Strategies for Wireless Intelligent Sensing Devices (WISDs)

N.A.J. Lieven*, P.J. Escamilla Ambrosio, S. Burrow and L. Clare

Abstract

The development of Wireless Intelligent Sensor Devices (WISDs) has led to significant experiemental and computational challenges. This paper descibes the development of low cost, self powered, wireless sensors with built-in intelligence capable of withstanding harsh environments, initially to be deployed for aerospace and automotive applications.

The scope of the paper encompasses the integration of key technology developments: sensors; energy efficient data processing and feature extraction; power scavenging; and, information communication between distributed elements using telemetry. Clearly it would be an abmitious task to cover all of these technologies in one paper, so we will three elements of research which are pertenent to the successful outcome of the work. Thus the paper outlines progress made by the authors in:

(i) Intelligent Active Sensing;
(ii) Statistical Pattern Recognition and Machine Learning; and
(iii) Energy Harvesting.

The primary aim of this paper is to discuss some of the issues which are of direct relevance to constructing and operating wireless sensor within harsh environment.

Introduction

Current designs of sensor networks typically relay information via a wired array to a central monitoring/acquisition facility. With the increasing complexty of structures and sensing arrays we are faced with oppressive data handing requirements and sensor networks which - due to their complexity – are prone to be less reliable than the systems they are required to monitor.

The move towards wireless data transmission raises new challenges for technology. In essence the robust tranmission of data via a wireless protocol is well established. However, streaming data from multiple sensing devices demands a significant power requirement, and also presents a data manangement challenge. The two key technologies which address these issues are energy harvesting and feature extraction. For a sensor to be truly wireless it must be able to operate autonomously and be independent of a wired power source (why transmit power through a wired link if the same link can be multiplexed to provide data transmission?). Furthermore, if data are to be sent wirelessly then there is a related required to reduce power demand. The most common strategy is to transmit data from the sensor node to a central monitoring point. This approach allows collection of all information for further processing and identification of feature which indicate a fault or deteriation of a component or system. The drawback of this method is that for the majority of the operation of the sensor, it is

*Corresponding Author: Head of Department, Department of Aerospace Engineering
University of Bristol, Bristol BS8 1TR,UK
Email: nick.lieven@bristol.ac.uk

streaming information which simply indicates that the system is functioning normally. Thus this information is redundant. The approach now being adopted by the health monitoring community is to process the the data locally and only transmit when a change is detected [1]. This form of data condensation and feature extraction is therefore ideally suited to wireless sensing applications.

Thus the complete system architecture for an intelligent wireless sensing system has three components:·

(i) self-powered, low-energy sensors with in-built computational intelligence to undertake local data processing, feature extraction and decision-making.·
(ii) embedding intelligent sensor systems within and throughout structures; and·
(iii) extraction of information, via a local microwave network, about health and remaining life of structures, collected at a central monitoring unit.

In its fully operational form, output from the intelligent sensor system will be coupled with adaptive fracture mechanics modelling and risk assessment to allow accurate computation of the structure's new state and provide the user with a prediction of the structure's remaining useful life on demand.

The key technological advance in WISDs is the ability of these devices to make decisions, not simply stream raw data. By making these devices self wireless, WISDs will be able to act autonomously and be triggered remotely to provide an intelligent assessment of the state of the structure.

The outcome of the development of WISDs is specifically to reduce the cost of ownership and improve reliablility of safety critical and/or high value products.

The primary objective of the programme is to demonstrate the technology of WISDs for aerospace and automotive applications. However, prognosis and health monitoring of civil, nuclear and petrochemical industries would also benefit in the longer term, with increasing demands for environmental security

Rationale for WISDs

The key attribute of WISDs is that they should provide only *relevant* information to assist damage prediction models. As stated earlier, this is the key difference embodied within WISDs, they have built in feature extraction that determines the state or change in the structure, before transmitting information to offline damage assessment models. Taking the aerospace industry as a sample industrial sector: the impetus for WISDs from airframe and engine manufacturers for effective health monitoring has been motivated by "power-by-the-hour", whereby manufacturers charge for usage and meet the cost of maintenance themselves. The escalating cost of aging aircraft is not simply restricted to the civil fleet. The US Air Force, through its Engine Rotor Life Extension program (ERLE) expects to commit 63% of its capital budget on sustainment and 16% and 18% respectively on development and acquisition [2]. On this basis alone there will be a major thrust in the next few years in the aerospace industry to reduce costs on maintenance. The current health monitoring approaches concentrate on safety critical components on the aircraft e.g. failure through disc burst results in catastrophic loss of the engine at best, or the aircraft at worst. Guidelines outlined by Larson and Russ dictate that a disc is discarded on the probability of a one in one thousand chance of failure after inspection (n.b. the cost of one disc is £200k-300k). In this case the probability is that 999 discs are being discarded before they have reached their full safe operating life. On this basis the minimum component cost saving – excluding benefits derived by reduced maintenance and inventory - achieved by even a 10% increase in life due to improved prognosis methods is up to £20m for 1000 discs.

In the civil engineering field the driver for prognosis is largely governed by large-scale discrete events rather than incremental degradation. Typical examples are aerodynamic gust loads on long span bridges and earthquake loading on buildings. Although, cyclic load caused by traffic is also a consideration it is the discrete events that require immediate prognosis for future use. Using the Kobe earthquake as an example, some buildings were subject to two years scrutiny before a decision was made on their future use or demolition [3]. Clearly this delay had a significant commercial impact on the economic capacity of the city beyond the reconstruction costs. In California the most densely instrumented building has ~75 sensors to measure seismic response. For damage detection a first or second order of magnitude increase in density is required. This increase can only be achieved economically by the use of COTS wireless self-powered embedded devices.

Perhaps the most advanced and scrutinised health monitoring systems are used in helicopters. A comparison between WISDs and existing HUMS systems for rotorcraft will be the primary industrial outcome of the project. Health and Usage Monitoring Systems (HUMS) have already been operating successfully in transmission monitoring and engine applications. Their effectiveness and reliability has been endorsed by the CAA and FAA and are now being considered for more general structural health monitoring. The most recent costs for implementation of whole vehicle HUMS depends on the level of coverage required Forsyth (2001), but current bespoke systems are >£250k. Although the cost of these units would fall by adoption of Commercial Off the Shelf (COTS) Forsyth identifies the data management as the largest single cost on some systems. This is significant in that Forsyth acknowledges that “considerably more data” would be required for robust verification of parameters needed for prognosis. Currently such systems are used for an indicator of damage. The options for prognosis have not been fully explored though HUMS, but the achieved life extension from the current implementation of usage monitoring of 73 Sructurally Significant Items (SSIs) has led to cost savings on replacement parts of £125/hour of operation, excluding the savings associated with installation and removal of components [4]. By using multi-channel component usage monitoring White reports an average increase in available structural fatigue life of 380% over the original design life.

Scope

Clearly the task of describing intelligent health monitoring and prognostics cannot be given justice in a short paper such as this. However, the elements of Data Interrogation i.e. what intelligence is it appropriate to build into a WISD and how power can be delivered remotely are keys to successful operation. It is these two aspects on which the paper will concentrate.

Data Interrogation

The term data interrogation is described by the two processes of feature extraction and statistical model development for feature classification. They are the essential components of a Structural Health Monitoring (SHM) System needed to convert the sensor data into useful information about the structural health condition

Feature extraction: Feature extraction is the process of identifying damage-sensitive information from measured data. A damage-sensitive feature is some quantities extracted from the measured system response data that is correlated with the presence of damage in a structure [5]. The main objective of the feature extraction process is to extract damage-sensitive features that change in some consistent manner with increasing damage level. Ultimately, the goal is to accurately distinguish a damaged structure from an undamaged one based on the extracted features. Two alternative feature extraction methods have been mainly proposed in the SHM literature, model based and waveform based. The model based feature extraction method consists on fitting some model, either physics based or data based, to the measured system response data. The parameters of these models or the predictive errors associated with these models then become the damage-sensitive features. Alternatively, the waveform based approach extract features by directly comparing the sensor waveforms or spectra of these waveforms.

Statistical model development:
This process is concerned with the implementation of the algorithms that analyse the distributions of the extracted features in order to determine the damage state of the structure. The algorithm used to perform this task can be categorised into three types: (1) Group Classification, (2) Regression Analysis, and (3) Outlier Detection. The selection of the appropriate algorithm to use depends on the data available. For example, algorithms performing supervised learning can be applied when examples of data are available from damaged and undamaged structures. If data were available only from the undamaged structure, then an algorithm implementing unsupervised learning would be more adequate. The statistical models are typically used to answer a series of questions regarding the presence, location, type and extent of damage.

Inherent in the data acquisition, feature extraction and statistical model development sections of the SHM process are data normalisation, cleansing, fusion and compression [5]. Under the context of SHM, data normalisation is the process of separating changes in sensor reading caused by damage from those caused by varying operational and environmental conditions. Data cleansing is the process of selectively choosing data to pass on to, or reject from, the feature selection process. Data fusion is the process of combining information from multiple sensors in an effort to enhance the fidelity of the damage detection process. Data compression is the process of reducing the dimensionality of the data, or the feature extracted from the data, in order to facilitate an efficient storage of information and to enhance the statistical quantification of these parameters. These four activities can be implemented in either hardware or software and usually a combination of the two approaches is used.

Thus, by embedding the common elements of data interrogation locally within the WISD provides the ability of these devices to make decisions, not simply stream raw data. By making these devices wireless, WISDs will be able to act autonomously and be triggered remotely to provide an intelligent assessment of the state of the structure. The work developed by the authors employs the concept of Fuzzy Associative Memory (FAM) for the prognosis of remaining life in helicopter rotor components. The specific example demonstrated in the paper through both experimental and theoretical modelling is that of a helicopter rotor tie-bar (see figure 1)

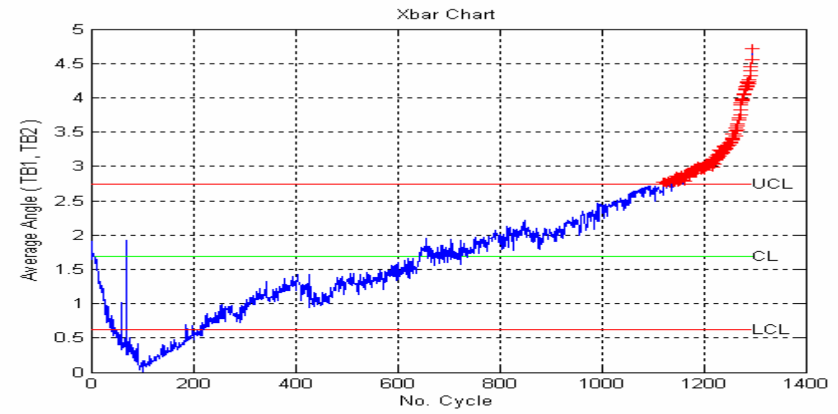


Figure 1 Life prognostics using FAM (test data).

Figure 1 shows the use of outcome of the FAM approach on lab based load/deflection tests on a tie bars in which the Upper Control Limit (UCL) defines the point at which the component should be taken out of service. In this case the prediction allows 100 cycles of safe operation before ultimate failure.

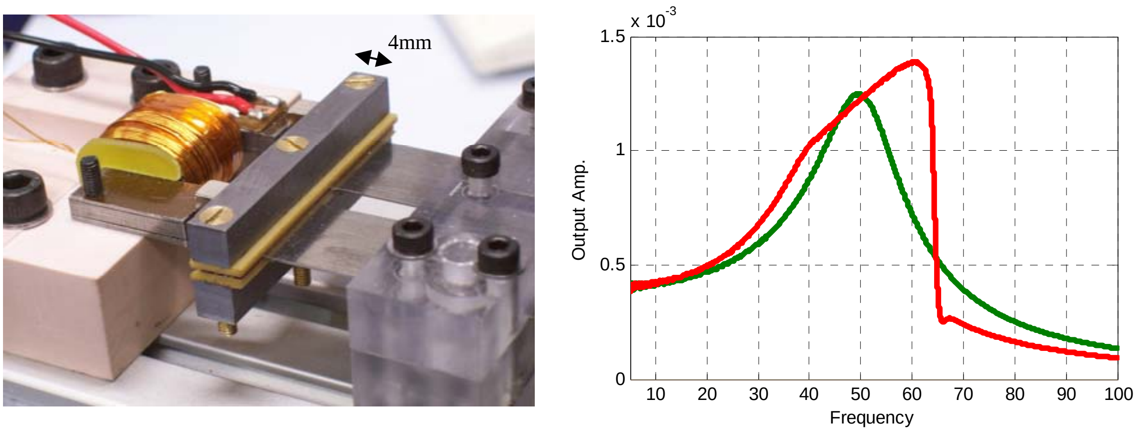
Energy Harvesting

It is the combination of appropriate sensors, micro-power signal processing, efficient & robust wireless data transmission, together with energy harvesting to enable self powered operation which brings innovation to WISDs. The particular attribute in the rotorcraft environment which enables energy harvesting is vibration; there is a certain irony that this source of energy is also the prime cause of damage accrual in the aircraft.

The environment local to the WISDs sensors is characterised by relatively high levels of vibration compared to other typical energy harvesting applications [6] and with a fundamental frequency of typically a few tens of Hertz. Significant harmonics are also present caused by the interaction of the rotor blades and the body of the rotorcraft.

The main hurdle to the implementation of a system where the power requirements are met fully by energy harvesting is the time domain mismatch between power demand and availability. The most obvious example of this is operation of the WISD when the rotorcraft is stationary. To overcome this limitation the WISD system uses an intelligent hybrid power system featuring a chemical storage battery. The capacity of the battery required for WISD is considerably less than that required for a battery only solution.

The design of the WISDs energy harvester follows the conventional resonant mass/spring arrangement, utilising electromagnetic coupling to damp the oscillation and hence generate electrical power. The high levels of vibration levels of the application have been exploited by developing a harvester with magnetically permeable materials in the stator: typically resonant energy harvesters use air-cored stators to reduce reluctance effects and magnetic losses. Through careful design, the use of an iron-cored stator has increased the power density of the device whilst minimising the negative effects: in this application vibration is abundant so losses are less significant, and effect of variable reluctance (which is seen as a non-linear compliance element by the mechanical system) has been exploited to soften a much stiffer mechanical spring, resulting in a robust device. The non-linearity introduced to the compliance also results in a wider frequency response and an output less sensitive to variation in excitation amplitude, Fig. 2. A resonant harvester of this type is more fully reported in [7]



a) Prototype resonant generator, showing iron on armature and stator

b) Frequency response of energy harvester compared to simple linear resonant mass/spring

Fig.2 *1st Prototype energy harvester and frequency response characteristic*

With the hybrid power system it is important to ensure that the power produced by energy harvesting is utilised efficiently and to this end research has been carried out into optimum power conditioning strategies. The challenge is to design systems that improve the utilisation of the energy harvester but at the same time do not consume such power as to negate the advantages.

Concluding Remarks

This paper has outlined some of the key design and operational constraints for future autonomous wireless sensors. The principal application for the techniques described in the work is for rotorcraft components operating in the rotating frame. Two specific technological challenges have been discussed which are key attributes for future WISDs namely: data interrogation and self power generation. The outcome of the work is to produce robust sensors which are able to classify changes in performance of local components through embedded intelligence.

Acknowledgements

The authors would like to thank the UK's Department of Trade and Industry for its funding for this work (see: http://www.dti.gov.uk/innovation/technologystrategy/successful_projects/page11996.html#_Toc93199511) and AgustaWestland, SEA and TRW as research collaborators and co-funders.

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