WISD: Wireless sensors and energy harvesting for rotary wing aircraft Health and Usage Monitoring Systems

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Abstract - The WISD project (Wireless Intelligent Sensing Devices) is a collaborative industrial/academic project developing wireless sensors for Health and Usage Monitoring (HUMS) on helicopters, and in particular sensors attached to rotating components. The project is led by Agusta-Westland with partners TRW Conekt, SEA (Systems Engineering and Assessment Ltd) and the University of Bristol. The project was funded through the UK government DTI Technology Programme (now TSB). As the project nears completion, this paper reviews the goals and achievements including: energy harvesting and power system, low power sensing, data processing, system architecture, implementation and flight trial of the devices.

I. Introduction

Rotary wing aircraft have many components that are highly stressed and safety critical. The safety margins that are currently applied to such components contribute greatly to the cost of operating rotorcraft, and hence techniques of health and usage monitoring (HUMS) and subsequent lifetime prediction are seen as key future technologies. HUMS are in turn greatly facilitated by wireless sensing, eliminating wiring harnesses and allowing measurements to be taken in the most inaccessible locations such as the rotating parts of the rotorcraft without the need for slip-ring connections, illustrated in fig.1.

Some of the greatest technical hurdles to implementing truly wireless sensors are associated with the power supply to the remote system components. Whether battery powered or powered from a more esoteric source, such as an energy harvester, the overall system must be optimised for low power operation or the power supply becomes physically too large or of insufficient capacity. The helicopter environment features large amounts of vibration and thus presents an ideal opportunity to explore energy harvesting alongside a conventional storage battery. The helicopter environment has a wide spectrum and relatively high levels of vibration compared to applications where vibration energy harvesting has been previously proposed.

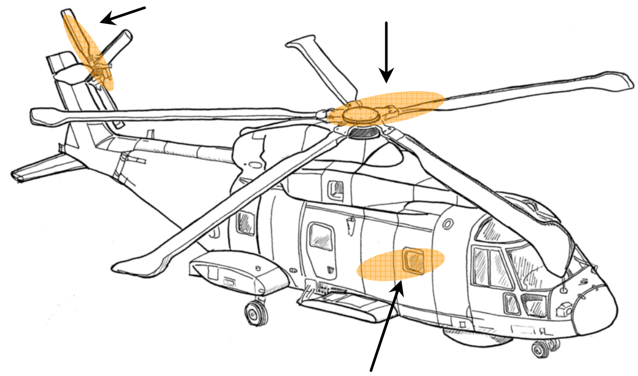


Fig. 1. Sketch showing how safety critical parts of a rotorcraft structure could be monitored with a wireless sensing system, particularly when the components to be monitored are in difficult to reach locations such as the rotor head.

Central to the WISD project is the concept of minimising the power consumption of the wireless sensing module by performing data processing locally, within the wireless sensing module itself. Transmitting the wide-bandwidth raw data required for many HUMs applications back to a base station for processing results in significant power consumption in the sensing module because of the high power required to broadcast data; however, it has been suggested that if the raw data is processed within the sensing module, and simple signal indicating the health of the component under observation is transmitted, then the sensing module will consume less power, computational operations being less power hungry than data transmission [1]. It follows from this argument that the most power efficient architecture for wireless HUMS would feature a wireless sensing module with local intelligence, hence ‘WISD’. In addition to considering the distribution of the data processing, the desire for low power operation also suggests that some operations, such as filtering, should be done in the analogue domain, where they can be performed with minimum power consumption.

II. Aircraft Health Monitoring

A. Background

Many components on aircraft have a limited wear life and are assigned a usage envelope based on a combination of testing and experience. This approach necessitates a servicing and maintenance regime that requires checking and replacement of components on an elapsed time or flight hourly basis with assumed wear rates based on 'typical' usage. In many cases the actual wear of the component will not correspond to this assumed usage pattern, requiring considerable excess margins to be built into the design, operation and maintenance. As a result many components are scrapped long before the end of their useful life, and many extra man-hours spent on maintenance.

Health And Usage Monitoring (HUMS) methodologies offer an alternative strategy. Ongoing measurement of instrumented parameters on critical components or assemblies during operation provides operational data. A wide range of parameters might be usefully monitored, typically vibration, acceleration or strain on aircraft mechanical components; for some applications temperatures, pressures, flow rates and other parameters would be relevant.

Measuring actual usage of components offers significant advantages over assumed usage. Monitoring of actual rather than assumed usage will warn of inadvertent operation close to or beyond maximum limits: for example aircraft operation in turbulent conditions might briefly produce excessive strains that are difficult to detect without instrumentation. The number of fatigue cycles a component is subjected to depends on operating conditions, not just flying hours.

In addition, monitoring of parameters such as vibration may be used to directly determine the state of wear of certain components and warn of the need for replacement, independent of assumed or actual usage. Potentially this might also detect manufacturing or similar defects that might shorten a component's life.

In order to replace traditional component lifetime determination HUMS must provide extremely reliable data and it is likely that there will be some degree of transition from one methodology to the other. For long term usage the components of the monitoring system must have minimal power consumption either to give extended battery life or to make energy harvesting feasible.

B. Feature Extraction

The implementation of HUMS can be summarised into the four-step flow chart shown in fig. 2. Feature extraction is the process of identifying damage-sensitive information from measured data. A damage-sensitive feature is some quantity, extracted from the measured system response data that is correlated with the presence of damage in a structure. 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 distinguish a damaged structure from an undamaged one based on the extracted features in a robust and accurate manner.

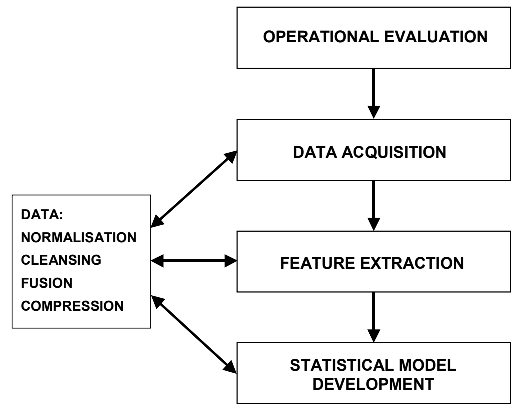


Fig. 2. Flow chart showing the principle data operations for the implementation of a health monitoring system [2].

Two alternative feature extraction methods are commonly proposed in the 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.

C. WISD example applications

Fig. 3a illustrates one target application of the WISD project system. The Lynx helicopter main rotor utilises a flexible cruciform, by monitoring the number and magnitude of the strain cycles this component experiences a cumulative damage figure can be determined. This figure could give a more accurate measure of component fatigue compared to estimation based on flying hours: for instance by taking into account effects such as flapping of the blades due to wind whilst the aircraft is stationary.

Fig. 3b illustrates a second target application, monitoring wear in a bearing surface. Similar to a 'knock sensor' in a combustion engine, sensors measuring strain in the component near to the wear surface will show a change in harmonic spectrum when the bearing is undergoing the cyclical loading cycles experienced in normal operation.

Fig. 3. Main rotor hub of a Lynx helicopter, made up of flexible and jointed components. The WISD project sought to measure the cumulative bending stress experienced by the flexible centre cruciform.

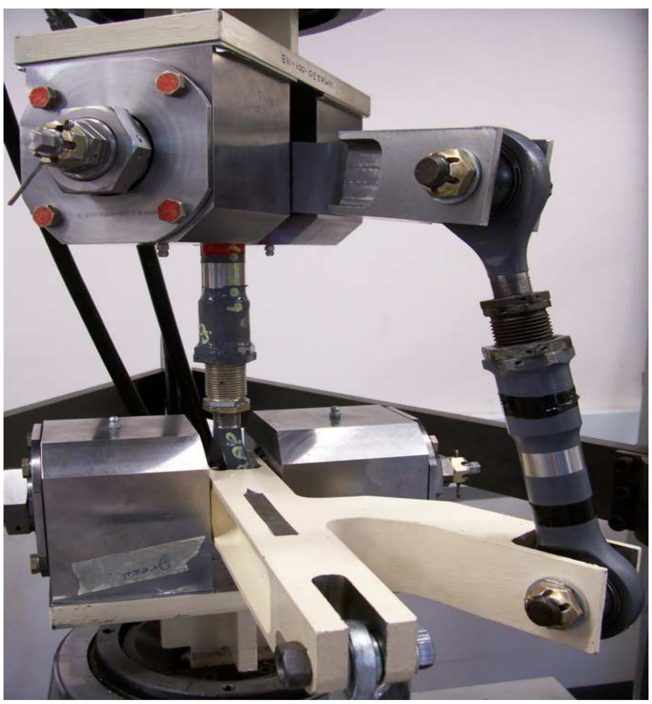


Fig. 4. The pitch link, shown here as a pair undergoing laboratory wear testing to gather data for developing feature extraction algorithms. The link has a ball joint at each end which the WISD project aimed to monitor.

III. Architecture

The generic architecture of the remote sensing modules used in the WISD project is shown in fig. 5. The module is made up of five sections:

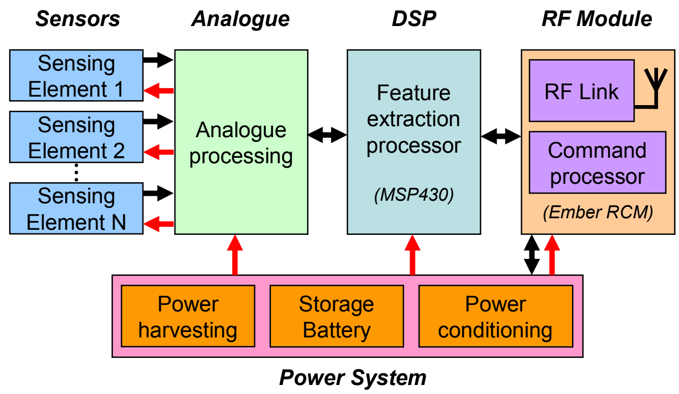


Fig. 5. Architecture of the remote wireless sensing node, showing the main sub-systems of the device.

Sensors: a range of sensing elements were used in the WISD project including strain gauges and piezo-electric based sensors.

Analogue: to minimise the power consumption ultra low power sensor interfaces were developed e.g. an asynchronous sampled strain gauge interface reduced the sensor bandwidth to the minimum needed by subsequent operations, whilst maintaining robust performance, this reduced the power consumption to 600µW per channel with 2kHz bandwidth (compared to 25mW for permanent excitation). In addition the power consumption of the overall data feature extraction can be reduced by moving operations from the digital to analogue domains, where possible, e.g one processing task involved sampling the data and then filtering the digitised waveform into two frequency bands for further calculation. This would have required a large amount of processing bandwidth. The analogue waveform was instead fed into a low-power analogue filter circuit to split the signal into the two frequency bands, these where then sampled as two signals using the on-chip ADC, resulting in an overall power reduction,

DSP: careful consideration was required in choosing the processing strategy to balance power consumption of the processing with the necessary performance. As one of the fundamental principals of the WISD concept is that of using processing within the sensing module to reduce amount of data transmitted, it is essential that the chosen processor provides sufficient bandwidth to execute any foreseeable algorithm. Low overall power consumption can be provided by using either a device with inherently low power consumption or one offering higher throughput but running on a low duty-cycle, shut down when not required. One particular example of high-bandwidth floating-point routine that is typical of the type of algorithm that an intelligent sensor may require was selected and the power consumption requirements to perform the calculations on a variety of commercial DSP platforms were calculated. The MSP430 emerged as the preferred device, offering an estimated power saving of over 2.5 times compared to the SHARC. Designed for low-power applications, the MSP430 offers a number of power-saving options through different power modes and flexible clocking strategies. Its I/O options allowed for easy connection to the RF module, and the various on-chip modules allows for certain tasks to be carried out with minimal intervention from the CPU itself, also helping to reduce power consumption e.g. data acquisition using a timer driven ADC.

RF Module: The RF module is based around an Ember RCM (Radio Communications Module). This module contains a ZigBee RF transceiver as well as a second processor. The decision to utilise commercially available RF hardware and protocol was taken to allow the sensing and processing aspects of the project to be research focused, whilst the communications aspects were focused on the application of COTS (commercial off the shelf) technologies to the target environment. The processor within the RF module has overall command of the remote sensing module, as this allows for the MSP430 processor to be put into its lowest power mode when idle and then woken when a command is sent to start acquiring data.

Power System: The power system has an architecture to accommodate both renewable and stored energy sources. Power conditioning is performed by multiple switched-mode elements which supply each component at the minimum voltage level compatible with correct operation. The command processor also controls the routing of the power system allowing sections to be shut down when not required.

IV. POWER HARVESTING

A. *Operating environment*

As previously mentioned the helicopter environment provides considerable scope for energy harvesting from vibrations. Fig. 6 illustrates the spectrum of vibration measured at several locations on the body of a helicopter in forward flight. The magnitude of the vibration has been removed for commercial reasons, however typically 1-2g of acceleration can be found if the harvesting device is located favourably. The development of the power harvester as part of the WISD project represents the most 'blue sky' activity within the project, and therefore the goal was to successfully demonstrate an energy harvester, excited by a accurate vibration spectrum, powering the WISD remote sensing module as a bench test. The location of the device in the target application makes it impossible to access the energy harvester to adjust or set-up during operation; however, the space available for the harvester does not place particularly onerous constraints upon the design and the approximate power consumption of the sensing module (100-150mW) can be met by a harvester built using conventional meso-scale techniques.

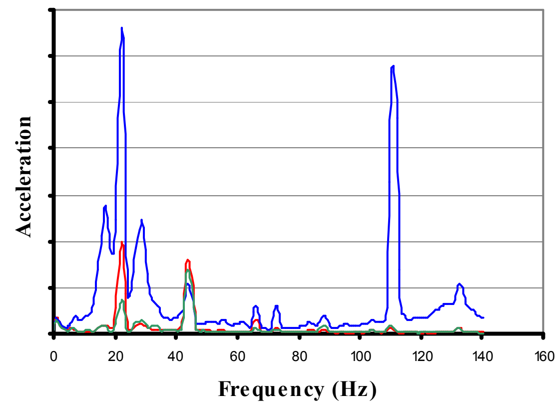


Fig. 6. Measured vibration spectrum at several helicopter body locations during forward flight. The amplitude data is omitted for commercial reasons, however vibration peaks of >1g can be found in some locations.

Several novel techniques resulting from the energy harvesting research for WISD have been published [3,4,5] including the application of non-linear dynamics to energy harvesting and active power conditioning.

B. *Vibration harvester with non-linear dynamics*

At the power level required for the application the most appropriate method of extracting power from vibrations is to use a mass/spring resonant generator with electro-magnetic coupling between the mechanical and electrical domains.

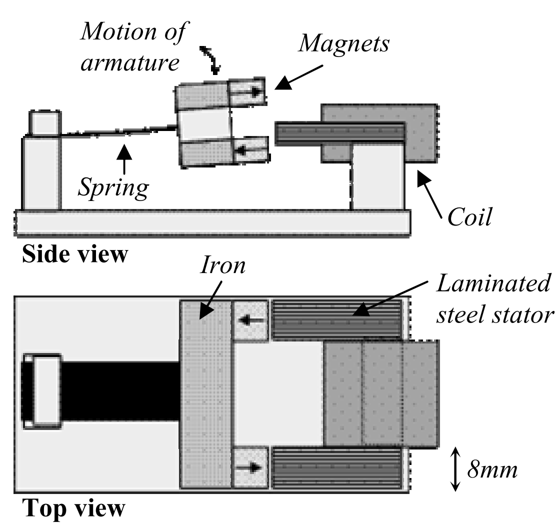


Fig. 7. Diagram of the harvester developed for the WISD project featuring nonlinear compliance response and high magnetic loading.

Typical linear systems have a narrow transmissibility and this causes difficulties when trying to harvest energy from vibrations in environments where the frequency of vibration changes or where the vibration energy is spread out over a wide bandwidth. It is also a problem for the manufacture of energy harvesting devices since it is necessary to have extremely high tolerance manufacture or provide physical adjustment to the resonant components in service. For the WISD project an energy harvester was developed featuring a high magnetic coupling by incorporating high permeability materials into the stator and armature of the device. As a consequence of this magnetic circuit design the armature experienced reluctance forces that summed with the compliance of the spring to give an overall non-linear compliance characteristic and a wider frequency response compared to linear devices. This harvester is shown in fig.7 and fig 8. Full details of the harvester behavior can be found in references 3 and 5.

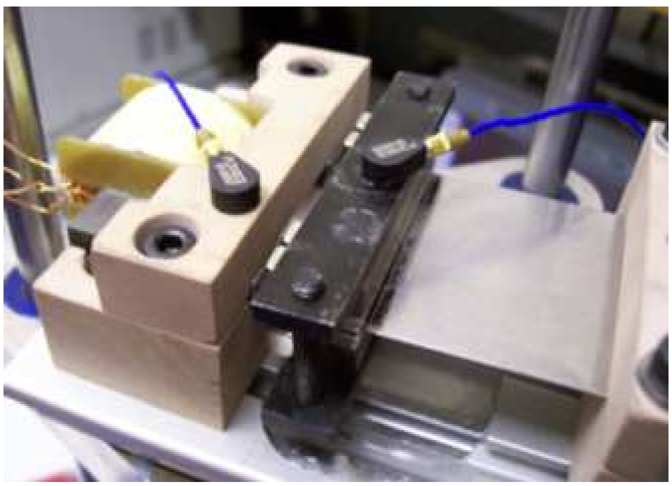
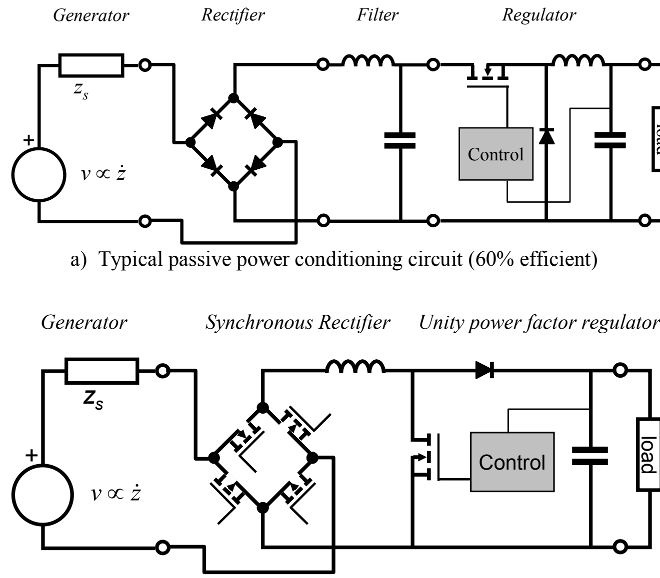


Fig. 8. Harvester prototype under test. The prototype is able to produce in excess of 200mW when excited by vibrations representative of the helicopter environment.

C. *Power conditioning*

Vibration powered electrical generators produce a raw AC electrical output that often needs to be converted into DC for use by the load systems. There are many possible ways to achieve this conversion (rectification) however the specific application of vibration energy harvesting requires a solution that is a delicate balance between efficiency, converter quiescent loss and impact upon the resonant generator operation. Fig 9a shows the typical converter topology.

For the WISD project bespoke analogue converter circuits were developed to address the inherent problems of passive rectification techniques, including a unity power factor power converter, realised at ultra low powers, suitable for energy harvesting applications. Fig 9b shows the active power conditioning circuit developed for the project. Measured results showed an improvement in efficiency, from 60% in the case of passive circuits to 80% for the active power conditioning. Further details of the power conditioning can be found in reference 4.



a) Typical passive power conditioning circuit (60% efficient)

b) Active power conditioning circuit developed for WISD (80% efficient)

Fig 9 Comparison of a typical passive power conditioning used for energy harvesting with the active system used in the WISD project to improve efficiency of the energy conversion process.

V. PROTOTYPE AND FLIGHT TRIAL

Several prototypes of the WISD system have been bench tested with promising results. A wireless sensor for assessing bending stress, as illustrated in fig.3, has demonstrated clearly the power savings that can be achieved by processing before transmission: The sensing module consumes 155mW transmitting raw strain data but only 26mW when implementing a cumulative stress algorithm and sending a condition report at regular intervals of several seconds.

In addition to bench prototypes a 'whirl tower' (a ground mounted, rotating, full rotor assembly) test of the wireless link has already been successfully completed, and is due to be followed a flying aircraft demonstration. The main goal of the flight trial is to explore the technical requirements and challenges in implementing a wireless link between rotating reference frames using the COTS Zigbee technology. To instrument the rotor head presents a thorough test of the technology: with a unit located on the rotor head there is a periodically occluded transmission path with a significant number of multi-path reflections and also Doppler shifts of the transmitted and received signals. The environment of operation is also one of high vibration and high levels of EMC from radio and other equipment.

The aircraft demonstrator will be used to recover strain information from the main rotor head of the Lynx helicopter shown in Fig. 10. The main rotor is a critical component and one that would benefit directly from operational measurement of strain and vibration parameters. The demonstration system has two main components; a unit mounted on the rotor head carrying electronics for signal conditioning, processing and the radio link and also a unit mounted in the cockpit.

Fig 10 The helicopter fitted with a reduced functionality WISD system to conduct the first flight trail of the system.

For the aircraft trial two strain gauges on the rotor head are monitored, one for flap bend and the other for lag bend of the hub. Whenever the unit is active the measured strain measurements were transmitted to the cockpit unit. The recorded values are logged and compared to strain measurements transmitted from the rotor head using conventional slip ring technology.

Fig 11 Two boards make up the sensing module for the flight trail system. The lower board is a low power strain gauge interface and the upper board carries the MSP430 processor. The RF board is removed in this photo.

Fig 12 The sensor module is fitted within a enclosure mounted on the rotor hub. The aerial of the WISD system can be seen.

Fig. 11 shows the electronic boards that make up the wireless sensing module and fig. 12 illustrates the location of the module within an enclosure on the rotor head. The flight trial is due to take place in May 2008.

VI. CONCLUSIONS

This paper has given an overview of the WISD project and a variety of the systems that have been developed. The central concept of remote data processing to reduce power consumption has been validated, reducing the power consumption of the wireless sensing module by up to 6 times. The project is due to end in July of this year with the goal of having successfully completed a flight trail of the system in addition to the several bench prototypes.

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