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Sensor Network Paradigms for Structural Health Monitoring

Charles R. Farrar*[+], Gyuhae Park*, David W. Allen*, Mike D. Todd**

* The Engineering Institute
Engineering Sciences & Applications
Los Alamos National Laboratory
Los Alamos, New Mexico 87545

** Department of Structural Engineering
Jacobs School of Engineering
University of California, San Diego
La Jolla, CA 92093-0085

ABSTRACT

Structural health monitoring (SHM) is the process of detecting damage in structures. The goal of SHM is to improve the safety and reliability of aerospace, civil and mechanical infrastructure by detecting damage before it reaches a critical state. A specific topic that has not been extensively addressed in the SHM literature is the development of rigorous approaches to designing the SHM sensing system that is used to address the data acquisition portion of the problem. To date, almost all such system designs are done somewhat in an *ad hoc* manner where the engineer picks a sensing system that is readily available and that they are familiar with, and then attempts to demonstrate that a specific type of damage can be detected with that system. In many cases this approach has been shown to be ineffective and as a result researchers have begun to develop sensor networks specially suited for SHM. Based on this research, several sensor network paradigms for SHM have immerged, and this paper is intended to provide an overview of these paradigms. This paper will first provide a brief summary of the statistical pattern recognition approach to SHM problem. The data acquisition portion of the paradigm is then addressed in detail where the various parameters of the system that must be considered in its design and subsequent field deployment are summarized.

[+] Author to whom correspondence should be addressed. Email:farrar@lanl.gov

1. Introduction

Structural health monitoring (SHM) is the process of detecting damage in structures. The goal of SHM is to improve the safety and reliability of aerospace, civil and mechanical infrastructure by detecting damage before it reaches a critical state. To achieve this goal, technology is being developed to replace qualitative visual inspection and time-based maintenance procedures with more quantifiable and automated damage assessment processes. These processes are implemented using both hardware and software with the intent of achieving more cost-effective condition-based maintenance. A more detailed general discussion of SHM can be found in [1].

The authors believe that all approaches to SHM, as well as all traditional non-destructive evaluation procedures (e.g. ultrasonic inspection, acoustic emissions, active thermography) can be cast in the context of a statistical pattern recognition problem [2]. Solutions to this problem require the four steps of 1. Operational evaluation, 2. Data acquisition, 3. Feature extraction, and 4. Statistical modeling for feature classification. A specific topic that has not been extensively addressed in the SHM literature [3,4] is the development of mathematically and physically rigorous approaches to designing the SHM sensing system that is used to address the data acquisition portion of the problem. To date, almost all such system designs are done somewhat in an *ad hoc* manner where the engineer picks a sensing system that is readily available and that they are familiar with, and then attempts to demonstrate that a specific type of damage can be detected with that system. If an appropriate level of damage detection fidelity can not be obtained, then the system is modified in some empirical manner with the hopes that the fidelity is improved. Alternatively, as new sensing systems are developed by engineers outside the SHM field, researchers in this field will apply these new systems to their respective SHM studies in an effort to see if these systems provide an enhanced damage detection capability. Through these approaches, several sensor network paradigms for SHM have immerged, and this paper will summarize and compare these paradigms. When making such a comparison, it should be noted that the authors do not believe there is one sensor network paradigm that is optimal for all SHM problems. All of these paradigms have relative advantages and disadvantages. Also, the paradigms described are not at the same level of maturity and, hence, some may require more development to obtain a field-deployable system while others are readily available with commercial off-the-shelf solutions.

This paper will first provide a brief summary of the statistical pattern recognition approach to SHM problem. Next, the data acquisition portion of the paradigm is addressed in more detail where the various parameters of the system that must be considered in its design and subsequent field deployment are summarized. Several sensor systems that have been developed specifically for SHM are discussed in terms of these parameters. These sensor systems lead to the definition of three general SHM sensor network paradigms that are then described along with a summary of their relative attributes and deficiencies. A fourth sensor network that is currently under development is proposed that provides an alternative approach to sensing for SHM. The paper concludes by summarizing the practical implementation issues of the SHM sensor system in an effort to suggest a more mathematically and physically rigorous approach to future SHM sensing system design.

2. The Statistical Pattern Recognition Approach to Structural Health Monitoring

A necessary first step to developing a SHM capability is *Operational Evaluation*. This part of the SHM solution process attempts to answers four questions regarding the implementation of a structural health monitoring system: (1) What are the life safety and/or economic justifications for monitoring the structure? (2) How is damage defined for the system being monitored? (3) What are the operational and environmental conditions under which the system of interest functions?, and (4) What are the limitations on acquiring data in the operational environment? Operational evaluation defines, and to the greatest extent possible quantifies, the damage that is to be detected. It also defines the benefits to be gained from deployment of the SHM system. This process also begins to set limitations on what will be monitored and how to perform the monitoring as well as tailoring the monitoring to unique aspects of the system and unique features of the damage that is to be detected.

The *Data Acquisition* portion of the SHM process involves selecting the excitation methods, the sensor types, number and locations, and the data acquisition/storage/processing/transmittal hardware. The actual implementation of this portion of the SHM process will be application specific. A fundamental premise regarding data acquisition and sensing is that these systems do not measure damage. Rather, they measure the response of a system to its operational and environmental loading or the response to inputs from actuators embedded with the sensing system. Depending on the sensing technology deployed and the type of damage to be identified, the sensor readings may be more or less directly correlated to the presence and location of damage. Data interrogation procedures (feature extraction and statistical modeling for feature classification) are the necessary components of a SHM system that convert the sensor data into information about the structural condition. Furthermore, to achieve successful SHM the data acquisition system will have to be developed in conjunction with these data interrogation procedures.

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. Ideally, a damage-sensitive feature will change in some consistent manner with increasing damage level. Identifying features that can accurately distinguish a damaged structure from an undamaged one is the focus of most SHM technical literature [3,4]. Fundamentally, the *Feature Extraction* process is based 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. An alternate approach is to identify features that directly compare the sensor waveforms or spectra of these waveforms. Many of the features identified for impedance-based and wave propagation-based SHM studies fall into this category [5,6,7,8].

The portion of the structural health monitoring process that has received the least attention in the technical literature is the development of statistical models to enhance the damage detection process. *Statistical modeling for feature classification* is concerned with the implementation of the algorithms that analyze the distributions of the extracted features in an effort to determine the damage state of the structure. The algorithms used in statistical model development usually fall into the three general categories of: (1) Group Classification, (2) Regression Analysis, and (3) Outlier Detection. The appropriate algorithm to use will depend on the ability to perform *supervised* or *unsupervised* learning. Here, supervised learning refers to the case were examples of data from damaged and undamaged structures are available. Unsupervised learning refers to the case were data is only available from the undamaged structure. 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 modeling portions of the SHM process are data normalization, cleansing, fusion and compression. As it applies to SHM, data normalization is the process of separating changes in sensor reading caused by damage from those caused by varying operational and environmental conditions [9]. 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 an effort to facilitate 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.

3. Structural Health Monitoring Sensor System Design Consideration

The goal of any SHM sensor system development is to make the sensor reading as directly correlated with, and as sensitive to, damage as possible. At the same time one also strives to make the sensors as independent as possible from all other sources of environmental and operational variability. To best meet these goals for the SHM sensor and data acquisition system, the following sensing system properties must be defined:

1. Types of data to be acquired,
2. Sensor types, number and locations,

3. Bandwidth, sensitivity and dynamic range,
4. Data acquisition/telemetry/storage system,
5. Power requirements,
6. Sampling intervals (continuous monitoring versus monitoring only after extreme events or at periodic intervals),
7. Processor/memory requirements, and
8. Excitation source (active sensing).

There can be even more issues that must be addressed when developing the sensing portion of the SHM process. Fundamentally, there are four issues that control the selection of hardware to address these sensor system design parameters:

1. The length scales on which damage is to be detected.
2. The time scale on which damage evolves.
3. How will varying and/or adverse operational and environmental conditions affect the sensing system, and
4. Cost

In addition, the feature extraction, data normalization and statistical modeling portions of the process can greatly influence the definition of the sensing system properties. Before such decisions can be made two important questions must be addressed.

First, one must answer the question, “What is the damage to be detected?” The answer to this question must be provided in as quantifiable a manner as possible and address issues such as 1.)

Type of damage (e.g. crack, loose connection, corrosion), 2.) Threshold damage size that must be detected, 3.) Probable damage locations, and 4.) Anticipated damage growth rates. The more specific and quantifiable this definition, the more likely it is that one will optimize their sensor budget to produce a system that has the greatest possible fidelity for damage detection. Second, an answer must be provided to the question, “What are the environmental and operational variability that must be accounted for?” To answer this question, one will not only have to have some ideas about the sources of such variability, but one will also have to have thought about how they are going to accomplish data normalization. Typically, data normalization will be accomplished through some combination of sensing system hardware and data interrogation software. However, these hardware and software approaches will not be optimal if they are not done in a coupled manner.

In summary, from the discussion in this section it becomes clear that the ability to convert sensor data into structural health information is directly related to the coupling of the sensor system hardware development with the data interrogation procedures.

4. Current Systems

Sensing systems for SHM consist of some or all of the following components.

1. Transducers that converts changes in the field variable of interest (e.g. acceleration, strain, temperature) to changes in an electrical signal (e.g. voltage, impedance, resistance).

2. Actuators that can be used to apply a prescribed input to the system (e.g. Lead-Zirconium Titanate (PZT) bonded to the surface of a structure)

3. Analog-to-digital (A/D) converters that transfer the analog electrical signal into a digital signal that can subsequently be processed on a computer. For the case where actuators are used a

digital-to-analog (D/A) converter will also be needed to change the prescribed digital signal to an analog voltage that can be used to control the actuator

4. Signal conditioning
5. Power
6. Telemetry
7. Processing
8. Memory for data storage

The number of sensing systems available for SHM is enormous and these systems vary quite a bit depending upon the specific SHM activity. Two general types of SHM sensing systems are described below.

4.1 Wired System

Here wired SHM are defined as ones that telemeter data over direct wire connection from the transducer to the central data analysis facility, as shown schematically in Figure 1. In some cases the central data analysis facility is then connected to the internet such that the processed information can be monitored at a subsequent remote location. There are a wide variety of such systems. At one extreme is peak-strain or peak-acceleration sensing devices that notify the user when a certain threshold in the measured quantity has been exceeded. A more sophisticated system often used for condition monitoring of rotating machinery is a piezoelectric accelerometer with built-in charge amplifier connected directly to a hand-held, single-channel fast-Fourier-transform (FFT) analyzer. Here the central data storage and analysis facility is the hand-held FFT analyzer. Such systems cost on the order of a few thousand dollars. At the other extreme is custom designed systems with hundred of data channels containing numerous types of sensors that cost on the order of multiple millions of dollars such as that deployed on the Tsing Ma bridge in China [10].

There are a wide range of commercially available wired systems, some of which have been developed for general purposed data acquisition and other which have been specifically developed for SHM applications. Those designed for general purpose data acquisition typically can interface with wide variety of transducers and also have the capability to drive actuators. The majority of these systems have integrated signal conditioning, data processing and data storage capabilities. The majority of these systems run off of AC power. Those designed to run off of batteries typically have a limited number of channels and they are limited in their ability to operate for long periods of time.

One wired system that has been specifically designed for SHM applications consists of an array of PZT patches embedded in Mylar sheet that is bonded to a structure [11]. The PZT patches can be used as either an actuator or sensor. Damage is detected, located, and in some cases quantified by examining the attenuation of signals between different sensor-actuator pair or by examining the characteristics of waves reflected from the damage. An accompanying PC is used for signal conditioning, A/D and D/A conversion, data analysis and display of final results. The system, which runs on AC power, is shown in Figure 2.

4.2 Wireless Transmission systems

Tanner, et al. [12] adapted an SHM algorithm to the limitations of off-the-shelf wireless sensing and data processing hardware because of the focus towards a proof of concept rather than designing a field installable product. A wireless sensing system of “Motes” running TinyOS operating system developed at UC Berkeley was chosen because of their ready-made wireless communication capabilities. A Mote consists of modular circuit boards integrating a sensor, microprocessor, A/D converter, and wireless transmitter all of which run off of two AA batteries. A significant reduction in power consumption can be achieved by processing the data locally and only transmitting the results.

The core of the processor board is a 4 MHz ATMEL AVR 90LS8535 microprocessor with 8 KB of flash program memory and 512 bytes of RAM. A 10-bit A/D converter is included in this microprocessor. This converter is capable of sampling 8 channels, but only by sequentially multiplexing the channels. A two-axis accelerometer mounted on a circuit board is integrated with the board as a sensing device. The processor board also contains three light emitting diodes (LED) and a short range 916 MHz radio transmitter. Structural health monitoring algorithms were written on a PC and compiled into a binary image file that was downloaded into the flash program memory on the processing board. A binary result could then either be shown on the mote’s LEDs or transmitted wirelessly to a base station. The system was demonstrated using a small portal structure with damage induced by loss of pre-load in a bolted joint. The tested mote system is shown in Figure 3. The processor proved to be, however, very limited, allowing only the most rudimentary data interrogation algorithms to be implemented.

Lynch et al. [13] presented hardware for a wireless peer-to-peer SHM system. Using off the shelf components, the authors couple sensing circuits and wireless transmission with a computational core allowing a decentralized collection, analysis, and broadcast of a structure’s health. The final hardware platform includes two microcontrollers for data collection and computation connected to a spread spectrum wireless modem. The software is tightly integrated with the hardware and includes the wireless transmission module, the sensing module, and application module. The application module implements the time series based SHM algorithm. This integrated data interrogation process requires communication with a centralized sever to retrieve model coefficients. The object of the close integration of hardware and software with the dual microcontrollers strives for a power efficient design.

Spencer [14] provides the state-of-the-art review of current “smart sensing” technologies that includes the compiled summaries of wireless work in the SHM field using small, integrated sensor, and processor systems. A smart sensor is here defined as a sensing system with an embedded microprocessor and wireless communication. Many smart sensors covered in this article are still in the stage of that simply sense and transmit data. The Mote platform is discussed as an impetus for development of the next generation of SHM systems and a new generation of Mote is also outlined. The authors also raised the issues on that current smart sensing approach scale poorly to systems with densely instrumented arrays of sensors that will be required for future SHM systems.

In order to develop a truly integrated SHM system, the data interrogation processes must be transferred to embedded software and hardware that incorporates sensing, processing, and the ability to return a result either locally or remotely. Most off-the-shelf solutions currently available, or in development, have a deficit in processing power that limits the complexity of the software and SHM process that can be implemented. Also, many integrated systems are inflexible because of tight integration between the embedded software, the hardware, and sensing.

To implement computationally intensive SHM processes, Farrar et al. selected a single board computer as a compact form of true processing power [15]. Also included in the integrated system is a digital signal processing board with six A/D converters providing the interface to a variety of sensing modalities. Finally, a wireless network board is integrated to provide the ability for the system to relay structural information to a central host, across a network, or through local hardware. Figure 4 shows the prototype of this sensing system. Each of these hardware parts are built in a modular fashion and loosely coupled through the transmission control protocol or Internet protocols. By implementing a common interface, changing or replacing a single component does not require a redesign of the entire system. By allowing processes developed in the Graphical Linking and Assembly of Syntax Structure (GLASS) client to be downloaded and run directly in the GLASS node software, this system becomes the first hardware solution where new processes can be created and loaded dynamically. This modular nature does not lead to the most power optimized design, but instead achieves a flexible development platform that is used to find the most effective combination of algorithms and hardware for a specific SHM problem. Optimization for power is of secondary concern and will be the focus of follow-on efforts [15].

5. Sensor Network Paradigms

The sensor systems discussed in the previous section have lead to three types of sensor network paradigms that are either currently being used for structural health monitoring or are the focus of current research efforts in this field. These paradigms are described below. Note that the illustrations of these systems show them applied to a building structure. However, these paradigms can be applied to a wide variety of aerospace, civil and mechanical system and the building structure is simply used for comparison purposes.

5.1 Sensor Arrays directly Connected to Central Processing Hardware

Figure 1 show a sensor network directly connected to the central processing hardware. Such a system is the most common one used for structural health monitoring studies. The advantage of this system is the wide variety of commercially available off-the-shelf systems that can be used for this type of monitoring and the wide variety of transducers that can typically be interfaced with such a system. For SHM applications, these systems have been used in both a passive and active sensing manner. Limitations of such systems are that they are difficult to deploy in a retrofit mode because they usually require AC power, which is not always available. Also, these systems are one-point failure sensitive as one wire can be as long as a few hundred meters. In addition, the deployment of such system can be challenging with potentially over 75% of the installation time attributed to the installation of system wires and cables for larger scale structures such as those used for long-span bridges [16]. Furthermore, experience with field-deployed systems has shown that the wires can be costly to maintain because of general environmental degradation and damage cause by things such as rodents and vandals.

5.2 Decentralized Processing with Hopping connection

The integration of wireless communication technologies into SHM methods has been widely investigated in order to overcome the limitations of wired sensing networks. Wireless communication can remedy the cabling problem of the traditional monitoring system and significantly reduce the maintenance cost. The schematic of the de-centralized wireless monitoring system, which is summarized in detail by Spencer et al [14], is shown in Figure 5.

From the large-scale SHM practice, however, several very serious issues arise with the current design and deployment scheme of the decentralized wireless sensing networks [14, 17]. First, the current wireless sensing design usually adopts ad-hoc networking and hopping that results in a problem referred to as data collision. Data collision is a phenomenon that results from a network device receiving several simultaneous requests to store or retrieve data from other devices on the network. With increasing numbers of sensors, a sensor node located close to the base station would experience tremendous data transmission, possibly resulting in a significant bottleneck. Because the workload of each sensor node cannot be evenly distributed, the chances of data collision increase with expansion of the sensing networks. In addition, this decentralized wireless sensing network scales very poorly in active-sensing system deployment. Because active-sensors can serve as actuators as well as sensors, the time synchronization between multiple sensor/actuator units would be a challenging task. Furthermore, the cost of implementing such a system into a large-scale structure is extremely prohibitive with increasing number of active-sensors. The cost of current de-centralized wireless sensor nodes is at least two orders of magnitude greater than that of an active-sensor, which can usually be obtained for less than $5. Because of the processor scheduling or sharing, the use of multiple channels with one sensor node would reduce the sampling rate, which provides neither a practical nor equitable solution for active-sensing techniques that typically adopt higher frequency ranges. Therefore, in real-life applications, the current design scheme could turn out to be a very expensive operation.

5.3 Decentralized Processing with Hybrid connection

The hybrid connection network advantageously combines previous two networks, as illustrated in Figure 6. At the first level, several sensors are connected to a relay-based piece of hardware, which can serve as both a multiplexer and general-purpose signal router, shown in Figure 6 as a black box. This device will manage the distributed sensing network, control the modes of sensing and actuation, and multiplex the measured signals. The device can also be expandable by means of daisy-chaining. At the next level, multiple pieces of this hardware are linked to a decentralized data control and processing station. This control station is equipped with data acquisition boards, on-board computing processors, and wireless telemetry which is similar to the architecture of current decentralized wireless sensors. This device will perform duties of a relay-based hardware control, data acquisition, local computing, and transmission of the necessary results of the computation to the central system. At the highest level, multiple data processing stations are linked to a central monitoring station that delivers a damage report back to the user. Hierarchal in nature, this sensing network can efficiently interrogate large numbers of distributed sensors and active-sensors while maintaining an excellent sensor-cost ratio because only a small number of data acquisition and telemetry units is necessary. This hierarchal sensing network is especially suitable for active-sensing SHM techniques, and is being substantially investigated by Dove et al [17]. In their study, the expandability or the sensing network was of the utmost importance for significantly larger numbers of active-sensors, as the number of channels on a de-centralized wireless sensor is limited due to the processor sharing and scheduling. The prototype of the “Blackbox” (shown in Figure 6) is illustrated in Figure 7.

6. Future Sensing Network Paradigms

The sensing network paradigms described in the previous section have one characteristic in common. The sensing system and associated power sources are installed at the fixed locations of the structural system. As stated, the deployment of such sensing systems can be costly and the power source may not be always available. A new, efficient future sensing network is currently being investigated by Los Alamos National Laboratory by integrating active Radio-Frequency Identification (RFID) sensing technology and remote interrogation platforms based on either robots or unmanned aerial vehicles (UAV) to assess damage in structural systems. This approach involves using an unmanned mobile host node (delivered via UAV or robot) to generate an RF signal near the RFID-tagged sensors that have been embedded on the structure. The sensors measure the desired response (impedance, strain, etc.) at critical areas on the structure and transmit the signal back to the mobile host again via the RFID communication. This “wireless” communications capability draws from the magnetic field that is induced between host and sensor, and uses it to both power the circuit and to transmit the signal back to the host. RFID does not require a line of sight, and only needs to be in a close proximity to the host. RFID technology has recently matured due to industrial development, costing as little as $0.50 per tag, allowing for many such devices to be placed on a large structure such as a bridge at numerous critical junctures. The host itself, with embedded computing circuitry, may be more expensive, e.g., ~$1000, but only one such host will be needed to interrogate an entire RFID sensor array placed on the structure. This research takes traditional sensing networks to the next level, as the mobile hosts (such as UAV), will fly to known critical infrastructure based upon a GPS locator, deliver required power, and then begin to perform an inspection without human intervention. The mobile hosts will search for the RFID tags on the structure and gather critical data needed to perform the structural health evaluation. This project will tailor a specialized UAV made of light-weight composite materials that will be less than 55 lbs in order get FAA approval for flying in populated air spaces and be able to access tighter spaces. A specialized autopilot will be designed to accommodate both sensor modalities and RFID tag tracking and control. This integrated technology will be directly applicable to rapid structural condition assessment of buildings and bridges after an earthquake. Also, this technology may be adapted and applied to damage detection in a variety of other civilian and defense-related structures such as, pipelines, naval vessels, and commercial aircraft.

7. Practical Implementation Issues for SHM Sensing Networks

A major concern in the current sensing network development is the long-term reliability and power source, although micro parasitic generators being developed may provide the solution to enable truly wireless sensors. Other concerns are the abilities of the sensing systems to capture local and system level response, that is, the need to capture response on widely varying length and time scales, and to archive data in a consistent, retrievable manner for long-term analysis. These challenges are nontrivial because of the tendency for each technical discipline to work more or less in isolation. Therefore, an integrated systems engineering approach to the damage detection process and regular, well-defined routes of information dissemination are essential. The subsequent portions of this section will address specific sensing system issues associated with SHM.

7.1 Sensor Properties

One of the major challenges of defining sensor properties is that these properties need to be defined *a priori* and typically cannot be changed easily once a sensor system is in place. These properties of sensors include bandwidth, sensitivity (dynamic range), number, location, stability, reliability, cost, telemetry, etc. To address this challenge a significantly coupled analytical and experimental approach to the sensor system deployment should be used in contrast to the current ad-hoc procedures used for most current damage detection studies. This strategy should yield considerable improvements. First, critical failure modes of the system can be well defined and, to some extent, quantified using high-fidelity numerical simulations or from previous experiences before the sensing system is designed. The high-fidelity numerical simulations/experiences can be used to define the required bandwidth, sensitivity, sensor location and sensor number. Additional sensing requirements can also be ascertained if changing operational and environmental conditions are included in the models so as to determine how these conditions affect the damage detection process.

Another potential level of integration between modeling and sensing resides in the integration of software and hardware components. Once the actuation and sensing capability has been selected, their location has been optimized and the specification of the data acquisition system have been met, it may be advantageous to integrate model output and sensing information as much as possible. For example, surrogate models can be programmed on local DSP chips and their predictions can be compared to sensor output in real time. One obvious benefit would be to minimize the amount of communication by integrating the analysis capability with real-time sensing. In an integrated approach, features can be extracted from sensing information and numerical simulation. Test-analysis comparison and parameter estimation can then be performed locally, which would greatly increase the efficiency of damage detection.

7.2 Power Consideration

A major consideration in using a dense sensor array is the problem of providing power to the sensors. This demand leads to the concept of “information as a form of energy”. Deriving information costs energy. If the only way to provide power is by direct connections, then the need for wireless protocols is eliminated, as the cabled power link can also be used for the transmission of data. Hence, the development of micro-power generators is a key factor for the development of the hardware if wireless communication is to be used. A possible solution to the problem of localized power generation is technologies that enable harvesting ambient energy to power the instrumentation [18]. Forms of energy that may be harvested include thermal, vibration, acoustic, and solar. Although this is new technology the overriding consideration of reliability still exists, as it does with any monitoring systems. With two-way communication capability, the local sensing and processing units can also turn themselves off-line for energy conservation and they can be resuscitated when a “wake-up” signal is broadcast.

7.3 Sensor Calibration and Ruggedness

Most sensors are calibrated at a specialized calibration facility. This type of calibration is expected to endure, but to be supplemented by self-checking and self-calibrating sensors. Calibration raises several important issues. It is not clear just what forms of calibration are essential, and what are superfluous. Some measurements are acceptable with 20% error, especially if sensor-to-sensor comparisons are accurate within a few percent. In other scenarios absolute accuracies better than 1% are required. The calibration community needs to address these issues, including both precision, for example how to calibrate a 32 bit digitize over its entire dynamic range, and flexibility (calibration of a precise sensor vs. calibration of a coarse sensor).

Confidence and robustness in the sensors are prime considerations for SHM. If this part of the system is compromised then the overall confidence in the system performance is undermined. For sensors implemented for SHM, several durability considerations emerge:

1. The nontrivial problem of sensor selection for extreme environments, e.g. in service turbine blades;
2. Sensors being less reliable than the part. For example, reliable parts may have failure rates of 1 in 100,000 over several years time. Sensors are often small, complex assemblies, so sensors may fail more often than the part sensed. Loss of sensor signal then falsely indicates part failure, not sensor failure;
3. Sensors may fail through outright sensor destruction while the part sensed endures;

False indications of damage or damage precursors are extremely undesirable. If this occurs often the sensor is either overtly or covertly ignored. Recently several studies are focused on issues of sensor validation [19,20].

7.4 Multi-Scale Sensing

Depending on the size and location of the structural damage and the loads applied to the system, the adverse effects of the damage can be either immediate or may take some time before it alters the system's performance. In terms of length scales, all damage begins at the material level and then under appropriate loading conditions progresses to component and system level damage at various rates. In terms of time scales, damage can accumulate incrementally over long periods of time such as that associated with fatigue or corrosion damage accumulation. Damage can also occur on much shorter time scales as the result of scheduled discrete events such as aircraft landings and from unscheduled discrete events such as enemy fire on a military vehicle. Therefore, the most fundamental issue that must be addressed when developing a sensing system for SHM is the need to capture the structural response on widely varying length and time scales. Sensors with a high frequency range tend to be more sensitive to local response, and therefore, to damage. This requires a sensor with a large bandwidth. Typically, as the bandwidth goes up, the sensitivity goes down. Also, it is harder to excite higher frequencies or else the excitation needs to be very local as is possible with piezoelectric actuators.

The sensing systems that is able to capture the responses over varying length and time scales has not been substantially investigated by researchers, although it is quite possible to use the same piezoelectric patches in both an active (high frequency) and passive (lower-order global) modes. When used in the passive mode, the sensors detect strain resulting from ambient loading conditions and can be used to monitor the global response of a system. In the active mode the same sensors can be used to detect and located damage on local level using relatively higher frequency ranges.

8. Summary

In this paper, the current research in the designing the sensing system that is used to address the data acquisition portion of the SHM problem is summarized. Several sensor systems that have been developed specifically for SHM are discussed in detail. These sensor systems lead to the definition of several general SHM sensor network paradigms. All of these paradigms have relative advantages and disadvantages. Also, the paradigms described are not at the same level of maturity and, hence, some may require more development to obtain a field-deployable system while others are readily available with commercial off-the-shelf solutions. The paper concludes by summarizing the practical implementation issues of the SHM sensor system in an effort to suggest a more mathematically and physically rigorous approach to future SHM sensing system design.

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LIST OF FIGURES

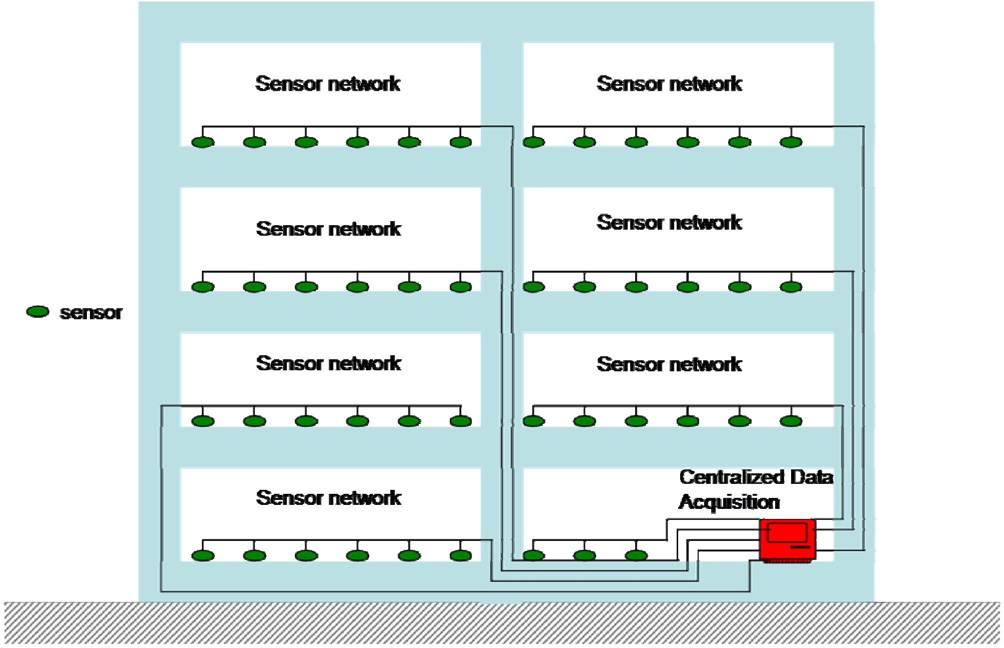

Figure 1. The wired sensing network

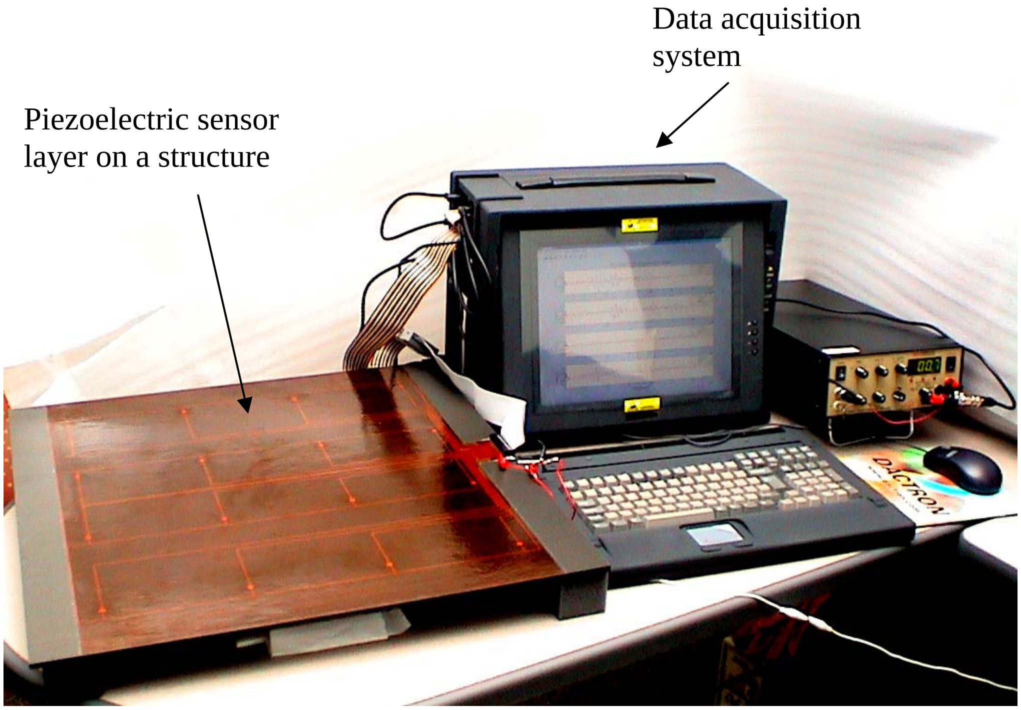

Figure 2. A data acquisition system specifically designed for SHM

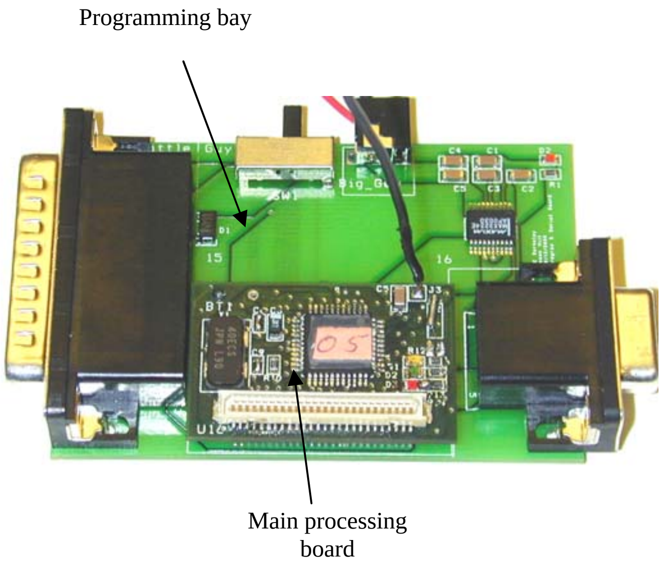

Figure 3: Mote Processing board mounted in programming bay.

Figure 4: The wireless communication board displayed on the prototype SHM system (Farrar et al. 2005).

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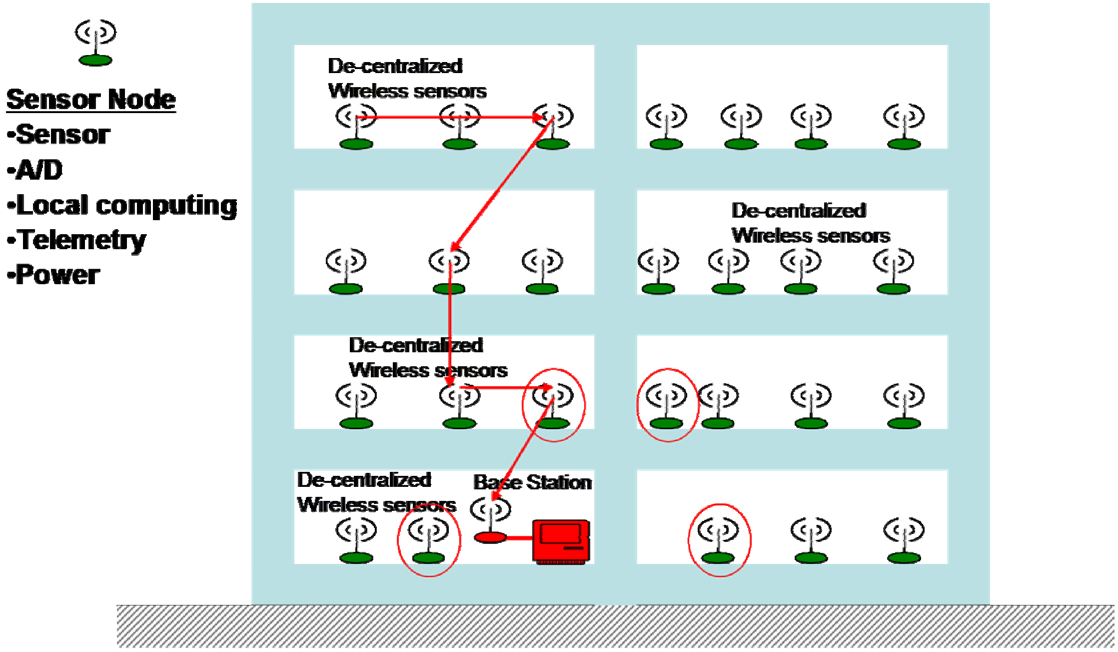

Figure 5: De-centralized wireless SHM system with Hopping connection

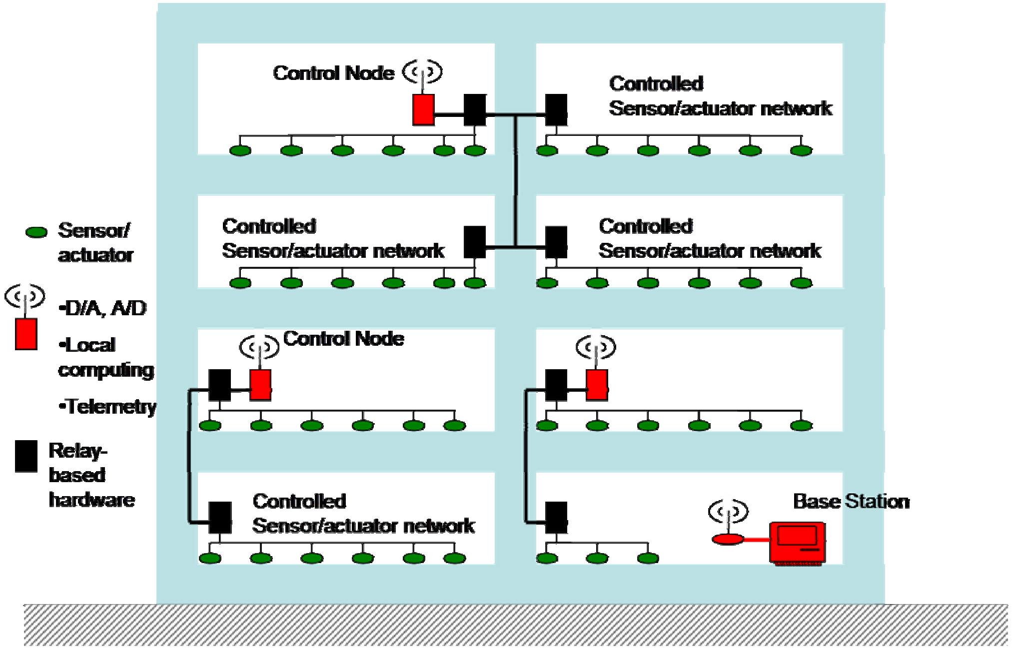

Figure 6: De-centralized wireless SHM system with hybrid connection

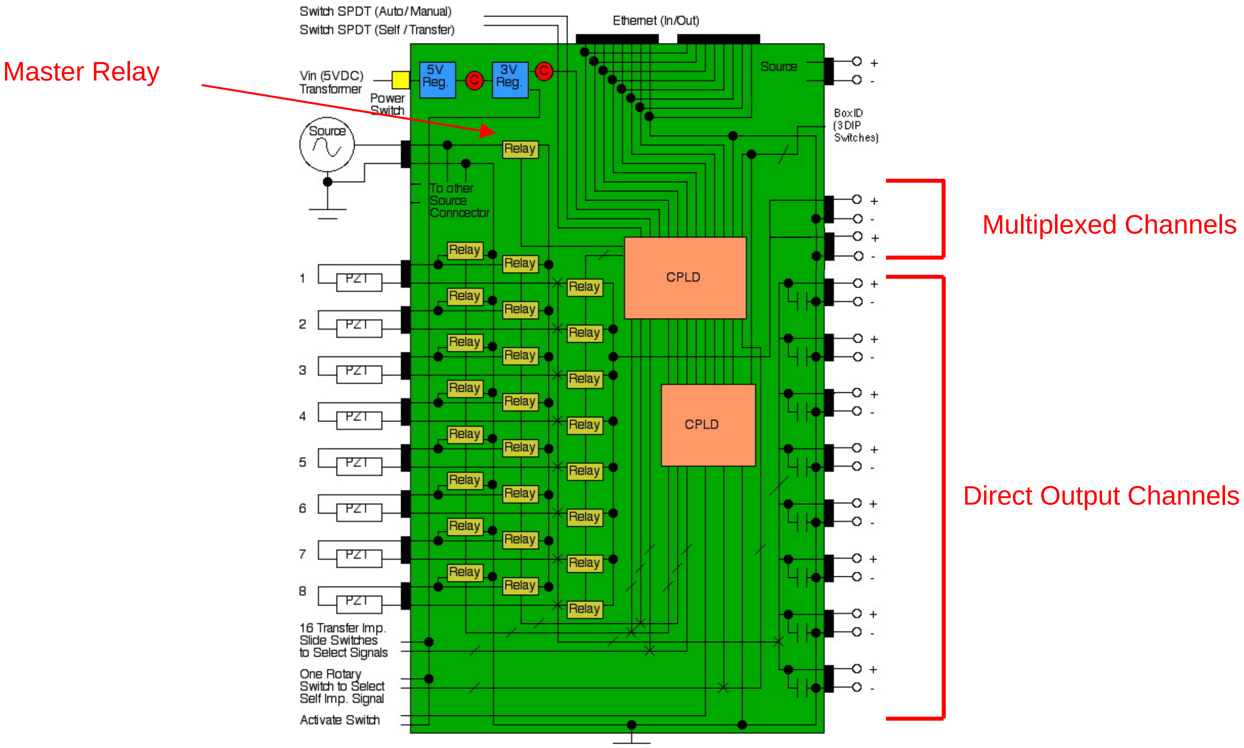

Figure 7: Relay-based hardware With Option Manual Controls Included