Development of a Wireless Network with Autonomously Powered and Active Long Range Acoustic Nodes for the Structural Health Monitoring of Bridges

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ABSTRACT

Maintaining the structural integrity of safety critical items of bridges becomes increasingly difficult as they age. A vital part is the periodic inspection for detecting defects such as fatigue cracks and corrosion that are not always visible to the typical manual and visual inspections alone but may lead to catastrophic failure. There are several aspects that need to be considered in periodic inspections using normal techniques only; defects may grow to failure between inspections, access to conduct the inspection may be poor and it may be difficult to determine the significance of any defect that has been detected – is failure imminent or can the defect be left until a more propitious time for repair?

There is therefore strong interest in replacing periodic inspections with continuous structural health monitoring (SHM), with networks of sensors that are permanently installed on the structure and sensitive to the defect. Where these structures are very large, wireless sensor networks offer significant benefits.

Such interest has led to a consortium of small-to-medium sized enterprises to sponsor research with support from the European Union's FP7 research programme to develop a wireless sensor network for SHM of bridges. The 2-year project commenced in October 2011 is called 'Wi-Health'.

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The proposed sensor network will be multi-purpose. The acoustic emission (AE) that are a consequence of active defect growth will be detected by sensors in network nodes permanently installed at damage-prone areas of the bridge such as welds, plates and expansion joints. The AE will be used to activate ultrasonic guided wave (UGW) transducers at the same nodes that will insonify the source of the AE in such a way that UGW reflections can be used to determine the nature, size and exact location of the defect. This information is needed to assess the defect in terms of the structure's fitness for purpose. As data streams are very dense, they will have to be processed and reduced by an order of magnitude in a central processing unit (CPU) at the network node before being transmitted wirelessly. Innovative embedded software will be able to drive the structural health monitoring system for defect identification by incorporating the use of trend analysis and data processing.

This paper will describe how the project intends to approach the expected technical challenges throughout the development and by the time of its presentation may be able to offer some of its solutions.

INTRODUCTION

There are many promising SHM technologies applicable to a variety of civil and defence infrastructure. Most use expensive components, bulky equipment and have power requirements which prevent permanent, ubiquitous installation at remote locations; they are inspection rather than monitoring technologies.

One such promising technology is the use of small, cheap, piezoelectric transducers to listen to structural elements for acoustic energy generated by fatigue and corrosion crack propagation within the element. If acoustic energy is injected into the transducer or array of transducers, a larger range of investigations becomes possible by examining the energy reflected by, and transmitted through the features in the structural element. Modal analysis and tomography may reveal the presence, size and location of the features of the element[1]. The quality and quantity of information that can be delivered by this technology and the cost of the components make it very attractive for structural health monitoring.

Current commercial AE monitoring equipment usually involves several transducers, each with an integral pre-amplifier, long copper cables from each transducer to carry power and signals and a bulky multi-channel acquisition and processing system. The integral pre-amplifiers are expensive and power consuming as they are required to continuously transmit, with high fidelity over long distances, analog signals from the transducer back to the data acquisition system. The bulky and expensive acquisition system needs to be carefully situated away from the potentially exposed transducers to avoid damage. The installation of the long, expensive copper cabling for signal and power transmission is, itself, very costly.

An autonomously powered AE monitoring system without power cabling and with very much reduced signal cabling should be simple to install at locations including remote or inconvenient locations and considerably cheaper to purchase than existing commercial systems[2].

Further cost and power budget reductions might be achieved by distributing the acquisition electronics out to the transducers so that the pre-amplifier is eliminated and the signals from the transducers are immediately digitised. If the distributed acquisition electronics are able to identify and isolate AE events, the information rate from the transducers is radically reduced. Many transducers would then be able to operate in concert on a single digital network without saturating it.

The value of the system might be increased, at marginal cost, by making the transducers active so that detection, sizing and location of defects might be possible rather than simply measuring the activity of defects.

This is the motivation for the Wi-Health project.

DESIGN

Smart Sensors

Only recently have microcontrollers become available which are capable of satisfying the needs described above e.g. the ARM Cortex™-M4 and the many manifestations thereof from NXP, STMicroelectronics, Atmel, Texas Instruments, Freescale et al. The architecture allows code execution at considerable speed with DSP capabilities while consuming minimal power.

In addition, some of the manifestations of the ARM Cortex™-M4 have integrated peripherals of particular utility for this project. Integrated high speed 12bit ADCs on the STM32F407 series of microcontrollers from STMicroelectronics have sufficient resolution and speed to be used for acquisition of acoustic emissions and Lamb wave signals from heavy steel up to lighter aluminium plates. The DMA controllers allow continuous signal acquisition into a ring buffer while the analog watchdog feature provides an interrupt on threshold transgression e.g. the arrival of an AE signal. All of this occurs without the involvement of the CPU leaving it free to process identified AE events while more signals are acquired.

The array of interfaces available in this range of microcontrollers provides wired connection options i.e. the controller area network (facilitates an attractive, low cost bus network[3]) and Ethernet, but also SPI interfaces to allow connection of commercial wireless devices e.g. the CC2520 from Texas Instruments and temperature measurement peripherals.

Synchronisation

Synchronisation is important for exploiting many of the techniques that employ AE signals and Lamb wave signals.

On receiving an AE burst, the relative time-of-arrival information for a sparse array of transducers facilitates a calculation of the position of the point from where the burst emanated. The technical challenges associated with synchronisation have led to systems which simply acquire event intensity information[4].

Many guided wave techniques require synchronisation of Lamb wave excitations and signal reception e.g. the phased array technique [5].

The STM32F407 range of microcontrollers provide peripherals for wired time synchronisation (time triggered CAN and the Precision Time Protocol). Low accuracy synchronisation is also useful for correlating AE events with other structural health measurements e.g. transient loading. Time information e.g. DCF77 signals, can be acquired through one of the many microcontroller interfaces.

We have developed a technique to distribute time information which can be acquired simultaneously with the acoustic signals i.e. clocks local to the transducer need not be synchronised. The signal is a single bit binary stream and can be distributed over unidirectional wired or wireless links. This facilitates AE signal triangulation and phased array techniques not requiring synchronised transmission e.g. the TFM[6] and the EUSR[7] techniques.

Modular Design

Figures 1 and 2 show two manifestations of the system where the connection between the smart sensors and the node is either wireless (802.15.4/ZigBee) or wired (controller area network) respectively.

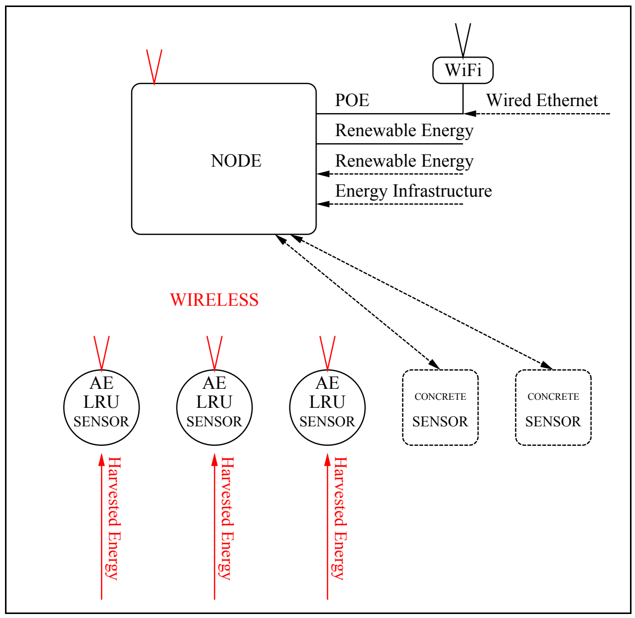

Figure 1.

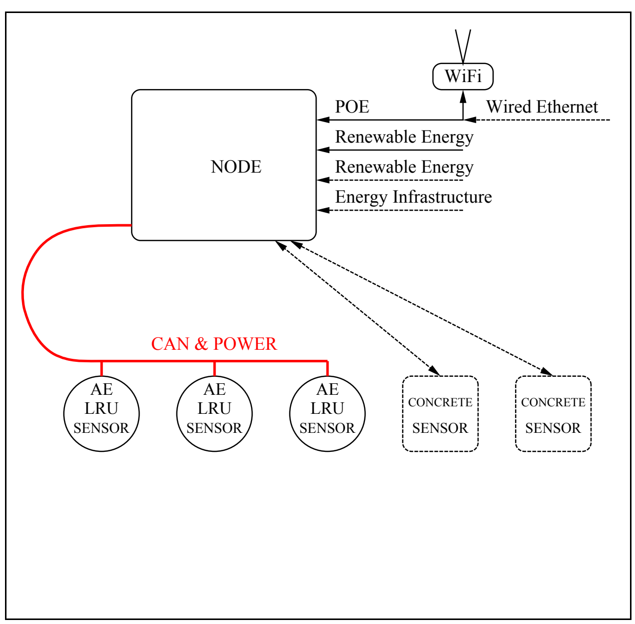

Figure 2.

Inter-sensor communications and power

Where energy is abundant and simple to harvest, throughout the area that the system will monitor, the wireless sensors are the preferred manifestation, despite the increased cost of the wireless interface and the increase in power consumption associated with continuous communication and synchronisation over the link. The consortium chose the 802.15.4/ZigBee wireless standard because of its suitability for wireless sensor networks, established utility and hardware availability.

If energy needs to be supplied to the sensors via cabling, the same cabling should be used for communication. The controller area network is a bus network so that the system will still realise the suggested cabling cost reductions and reduced power supply requirements, especially when monitoring long linear structures e.g. suspension cables.

Acceptable synchronisation over the wired or wireless networks is still a challenge but the consortium believes that the networks and integrated microcontroller peripherals will support this. The time distribution technique mentioned earlier may be required as a contingency.

Inter-node communications

The consortium chose to use 802.11g based wireless communication technology for medium and long range communications between nodes and also the base station; the conduit for information moving between the structure and the outside world. The technology is attractive because of its wide application, low cost, availability of hardware, proven mesh establishment and routing protocols and ability to communicate over long ranges, especially with a directional antenna.

A permanently maintained 802.11g wireless mesh network across the structure would unnecessarily consume energy. The consortium believe that the network need not be maintained permanently but be periodically established under the control of the node. The data reduction courtesy of the smart sensors and the high bitrate of 802.11g should facilitate this. Each node will maintain a sufficiently accurate clock so as not to require continuous synchronisation with the outside world. High accuracy synchronisation or time distribution is only necessary within the sensor network.

Inter-node communications are often subject to similar challenges to those described for the energy harvesting; the immediate environment being monitored is not ideal for inter-node communication but an ideal antenna position is often close by. The consortium chose to separate the 802.11g implementation from the main node with an Ethernet connection to allow mounting of antennae and radios in an optimal position. There is another advantage to this separation: the Ethernet interface allows the node to take advantage of existing network infrastructure in some structures.

Energy harvesting

The consortium is investigating a variety of energy harvesting and energy storage systems but is currently planning to use modern, established photo-voltaic, wind turbine and accumulator technologies.

The consortium has identified that structures to be monitored are often shielded from, but very close to, sources of harvestable energy. The Humber Bridge is a case in point. Systems which monitor the internal structures of this suspension bridge are able to be powered by harvesting wind and solar energy outside the sections of the bridge. The proposed wired manifestation of the monitoring system is most suitable for this application.

By separating the energy harvesting sub-systems from the main monitoring node, the system is also able to take advantage of power networks which are already installed in some structures.

Reinforced concrete monitoring

The monitoring node will have several serial communications interfaces to allow connection of established reinforced concrete monitoring technologies[8] and newer corrosion detection technologies[9]. In those reinforced concrete structures where the smart sensors would be of limited utility, the main node, managing energy generation, storage and medium-to-long range wireless communications, would still be applicable.

Software

The following is a brief summary of the activities in each of the processing centres of the system.

Smart Sensor

- On acquisition of an AE burst, establish time (copy of internal clock or decoded time from acquired signals) and store.
- Examine list of pending stored events and schedule transmission over the network.
- Periodic synchronisation of internal clock with that of the node over the network.
- Management, storage and possibly calculation of arbitrary waveforms for guided wave inspections.
- Storage of received signals from those guided wave inspections with a time reference.
- Management of sampling rate differences between smart sensors.

Node

- Energy store management and scheduling of tasks e.g. guided wave inspections, establishment of 802.11g mesh, according to energy available.
- Maintenance of the reference clock for the system, synchronisation with sensors and synchronisation with external time references e.g. NTP over Ethernet and DCF77.
- Storage and compression of data prior to transmission over the 802.11g mesh.

Base station

- Collection, processing and correlation of AE bursts from each of the sensors connected to a node. Storage of the data.
- Monitoring of burst intensity, 3D representation of location of transgressions of AE burst intensity thresholds.
- Scheduling of guided wave inspections according to AE activity and creation of experimental variants as required.
- Time correction of acquired guided wave signals, compensation for temperature. Implementation of detection and tomography algorithms. Storage of data for historical and difference methods.
- UI to correlate AE intensity and defect size trends to dynamic loading of the structure.

802.11g Network

- Establishment of mesh – dynamic to cope with loss of a node.
- Security and intrusion detection.

CONCLUSION

The consortium believes that the espoused architecture is a realistic basis for future work.

The continued staged development, implementation and testing of the hardware will soon support testing of the accuracy with which AE bursts can be triangulated in the orthotropic stiffened steel plate road deck of the Humber Bridge. Meanwhile, investigations into suitable guided wave modes for defect detection and tomography within the decks will inform the final active transducer design and excitation electronics.

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REFERENCES

1. Giurgiutiu, V. (2008) Structural Health Monitoring with Piezoelectric Wafer Active Sensors, Academic Press, 747 pages, ISBN 9780120887606.
2. Matta, F., Ziehl, P., Ozevin, D., Inman, D., Giancaspro, J., Metrovich, B., Nanni, A., Caicedo, J., Gassman, S., Giurgiutiu, V., Huynh, N., Yu, L., Zarate, B., Godinez, V., Gostautas, R., Momeni, S. and Priya, S., "Self Powered Wireless Sensor Network for Structural Bridge Health Prognosis: A 5-Year Research and Development Project for Infrastructure Sustainability," Proc. 7th International Workshop on SHM., Vol. 2, 1747-1754 (2009).
3. Yong-Jae Eum, Min-Cheol Lee, Communication of system based on CAN for acoustic emission diagnostic, Control, Automation and Systems, 2008. ICCAS 2008. International Conference on, pp 1789 – 1792.
4. Sebastian A. Bachmaier, Event-based Acoustic Emission Technique for Structural Health Monitoring using Wireless Sensor Networks, NDT.net - The e-Journal of Nondestructive Testing (December 2008).
5. Fromme, P, Wilcox, PD, Lowe, MJS & Cawley, P. A guided ultrasonics waves array for structural health monitoring, Annual Review of Progress in QNDE 2005.
6. C Holmes, B W Drinkwater and P D Wilcox, The post-processing of ultrasonic array data using the total focusing method, Insight, 46(11), 677-680, 2005.
7. Victor Giurgiutiu∗ and Lingyu Yu, Embedded Ultrasonic Structural Radar with Piezoelectric Wafer Active Sensors for Damage Detection in Cylindrical Shell Structures, 45th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics & Materials Conference and 12th AIAA/ASME/AHS Adaptive Structures Forum, Palm Springs, CA, 19-22 Apr. 2004.
8. Birit Buhr Jensen, Keld Schultz, Frits Gronvold, Management System for Corrosion Monitoring in the Copenhagen Metro, Corrosion 2010, March 14 - 18, 2010 , San Antonio, TX.
9. L . J . North , P . W . Haycock , S . R . Hoon , S . L . Sherratt , and N . J . Cassidy, A Ferromagnetic Resonance Probe, Concrete Solutions, CRC Press 2009 ISBN: 978-0-415-55082-6.