Microsensors, arrays and automatic diagnosis of sensor faults

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ABSTRACT

As man-made dynamical systems become increasingly complex, there is an ever-present need to ensure their safe and reliable operation. These requirements extend beyond the normally accepted safety-critical systems (e.g. nuclear reactors, chemical plants, and aircraft) to new systems such as autonomous vehicles and rapid transport systems. Early detection of faults and/or malfunctions in industrial processes and systems can help reduce downtimes and the incidence of catastrophic events. Sensors are essential components of any process or system which makes use of automatic control. It follows that an important aspect of any process/system fault diagnosis strategy is to attempt to determine their state of functionality.

The paper opens a discussion on the appropriateness of local sensor health monitoring, fault diagnosis and measurement confidence indices. It looks at the techniques currently used for process fault detection, both centralised and hierarchical, and explores further the possibilities of transposing some of the design concepts from macrosystem level to microsystems, in respect to fault diagnosis.

The use of Artificial Intelligence techniques is suggested for implementing on-chip sensor diagnosis. Micromachined accelerometers are considered as a case study.

Keywords: Sensors, fault diagnosis, artificial intelligence.

1 INTRODUCTION

During the last two decades, fault detection theory has attracted considerable academic interest and as a result, a variety of techniques for fault diagnosis have been developed. Most of these techniques are designed to work in a 'centralized' manner, by accounting simultaneously for sensors, actuators and process/system component faults. The idea of 'hierarchical' system design with respect to sub-components fault diagnosis can be explored further, with the possibility of 'local' diagnosis for sensors being questioned and the need for sensor self-diagnosis, self-validation and monitoring justified. It is intended to argue the feasibility of using Artificial Neural Network (ANN) techniques for implementing the above.

ANNs have been successfully used in a variety of applications for complex data analysis and feature extraction [1]. In the context of the proposed discussion, some of their main advantages are:

- the majority of intensive computation takes place during the training process.
- due to the self-learning capability of neural networks, no detailed a priori information regarding the system under analysis or design is required.
- the massive parallelism of neural networks offers a very fast and robust multiprocessing technique when implemented using neural chips or other types of parallel hardware.

Once the ANN is trained for a particular task, operation consists of propagating the data through the mapping produced by the ANN, thereby making possible real-time self-diagnosis, self-validation and monitoring. Acceleration sensors provide a good example for the discussion, as their lack of accessible internal signals makes the tasks of diagnosis and validation particularly challenging.

2 SENSOR SELF DIAGNOSIS

In most applications, accurate and reliable sensor readings are vital for good overall system performance [2]. Despite advances in fabrication technologies, sensors generally exhibit imperfections (for acceleration sensors, for example, common imperfections are: offset, drift, non-linearity and noise) and the magnitude of these imperfections is found to vary both from sensor to sensor and with time. Fundamental characteristics of the sensor, e.g. sensitivity, may be subject to manufacturing tolerances, varying material properties and ambient effects [1]. Moreover, during operation, as with any other system component, sensors may develop several types of faults and fail in a variety of ways. Over the last few years sensors have evolved into 'smart' or 'intelligent' versions.

In safety-critical systems, (e.g. civilian aircraft) typical solutions for overcoming the sensor fault problem are the use of hardware redundancy or majority voting [3]. Such a 'collective' measurement validation technique is often prohibitive. For example, one of the problems associated with systems comprising large number of accelerometers, is that of data analysis bottlenecks. The data analysis generally includes: (1) Fourier analysis; and (2) statistical methods for determining outliers and inconsistent measurements, both of which are computationally expensive processes.

Another approach to validate measurements obtained from sensors and to diagnose sensor faults is to use mathematical/knowledge-based modelling of the system under measurement [1,4], to identify inconsistencies in measurement data. Such a system/process specific approach has two major drawbacks [4]:

- detailed mathematical models of the system/process are required; these are generally extraordinarily complicated to construct and may have significant errors (although some success has been recently reported on using ANN techniques for the modeling and fault detection of such systems, [3]);
- the validation algorithms are 'tuned' for each system/process. Retuning, due to a slight modification of the system or the introduction of the same techniques to a new application, is extremely expensive and demands a high degree of expertise.

Considerable research effort has been expended on sensor self-validation techniques. No definitive results have been found in the literature referring to self-validating and diagnosis of acceleration sensors, although some interest in the field was shown by NASA, PNRL and Berkeley University.

A variety of fault detection methods could be considered in this context, including:

- analytical methods – the simplest being the threshold analyzer that performs limit checking on the sensor signals;
- signal processing techniques – signature analysis and spectrum analysis;
- statistical - mean and variance analysis.

It is anticipated that sensor signature analysis (in the time and/or frequency domain) will probably be the dominant technique, and ways to implement such a technique using ANN could be explored.

The embedded microprocessor market is growing very fast, and embedded modules reported in the literature, are capable of not only computation but also communication; take for example wireless integrated network systems, where it is proposed that systems consist of self contained nodes composed of sensor, actuator, interfaces, data fusion circuitry, general purpose signal processing and microcontrollers.

With modern integrated fabrication technologies it is possible to design and fabricate complete systems in a low cost module, including sensing and powerful signal processing. As well as the analog and digital signal processing required for the function of the sensor itself there can be sufficient capacity to allow the sensor to take on more advanced computational functions, so that system level functionality can be deployed in the sensors themselves.

Such sensors provide the opportunity to build sophisticated systems consisting of many collaborating sensors, but diagnosis and maintenance of such a system is problematic. Some of these problems can be addressed by providing the sensors with self-validation and self-diagnosis. Additional, this facility will provide advantages at the level of the overall operation of the industrial systems and processes that the sensor network is part of.

Localized, real-time sensor self-validation, self-diagnosis technology will enable improved automatic process/system monitoring and control, removing this overhead from a central process controller. Early detection of small, incipient (rather difficult to detect) sensor faults can be achieved and therefore downtime can be reduced and catastrophes can be avoided. More robust, fault-tolerant control can be designed on the above basis, to accommodate/compensate for soft sensor failures (i.e., recoverable sensor failures that leave no permanent damage). Finally, easy identification of sensors which have suffered hard failures (irrecoverable sensor failures) can be achieved.

The design requirements are to enable unique sensor failure diagnosis and measurement validation with minimal sensor requirements (no hardware redundancy is necessary), by exploiting the information content of readily available signals: the sensor output signal and contextual information gathered from the sensor's working environment. The above capabilities could be incorporated into a validation and diagnosis module (VDM), which, associated with the sensor, should be able to detect, in real-time, several common sensor faults and failures and issue specific warnings and provide confidence indices for each validated measurement value.

Prerequisites for this design activity are:

- identification (based on experimentally obtained sensor signatures) of features which characterise several common sensor faults.
- determination of the nature of additional, application related information, which can be used in conjunction with the sensor output for fault diagnosis and measurement validation purposes.
- assessment of the feasibility and applicability of using ANN techniques for qualitatively and quantitatively representing the information gathered above.

The remainder of this paper presents an initial analysis of some of these prerequisites, using acceleration sensors as a working example.

3 ACCELERATION SENSORS – EXAMPLE

In the development of a reliable signal-based diagnosis and validation strategy, there is a need to consider not only sensor failures (soft and hard) but also situations which can give rise to faulty (false) measurement data, in the specific application where the sensor is used. For the chosen case study, a set of fault signatures for acceleration sensors could be obtained under laboratory conditions for several different scenarios.

To gain an initial idea of the nature of these signatures we develop a number of scenarios relating to the type of information regarding different types of sensor fault condition that might be obtained from the data available to the processor of the smart sensor and perform a simple analysis using electrical equivalent circuits.

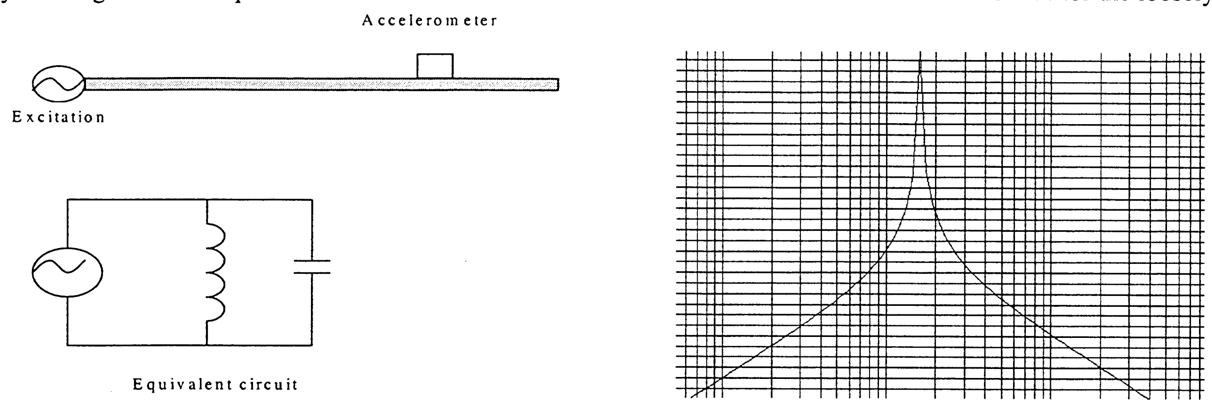

Figure 1: Beam model of structure under test, equivalent circuit and resonance

Case 1. The sensor being not rigidly attached to the structure under test. We can imagine a simplified version of this case as illustrated in Figure 1. The test structure is represented by a beam, which will have some characteristic vibration frequency. The improperly mounted sensor is mounted on this beam by a compliance or spring. This is in itself a resonant system, with some characteristic resonance given proportional to the mass of the sensor and the stiffness of the spring. We can produce an electrical analogue of this system, as shown in Figure 2.

So long as the resonant frequency of the poorly mounted sensor is widely separated from that of the beam, then the symptoms of the mounting fault can be clearly differentiated. Since a micromachined sensor is likely to be very light, and even a poor mounting quite stiff, it can be expected that the symptomatic resonance of the sensor mounting will be very high. Thus, at first sight it appears that a properly designed sensor should be capable of self-diagnosis of such a fault by itself.

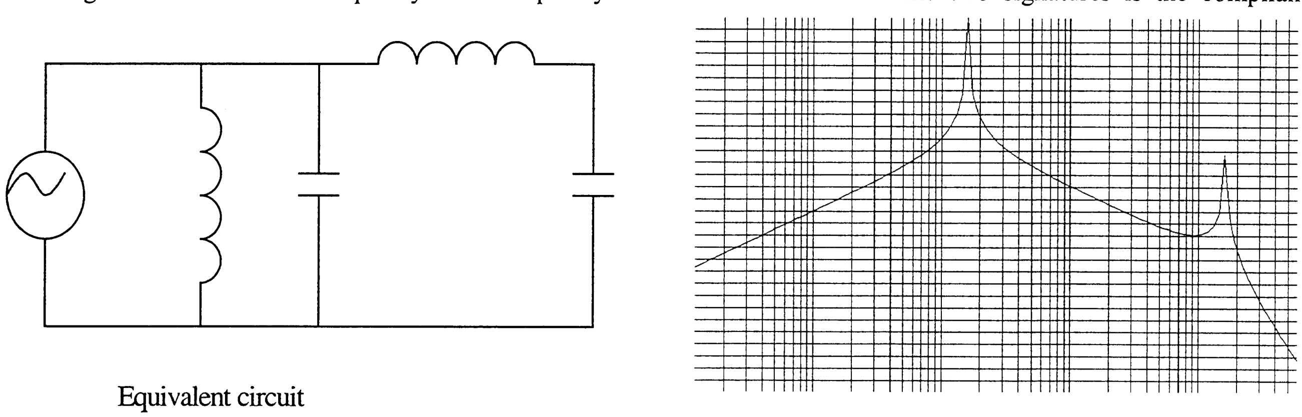

Figure 2: Detached accelerometer model and resonance

However, we should also consider the way in which faults in the structure are likely to manifest themselves. Imagine that the beam shown above suffers an incomplete fracture, as shown below. This results in two beams, connected by a compliance, giving an electrical analogue shown here. . This is similar to that for the loosely mounted sensor, with the exception of the coupling compliance Now there are two beam resonances of concern, but in most cases it is likely that they will be at a much lower frequency than the symptomatic resonance of the sensor. The only case in which there might be some scope for misidentification is if the sensor is located close to the end of the beam and the fracture is located close to the sensor, resulting in a very high resonant frequency for the piece of the beam close to the sensor. If this frequency is in the range of that expected from a loose sensor, then the difference between the two signatures is the compliance linking the two resonant systems which occurs if the fault is in the beam, rather than the sensor mounting. The effect of this compliance is shown in the frequency plot in Figure 3. It is possible that a suitably designed diagnostic could detect such a characteristic, but the presence of information from adjacent sensors as to the magnitude of such a resonance would certainly make diagnosis easier.

Case 2. An extreme case of the above is if the sensor detaches completely from the structure under test, in which case no resonances will be detected. Such a condition may occur simply because there is no stimulus to cause resonance. Information from other sensors in the locality can be used to identify whether this is the case, a detached sensor being indicated by a single sensor detecting no resonances surrounded by ones which do. Complete loss of function of a sensor, for instance due to loss of power supply, would cause similar symptoms, except that there would not even be residual noise detected.

Case 3. Another related case is if the sensor housing suffers some structural damage. Such a problem may include a number of cases, the simplest of which is a small part of the housing becoming partially detached. Once again this takes the form of a small mass attached to the sensor by a compliance. The difference from the case discussed earlier is that the mass is still smaller and so the resonance will be higher, thus the discussion above applies, although the two symptoms should be more easily separated.

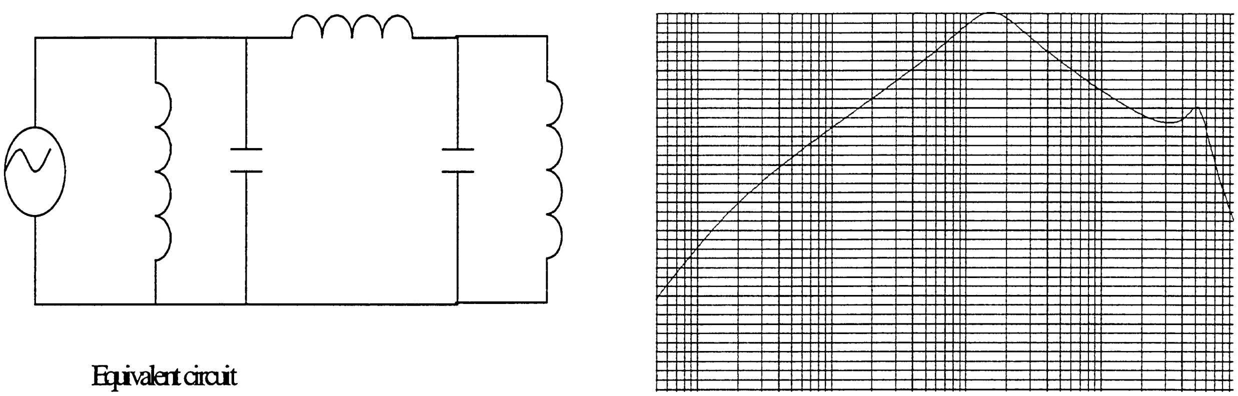

Figure 3: Beam fractured near accelerometer, model and resonance

Case 4. Changes in ambient conditions can be detected at the sensor, if properly equipped and compensated for appropriately.

Case 5. Detection of parameter drift of an individual sensor, or of internal damage to its structure would cause would depend on detection of variation of the output of that sensor from its neighbors, once again in a way which could not be confused with symptoms of the structure under test. The nature of these variations would need to be characterized to be detected.

The faulty and healthy sensor signatures will be analyzed with a view to extracting their characteristic features. It is intended to use previously developed methodologies for sensor identification based on ANNs together with conventional signal processing techniques.

A set of rules based on these physical principles can be deduced for the data expected from these sensors. (For example, acceleration measurements from sensors situated at adjacent locations along a cantilever will only be permitted to be different within certain limits imposed by the expected accelerations to which the object is subjected.) The application-related reasoning should be kept to a minimum, in order to maintain the overall generality of the method. In designing the experiment it will be necessary to ensure that the range of accelerations used for developing the rules encompass the accelerations used for fault identification.

The respective suitability of various neural networks for the given problem should be assessed according to their sensitivity to the faults and failures under consideration. Combinations of ANN types will need to be considered in order to accommodate the range of faults.

4 CONCLUSIONS

The paper discussed the suitability and feasibility of enhancing the reliability of microsensors by adding an on-chip self-diagnosis capability. The approach taken is based on Artificial Intelligence techniques and sensors with no accessible internal signals are taken as an example. Some common acceleration sensor faults are considered and an indication is given of the manner in which these faults can be detected and isolated, either on an individual sensor basis or based on cooperative work within a sensor network. The design requirements for such self-diagnosable measurement systems are set and further practical implementation issues are raised.

REFERENCES

[1] Gaura, E. Neural Network Techniques for the Control and Identification of Acceleration Sensors. PhD Thesis, Coventry Univ., UK, 2000

[2] NASA TechTracS. System Fault Detection and Accommodation, Technology Opportunity Sheet, http://technology.larc.nasa.gov/scripts/nls_ax.dll/twDispTOPSItem(111;TOP3-2;0;1), 2000

[3] Patton, R., Uppal, F., Lopez-Toribio, C. Soft computing approaches to fault diagnosis for dynamic systems: a survey, IFAC Safeprocess, Hungary, Proceedings, pp. 298-311, 2000.

[4] Henry, M.P. Validating data from smart sensors, J. of Control Engineering, vo.41, no.9, pp. 63-66, 1994