speed trains and highway/road infrastructure is already relatively well advanced in the use of SHM systems especially in Europe and Japan. Improved standardization and predictive modelling systems are the main future demands. Furthermore, large ships today already have 'black box' monitoring systems (Voyage Data Recorders) required by "SOLAS", the Internatioanl Convention for Safety at Sea that although not strickly condition monitoring is evidence of trends.

The world energy market is highly active in seeking all weather SHM systems to assist in maximising uptime of oil platforms, low cost maintenance of in particular off-shore wind turbines and in improved safety systems throughout the mining industry.

Key Applications issues:

In a general sense, availability, safety and lower maintenance cost are the main generic applications drivers. Operational uptime 'availability' is especially important for intensively used infrastructures such as highway bridges and airplanes, and periodic applications including structural measurements following earthquakes to support safety assessments for building and 'plant' certification.

Integration technologies are seen as crucial in the medium to long-term. This involves high reliability system design that embraces materials, components sub-systems, software and packaging. Advances in appropriate system architectures are considered crucial in the short to medium term that can support low-cost manufacture & test, and reliability higher than the structure being monitored. Applications identified included offshore windmills, hydrogen storage tanks, tanks and piping in the chemical and energy industry, aerospace and transport in general.

Corrosion is an area that was specifically identified and seen as a high priority mechanism for health monitoring in most application areas.

The use of SHM generated data for diagnostics and prognosis is an important priority area. Specific challenges include threshold generation for structural health parameters and supporting safety whilst minimising false warnings. A medium to long term need exists for richer data that can effectively provide reliability indicators on which prognostic models can be based.

To be noted also, the experts clearly confirmed the challenges to upgrade existing systems are substantially more difficult than installing new systems into new markets. This will clearly severely constrain the size of the serviceable available market.

Generic Themes and Recommendations:

The following general themes were identified at a microsystems level:

- **From diagnostics to prognostics:**
  - Low cost automated inspection systems for corrosion, specially, but not exclusively, for the chemical, oil & gas industry; the proposed approaches should also include models for the prediction of remaining lifetime.
  - Sensor systems for cracking and/or delamination in, for instance, new aerospace materials, off-shore windmills and hydrogen storage/ handling installations. The proposed approaches should also include models for the prediction of remaining lifetime.
- **Embedding of reliable sensor systems:**
  - Zero maintenance, long life and installation friendly SHM systems for critical infrastructure.
  - Autonomous wireless sensor systems with a working life over 30 years, high reliability and dependability of both the hardware and data output.
  - Solutions could include sensors which are integrated into the materials: smart pebbles, asphalt etc.
  - Low power systems, especially wireless with integrated energy harvesters with applications in challenging environments including aerospace and the chemical industry.
  - Low weight diagnostic systems for in-flight monitoring of aircraft structural elements, using predictive modal analysis.
  - Small and zero maintenance systems for difficult to access areas.
- **Generic issues that are recommended for further development include:**
  - Modelling and prognosis and Physics of Failure for corrosion and cracking in a diverse range of applications.
  - Extension of condition based maintenance, also including the stimulation of innovative and holistic solutions including new business models that transfer responsibility of uptime from the owners of infrastructure assets to spare part suppliers who embedded the SHM system in the spare parts. A further example could include suppliers using information from embedded sensors to reengineer (sub) systems and its components.
  - Support for the formation of cross-disciplinary teams including material scientists, modelling and simulation experts, hardware suppliers (wireless, energy harvesters, sensors, system design) and application specialists.
  - Stimulation of standardization activities in data communication, storage and interchange ability, pan European activities to promote the use of SHM by removing barriers, promoting standardization and support adaption of regulation to enable the use of SHM.
  - The applications are by nature safety critical and as such extremely conservative in adopting new technologies or standards. Financial support for trials of new systems would be useful in accelerating the adoption of new systems
  - Training in standards especially need for digital systems to comply with ‘safety critical’ software standards.

List of contributors

Industrialists

Sean Neylon	Colibrys & NEXUS
James Gale	Strainstall UK Ltd.
Chris Pickering	QinetiQ
Felix Rudolf	Colibrys
Alastair Sutherland	Ultra-BCF
Matthew Roberts	BAE Systems
Roger Lambert	Scisite
Siro Mancin	AgustaWestland
Jeffrey Sargent	BAE Systems
Matt Mapleston	BAE Systems
Peter Carden	Lloyd’s Register EMEA.
Julia Payne	Messier-Dowty
Peter Haycock	SciSite/Keele University
Hervé Lançon	Sites
Sophie Costes	Sol Data group
Henne van Heeren	enablingMNT

Academic	
Andrew Richardson	Lancaster University
Jari Hannu	University Oulu
David Gregson	Lancaster University
Dennis Koltsov	Lancaster University
Dominik Weiland	iSLI
Claus-Peter Fritzen	University Siegen
Erik Puik	Holst Centre
Marc Desmuliez	Heriot Watt University
Markku Moilanen	University of Oulu
Brian Moffat	Heriot Watt University
Chantal Khan Malek	Femto-st, CNRS
Thilo Bein	Fraunhofer Institute for Structural Durability and System Reliability
Rob van Schaijk	Holst Centre
Jo de Boeck	IMEC
Bart Onsia	IMEC
Carmen Moldovan	IMT
Bahram Honary	Lancaster University
Sorin Axinte	MINATECH-RO
Theo ter Meer	National Aerospace Laboratory NLR
Carsten Heinks	RTRC Germany
MaGert-Jan Heerens	TNO
Peter Kraemer	University of Siegen
Juha Hakkinen	University of Oulu

Summary of the First workshop

The first workshop held in Lancaster on April 17th 2008 focused on evolving SHM markets and the technical requirements of these markets. This analysis formed a key input into the 2nd workshop in Eindhoven.

It was noted that in essence Structural Health Monitoring is about generating information that provides confidence in the structural integrity of an asset; minimises the risk associated with utilisation of the asset; minimise downtime and enabling safe and cost effective operation.

Four levels of functionality based on damage assessment where defined that were seen to hold for most SHM applications:

Level I: Damage detection;
Level II: Damage localization;
Level III: Damage quantification; and
Level IV: Prognosis of remaining service life.

Level I only provides information that damage is present in the structure. For many practical applications this is sufficient. The challenge for future markets is to achieve high sensitivity to enable damage detection at an early stage without generating false alarms. Separation of the effects resulting from damage from those originating from changes in environmental conditions were considered essential and recognized that this level of functionality could deliver dual use SHM systems where the SHM function could form part of the compensation / calibration structure for harsh environment applications. Level II increases the knowledge around the source of damage by determining the location(s) of single or multiple damage sites. Most methods make use of a structural model to map measurement data to a specific location. At level III the extent of the damage is assessed. For this purpose the model must be able to describe the effect of damage (by means of parameters like crack length, size of delamination or reduction in stiffness etc.) on the dynamic behavior. If no such model exists the damage metrics have to be determined by calibration experiments. The highest level and the most sophisticated is the prognosis of the remaining lifetime. This requires the combination of a global structural model with local continuum damage or fracture mechanics models which can reliably describe the evolution of damage or fatigue crack growth.

Inspection and insurance are two cost factors that could be lowered in the short term when using SHM, assuming there is confidence in the validity of the information generated and the prediction models used.

Geoscience is a government driven, more or less established market. Although there are several needs to be met, it is not the area where we can expect a drive for breakthrough developments.

Summary of Second Workshop

The second workshop focused on the technical challenges that need to be solved to enable acceleration of the adoption of solutions within existing markets, penetration into new markets and enhanced global competitiveness. Recommendations for how to drive forward technical, solutions are summarised in this final report. In addition the following focal areas were identified for future or extended use of structural health monitoring:

Application	Driver (s)	Main challenge	Issues
Offshore windmills	Cost of maintenance	Delamination of blades; integrity of structure (corrosion)	Predictive modal analysis
Hydrogen storage tanks	Safety	Prognosis of integrity of high pressure installation	
Tanks and piping in the chemical and energy industry	Cost of shutdown and inspection	Corrosion inspection in non pigable piping and storage tanks	Existing regulations*
Aerospace & transport	Safety, cost of inspection, downtime	Difficult to access area, new materials	Existing regulations*
All	Cost of sensor installation and ownership	Integrated sensor systems to be used in wireless networks. Self-sustaining sensor systems through the use of for example energy scavenging technology	Standardization
All	Condition based maintenance, extension of life time.	Modelling of degradation, prognosis of damage.	

* Existing BS/CEN/ISO standards on condition monitoring.

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The authors would like to acknowledge EC for the financial and logistical support in the facilitation of the SHM workshops and for all those who took time from their busy schedules to contribute to the meetings. Specifically we would also like to thank Andreas Lymberis from the Information Society and Media Directorate-General of the European Commission in recognizing the need for these workshops.

We also would like to thank all the other experts who helped us generate the information and advice needed to compile this report.

Finally we thank the Lancaster University for hosting the first workshop and the Holst Center for hosting the second workshop.

Appendix 1:

Nexus Structural Health Monitoring First Workshop Report

The Nexus consultation meeting on "Microsystems for Structural Health Monitoring was held at Lancaster on April 17 2008.

As part of an European funded project NEXUSplus, the Nexus Association has invited experts to attend a workshop designed to address the barriers to commercialization around the deployment of Microsystems within the structural health monitoring market. The output of the first meeting that focused on current and emerging markets is presented in this report making recommendations for future research and guidelines for how to improve exploitation of structural health monitoring technology and systems within Europe.

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Henne van Heeren
enablingMNT/Nexus Task Force on Structural Health Monitoring
Drakensteynlaan 34
3319 RG Dordrecht
The Netherlands
Tel: 0031 78 6300748
Mobile: 0031 654 954 621
Email: henne@enablingm3.com
Web: www.enablingmnt.com

Andrew Richardson
Director - Centre for Microsystems Engineering
University of Lancaster
Email: A.Richardson@lancaster.ac.uk

Sean Neylon
Nexus Association/Colibrys
Email: office@nexus-mems.com

Executive Summary

In essence, Structural Health Monitoring (SHM) is about extracting and delivering information that can provide intelligence on the integrity of a structure and confidence in its reliability and safety. The data generated by structural health monitors can be used to minimise the risk associated with using the structure, minimise downtime and to enable safe and cost effective use. The solution should in all cases embrace sensor development through to the distribution and processing of data to deliver meaningful information on which decisions can be made. Measurements include the response of a structure to static and dynamic load including deflection, displacement, movement, cracking, strain and vibration. All these methods have in common change in one or more structural parameters due to damage or wear that result in a change in the dynamic behavior of the structural system. In addition, measurement of pre-cursors such as corrosion or by-products of degradation (e.g. gases, reaction products, radiation etc) are of equal importance.

Robust identification techniques that are able to locate damage based on realistic measured data sets is still far from reality. During the last 8 years the SHM community has made considerable progress in diverse areas but some of the basic difficulties are still unsolved.

From the initial meeting the following hotspots where technology development is needed were identified:

- SHM for civil infrastructure, offshore windmills, aerospace, chemical industry.
- Integrated sensor systems to be used within wireless networks.
- Self-sustaining sensor systems through the use of for example energy scavenging technology.
- Long term visions on SHM: smart pebbles etc.
- Modeling of degradation, prognosis of damage.
- Standards, etc.

These issues are recommended for further discussion at a second meeting of the group to be held in Eindhoven on June 9th 2008 hosted by the Holst Center. This meeting will address technical need, direction and strategy in addition to further market opportunities.

Objectives

The goal of this workshop is to identify barriers and opportunities to the implementation of Structural Health Monitoring and to table solutions for overcoming these barriers. This will be used by the European Commission as input for future calls in the Framework 7 Program.

Scope of the Workshop

The first workshop focused on Markets, Applications & Business Opportunities although it also identified some technical challenges as input to the 2nd workshop (Eindhoven on June 9th 2009) that will specifically identify where progress is needed to realise technical solutions for markets and applications identified

Contributors

List of attendees first workshop

Industrialists

Sean Neylon	Colibrys & NEXUS
James Gale	Strainstall UK Ltd.
Chris Pickering	QinetiQ
Felix Rudolf	Colibrys
Alastair Sutherland	BCF Design
Matthew Roberts	BAE Systems
Matt Mapleston	BAE Systems
Roger Lambert	Scisite

Academic

Chantal Khan Malek	Femto-st, CNRS
Bahram Honary	Lancaster University
Sorin Axinte	MINATECH-RO
Jari Hannu	University Oulu
David Gregson	Lancaster University
Dennis Koltsov	Lancaster University
Dominik Weiland	iSLI
Claus-Peter Fritzen	University Siegen
Erik Puik	Holst Centre
Marc Desmuliez	Heriot Watt University
Markku Moilanen	University of Oulu
Brian Moffat	Heriot Watt University

Facilitators

Henne van Heeren	enablingMNT
Andrew Richardson	Lancaster University
Sean Neylon	Colibrys & NEXUS

Other Contributors

Patric Salomon	enablingMNT
Marcel Verhoef	Chess
GertJan Heeres	TNO
Mark Begbie	iSLI
Gilles Hovhanessian	Advitam Group

General Trends and Background

Definitions

Structural Health Monitoring (SHM) was defined as the continuous and autonomous monitoring of defects, stress/strain, environmental and usage related parameters by means of permanently attached or embedded sensor systems and "decision making computing" in order to ensure the structural integrity of large structures like, airplanes, bridges, dikes, buildings etc.

Issues including the monitoring of equipment, soil contamination, underground water level etc. will not be addressed nor will asset management or Health and Usage Monitoring Systems (HUMS) in a general sense.

General Trends Relevant for SHM

There is an increasing trend to accept less risk in the public domain, governments are being regarded as responsible and accountable to a larger extent than ever before. There is also an increasing awareness for the risk associated with the extended life of many civil structures airplanes etc. Also of importance are the expected consequences of global warming in the form of hurricanes, floods, landslides etc. and the increasing number of buildings in high risk areas such as low laying lands etc. A further driver is the decreasing number of technical staff in the developed countries and the continuous drives to decrease the cost of maintenance.

There is also an interesting technology trend of importance for the SHM market: the increasing availability of miniaturized sensors and the increasing integration of those sensors into small packages with other functionalities like data storage & processing, energy scavenging and wireless interconnect. (See next Figure)

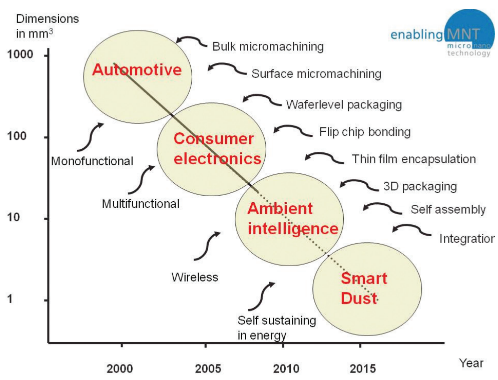

Figure 1: development of miniaturized integrated sensor systems

Miniaturization here is seldom a goal in itself, but a way to achieve price reduction and make the system more energy efficient. This will increase the time between battery change or enable the use of energy scavengers. Together with wireless communication and sensor networks this makes cable free monitoring possible. (See next Figure)

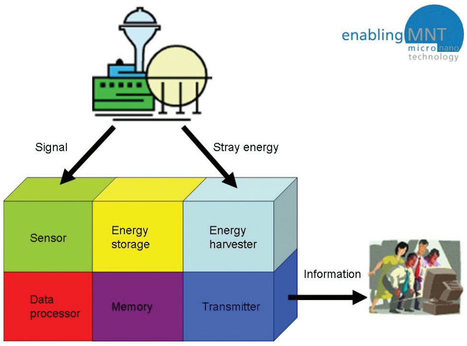

Figure 2: integrated sensor system for Structural Health Monitoring

As information transmission needs considerable energy, the amount of information sent needs to be kept as low as possible. This drives the need for integrated processing of data. The ultimate goal being to create networks of autonomous sensors, collecting data related to the structure integrity and transferring meaningful information for asset management.

Applications

The following areas were identified as (potentially) interesting for SHM:

- Geophysics
  - Soil mechanics
  - Volcanoes
  - Earthquakes
- Aerospace
  - Civil and military airplanes
  - Space craft
  - Helicopters
- Civil engineering
  - Buildings
  - Bridges
  - Dams
  - Tunnels
  - Mining
- Transport
  - Automotive
  - Trains
  - Ships (large and small)
- Energy
  - Oil & gas installations and pipelines
  - Wind turbines
  - Nuclear Plants
  - Tidal wave generators
- Chemical installations
  - Piping
  - Tanks
- Defence (see also aerospace/transport)
  - Transport and storage of munitions

Geoscience

Driving forces for SHM

An important driver for SHM is the demand for public safety by delivering early warning for earthquakes, volcano eruption, landslides etc. It is to be expected that due to global warming there will be an increased risk of flooding, hurricanes etc. that threatens infrastructure. The growing Chinese and Indian economies offer opportunities, especially as an increasing number of people are living in high risk areas close to the sea etc. which were avoided in the past, but are now needed due to increasing population.
The European parliament has recently (November 07) asked to increase earthquake research and promote prevention in Europe.

Key stakeholders / who will benefit?

Although the public is the main beneficiary, it will be governments who will drive implementation. In some cases industry (and its insurance companies) will have an interest by creating the ability to shut down installation, close pipelines in a timely manner etc.

There is a huge potential need for early landslide warning in areas suffering from deforestation. However, these areas are often in development countries with a lack of money.
There are also several important areas that include the Swiss Alps, which could become unstable due to melting of the permafrost ground.
In addition, researchers are using these sensor systems to understand the behaviour of these kinds of structural systems and to create prediction models.

Drive for miniaturisation/microsystems

There is no specific need for miniaturization or cost reduction of the sensor systems as most of the cost is related to the installation and implementation. There are other needs which could be met by miniaturization including: increase of sensitivity, reduce weight, enhanced power efficiency and increased robustness through integration of functionalities thereby limiting part and interconnect count.

Market characteristics

The 120 M$ seismic market is more or less equally divided between Japan, USA and ROW. Strong motion systems account for half of the market. The main business is in the implementation of the sensor system. The sensor, although enabling, is a relative small part of the total cost/value.

Barriers to implementation

- Data analysis
  - -Link between structural properties and sensor measurements
  - -Variety of structures: standard structures versus custom structures
- Data protocol & transmission
  - -Analogue versus digital
  - -RF versus cable
- Fixed installation versus portable
- Lack of Standardization
  - -Sensor types (strain, seismic, high frequency vibration, temperature)
  - -Sensor performance
  - -Sensitivity
  - -Stability
  - -Power consumption
  - -Reliability
- Sensor networking (ambient)
- Local versus regional versus national
  - -Building codes
- Awareness

Other remarks

Contrary to some other applications, there is a need for continuous uptime of the sensing system and ability to transfer the information at all times including when the normal communication infrastructure is damaged or destroyed.

Aerospace

General market trends

While monitoring and diagnostics has always been an important field in rotating machinery in order to increase reliability and safety, in the aerospace industry visual, interval driven inspections are the predominant types of checks to date. These are very time-consuming and labor intensive. Furthermore free access is required to the components to be inspected which mean that peripheral parts have to be disassembled.

Market drivers

- weight reduction,
- cost reduction,
- simplified systems,
- safety and environmental concerns,
- through life management,
- availability improvement and reliable prognostics.

Other trends

- lighter structures, increasing use of composites instead of metals,
- development of smaller airframes (Unmanned Aerial Vehicle),
- trend to electrical drive and actuation,
- more compact engines,
- smart wings.

Driving forces for SHM

The possibility of continuous monitoring of structures by integrated sensor networks instead of only at the scheduled inspection intervals can lead to the improved situation of discovering damage at a much earlier stage and enabling the continuous detection of evolving damage. This clearly can have a strong economical impact and can improve the safety of the structure. It can also lead to the development of new methodologies in design and engineering. In summary the key drivers are:

- Availability.
- Cost of preventive maintenance is a key drive for condition based maintenance.
- Cost of failure.
- Safety.
- Real time monitoring (as stress in a structure is only to be seen during use, there is a need for monitoring during flight).
- Difficult to inspect areas are hotspots for early implementation.
- Redundancy reduction by targetting condition based maintenance based on SHM.
- Reduction of wiring could be a driving force for SHM in satellites.

Wiring specific:

The several hundreds of km of wiring in an average plane can also be regarded as a system to be monitored. Some information needs to be available instantaneously (for the pilot) other information can be stored for later read out.
There are 1 million maintenance hours per year spent on wiring repairs, $10M is spent on finding and replacing wire faults. There is a need for intelligent enhanced monitoring (in-situ, in real time), to enable predictive & proactive maintenance, i.e. from diagnostics to prognostics. There is a need for high fidelity reliability model for through-life support, especially for ageing aircraft and autonomous vehicles.

It was noted that rotary wings, helicopter shafts and gears have similarities with windmills in the context of SHM requirements.

In summary to enable SHM the following building blocks, tools and functions were felt to be needed:

- Novel sensing and test technology and sensor miniaturisation.
- System architectures and modelling.
- Power and thermal management.
- Communications and man/machine interface.
- Signal processing, pattern recognition, advanced software.
- Data interrogation and data fusion.
- Systems integration, calibration and self-test.
- Design for manufacture and for reliability.
- Harsh environment design and packaging.
- Predictive modelling, validation, failure criteria.

Key stakeholders / who will benefit?

- Benefits for:
  -Aircraft manufacturers, fleet operators, designers.
  -Insurance Companies
  -Government, tax payers.

Drivers for miniaturisation/microsystems

- Sensors needed for difficult to reach inspection areas, often cramped place.
- Availability of cheaper sensors enabling more densely distributed networks of sensors. Embedded sensors (smart dust) could be a future enabler.
- In weight sensitive application, storage of large amounts of data is not an option. This will lead to solutions containing integrated data processing based on prognostic models.
- Smaller sensors consume, in general less power (energy scavenging may become possible?).

Market characteristics

Conservative customer base, a "wait and see" attitude to wireless communication; this industry will wait for the appearance of robust and proven solutions.

Holy grails / need for technology development

Through-life management supporting sensors, self diagnostics long life sensors (20+ years). Small sensors able to be placed at difficult to inspect places.

Specific technical issues that needs to be addressed

- Thin sensors to be integrated into laminated materials, becoming small enough not to distort the structure or obstruct normal operation.
- Improved robustness.
- Methods to verify the integrity of metallic and composite structures.
- Devices to measure key parameters.
- Comparative studies to establish variation to base case.
- Sensing and data logging of the history of environmental load.
- Onboard or off-board processing – embedded processing? Distributed or centralised? Reducing number of sensors – efficient protocols (network coding).
- Self-test sensors and standardization of interface.
- Alarm systems.
- Data security and ownership.
- Timely management of data to convert into decisions.
- Energy harvesting.
- Small size to improve accessibility.
- Reduced weight, wireless.
- System flexibility to upgrade or expand system.
- Smart reconfigurable sensors.
- Improved reliability.

Barriers

- Evolution from diagnostics to prognosis. Do we have meaningful data and a model to relate SHM measurement data to life time prognosis?
- Lightning resistance of sensors and sensor networks.
- Embedding of sensors (e.g. fibre optic based) in the structure, without degrading structural integrity.
- Robustness over temperature change.
- Corrosion monitoring could lead to a requirement for a network of sensors therefore creating the need for low cost self-sustaining wireless sensor systems, which must include data processing and energy scavenging.

Other remarks

Efficient integration of existing technologies could lead to significant advances in the next 5 to 10 years if appropriate system architectures are agreed.

Energy

General market trends

Windmills together with solar energy are today the biggest growth area in renewable energy. The installed base worldwide is about 117 GW of which 60% is in Europe.

Driving forces for SHM

Cost of maintenance and repair, especially for offshore windmills. In this case, operation and maintenance accounts for 23% of the cost. Classical inspection is not always possible due to weather conditions, and where practical, very costly. SHM is also relevant to insurance companies with evidence provided that this industry may evolve to a point where some form of continuous monitoring becomes mandatory. Key items to be measured on engines and blades are:

- vibration,
- temperature,
- oil quality,
- electrical parts,

Windmill tower related problems:

- damage during transport or faults from manufacturing,
- impact with ships,
- ground erosion,
- seaquake,
- extreme loads from wind and waves (in 20 years more than 2x108 load cycles),
- damages due by overloading (waves, wind, ice-foundation, etc.),
- structural damage due to manufacturing defects, or as result of design,
- release of bolts between the tower parts, and
- weld failure.

Key stakeholders / who will benefit?

Windmill park owners, manufacturers and suppliers and insurance companies

Drive for miniaturization/microsystems

Not necessarily a drive to miniaturize per se, but rather a drive to get the cost down and the reliability up, which could be achieved by miniaturization.

Market characteristics

Market share for renewable energy sources is growing and current energy costs rising. It is expected to soon be cost effective to produce electricity on a mass scale from wind and waves. The main drivers will be governments trying to reach their Kyoto quotas and large energy companies. The market for SHM in such installations will scale together with the number of units deployed. The main drive is to reduce the maintenance cost and down time of installations.

Barriers

Windmills

- Vibration monitoring challenges:
  - -slowly rotating machines (low level excitation),
  - -interaction with vibrations from blades,
  - -change in the rotational speed of the components (order tracking),
  - -long transmission paths between sensors and machine components, and
  - -measured signals superimposed from different sources.
- Requirements/problems for SHM in towers and foundations:
  - -low frequency vibration of the tower,
  - -vibration magnitude depends on wind velocity and waves height,
  - -foundation and hot spots of the structure are under the water level, and
  - -erosion, temperature, etc. influence the dynamics of the structure.
- Reliability of the SHM function to continue to perform to specification? There is a clear need for multifunctional teams to develop reliability technology and the application focused solutions.
- Radiation tolerant sensor systems for Nuclear Plant
- General requirement for sensor systems under harsh off-shore conditions
  - -robust, stable over time: lifetime of OWEP is 20 years!
  - -corrosion resistant,
  - -protection with respect to lightning
  - -self-diagnostic capability for the sensors.
- System integration.
- Interfacing and synchronization of different measurement systems, data bases.
- Multidisciplinary teams of structural, mechanical, electrical engineers and computer scientists.

Other remarks

SHM could lead to better design through feedback and associated learning from the measurements.

Other energy areas:

- Nuclear, oil & gas etc.
- Hydrogen storage: this upcoming industry should embrace structural health monitoring. If hydrogen will become the energy carrier of this century, it is likely that a significant market sector will be high risk installations!
- Power transmission lines.

Transport

(Transport infrastructure will be discussed in the section on civil engineering.)

- Automotive
- Tanks
- Trains
- Marine

General market trends

Market drivers include:

• Ship specific: environmental concerns, insurance companies moving towards obligatory use of SHM.

• Monitoring suspension

Driving forces for SHM

Difficulty to inspect areas in submarines, especially nuclear. Sensors need to be very robust!

Other remarks

Marine: continuous measurement of hull stress levels enhances vessel safety by providing warnings of overstress and/or bow slamming. Structural Monitoring of rigs, platforms, TLP's (Tension-leg platforms); failure testing of pipelines, ROV's

Civil infrastructure

Tunnels, railroads, building, bridges, dikes, runways, harbour installations, roads, bridges, high and old buildings, railroad embankments, etc.

General market trends

Higher utilisation of highway and railway infrastructures, heavier aircraft. Higher buildings, anticipation of increased risks of flooding, hurricanes etc, due to global warming. Terrorism risks. An example of an application is railway bridges that are now experiencing more frequent trains with higher axle loads and increased train speeds compared to the expected requirements/ loadings during construction.
In Europe, many structures originate from the late 40's or 50's of the last century replacing structures destroyed during the Second World War. In the UK there are a significant number of structures over 100 years old and still in active use, particularly on the railways....
Regarding concrete, many structures will reach their typical lifetime of 50 to 80 years soon.

Driving forces for SHM

Unexpected failure may lead to highly expensive collateral damage and safety risks, for instance when a bridge collapses due to corrosion of the rebar or when a train runs of the rails due to corroded rails or shifted railroad earthworks. Key divers are:

- Reuse of older buildings for other purposes.
- Extending the life of structures.
- Monitoring of existing defects/faults identified in a structure that are likely to further degrade.
- Building extreme structures like very high buildings.
- Use of new construction principles.
- Cultural heritage buildings.
- Backlog in maintenance.
- Insurance claims for lost business, - lack of structural engineers who have to check the integrity of a building after an earthquake.
- Cost of unavailability during checking drives the need for non destructive non disruptive inspection.
- Seasickness in high rising buildings, measurement of vibration to guide installation of dampers.
- Corrosion of metallic structures.

Key stakeholders / who will benefit?

Government, railway owners, asset owners, insurance companies, semi government bodies like Road Agencies etc.

Market characteristics

Building or structure owner is the final customer. Monitoring system specifications are often created by civil engineering consultants working for the asset owner, based upon government or industry regulations.
Three major materials: steel, concrete and earth (dikes), they are different in specific sensor demands, but there are synergies at the system level. Some overlap is seen in asset ownership.
Sensors should not be seen and/or have to be vandal proof.
It was stated by one of the attendees that the disruption cost due to problems associated to corrosion could be in the order of 3-4 % of GDP.

Holy grails / need for technology development

- Development of robust, reliable, easy to install, self sustaining, low power devices including energy harvesting, wireless operation, data fusion. Measurement of strain, vibration, corrosion, cracks.
- Smart pebbles, intelligent paint.

Barriers

- Lack of agreed criteria for inspection, also not quite sure what to measure and how to interpret the data.
- Availability of self diagnostic low power systems.
- Conservative audience, without much experience of high tech systems.

Other remarks

Examples:
- Monitoring deck profile, cable load, hanger & deck vibration of bridges.
- Rail Points/switch monitoring: monitoring force required for operation, providing information on health and performance of the points.

Although monitoring the existing infrastructure is far out the biggest market sector, a long term opportunity exists for built-in sensors during construction of the buildings, bridges, roads etc. It must be said that the challenges associated with this are very high, needing extremely robust sensors to withstand the conditions during mixing of concrete, preparing asphalt etc.

An interesting subject could be the learning cycle: information generated by SHM could be used for improvements on design, building practices and materials.

Environment is generally not very harsh.

In some cases imaging systems are an alternative for distributed sensor networks. Fibre optics is a relatively easy installation option for sensor networks and an alternative for wireless systems, but the fibre sensors and cables have to be carefully protected to avoid damage during installation and service life. Fibre optic technology (particularly the signal interrogators) are relatively expensive compared to traditional systems.

Detection of corrosion within steel reinforcement of concrete is possible by applying and detecting electromagnetic signals. This scanning is done by using portable equipment, can be done rapidly and is a non destructive method.

Oil, gas, chemical industry etc.

Market drivers

The Chemical industry is currently looking for ways to extend the life span of older plants. One of the major problems is corrosion, more specifically corrosion under isolation and corrosion of the interior of pipes and tanks. Both need taking off-line for inspection, with consierable associated cost. Even then, the method of regular inspection (for instance the sending of "pigs" through pipes) is not 100% foolproof. Costs are difficult to pin down.

State of the art:

Online pipe wall thickness measurement through isolation.
Fibre optics for remote monitoring of pipelines: optical fibre in armoured cable wound at joints, measures temperature, axial and flexural strain. Extendable to vibration, pressure and leak detection. Intrinsically safe while there is no electrical power needed in the cable. However, easily damaged and relative expensive.

Driving forces for SHM

Extending the life of gas, chemical and power industrial facilities. The majority of the plants have remaining useful life after the designed life span has passed, providing that they are maintained properly. SHM could play an important role here as it can reduce downtime, and it can reduce energy consumption, thus improving business performance.

Risk of environmental damage by leakages of pipes and tanks. Cost of inspection of tanks, which have to be emptied before inspection (disruption of operation, downtime).
Continuous use of older installations.

Key stakeholders / who will benefit?

Asset owners.

Market characteristics

Conservative market

Other remarks

Very strict regulations regarding electromagnetic radiation, sparks etc.

Horizontal issues

- Sensors
  - -Self sustaining, low maintenance, easy to install sensors and sensor networks, also installation of new sensors from different vendors in one network.
  - -There are several applications where a large number of sensors are needed (cost!), these applications need low cost sensors.
  - -How to design and test sensors for a life as long as the monitored structure?
  - -Self diagnostic/self testing devices are needed.
  - -Thin sensors to be integrated into laminated materials.
  - -Methods to verify integrity of metallic and composite structures.
  - -Self testable sensors.
  - -Smart reconfigurable sensors.
  - -Integration of several sensors on one platform (ideally one standardised process). This is very demanding due to the different materials processes currently used for the different sensors.
- Wireless
  - - Installation (wiring) cost is up to 50% of total cost, this is clearly a motivation behind wireless communication, low power devices and energy scavenging. The combination of low power and wireless will lead to embedded data-processing to decrease the amount of energy spend on communications.
  - - Reliability and unauthorized access (industrial espionage, terrorism) are key concerns for wireless communications.
- Communication, networks etc.
  - -Ad hoc networks are needed, where new sensors from different type and manufacturers can be easily added to.
  - -Data fusion (applications able to combine input from sensors locally or from a group, only giving alerts to a higher level if really needed).
- System
  - -Improved robustness.
  - -Sensing and datalogging of history of environmental load.
  - -Onboard or off-board processing – embedded processing? Distributed or centralised? Reducing number of sensors – efficient protocols (network coding).
  - -Standardization of interface and sensor outputs to allow simple exchange of one type of sensor against another.
  - -Integration of signal conditioning circuitry and sensors Smart sensors.
  - -Alarm systems.
  - -Energy harvesting.
  - -Small size to improve accessibility.
  - -Reduced weight, wireless.
  - -System flexibility to upgrade or expand system.
  - -Improved reliability.
- Organisation
  - -Comparative studies to establish variation to base case.
  - -Data security and ownership.
  - -Timely management of data to convert into decisions.
  - -A key issue is the transformation of data, especially a large amount of data into meaningful information. Here the designers, material specialists, sensor experts come together. Each with his / her own language and disconnected expertise.
  - -Whatever solution is proposed, it should include the whole trajectory from sensor development to acquiring meaningful information on which decisions can be made.
  - -Most SHM project are too short to get meaningful data, the needed long term vision conflicts also to the industry short term vision.
  - -Convincing asset owners to invest in SHM is not an easy task; there is a lack of awareness of SHM benefits.
- Visions:
  - Short term vision: use MST sensors and technologies in existing applications.
  - Medium term vision: stick on sensor of the below 10 $ level, autonomous self diagnostic and self sustaining.
  - Long term vision: smart pebbles, intelligent paint, autonomously operating miniature inspection systems etc (‘inspection crawlers”).

• From outside mobile systems, to attached self-sustaining sensor systems to embedded systems.
• Solutions not restricted to damage detection and damage localization, but also providing damage quantification and providing a prognosis of remaining service life. This not only requires specific sensors but also the ability to combine the global structural model with local damage models or fracture mechanics models which can reliably describe the evolution of the damage and its influence on the structural integrity.

A hotspot for early implementation could be places that are difficult to reach or inspect (in airplanes, on offshore windmills etc.). Another area of interest is marine where insurance companies have a strong interest.

Summary

In essence Structural Health Monitoring is about generating data that provides confidence in structural integrity, minimises the risk associated with using the structure and minimise s downtime, enabling safe and cost effective operation. Whatever solution is proposed, it should include the whole trajectory from sensor development to the acquisition of meaningful information on which decisions can be made.

There are 4 levels on the damage assessment scale, where the information associated with the damage increases:

Level I: Damage detection;
Level II: Damage localization;
Level III: Damage quantification; and
Level IV: Prognosis of remaining service life.

Level I only provides information that a damage is present in the structure. For many practical applications this is absolutely sufficient. The challenge for future work is to handle sensitive features and detect low-levels of damage at an early state without getting false alarms and separating the effects resulting from damage from those originating from changes in environmental conditions. Level II increases the knowledge on the damage by determining the location(s) of single or multiple damage sites, respectively. Most methods make use of a structural model to discover the damage location. On level III the extent of damage is evaluated. For this purpose the model must be able to describe the effect of damage (by means of parameters like crack length, size of a delamination or stiffness decrease etc.) on the dynamic behavior. If no such model exists the damage metrics have to be determined by calibration experiments. The highest level and the most sophisticated one is the prognosis of the remaining lifetime. This requires the combination of the global structural model with local continuum damage models or fracture mechanics models which can reliably describe the evolution of damage or fatigue rack growth.

Inspection and insurance are two cost factors that could be lowered in the short term when using SHM, assuming there is confidence in the validity of the information generated and the prediction models.

Aerospace is today the strongest for structural health monitoring. It is expected to continue to lead, especially in the domain of SHM specific sensor development.

Civil engineering could well become the driving force for SHM based on self-sustaining sensor networks. In a general sense, availability is a major driver, besides safety and decrease of maintenance cost. The availability driver is seen as applicable to both intensively used infrastructures such as highway bridges and airplanes, but also periodic systems such as building assessment following earthquakes.

Efficient integration of existing technologies could be a significant advanced in the next 5 to 10 years if appropriate system architectures become available within the short-term..

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We also would like to thank all the other experts who helped us compile the right information and providing us with valuable advice.

Finally we thank the Lancaster University for hosting the first workshop and the Holst Center for offering to host the second workshop.

Appendix 2:

Nexus Structural Health Monitoring Second workshop Report

The second Nexus consultation meeting on “Microsystems for Structural Health Monitoring” was held at Eindhoven June 9th 2008.
As part of an European funded project NEXUSplus, the Nexus Association has invited experts to attend a workshop designed to address the barriers to commercialisation around the deployment of Microsystems within the structural health monitoring market. The first meeting focused on current and emerging markets; the results were presented in an earlier report. The second workshop identified specific drivers and barriers, the results are summerised in this appendix. This report summarizes the findings and translates them into specific recommendations.

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Henne van Heeren
enablingMNT/Nexus Task Force on Structural Health Monitoring
Drakensteynlaan 34
3319 RG Dordrecht
The Netherlands
Tel: 0031 78 6300748
Mobile: 0031 654 954 621
Email: henne@enablingmnt.com
Web: www.enablingmnt.com

Andrew Richardson
Director - Centre for Microsystems Engineering
University of Lancaster
Email: A.Richardson@lancaster.ac.uk

Sean Neylon
Nexus Association/Colibrys
Email: office@nexus-mems.com

Objectives

The goal of this workshop is to identify technical barriers and opportunities to the implementation of Structural Health Monitoring and to table potential solutions to overcoming these barriers. This will be used by the European Commission as input for future calls in the Framework 7 Program. The workshop should build on the market analysis reported from the 1st SHM workshop held at Lancater on April 17th 2008.

Scope of the Workshop

The first workshop focused on Markets, Applications & Business Opportunities although it also identified some technical challenges as input to the 2nd workshop (Eindhoven on June 9th 2008) that will specifically identify where progress is needed to realise technical solutions for markets and applications identified

Contributors

List of attendees

Industrialists

Siro Mancin	AgustaWestland
Jeffrey Sargent	BAE Systems
Matt Mapleston	BAE Systems
Felix Rudolf	Colibrys
Peter Carden	Lloyd's Register EMEA.
Julia Payne	Messier-Dowty
Theo ter Meer	National Aerospace Laboratory NLR
Carsten Heinks	RTRC Germany
Peter Haycock	SciSite/Keele University
Hervé Lançon	Sites
Sophie Costes	Sol Data group

Academic

Chantal Khan Malek	Femto-st, CNRS
Thilo Bein	Fraunhofer Institute for Structural Durability and System Reliability
Erik Puik	Holst Centre / Hogeschool Utrecht
Rob van Schaijk	Holst Centre
Jo de Boeck	IMEC
Bart Onsia	IMEC
Carmen Moldovan	IMT
Bahram Honary	Lancaster University
Sorin Axinte	MINATECH-RO
Matt Mapleston	SEIC
Gert-Jan Heerens	TNO
Peter Kraemer	University of Siegen
Juha Hakkinen	University of Oulu

Workshop Facilitators

Henne van Heeren	enablingMNT
Andrew Richardson	Lancaster University
Sean Neylon	Colibrys & NEXUS

Summary of first workshop

In essence Structural Health Monitoring (SHM) is about extracting and delivering information that can provide intelligence on the integrity of a structure and confidence in its reliability and safety. The data generated by structural health monitors can be used to minimize the risk associated with using the structure, minimize downtime and enable safe and cost effective use.
The solution should in all cases embrace sensor development through to the distribution and processing of data to deliver meaningful information on which decisions can be made.

From the initial meeting, the following areas for Technology Development were identified:

- SHM for civil infrastructure, offshore windmills, aerospace, chemical industry.
- Integrated sensor systems to be used within a wireless network.
- Corrosion sensing in the chemical industry.
- Self-sustaining sensor systems through the use of for example energy scavenging technology.
- Long term visions on SHM: smart pebbles etc.
- Modelling of degradation, prognosis of damage.
- Standards

Aerospace

- Applications:
  - In-flight and ground based health monitoring
- Drivers:
  - Cost effectiveness: reduced ground time / increased airtime of aircraft
  - In flight dynamic measurement
  - Faster evaluation
  - Increased safety/reliability of aircraft
  - Diagnostic to prognostic
- Application segmentation
  - Interconnect reliability and weight
  - In flight monitoring (vibration, stress, corrosion - macro/micro modal analysis)
  - High and low temperature
  - Ground based instrumentation
- Product families
  - Sensors, interconnects, dataloggers, software
- Primary problems
  - Reliable reduced weight wiring
  - Small, low cost, high sensitivity, high reliability sensors
  - High temperature sensors
  - Predictive modal analysis

Geotechnical – Above Surface

- Applications:
  - Dams, bridges, levees, roads, nuclear plants, buildings, ships, oil rigs, oil pipes, wind turbines
- Drivers:
  - Large ageing infrastructure needs prioritized programme of repair, 3400 dams in USA classified to date as 'dangerous'
  - Insurance – Building/Shipping standards & codes exist, seismic survey infrastructure partially established
  - Public safety concerns amplified recently by evidence of non-compliance in China
- Application segmentation
  - External monitoring of environment (temp, humidity, windspeed, vibration – trucks, earthquakes etc)
  - Internal monitoring of effects (cracking, stress, corrosion - macro/micro modal analysis)
- Product families
  - Sensors, dataloggers, interconnects, modal software, data interpretation
- Primary problems
  - Consistent, standard modelling for fixed and variable structures.
  - How to interpret data
  - Significantly more difficult to retrofit into established structures

-Adoption of new interconnect standards: RF; Analog or digital cabling

Geoscience - Subsurface

- Applications:
  - -Subsidence of mines, buildings
- Drivers:
  - -Large ageing infrastructure needs prioritized programme of repair, 3400 dams in USA
  - -classified to date as 'dangerous'
  - -Mining industry safety
  - -Lower cost road maintenance
  - -Increased security in Building construction
- Application segmentation
  - -Subsurface imaging
  - -Radar, seismic, magnetic
  - -Core sampling
  - -GPS, LIDAR surface mapping
- Product families
  - -Sensors, dataloggers, interconnects, software, data interpretation
- Primary problems
  - -Speed of information/Surveying timescales, mobility, robustness, low power, integrated
  - -multi-imaging, precision/resolution

Comments and Suggestions to the First Workshop Report

- Add wireless as a separate item under connectivity.
- Corrosion sensing is an issue for practically all application areas. Might be seen as a horizontal technology.
- It was stressed again that SHM sensors should be more reliable and long lasting then the structure, this might drive a need for sensors designed for reliability.
- Transport: divide into trains, trucks and ships; airplanes are discussed in aerospace.
- A key item is how to move from diagnostics to prognosis, there is a need for algorithms based around pass / fail thresholds that prevent false warnings! There is a need for richer data on which a better understanding of damage can be generated and that can lead to prognostics.
- Environmental parameters including wind, humidity etc. are much easier to detect then internal changes due to damage and degradation effects.
- Cost benefit analysis should be a core component of each proposed project; what are the benefits and how do they compare to to the investment needed.
- New business models are feasible – eg. spare parts with embedded SHM sensors made available. Better planning of spare part stock and direct communication between the structure and an external maintenance organisation!
- Input from SHM sensors can also be used to reengineers parts.
- Fatigue cracking and delamination.
- Three focal area:
  - -Civil engineering and geophysics
  - -Aerospace and other transport sectors
  - -Chemical plants and energy installations
- Include stress induced corrosion.

Discussion on Key Barriers

Aerospace & Transport

Drivers

Sector	Corrosion	Delamination	Stress, strain, load impact	Wear	Electro magnetic stress
Aerospace : cost reduction, simplified systems, safety and environmental concerns, through life management, availability improvement reliable prognostics, increasing service intervals, CO2 reduction, mis-use of storage for hydrogen (and other) fuel cells	In-flight monitoring, aging fleet, reduced inspection time, weight saving, residual life assessment	Weight saving, diagnostics, MEA (embedded electronics)	In-flight monitoring, on-ground (e.g. landing gear), new design rules predictive modal analysis.	Engine maintenance,	Wiring systems monitoring & prognostics
Transport : Ship specific: environmental concerns, insurance companies making SHM obligatory.? Maintenance on demand, new business models maintenance & repair					

Additional drivers:

- Vehicle availability (different to reliability).
- Reliability of the SHM must be more reliable than the system (use confidence at the least).
- Integration of SHM into materials (inc. composites).
- Monitoring environmentally sensitive substances (e.g. propellant).

Generic issues to be considered: data interpretation, power sources, robustness, precision & resolution, integration, prognostics from SHM data.

R&D Challenges to Address Barriers to Commercialisation

- Architectural solutions for SHM concepts.
- Prognostics (sensing, data processing and decision management).
- Physics of failure (especially for corrosion, new materials, active systems).
- Miniaturized and low weight smart sensors for inaccessible areas.
- Network optimisation for distribution and management of SHM data.
- SHM based solution for diagnostics in particular intermittent faults and no-fault found.
- SHM based solutions for reduction of weight and operating costs.
- Support for condition based maintenance.
- Maintenance management based on SHM generated data.
- Reuse of existing functional infrastructure through system optimization processes and new sensor availability (reconfiguration, use of cross-sensitivities, multi-calibration units). Algorithm development and data handling (both built-in and remote).
- System level Security & integrity.
- Use of SHM data for fault tolerance & self-repair & self-heal (solutions for inflatable structures already exists).
- New and re-engineered miniaturized sensors featuring low-power, high reliability and dependability, longevity, reconfigurability (eg. active and passive corrosion sensing).
- Through life support concepts (manufacture to end-of-life).
- Low-power, reconfigurable, miniaturized sensors to expand measurement capability.
- Standardisation initiatives for data communication and storage.

Generic issues

- avoidance of false positives or negatives.
- cost / benefit analysis, services based on SHM data.
- multi-use SHM (assist in production and in-field).
- power management for harvesters and the complete system.
- systems approach.
- reliability of SHM systems.
- safety implications.

Chemical Industry and Energy

Drivers

Sector	Corrosion
Energy : Cost of maintenance and repair, especially for offshore windmills, trend towards off-shore, mis-use of storage for hydrogen	Oil & gas – pipeline environmental / safety – low cost testing of cracking

Additional drivers:

- Ageing infrastructure, extend lifetime.
- Uptime (storage of chemicals, oil, gas, hydrogen).
- Safety, environment (pipelines for the same).
- Hydrogen specifically: less corrosion (only outside), new infrastucture, but high pressure & unproven materials.
- Oil and gas thieving, terrorism, and especially third party contact.
- Vision: Integrate sensors in coatings etc: real time detection of leakages, vibration (accelerometers), smart plasters.
- New laws can become a barrier, e.g. pipeline inspection with pigs.

R&D Challenges to Address Barriers to Commercialisation

- Hydrogen installations, integrity of the structure.
- Third party contact.
- Connection leakage.
- Storage tank corrosion.
- Corrosion of multi-diameter and small pipelines; metallic columns.
- Corrosion outside of metallic structures.
- Water pipelines.

Solutions are needed for:

- Storage tank corrosion without emptying the tank.
- Corrosion of multi-diameter & small pipelines; metallic columns (50% of all pipelines are unpigable).
- Third party contact of installed infrastructure, i.e. existing pipelines.

Civil Infrastructure

Drivers

Sector general drivers	Corrosion	Delamination	Stress, strain, load impact	Wear	Contamination (nuclear)	Electro magnetic stress
Dams, bridges, levees, roads, nuclear plants, buildings, ships, oil rigs, oil pipes, wind turbines, mining industry safety, lower cost road maintenance, Increased security in Building construction, System performance modelling	Ageing infrastructure repair, decreased disruption, discrimination of severity, modelling, different corrosion processes in one model	Wind turbine blades, more ambitious building programs (material monitoring), reinforcement of existing materials	Ageing infrastructure repair, fatigue life assessment, monitoring crack growth, load control in turbines, more ambitious building programs, reinforcement of existing structures	Load monitoring, road infrastructure maintenance, sub-surface erosion	Leakage of hazardous materials, civil confidence, storage tanks, radiation and contamination is different	Radiation induced

Barriers to Commercialization

Corrosion	Stress, Strain, Load, Impact	Contamination (nuclear)
Duplication of costs during qualification of new technologies. Customization for each unique systems. Retrofit different from new systems to have embedded functionality – new load conditions with time (trucks). Existence and accessibility of modelling tools? Lack of confidence in expert free autonomous systems – basis of value proposition	Cost effectiveness of land based systems; regulations do not recognize cost benefits of SHM systems; delay in standards in adopting new technologies. Lack of national regulations. Lack of criteria for inspection. Quantitative not just qualitative. Validation of existing constructions comply with regulations. Cost of interconnectivity. Complexity of interpretation of information – need for data mining and specialists for interpretation. Automated intelligent interpretation. Trustworthiness of algorithms.	Lack of experience to demonstrate integrated SHM systems to demonstrate compliance to off-shore wind turbine systems. Robustness and Reliability of sensors (eg 20 years, underwater for wind turbines)

Other barriers to be considered:

- Diversity in constructions, leading to a high level of customization.
- Regulations do not recognize new ideas.

R&D Challenges to Address Barriers to Commercialisation

Corrosion	Delamination	Stress, strain, load impact	Wear	Contamination (nuclear)	Electro magnetic stress
Create a pan European SHM standardization group	Improved algorithms. Automation data interpretation. Validation of algorithms. Funding for benchmarking of new technologies. More reliable sensors	Reliability testing of energy harvesting systems. New corrosion sensors Lower cost, integrated sensors, self test standardization.	Training courses, dissemination of technologies. Sensors for slow rotation machines	Regulate for SHM in traffic management systems	Energy harvesting and wireless systems in context of power management of entire systems. Roadmap Conclusions

Conclusions

The following focal areas were identified for future or extended use of structural health monitoring:

Application	Driver(s)	Main Challenge	Issues
Offshore windmills	Cost of maintenance	Delamination of blades; integrity of structure (corrosion)	Predictive modal analysis
Hydrogen storage tanks	Safety	Prognosis of integrity of high pressure installation	
Tanks and piping in the chemical and energy industry	Cost of shutdown and inspection	Corrosion inspection in non pigable piping and storage tanks	Existing regulations
Aerospace & transport	Safety, cost of inspection, downtime	Difficult to access area, new materials	Existing regulations
All	Cost of sensor installation and ownership	Integrated sensor systems to be used in wireless networks. Self-sustaining sensor systems through the use of for example energy scavenging technology	Standardization
All	Condition based maintenance, extension of life time.	Modelling of degradation, prognosis of damage.	

Corrosion sensing is an issue for practically all application areas and is considered as a horizontal issue. It was stressed that the SHM sensors should be even more reliable and long lasting then the structure itself, there is hence a need for sensors and sensor systems designed and validated for long term reliability.
A key item is how to move from diagnostics to prognosis, there a demand for algorithms capable of establishing pass / fail thresholds for structures. We have to learn to navigate between safety and many false warnings! There is a need for richer data on which we a better understanding is reached on which we can base prognostic models.

The following general themes were identified:

From diagnostics to prognostics:

-Low cost automated inspection systems for corrosion, specially, but not exclusively, for the chemical and oil & gas industry; the proposed approaches should also include models for the prediction of remaining lifetime.

-Sensor systems for cracking and/or delamination in, for instance, new aerospace materials, off-shore windmills and hydrogen storage/ handling installations, the proposed approaches should also include models for the prediction of remaining lifetime. Proposals could included sensors incorporated in the materials.

• Embedding of reliable sensor systems:

-Zero maintenance, very long life and easy to install SHM systems for infrastructures. Autonomous wireless sensor systems designed and tested for long working life (over 30 years), high reliability and high level of trustworthiness of the data generated. Solutions could include sensors which are integrated into the materials: smart pebbles, asphalt etc.

-Power management friendly systems, wireless systems and energy harvesters fit to be used in the often challenging conditions of aerospace and the chemical industry. Low weight diagnostic systems for in-flight monitoring of aircraft structural elements, using predictive modal analysis. Small and zero maintenance systems for difficult to access area.On top of that we recommend that the following generic issues which should be addressed:

- Modelling and prognosis of corrosion and cracking in a diverse range of applications; physics behind the processes.
- Be not restricted to just condition based maintenance, but also stimulate innovative and holistic ideas to the problem:

-New business models transferring responsibility of uptime from infrastructure asset owners to spare part suppliers, using SHM systems embedded in the spare parts. Suppliers could use information from embedded sensors to reengineer the (sub) system and its components.

- Promote the working together in of material scientists, modelling and simulation experts, hardware suppliers (wireless, energy harvesters, sensors, system design) and application specialists.
- Standardization in data communication, storage and interchange ability, pan European activities to promote the use of SHM by removing barriers, promoting standardization and support adaption of regulation to enable the use of SHM.

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We also would like to thank all the other experts who helped us getting the right information and providing us with valuable advice.

Finally we thank the Holst Center for hosting the second workshop.

• Microsystems research solutions, future partnerships, recommendations for future action
• Meeting outcomes: problems largely in areas of data analysis, interconnectivity protocols,
lack of fixed standard structures leads to fragmented supply, not primarily sensor issues, conservative nature of market means support required for adoption and standards –
• Ambience of meeting: good, animated, interest from participants to continue to do periodically (twice yearly)

Report issued: June 2008

• **Final report issued August 2008.**

In all 38 experts and y enterprises contributed to the two workshops, from 8 different countries from the EC and from across the supply chain – sensor supplier to systems integrators, 16 industrialists and 22 academics. A core of people participated in both workshops to help the consultant retain continuity between the two sessions. Feedback from participants confirmed their interest in the outcome of the workshops, the quality in the methodology of the workshops and an interest to see future such workshops to be held periodically in the future.

Appendix 3:

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Sensors Deliver Real-Time Info on New Minnesota Bridge

Sub-structure, super-structure incorporate strain gauges, accelerometers

Charles J. Murray, Senior Technical Editor -- Design News, September 25, 2008

Using a complex array of more than 300 sensors, engineers say they can now remotely monitor the structural health of the new I-35W bridge in Minneapolis.

The concrete bridge, which replaces the steel spans of the old bridge that collapsed and killed 13 people in 2007, incorporates sensors in the foundation elements, sub-structure columns, main span, box girders, expansion joints, bridge deck and bearings.

The bridge's engineers, Figg Engineering Group, Inc., say they outfitted the new structure with the sensor system because they wanted to monitor its "health" and because they wanted to participate in advanced engineering research on the new structure with the University of Minnesota's Institute of Technology.

"It's unusual to do this on a new bridge, even today," says Alan Phipps, design manager for the I-35W project at Figg Engineering. "Structural health monitoring systems are typically applied to older structures."

Figg outfitted the new bridge with at least six different types of sensors. In all, the company embedded 323 sensors, including: vibrating wire strain gauges in the concrete; temperature sensors on the top of the bridge deck and on the underside of the bridge; accelerometers to measure forces near the center of each box girder span; long-gauge strain gages in the main span; linear potentiometers to monitor movement of the expansion joints and bearings and embedded corrosion sensors to monitor corrosion to the reinforcing bars at various depths of the concrete.

"Minnesota uses a lot of salt, so the top 2.5 inches of the wearing surface is intended to be replaceable," Phipps says. "It's like the shingles on your house; eventually you have to put a new roof on."

Figg worked with sub-contractors to outfit the bridge with the sensors. Roctest Telemac provided wire strain gauges, temperature sensors and corrosion sensors. Accelerometers came from Minnesota Measurement Engineering.

Engineers can monitor the strains in the bridge in real-time over the Internet. All 323 of the sensors are connected by wire to a central computer, which collects data and stores it. The sensors made their debut recently when the Department of Transportation placed eight 25-ton trucks in various patterns atop the bridge deck and then monitored strains on the central computer.

University of Minnesota engineering professors are said to be interested in examining the effect of temperature differentials between the top of the bridge – which can be exposed to sunlight – and the structure's underside, which is in the shade and faces down at the river below.

"This is just a way of starting off on the right foot with this new bridge," Phipps said. "It provides information on how to maintain the bridge, starting with Day One. We think this kind of structural health monitoring is going to become more and more common in the future."

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