An Integrated Health Monitoring System for an Ageless Aerospace Vehicle

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ABSTRACT

This paper describes, from a systems perspective, some of the considerations involved in the development of an intelligent structural health monitoring system for an aerospace vehicle. It also outlines the design of an experimental test-bed and concept demonstrator system that is currently under development.

INTRODUCTION

Recent interest in smart sensor networks, and developments in technologies such as MEMS, microelectronics, nanotechnology, communication networks and distributed computing, have encouraged interest in the development of integrated vehicle health monitoring (IVHM) systems. In the longer term, such systems will provide a basis for the development of self-repairing, and perhaps even ageless, structures. In the shorter term, IVHM could reduce or eliminate a number of present design constraints (e.g. relating to redundancy and inspectability), allowing more efficient designs, and should reduce maintenance and inspection requirements.

An IVHM system is an example of an intelligent sensing system. The purpose of such a system is to detect and measure certain quantities, and to use the information and knowledge obtained from the measured data, and any prior knowledge, to make intelligent, forward-looking decisions and initiate actions. One of the important characteristics of practical IVHM systems is that they will generally consist of thousands, and perhaps millions, of sensors of different types measuring different quantities. It is therefore essential that strategies for efficient handling and usage of the vast amount of data generated are an integral component of the system design. It will simply not be possible to communicate all this raw data to a central processor: some form of local data reduction, and the communication of information rather than data, will be essential. It is also most important that the system is robust: its purpose is to detect damage, so it must continue to operate effectively in the presence of damage. This paper describes the current status of an approach to the development of an IVHM system for an Ageless Aerospace Vehicle from a "top-down", systems perspective.

This paper will focus on the design and development of an experimental test-bed and concept demonstrator system, whose aim is to detect, locate and evaluate impacts by fast particles, and of a software simulation package. The purpose of these two tools is to provide versatile research platforms for investigations of sensing, data processing, communications and intelligence issues, and for demonstrating solutions for some of these issues. The architecture of the system is

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highly modular, based on the achievement of intelligent behaviour via a multi-agent system (MAS) approach. Each module (or "cell") of the structure contains a group of sensors, in this case passive piezo-polymer sensors bonded to an aluminum skin panel, and two processors, one of which acquires data from the sensors while the other runs the agent-based software and controls the communications with its neighbouring cells. The initial development of the system consists of 192 such cells forming the outer skin of a hexagonal prism structure. The software package is used to develop and evaluate robust agent-based algorithms to produce self-organizing network behaviour, by simulating the essential features of the hardware system.

SYSTEM PRINCIPLES

The key requirements of an advanced health monitoring system are that it should be able to detect damaging events, characterize the nature, extent and seriousness of the damage, and respond intelligently on whatever timescale is required, either to mitigate the effects of the damage or to effect its repair. These requirements have been discussed in some detail in earlier reports [1-3]. Strictly speaking, a pure monitoring system is expected only to report damage rather than to formulate a response, but it is preferable that the ultimate objective of responding to damage be borne in mind from the outset.

The statement of key requirements serves to sub-divide the problem as follows.

i) Detection of damaging events, which requires some knowledge of the environment in which the vehicle will be operating, the threats it will face, and the development of sensors and a strategy for using them to detect damage events well within the time required for the system to respond. For events that require a rapid response, the best solution will often involve the use of passive, embedded sensors.

ii) Characterization of the damage. This may or may not be a separate process from event detection. It may use different sensors, or the same sensors may be used in a different way. It is more likely to employ active sensors, which may be embedded in the structure or could be mobile and autonomous.

iii) Prioritization of the seriousness of the damage. The first step of an intelligent response is to determine the seriousness of the damage in terms of its ability to compromise the mission of the vehicle, and consequently to determine the urgency (both relative and absolute) with which a response is required.

iv) Identification of the cause of the damage. An intelligent system should be able to utilize data from a vast array of sensors to deduce information about the events that have occurred and the resulting damage, on a whole-of-vehicle basis.

v) Formulation of the response: intelligent decision-making. The nature of the response will depend on a number of factors such as the range of possible response mechanisms, the nature and severity of the damage, the available response time, etc. A response may consist of a sequence of actions. Major damage may demand an immediate "panic response", such as the rapid isolation of a whole section of the vehicle, followed by a more considered damage evaluation and repair strategy.

vi) Execution of the response. In addition to repair, a holistic response may involve changes to the flight or operational characteristics of the vehicle, either to mitigate the effects of the damage or to assist in the avoidance of further damage.

INTELLIGENT SYSTEM

The major thrust of this work, at least initially, is to develop solutions to some of the broader systems issues: how to handle vast quantities of data from a large array of sensors, how to communicate data and/or information around the structure, how to use it to draw conclusions about the health of the structure, and, ultimately, how to make actionable decisions that show aspects of intelligence [2, 3].

It is most important to recognize that the purpose of a health monitoring system is to detect damage, so it must be able to function effectively in the presence of damage. It should also be capable of distinguishing between (inevitable) failures of the system itself and damage to the vehicle structure. It must therefore be robust, adaptive, flexible, re-configurable and self-diagnosing.

These requirements have led to the adoption of an approach based on a multi-agent system (MAS) that consists of modular units that will be referred to as cells. These cells will not only form the physical structure of a vehicle, but will also have sensing, processing and communications capabilities. Other cells may be mobile, carrying their physical and logical capabilities to wherever they are needed, perhaps performing active measurements using built-in sensors, making repairs or carrying out other functions. Simple cells may need to make fast and automatic responses to sudden damage, while collections of cells may solve more complex tasks.

The primary principal that is applied in this work is the *emergence of a global response* as a result of local interactions involving the transfer of locally embedded information. Such a system contains no supervisor and no central intelligence: agents (cells) are expected to self-organize on the basis of local, rather than global, information. From the point of view of a robust health monitoring system, one of the attractive features of an MAS is that the communications and processing functions are widely distributed throughout the structure. There is no “central nervous system” to provide a point of vulnerability.

Recent advances in sensor networks and MEMS devices led to the idea of localized algorithms, in which simple local node behaviours achieve a desired global objective [4], while communicating only with nodes within a neighborhood.

However, despite some progress there is a lack of a unifying methodology underlying the design of localized algorithms. The main problem that has to be solved is how to produce and retain desired emergent behaviour while avoiding potentially damaging patterns of agents’ interactions, or how to systematically transform the global task to individual behaviour models. Some promising results, in the context of amorphous computing, have been reported by Nagpal [5] who showed that a small class of biologically-inspired primitives for organization at the local level can be defined, and that these can be combined in robust and predictable ways to fulfill a global task. Thus, in this case there is a clear relationship between local and global behaviour. Nagpal showed that the problem of mapping a desired global goal to the behaviour of individual agents could be broken into two parts: defining an appropriate set of primitives, and achievement of the global goal in terms of the set of primitives.

At this stage, however, there are no generic techniques or guidelines for finding the most effective primitives, and translating them into localized agent programs. Thus, the problem of global response engineering in multi-agent networks is a central research issue for this project. Our proposed methodology is based on an iterative process that includes the following steps:

- forward simulation, for a class of localized algorithms dealing with impacts of various energies, leading to emergent behaviour [6,7];
- measurement of emergent behaviour based on information-theoretic metrics [8];
- evolutionary modeling of the desired global emergent behaviour, where the fitness functions correspond to the metrics obtained in the preceding step.

Our work so far has concentrated mainly on the first two of these steps, for which results are contained in references [6-8].

DESIGN OF THE EXPERIMENTAL TEST-BED

The design of a health monitoring system requires knowledge of the types of damage that may occur in various parts of the structure, and of the possible events (threats) that may cause damage. This knowledge allows decisions to be made about the required types, numbers and locations of sensors, and strategies for their use. The test-bed system (or concept demonstrator) is designed initially for a simple environment in which the only significant threats are from high velocity impacts by small particles, such as might be encountered from micrometeoroids in space.

The physical structure of the test-bed is a hexagonal prism 800 mm in length and ~ 800 mm across the hexagonal cross-section at the widest point. Each face of the prism is a 400 mm x 800 mm rectangle. A modular aluminum frame is covered by 200 mm square, 1 mm thick aluminum panels that form the outer skin of the structure. Thus, each rectangular face of the prism is covered by 8 of these panels in a 4 x 2 array.

Each panel consists of four 100 mm x 100 mm cells, which are the elementary units of the modular sensing structure. Each cell has a group of sensors connected to a data processing and communications processor, and is a node of the multi-agent system.

Sensors and Sensing

In the initial implementation of the test-bed system, the purpose of the sensors is to detect and locate impacts on the surface of the skin by small, high-velocity particles. An indication of the severity of the damage would be beneficial, but this will be the subject of further development.

The requirement for real-time sensing of impacts favors the use of passive, embedded sensors. In order to protect the sensors from impact damage, as far as possible, it is desirable to have the sensors embedded within the skin or bonded to the inner skin surface. These requirements have been met by the use of piezoelectric sensors bonded to the inner side of each aluminum skin panel to detect the propagating elastic waves produced by an impact. There have been many previous reports of the use of such sensors for impact detection (e.g. [9,10]).

The initial sensor design for each cell consisted of a sheet of piezoelectric polymer (PVDF) approximately 90 mm square bonded to the inner surface of the

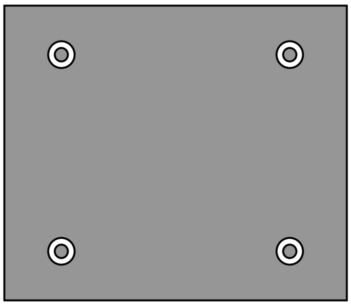

Figure 1: Schematic diagram of the electrode patterning on the piezoelectric polymer sensors.

aluminum skin. The four sensors bonded to each 200 mm square panel thus occupied most of the available area of the panel apart from edge regions that overlap the frame. The electrodes were patterned as shown schematically in Figure 1, to divide the area into a large 'direct impact' sensor and four small (2.5 mm diameter) acoustic emission sensors. The intention was to use the 'direct impact' signal received by the large sensor to localize the point of impact to the specific cell, and to provide the impact time, while the signals received on the small sensors would be used to locate the impact point within the cell.

Tests of these sensors have been carried out using short (8 ns FWHM) high energy (0.5 J) pulses from a Q-switched Nd:YAG laser focused onto the surface to simulate particle impacts by ablating material from the aluminum, and using small (~1 mm diameter) stainless steel spheres propelled at velocities from ~ 0.2 to ~1.25 km/s by a light-gas gun. The former were carried out in our laboratories, and the latter at the Centre for Hypersonics, University of Queensland, Australia.

This testing has, *inter alia*, led us to drop the idea of using the signals from the large area sensor, at least until further analysis of its response can be carried out. Reasons for this include the large sensor capacitance, the relatively long rise-time of the signals for particle velocities of ~1 km/s (such a particle takes ~2 μs to decelerate to zero velocity within a distance of 1 mm, in which time the S_0 Lamb mode can propagate a distance of ~10 mm), the difficulty of adequately shielding the sensor from electrical noise, and the difficulty of achieving uniform, repeatable bonding over a large area.

Signals recorded from three of the small sensors, for both particle impact and laser pulse "impact", are shown in Figures 2 and 3. Figure 2 corresponds to a particle impact that did not pierce the skin, but left a significant crater in the aluminum surface. Figure 3 corresponds to a higher velocity particle (~1 km/s) that pierced the skin, leaving a clean 1 mm diameter hole.

In all of these signals, the first arrival corresponds to the S_0 Lamb wave (the lowest order extensional wave), whose faster low frequency components propagate at ~5.3 mm/μs in this material. This is followed by the A_0 (flexural) wave, for which the higher frequency modes propagate faster than the lower frequency components, at the Rayleigh wave velocity (~3 mm/μs in aluminum). The S_0 arrival generally shows higher frequency components for particles that have pierced the skin than for those that have not. This may be due to the shorter interaction time of a high velocity particle with the skin.

It will clearly be important to distinguish impacts that pierce the skin from those that do not. The possibility of using the S_0 spectrum to do this is being investigated. Other approaches that will be considered include the subsequent use of active sensing (possibly ultrasonic) to evaluate damage, or the measurement of other quantities such as an internal pressure drop or air flow. Major damage that results in electronic malfunction of a cell will be automatically detected by the system.

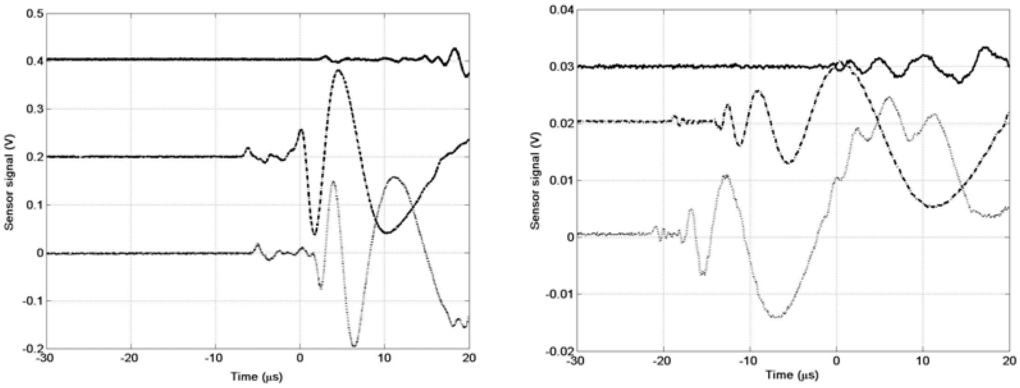

Figure 2: Signals received by three of the four small sensors on a cell that has been impacted by a 1 mm stainless steel sphere (left) and a 0.5 J laser pulse (right) within approximately 10 mm of each other. The sphere had a sufficiently low velocity (~ 0.2 km/s) that it caused only a shallow surface crater on the 1 mm aluminum skin. Note the large difference in the signal amplitudes of the impact and laser generated signals, and of the bandwidth of the first arrival signals that correspond to the S_0 Lamb wave. The absolute values of time on the horizontal axes are arbitrary, but the relative values are significant. In each figure, the vertical scales of the signals have been displaced for clarity.

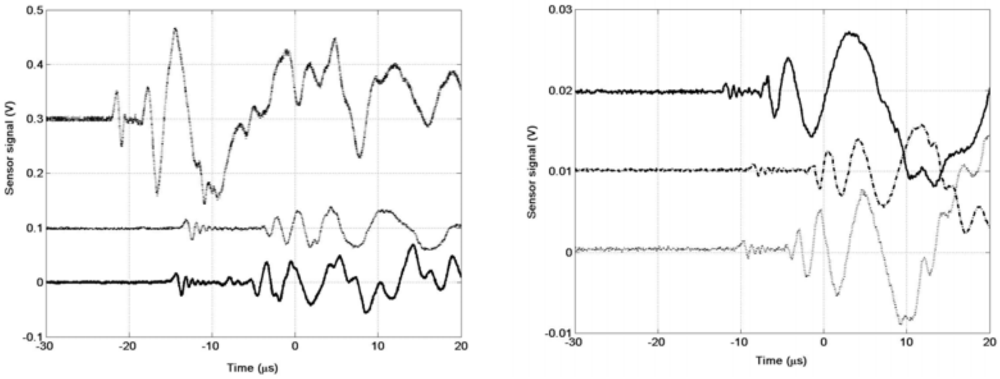

Figure 3: Signals received by three of the four small sensors on a cell that has been impacted by a 1 mm stainless steel sphere (left) and a 0.5 J laser pulse (right) within approximately 10 mm of each other. The sphere had a sufficiently high velocity (~ 1 km/s) that it pierced the 1 mm aluminum skin, leaving a clean hole. Note the large difference in the signal amplitudes of the impact and laser generated signals. The absolute values of time on the horizontal axes are arbitrary, but the relative values are significant. In each figure, the vertical scales of the signals have been displaced for clarity.

Electronic and Communications Software Architecture

The electronic architecture of each cell consists of two layers: a Data Acquisition Layer (DAL), whose primary function is to acquire data from the sensors and to perform the first level of processing on this data (e.g. detecting the arrival of an impact signal), and a Network and Applications Layer (NAL). These layers each contain, for each cell, a fast Digital Signal Processor, and are connected by a high-speed synchronous serial link. The cells communicate with their immediate neighbors via 1.5 Mb/s serial links.

The Data Acquisition processors selected for the initial implementation (Texas Instruments TMS320F2810) operate at 150 MIPS and have the ability to acquire data from four channels at ~ 3 MS/s each, with 12 bit resolution. This sampling rate should be just adequate, given the signal bandwidths observed in Figures 2 and 3.

The communications software, which runs in the NAL processor (Texas Instruments TMS320C5509), contains a number of different protocols to control communications with the network and with the DAL processor. Network communications must allow for rapid re-programming of both processors, the transmission of diagnostic information, transmission of information about the state of the system (e.g. for state visualization), as well as communications with agents on neighboring cells, which provide the essential interactions of the multi-agent system.

Further details of the electronic and communications software architecture may be found in [11, 12], along with discussion of the considerations that led to the selection of specific processors. The system is not yet complete, but development of both the hardware and software are well advanced.

Self-Organizing Identification of Damage

Development of the multi-agent system algorithms have so far concentrated on a self-organizing approach to the identification of damaged cells or clusters of cells. This is a "bottom up" approach to show that useful self-organizing behavior can be developed, and to provide some experience of the development of primitive behaviors analogous to those described by Nagpal [5].

The algorithms developed to date enable a self-organized boundary to be constructed around a region containing at least one fatally damaged cell (i.e. a cell whose communication and/or processing capability has suffered major damage), and a minimum spanning tree to be formed to connect cells that have suffered non-fatal damage. The former algorithm is based on mutual checking of the functionality of neighbors, and dynamic activation/deactivation of communication links. The latter employs software "ants" that start from a cell that has experienced an impact, and explore the network using "pheromone" trails until they find another cell that has been hit.

Further details of these algorithms may be found in [6,7,11]. An approach to developing quantitative measures of self-organization, which can ultimately be used as the basis of fitness functions for evolutionary algorithms, is outlined in [8].

SUMMARY AND CONCLUSIONS

This paper reports on the design of an experimental system that is being developed to test and demonstrate concepts and practical aspects of an intelligent vehicle health monitoring system. The initial hardware implementation of the system is well advanced, and is expected to be completed within the next few months. Its modular construction will readily allow testing of different skin materials, sensors and sensing strategies, electronic hardware, communications media and protocols, and software concepts and algorithms. It should be emphasized that the test-bed has been designed to be a powerful and flexible experimental platform. It is not intended to be a realistic practical prototype.

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REFERENCES

1. Abbott, D., et.al. 2001. “Development and Evaluation of Sensor Concepts for Ageless Aerospace Vehicles”, Report 1, CSIRO TIP Report no. TIPP 1516. Also available as NASA Report no. NASA/CR-2002-211772, at http://techreports.larc.nasa.gov/ltrs/PDF/2002/cr/NASA-2002-cr211772.pdf
2. Abbott, D., et.al. 2002. “Development and Evaluation of Sensor Concepts for Ageless Aerospace Vehicles”, Report 2, CSIRO TIP Report no. TIPP 1517. Also available as NASA Report no. NASA/CR-2002-211773, at http://techreports.larc.nasa.gov/ltrs/PDF/2002/cr/NASA-2002-cr211773.pdf
3. Abbott, D., et.al. 2003. “Concepts for an Integrated Vehicle Health Monitoring System”, *Review of Progress in QNDE*, Vol 22, AIP Conference Proceedings 657:1606-14.
4. Estrin, D., R. Govindan, J. Heidemann, S. Kumar. 1999. “Next Century Challenges: Scalable Coordination in Sensor Networks”. In *Proceedings of the Fifth Annual International Conference on Mobile Computing and Networks (MobiCOM '99)*, Seattle, August 1999.
5. Nagpal, R. 2002. “Programmable Self-Assembly using Biologically-Inspired Multiagent Control”. In *Proceedings of the First International Joint Conference on Autonomous Agents and Multi-Agent Systems (AAMAS '02)*, Bologna, Italy, July 2002.
6. Wang, P., P. Valencia, M. Prokopenko, D. C. Price, G. T. Poulton. 2003. “Self-Reconfigurable Sensor Networks in Ageless Aerospace Vehicles”. In *Proceedings of the 11th International Conference on Advanced Robotics (ICAR-03)*, Coimbra, Portugal, July 2003.
7. Lovatt, H., G. T. Poulton, D. C. Price, M. Prokopenko, P. Valencia, P. Wang. 2003. “Self-Organising Impact Boundaries in Ageless Aerospace Vehicles”. In *Proceedings of the 2nd International Conference on Autonomous Agents and Multi-Agent Systems (AAMAS '03),* Melbourne, Australia, July 2003.
8. Foreman, M., M. Prokopenko, P. Wang. 2003. “Phase Transitions in Self-Organising Sensor Networks” To appear in *Proceedings of the 7th European Conference on Artificial Life (ECAL '03)*, Dortmund, Germany, September 2003.
9. Choi, K., F-K. Chang. 1996. “Identification of Impact Force and Location Using Distributed Sensors”, *AIAA Journal,* 34(1): 136-142.
10. Prosser, W. H., M. R. Gorman, D. H. Humes. 1999. “Acoustic Emission Signals in Thin Plates Produced by Impact Damage”, *J. Acoustic Emission,* 17(1-2): 29-36.
11. Abbott, D. et.al. 2003. “Development and Evaluation of Sensor Concepts for Ageless Aerospace Vehicles”, Report 3, CSIRO TIP Report no. TIPP 1628.
12. Hedley, M., M. Johnson, C. Lewis, D. Carpenter, H. Lovatt, D. C. Price. 2003. “Smart Sensor Network for Space Vehicle Monitoring”. In *Proceedings of the International Signal Processing Conference,* Dallas, Texas, March 2003.

Presented at *4th International Workshop on Structural Health Monitoring*, Stanford University, USA
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