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# Intelligent sensing systems for monitoring impact damage in spacecraft

D.C. Price, D.A. Scott, N. Hoschke, C.J. Lewis

CSIRO Materials Science & Engineering, Lindfield, NSW 2070

Networks of sensors that employ computational elements to intelligently process the sensed data to deduce or infer information about the state of the sensed system represent an important class of cyber-physical systems. This and a companion paper describe two distinctly different types of intelligent sensing systems, both of which have been developed to monitor aspects of the state (health) of aircraft or space vehicles. This paper describes a sensor network whose purpose is to detect and locate potentially damaging impacts, which may be caused by, for example, micrometeorites, space debris, human activity, bird strike, etc., and to evaluate the severity of any resulting damage. An important characteristic of this application is the fact that individual impact events and the resulting damage occur rapidly on the time-scale of the sensing and analysis processes. Thus, while the state of the sensed structure may change with time due to multiple impacts, the effect of an individual impact may be considered to be instantaneous and subsequently static. The companion paper, on the other hand, is concerned with damage, in this case produced by corrosion, which develops very slowly and may be monitored and evaluated as it develops. This allows the sensed data to be used to develop prognostic models for forward estimates of damage development.

Impact damage is a significant concern in both aircraft and spacecraft, though the sources and nature of damaging impacts may be very different for different vehicles in different environments. However, a general characteristic of damaging impacts is that they occur rapidly and unexpectedly. Detection therefore requires a sensing system that can be monitored continuously, and that is sufficiently robust that it will continue to operate following an impact. The approach adopted in this work is to utilise a two-stage sensing process: passive piezoelectric sensors are used to detect and locate an impact (primary sensing), by detecting the elastic waves that propagate through the structure from an impact site, and a secondary (active) sensing system is used to evaluate the damage. The primary system can also make an estimate of the magnitude of the impact, which may be important for rapid response to large impacts. Two systems we have developed make use of different secondary sensing systems, but both rely for sensor guidance on the principle of self-organisation. In one, a robot carrying a camera moves to the impact site for optical inspection, while in the other, for monitoring a thermal protection system, a heat source and distributed temperature measurement system is used to measure impact-generated anomalies in the thermal properties of the material.

The requirement for a sensing system that is robust to impact damage, particularly in spacecraft on long missions, has led to the development of a decentralised multi-agent architecture. The agents are autonomous intelligent network nodes, each of which controls a group of sensors in its local neighbourhood, and communicates with its neighbouring nodes. Thus each agent gathers sensed information about its local region (a cell), but has no direct information about the global state of the structure apart from that which is communicated by its neighbours. The network of agents has no central control, but it can produce a coherent response to a sensed event (in this case an impact) if appropriate information is communicated around the network. For the networks outlined in this paper the initial response required is to guide the secondary sensing system so that it can evaluate the impact-induced damage.

Because the network has no central control it therefore has no single point of failure. If a sensor fails or is damaged, its node will continue to read data from the other sensors, and if an agent is damaged the rest of the network will continue to operate. The network is therefore highly robust to damage or component failure.

Both impact sensing systems use small piezoelectric sensors bonded to the structure for the primary impact sensing. The impact location is determined by triangulation of the arrival times of the impact-induced elastic waves at the different sensors. In the first system, an impact sensing demonstrator that has been described previously (Hoschke et.al., 2008), a group of four such sensors arranged in a square array is monitored by each agent. In this system the mobile sensing robot that performs the secondary sensing navigates its way to the impact site using a guiding field established as a result of the impact. This field is initiated by the impacted cell and is propagated through the structure by the inter-cellular communications using a distributed dynamic algorithm (Prokopenko et.al., 2005, Hoschke et.al., 2008). The robot communicates with the agent on whose cell it is located via ultrasonic sensors in its feet, and in this way obtains information about the local value of the field and its gradients. The robot may be regarded simply as another agent in the system: it communicates only with its local neighbours and acts only on the basis of this local information. It follows the maximum field gradient to achieve the shortest path to the impact site. The field can be up-dated dynamically in response to new impacts or failures and it allows higher response priorities to be set by more severe impacts.

The second system, for monitoring damage to thermal protection systems (TPS), is at the design and feasibility study stage and has not yet been built. Primary impact sensing will be done similarly to that described above, with local agents detecting impact-generated elastic waves with embedded piezoelectric sensors and locating the impact site using triangulation. In this case however, since the property of primary concern is the thermal conductivity of the TPS, secondary sensing is based on evaluating thermal properties. Heat will be applied to the region containing the impact site, from the sun or from a local source, and the temperature distribution within and below the TPS monitored for anomalies. Temperature monitoring will be done with embedded optical fibre Bragg grating (FBG) sensors, with the fibres arranged in a two-dimensional switched network that will allow multiple optical paths from the point of interrogation to any region where an impact might have occurred. Optical frequency domain reflectometry (OFDR) will be used to measure the temperature at each sensor along the selected optical path. This technique can interrogate several thousand FBG sensors.

As in the first system, detection of an impact initiates the establishment of a guiding field through the structure. However, instead of a sensing robot following the maximum field gradient to the impact site, in this case an optical path is formed similarly by the actuation of optical switches by the agents. In this way the shortest path to the impact site can be established, by-passing any damaged cells. The route of this path, and therefore the locations of all the FBGs along the path, including those in the impact region, can be passed back to the OFDR interrogation instrument by the agents along the path, for damage location and evaluation. A computer simulation of this system has been developed, and technology feasibility completed.

Both of these systems rely on self-organisation to effect secondary sensing and damage evaluation, through the distributed guiding field algorithm. The benefits of the self-organising approach include the essentially dynamic nature of the solution, for which the shortest path to the impact site can be formed, even through a damaged network, and automatically re-formed should additional impacts or further damage occur; and the robust nature of the approach to damage.

**References**

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