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A Comprehensive Study on Structural Health Monitoring of Structural System

Priyanka Singh[1] and N.D. Shah[2]

[1]*Galgotias University*
[2]*Dean, P. P. Savani University Surat, Gujarat*
E-mail: [1]priyankasingh@galgotiasuniversity.edu.in, [2]niraj.shah@ppsuni.ac.in

Abstract—*Structural Health Monitoring (SHM) objective is to improve knowledge of the safety and maintainability of civil structures and infrastructures. This paper presents an analysis of a method for damage detection based on a statistical approach that uses the most significant data. SHM is a new and improved way to make a Non-Destructive Evaluation. This is partially true, but it is much more. It involves the integration of sensors, possibly smart materials, data transmission, computational power, and processing ability inside the structures. It makes it possible to reconsider the design of the structure and the full management of the structure itself and of the structure considered as a part of wider systems. It provides, at every moment during the life of a structure, a diagnosis of the "state" of the constituent materials, of the different parts, and of the full assembly of these parts constituting the structure as a whole. The state of the structure must remain in the domain specified in the design, although this can be altered by normal aging due to usage, by the action of the environment, and by accidental events.*

Keywords*: Structural Health Monitoring, Structural Health Management, Non-destructive Evaluation, Data Interpretation, Damage Detection.*

1. INTRODUCTION

Structural Health Monitoring (SHM) - the scientific process of nondestructively identifying four characteristics real-time or near real-time related to the fitness of an engineered component (or system) as it operates using a built-in sensory and reasoner system with the operational and environmental loads that act on the component such as the mechanical damage that is caused by that loading, the growth of damage as the parts operates and the future performance of the component as damage accumulates[1-3].Structural Health Management (SHM) – the process of determining the ability of the structure to continue to perform its desired decisions/recommendations about mission and maintenance actions based on structural health assessment data in light of the inevitable ageing and degradation resulting from the operational environments.

A key to enabling management as opposed to simple monitoring is prognosis. SHM systems have been used to monitor critical infrastructure such as bridges, high-rise buildings, and stadiums and has the potential to improve structure lifespan and improve public safety[2-4].. The high data collection rate of WSNs for SHM pose unique network design challenges. Structural Health Monitoring (SHM) is one such application in which sensors distributed throughout a structure are used to assess the structure's health.

Historically, SHM systems were designed using wired sensor networks; however, the high reliability and low installation and maintenance costs of WSNs have made them a compelling alternate platform over the last decade Wireless Sensor Networks (WSNs) have emerged as a powerful low-cost platform for connecting large networks of sensors [5-6]. These networks have found applications in commercial, health, military and industrial settings.

Due to their high installation costs wired sensor networks are generally only feasible for long-term SHM applications where the structure's health is of critical importance. The significant cost reductions of using WSNs for SHM would enable their utilization in important public and private infrastructure and increase the use of applications such as short-term structural monitoring.

Such systems could extend the lifespan of numerous structures by enabling earlier damage detection, eliminate the cost of routine inspections and most critically of all, improve public safety [6-7].

In WSNs for SHM sensors are deployed at various locations throughout a structure. These sensors collect information about their surrounding such as acceleration, ambient vibration, load and stress. The SHM using WSNs is shown below in Fig.1.

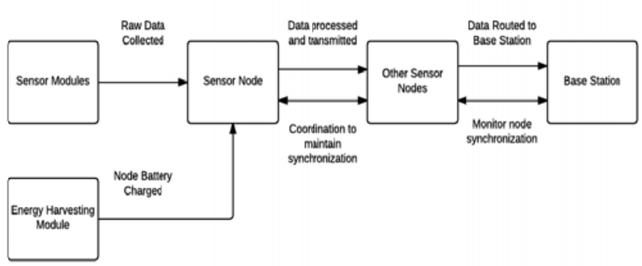

Fig. 1: SHM using WSNs

Sensor Parameters:Parameters commonly detected, recorded and monitored in systems can be broadly classified as the following types: Load - Loads are the forces applied to the structure.Possible loads are environmental loads such as wind speeds, and loads due to passing vehicles. Loads can be static or dynamic. Typically, the response of the structure to these loads can be measured by the SHM system.Global Load Response are the structure's response to a given load that can be measured throughout the entire structure. Typically, measured parameters are a structure's acceleration and velocity.Local Load Response are the structure's response to a given load that can only be measured in a specific part of the structure.

Typically, measured parameters are strain, crack and tension forces.Environmental Factors – Environmental factors are external to the structure itself and relate to the structure's environment. Measured parameters include temperature, salinity, humidity, and atmospheric acidity. These parameters can be used in the estimation of environmental loads such as winds.

To date, out of all of the above parameters, the most commonly measured are the structure's acceleration and velocity. One of the unique challenges posed by measuring global load response variables such as acceleration and velocity is that due to their global nature, it is difficult to detect the exact location of the damage.

Sensors and Parameters: One of the most important considerations when designing an SHM system is the selection of sensors and sensed parameters. Factors such as sensor power consumption and sensed parameters influence overall network design by influencing routing protocol selection, damage detection algorithm selection, damage localization algorithm selection, and network lifespan.

Hence, the sensing and sampling rates and amount of collected data are much higher than those in other applications in WSNs and as a result WSNs for SHM introduce challenges in network design. Sensor nodes transmit the sensed data to the sink either directly or by forwarding each other's packets.

Data aggregation and processing is necessary for the detection and localization of structural damage and can occur in different locations (e.g., nodes, cluster-heads, and/or central server) depending on the network topology. Typically, damage detection requires the comparison of the structure's present modal features to those associated with the structure's undamaged state. Modal features of a structure are mainly represented by the mode shapes – the natural vibration pattern for a given structure.

2. IMPETUS FOR STRUCTURAL HEALTH MONITORING

Knowing the integrity of in-service structures on a continuous real-time basis is a very important objective for manufacturers, end-users and maintenance teams. In effect, SHM allows an optimal use of the structure, a minimized downtime, and the avoidance of catastrophic failures, gives the constructor an improvement in his products, drastically changes the work organization of maintenance services by aiming to replace scheduled and periodic maintenance inspection with performance-based (or condition-based) maintenance (long term) or at least (short term) by reducing the present maintenance labor, in particular by avoiding dismounting parts where there is no hidden defect and by drastically minimizing the human involvement and consequently reducing labor, downtime and human errors, and thus improving safety and reliability.

These drastic changes in maintenance philosophy are described in several recent papers, in particular for military air vehicles for Army systems, civil aircraft and for civil infrastructures. The improvement of safety seems to be a strong motivation, in particular after some spectacular accidents due to unsatisfactory maintenance in the aeronautic field, civil engineering field. Nevertheless, analysis of the various causes of aircraft accidents points to the relatively low influence of maintenance deficiency.

Furthermore, it should be noted that only 4% of all accidents are due to structural weakness. It can be determined that the introduction of SHM is an improvement in maintenance and a decrease of structure-caused accidents by a factor of two would lead to a global reduction of accidents of less than 10%, which is far from what is needed to avoid a significant increase in the number of accidents in the near future if air traffic continues to increase.

The economic motivation is stronger, principally for end-users. In effect, for structures with SHM systems, the envisaged benefits are constant maintenance costs and reliability, instead of increasing maintenance costs and decreasing reliability for classical structures without SHM.

It involves the integration of sensors, possibly smart materials, data transmission, computational power, and processing ability inside the structures. It makes it possible to reconsider the design of the structure and the full management of the structure itself and of the structure considered as a part of wider systems. This is schematically presented in Figure 2.

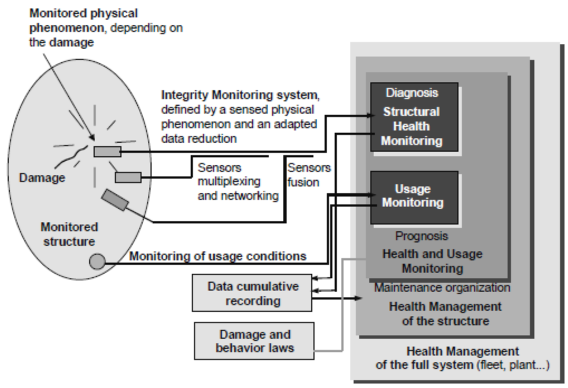

Figure 2: Principle and organization of a SHM system

In the figure, organization of a typical SHM system is given in detail. The first part of the system, which corresponds to the structural integrity monitoring function, can be defined by, the type of physical phenomenon, closely related to the damage, which is monitored by the sensor, the type of physical phenomenon that is used by the sensor to produce a signal (generally electric) sent to the acquisition and storage sub-system.

Several sensors of the same type, constituting a network, can be multiplexed and their data merged with those from other types of sensors. Possibly, other sensors, monitoring the environmental conditions, make it possible to perform the usage monitoring function. The signal delivered by the integrity monitoring sub-system, in parallel with the previously registered data, is used by the controller to create a diagnostic.

Mixing the information of the integrity monitoring sub-system with that of the usage monitoring sub-system and with the knowledge based on damage mechanics and behavior laws makes it possible to determine the prognosis (residual life) and the health management of the structure (organization of maintenance, repair operations, etc.). Finally, similar structure management systems related to other structures which constitute a type of super system (a fleet of aircraft, a group of power stations, etc.) make possible the health management of the super system.

3. SHM- TECHNIC OF CONSTRUCTING STRUCTURES

The concept of smart or intelligent materials and structures has become more and more present in the minds of engineers. These new ideas were particularly welcome in the fields of aerospace and civil engineering. In fact, the concept is presently one of the driving forces for innovation in all domains.

The concept of Smart Materials/Structures (SMS) can be considered as a step in the general evolution of man-made objects as shown in Figure 3. There is a continuous trend from simple to complex in human production, starting from the use of homogeneous materials, supplied by nature and accepted with their natural properties, followed by multi-materials (in particular, composite materials) allowing us to create structures with properties adapted to specific uses.

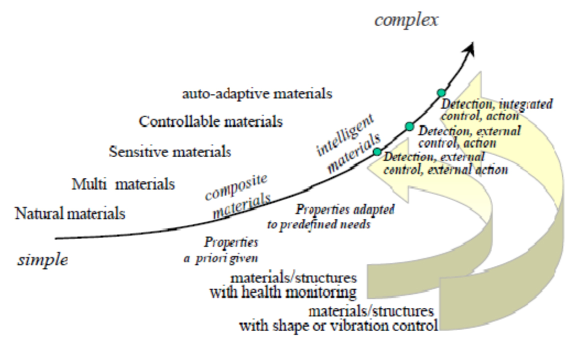

Figure 3: General evolution of materials/structures used by people, and the place of smart structures with SHM

In fact, composite materials and multi-materials are replacing homogeneous materials in more and more structures. This is particularly true in the aeronautic domain. The common basis and complementarity of SHM, shape control and vibration control is shown below in figure 4.

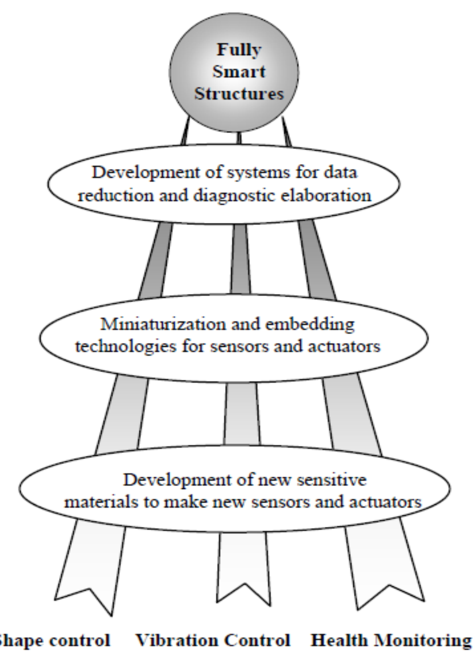

Figure 4: Common basis and complementarity of SHM, shape control and vibration control

Very often, sensitive structures equipped with various types of sensors are compared to living skin. This analogy remains superficial because skin is really an auto-adaptive smart structure controlling its integrity. This is possible due to the presence of actuators that can counterbalance environmental aggressions. The Parallelism between medical activities and SHM is shown below in Table 1.

Table 1: Parallelism between medical activities and SHM

Phase of life	Man	Structures
Birth	Birth monitoring	Process monitoring
Sound life	Health check-up	Health and usage monitoring
Illness and death	Clinical monitoring	Health (damage) monitoring

At the micro scale, the number and variety of skin sensors is way beyond what is possible with man-made sensitive structures (in one human hand there are more than 100,000 sensors!). Finally, the reconstruction ability of living tissues is certainly the most difficult function to reproduce. Over the last decade Wireless Sensor Networks have emerged as a powerful low-cost platform for connecting large networks of sensors. These networks have found applications in commercial, health, military and industrial settings. Structural Health Monitoring (SHM) is one such application in which sensors distributed throughout a structure are used to assess the structure's health.

4. CONCLUSIONS

Structural Health Monitoring together with all the dynamic identification techniques is increasing in popularity in both scientific and civil community. The assessment of an increasing number of aged structures and infrastructures requires a huge effort, especially if the purpose is to provide a faithful evaluation of seismic risk. The current practice of periodic visual inspections, for the safety evaluation appears more and more inadequate. To obstruct classical techniques, it is not necessary that a building reaches damage, even the non-stationarity of the input and the possible interaction with the ground and/or adjacent structures can show the inadequacy of classic techniques. SHM systems. In this paper background information relating to structural health monitoring such as common sensors, commonly measured parameters and damage detection were discussed. The main challenges are scalability, time synchronization, sensor placement optimization and data processing.

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