Sensor Network Applications in Structures – A Survey

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ABSTRACT: Sensor networks play a significant role in modern day structures. From large bridges to sky scrapers, application of sensor networks – both wireless and wired – has strengthened the structural reliability and hence the safety of their users. The objective of this survey paper is to identify different usages of sensor networks in structures and further elaborate on different types of sensing together with the techniques associated with processing the parameters sensed by the sensor networks to achieve the desired implementation goals.

KEYWORDS: sensor networks, structural health monitoring, damage detection, active control, parameter estimation, modeling, building automation

1. INTRODUCTION

Sensor network application in civil structures is a broad area. This survey first identifies the key application areas of sensor networks in civil structures. Structural health monitoring is the continuous evaluation of the strength and reliability of a civil or mechanical structure with time so that the monitoring system can trigger alarms when it detects a possible failure mode. The advantage of this type of early warning system is that it will then be possible to carryout preventive maintenance and avoid heavy level of causalities due to unexpected collapse of the structure. Such systems therefore reduce preventive maintenance costs too. Another application area of sensor networks is the structural damage detection. As an example, the maintenance engineers of a large building would like to know whether the building structure has been subjected to any damage after it undergoes some seismic vibrations. On the other hand, sensor networks can be used in large civil structures to sense harmful vibrations it is undergoing and implement active feedback control schemes to damp out such vibrations and hence prevent any structural damage. This application area is identified in this paper as active control of structures. Another category of research publications address the problem of parameter estimation and modeling of structures using sensor networks. Building automation is another emerging application area for sensor networks though it is not directly related to the civil structure. Therefore the paper briefs this application area also. The remaining sections of this paper is devoted to summarizing the various sensor network applications in the above areas identified, namely; structural health monitoring, structural damage detection, active control of structures, parameter identification and modeling of structures and building automation.

2. STRUCTURAL HEALTH MONITORING

Structural health monitoring (SHM) in this paper is discussed under two main categories, namely, civil structural health and mechanical structural health. Both these fields have common system demands but the loading conditions may differ significantly from each other. Especially civil structures undergo low frequency loading conditions compared to mechanical structures such as turbines and aerospace vehicles.

Civil Structural health monitoring under operating conditions has an enormous potential for pre accident prevention and can effectively reduce regular manual checks. Data produced by the continuous monitoring devices at regular intervals with higher accuracy will pave the way to automated asset management. Active sensor nodes attached into large civil structures was not a reality in the past with the amount of power needed for each node and

the cost of them [1]. However, with the rapid development of low power semiconductor devices and high functionality microcontroller units, SHM sensor networks became a topic of interest in the field [2].

Due to the large volume of data transmission over the sensor network, efficient data compression algorithms play a vital role in large SHM systems. There are many data compression algorithms proposed in the literature and Liu and Cheng reports 1:27 to 1:80 data compression ratio without a significant loss of sensor information [14]. Their proposed lifting scheme wavelet transforms (LSWT) and distributed source coding (DSC) algorithms are promising examples of data compression for large scale sensor networks. Barua et. Al [3] propose a hierarchical fault diagnosing system for space missions with a comparison on Bayesian network-based and Fuzzy reasoning based fault diagnose systems. The proposed hierarchical system will assist even a less experienced person to analyze the network data in order to make a decision on structural health. Grey et. al. presents a Neuro-Fuzzy algorithm for machine health monitoring [9]. Another approach using a fuzzy-neuro algorithm for processing continuous vibration data from a long bridge is presented in [18]. Wang et. al. suggest a multi-level data fusion algorithm for a distributed active network [36]. These methods provide active support for the asset management processes involve with such structures.

Instrumentation is another very important part of the total systems for structural health monitoring today. As the large civil structures have relatively low dynamic response frequencies, it is vital to develop near 0 Hz transceivers for analog devices [21]. The usage of structural health monitoring data is not limited to preventive maintenance. With proper design processes active control of structures can be implemented [41]. The whole system includes smart materials, sensors, actuators, active and passive control systems, and proper instrumentation to deliver a stable structure against regular and undesired loading.

2.1 Wireless sensor networks

Since the health monitoring of massive civil infrastructures is becoming more and more automated, number of nodes deployed for the network is on increase. The hard wired SHM sensor networks are no longer preferred for such structures due to technical as well as architectural reasons. On the other hand, wireless sensor nodes (or motes) gear up their power due to ever developing microcontroller and wireless communications

embedded systems [40], [43]. Lifetime of wireless sensor networks for SHM highly depend on the battery lifetime if the motes are to be embedded to the structure. Therefore efficient battery systems and alternate energy harvesting systems are very important. Solar powered sensor nodes are commonplace in outside structures and Musiani et. al. propose a smart radio triggering circuit for energy saving [6]. They use a 2.4 GHz transmission signal to trigger the microcontroller between working and sleep modes, so that it can isolate the complete circuitry when not in function and save energy. Kim et. al. propose another approach to reduce the power consumption by employing an all-digital system with digital to analog converter (DAC) sampling frequency is overlaid in time domain to generate a sine waveform that requires only l/N_{freq} excitation time while covering the entire target frequency range, where N_{freq} is the number of frequency components in the target frequency range [8].

Sensor network configuration and reliable data transfer are two important factors addressed by many sensor network designers as they play a vital role in network performance [5]. Fixed configuration is acceptable in single-hop data transmission networks but in multi-hop systems it is critical to have the ability to self configure the network in case of node failures [31], [24].

Networking protocol is another issue of concern when thinking of future development. When going for a proprietary network protocol may be efficient but it comes with an additional cost as the end user has to stick to one or a small set of manufacturers for future developments. In contrast, if there is a common protocol for the industry, it will be beneficiary for the users. IEEE802.15.4 which works in international unlicensed frequency band with 16 channels in the 2.4 GHz ISM band, 10 channels in the 915 MHz band and one channel in the 868 MHz band [34] is a candidate for SHM sensor networks. However, for small area networks Bluetooth is a low-cost option as proposed by Metha and Zarki [26].

2.2 SHM Techniques

There are well established techniques in civil structural health monitoring such as vibration testing [19], acoustic emission (AE) testing [35], and optical sensing. Optical sensing has become the frontier technology in the field due to its accuracy in monitoring small scale deformations in structures [12], [16], [44]. There are several types of fiber optic strain sensors, including those based on intensity, polarization, interferometry, and fiber Bragg gratings (FBGs) [28], [29], [30]. The fiber optic sensors have become popular due to their inherent properties of small physical size compared to the structures and

multiplexing capability [42], [33]. In addition, their low-cost and ability to be embedded made them a promising candidate for embedded sensors for structures of any shape. Li et. al. reports the fiber sensor technology used in civil structural health monitoring as in Table 1 [39].

Passive RFID (Radio Frequency ID) systems developed by Ikemoto et. al. is a convincing technology as it does not come across of battery life time problems of sensor nodes [17]. Each sensor node consists of a passive RFID tag only and it can either be embedded into the structure during construction or can be surface mounted later on. Further the surface mounted ones can easily be replaced later on. The development of this device has mainly focused concept of *zero battery power on sensor*. The sensor module consist of two RFID tags where one works as the RF power receiver to power up the internal circuitry of the mote, and the remaining RFID works as the signal transmitter to send the strain gage signal from the mote to the base station. The base station has to send enough RF power to energize the mote. This may have some consequences of low efficiency of energy transfer at RF frequencies at distance, but will not over shadow the advantage of a battery-less mote.

Kim et. al propose a digital excitation technique for impedance based SHM systems [11]. They reveal that the impulse excitation system they proposed has slashed down the total power consumption by 17%. Impedance based SHM is proposed by John et. al. [38]. Galbreath et. al. propose a sensor network where each mote is with supplied by a one 3.6V AA LI-Ion battery for an estimated 5 year lifetime [27]. These motes were designed to have 30 minute sampling interval with low power sleep mode.

2.3 Mechanical structural health monitoring

Another important aspect of SHM is the mechanical structural health monitoring. Detecting damage and/or predicting structural life of mechanical entities help improving reliability and reducing life-cycle cost of mechanical structures such as gas or hydropower turbines, Aerospace structures and Aircrafts, industrial machinery and vehicles [4], [25], [32].

Wei-Bin Zhang [45] has suggested that health monitoring system must monitor at least three objects, including the components which perform normal management and control functions, the components which perform malfunction management (if' it differs from the components to be monitored), and the monitoring system itself regarding vehicle monitoring systems.

According to the paper published by Kumagai et.al., Brillouin optical correlation domain analysis (BOCDA) has a unique advantage of high spatial resolution and high-speed measurements for the aircraft SHM application [15]. Mukkamala R. has identified key characteristics relevant to SHM architectures of Aerospace structures as scalability, legacy systems, openness, flexibility, robustness, extendibility and intelligent monitoring. Unlike other projects that deal with developing operational systems for a specific component, he has concentrated at the higher architectural issues [13]. Use of Index Based Reasoners (IBR) has been proposed for interpretation of the sensory signals of Integrated Systems Health Management (ISHM) by Tansel et. al. for autonomous space access vehicles and satellites [22].

Table 1. Fiber optic sensors for civil SHM [39].

	Sensors	Mesurands	Linear response	Resolution	Range	Modulation method	Intrinsic/ extrinsic
Local	Fabry–Perot	Strain[a]	Y	0.01% gage length[c]	10,000$\mu\epsilon$	Phase	Both
	Long gage sensor	Displacement	Y	0.2% gage length[d]	50 m	Phase	Intrinsic
Quasi-distributed	Fibre Bragg grating	Strain[b]	Y	1 strain	5000$\mu\epsilon$	Wavelength	Intrinsic
Distributed	Raman/Rayleigh (OTDR)	Temperature/ strain	N	0.5m/1˚C	2000m[e]	Intensity	Intrinsic
	Brillouin BOTDR)	Temperature/ strain	N	0.5m/1˚C	2000 m	Intensity	Intrinsic

a Can be configured to measure displacement, pressure, temperature.
b Can be configured to measure displacement, acceleration, pressure, relative fissure and inclination, etc.
c Resolution as high as 0.1 l strain.
d Resolution as high as 0.2 l strain.
e Up to 25 km with spatial resolution of 5 m.

Some novel diagnostic and prognostic technologies for dedicated, real-time sensor analysis, performance anomaly detection and diagnosis, vibration fault detection, and component prognostics has been described by Roemer et. al. regarding gas turbine engine risk assessment. They have illustrated how prognostic technologies can be integrated within existing diagnostic system architectures and the prognostic modeling approach implemented in this paper takes advantage of the directly sensed parameters, fused and diagnostic Engine Health Monitoring (EHM) system results, as well as inspection and historical reliability data - to provide critical inputs for producing accurate failure predictions [7]. A health monitoring system integrated within the turbine could locate blade failures, reducing hydropower turbine life-cycle costs and the costs of energy according to Suyi et. al. [23]. A signal analysis technique for machine health monitoring presented by Yan R. is based on the Hilbert-Huang Transform (HHT). He has shown how HHT represents a time-dependent series in a two-dimensional (2-D) time-frequency domain by extracting instantaneous frequency components within the signal through an Empirical Mode Decomposition (EMD) process [20].

There are special kinds of sensors developed for aerospace mechanical structural health monitoring. Ceramic strain gages developed by Gregory and Luo are a typical example for this [10]. The piezoelectric wafer embedded sensor proposed by Victor et. al. is another example for specific type of sensors developed for aircraft structural health monitoring [37].

3. STRUCTURAL DAMAGE DETECTION

Another widely used civil structural application of sensor networks is the structural damage detection. Particularly large building that survive after seismic activities, nearby explosions, Tsunami waves and collision of flying objects (such as light aircrafts) etc. must be tested and cleared of possible structural damages before they are reoccupied. Even without undergoing such impacts, civil structures such as skyscrapers, huge bridges, tunnels, and highways can get damaged due to the existence of some types of cracks in concretes, corrosion on steel materials and the looseness of bolts.

Similar damage detection requirements may arise in case of aerospace structures when they undergo significant operational impacts and high stress loading.

Some already reported methods that address these requirements will be summarized here. Sensing techniques that has been reported as well as detection methodologies adopted, based on the sensing techniques will be given emphasis.

3.1 Available sensing techniques

The impedance-based damage detection technique has been developed as a promising tool for real-time structural damage assessments. The basic concept of this method is using the electromechanical coupling property, in which the electrical impedance of piezoelectric materials is directly related to the mechanical impedance of the host structure [46]. In this method piezo-electric elements are bonded symmetrically on the both sides of the main structural members (central beam etc), so that a longitudinal elastic wave could be generated traveling through the beam by applying an alternating voltage to the patches.

Another detection sensing method is microwave sub-surface imaging system using cylindrical array, developed and verified for its capabilities to assess damages inside concrete structures [47], [48], [49], [50]. The proposed sub-surface imaging system uses an arrangement consisting of several cylindrical/planar arrayed antennas for transmitting and receiving signals, and a numerical focusing operator is applied to the external signals both in transmitting and in receiving fields.

Another common sensing technique is to use strain gauges to measure the actual deflection on the structural members and develop the damage detection based of those deflections and strain energy [51], [52], [53].

Vibration analysis in a vibroacoustic environment such as a highway bridge assumes the sensors to be placed directly on the vibrating structure. That is, if we consider the sensors on the bottom of a girder, the input to the system is the random traffic on top of the deck, and the vibration is the propagating vibration generated by the traffic on the structure. This type of vibroacoustic sensor technique is reported in [54].

Most of other vibration sensing techniques are based on networks of accelerometers [56], [57], [58], [59]. Use of tri-axial accelerometers is also quite common in these applications [60].

Apart from these sensing techniques, there is reported work on the use of remote sensing techniques for structural damage detection particularly after severe earthquakes [61], [62], [63].

3.2 Damage detection methodologies

Various damage detection methodologies have been reported in literature, which employs several modern techniques.

Wavelet packet analysis is used as the basis of damage detection in [55], [57], [59]. In [55], a two-step structural damage detection approach based on wavelet packet analysis is presented. Firstly, the

location of the damage member is determined by probabilistic neural network according to the wavelet packet node energy change. Secondly, the damage extent of the damaged member is determined by back –propagation network according to the wavelet packet node energy. In contrast to [55], a delamination wavelet transform search method is derived to diagnosis the structure damage in [57] and then decompose the energy in the different band, through the energy changes to determine the extent of structural damage.

Neural network (NN) based approaches are also commonly used as the detection technique. In [55] as mentioned earlier, NN is also used in combination with wavelet packet analysis. In addition to that, [64] presents a method for damage detection in multi-bay planar truss structures. A neural network is trained by transfer functions of the structural system. The approach allows one to avoid all the problems which characterize the techniques based on system parameters identification. Time-delay neural networks (TDNNs) have been implemented in detecting the damage in bridge structure using vibration signature analysis in [58].

Linear Matrix Inequality (LMI) based approaches can also be found in literature. In [66], an LMI formulation for the reduced model damage detection problem using a parameter update approach can be found. A hybrid modal expansion and model reduction techniques are applied to overcome the incompatibility between the experimental and the analytical degrees of freedom. An LMI formulation and solution to the strain-based damage detection problem using both a parameter update approach and sensitivity analysis method is presented in [53].

Other reported methods worth mentioning here are genetic algorithms [66], particle swarm optimization [67], Parallel Bionic Algorithm [68] and etc.

Application of sensor networks for damage detection of space structures can be found in [69].

4. ACTIVE CONTROL OF STRUCTURES

Civil structures are often exposed to strong winds and seismic loads resulting in large structural deflections. These undesirable deflections can be reduced by installing a structural control system within the structure. Such control systems involve installation of a network of sensors to be able to measure structural deflections. The recent trend is to reduce the costs associated with structural control systems, by the eradication of expensive wiring required to transmit sensor data to a centralized controller. This section of the paper will summarize some of the reported work in active and semi-active control of building structures.

4.1 Active control of civil structures

Environmental forces, like wind and earthquake, induce motion in tall civil structures. To mitigate these vibrations, an active control scheme is built into the structure. These controllers require displacement measurements from different key locations of the building structure which forms a sensor network. An overview of available control strategies for this type of applications can be found in [70]. [71] provides a review of the rapid recent developments which have been occurring in the area of controlled civil structures, including full-scale implementations, actuator types and characteristics, and trends toward the incorporation of more modem algorithms and technologies. A detailed description of the fundamentals of active control of flexible structures can be found in [72]. The same issue has been addressed from the point of view of risk-sensitive optimal stochastic control in [73].

Application of more modern control techniques such as Multiple Model Adaptive Control [74], Self-Learning Fuzzy Control [75] can also be found in this area.

The incorporation of wireless technology into this area has opened up another domain for researchers – distributed or decentralized control of civil structures. The study in [76] presents the feasibility of employing a wireless sensor network to both collect state-response data from sensors and to determine control forces is explored in detail. Wireless active sensing units designed to collect data from sensors, execute embedded algorithms and command actuators are adopted to serve as sensor/controller nodes within the wireless structural control system. In [77] a wireless sensor network is developed composed of wireless sensors employing identical static Kalman estimators, which is a good example for a partial decentralized wireless control through distributed computing. The wireless sensors command actuators with LQR derived state-feedback control forces based on state vectors locally calculated from embedded Kalman estimators. Each unit compares the estimated state values to their local measured state data; in the case where the estimate error exceeds a predefined threshold, replaces the estimated value with the measured value and transmits the update to the entire wireless sensor network. Work in [78] is also a good example of distributed control of civil structures through wireless sensor networks.

4.1 *Semi-active control of civil structures*

Semi-active control is a relatively new approach for protecting civil structures against seismic induced damage. A semi-active controller modulates in real-time the energy dissipation rate of the structure. According [79], these techniques can achieve a

performance that is better than that achieved by passive isolation systems and comparable with that of active control systems. The underlying principal in [79], [80], [81], [82] in developing semi-active control schemes for protecting structures against earthquakes is by using magnetorheological dampers as control devices.

In [83], effectiveness of low power, inexpensive semi active control hardware to provide vibration attenuation, for structures is investigated. While there are a number of electro-mechanical devices that might provide semi active (SA) control forces, our investigation analyzes the use of an automatically adjustable hydraulic actuator. The variation in damping characteristics is accomplished by using variable orificing. While semi active hydraulic actuators are a relatively cheap means of providing smart damping for a structure, the development of effective closed loop control strategies for these devices is not a completely resolved issue.

5. STRUCTURAL PARAMETER IDENTIFICATION AND MODELING

Structural parameter identification is becoming an important area day-by-day due to growing needs of ensuring safety of the inhabitants in civil structures; the main reasoning being the fact that certain predictions on the structural health can be made based on the estimated parameters and models. There are several methods reported such as vibration measurements using accelerometers [84], [85], Lead Zirconate Titanium (PZT) Electromechanical (EM) impedance [86], nondestructive evaluation of civil structures using microwaves [87], etc.

Parameter identification or estimation is done using well-known system identification techniques as well as other special estimation procedures.

Frequency domain system identification is a well known basic technique to estimate a mathematical model that closely matches the frequency response function (FRF) of the physical system. One common approach in structural engineering is to curve-fit the FRF data with a transfer function matrix (TFM), based on which a state–space model is derived using available system realization algorithms. This is the approach proposed in [88] for modeling controlled civil structures. In [89] recursive least square estimation with unknown inputs (RLSE-UI) approach is proposed to identify the structural parameters, such as the stiffness, damping and other nonlinear parameters. Adaptive parameter identification results for a complex flexible structure with many closely packed natural frequencies are presented in [90]. Least-squares lattice filters are used to estimate the number of excited modes,

natural frequencies and damping ratios from input/output data. Dithering technique for enhancing uncertain parameter identification with moving-bank Multiple Model Adaptive Estimation (MMAE) and Control (MMAC) are analyzed in [91]. In [86], genetic algorithms are used to search for the optimal solution for the unknown dynamical system parameters by minimizing objective function. A gradient algorithm to estimate the unknown model parameters such as damping and stiffness is proposed in [92]. In [87] an application of the element free Galerkin (EFG) method in modeling nondestructive evaluation of civil structures using microwaves is presented. Use of the EFG method avoids mesh generation that is cumbersome in conventional finite element methods, when complex geometries are to be modeled.

Other methods worth mentioning here are the Hilbert-Huang Transform (HHT) for identification of structural modal parameters reported in [85] and Smart Structure Damping Modeling in [93].

6. BUILDING AUTOMATION

The concept of "intelligent homes" or "intelligent buildings" also known in more technical terms as building management systems involves a great deal of sensor networks. The parameters sensed can vary from basic physical quantities such as light intensity, temperature, humidity, energy consumption to somewhat more complicated parameters such as human images, thermo graphic images, finger prints and blood glucose etc. It must first be mentioned here that this concept does not directly involve with the building structure, its structural health and control, but the services overlaid inside a completed building structure that is ready for human occupation. As such building automation is considered as falling outside the main scope of this paper. However, being an area that involves an extensive amount of sensor networks, only an overview of this vast area is presented here.

The world energy crisis and the need to get the optimum usage of the limited energy resources is the prime reason for researchers to focus on building automation [94]. This basic requirement was further developed with already developed theoretical findings in the areas of automatic control [95] as well as application specific industry solutions such as dedicated field bus systems for building management systems [96]. Application of artificial intelligence further improved the system performance in certain aspects [99]. Emergence of Ethernet and information technology further enhanced developing various additional features into building management systems, which lead the way for modern day intelligent buildings/homes [97],

[98]. Wireless technology and its recent wireless networking solutions such as ZigBee have further enhanced the development possibilities in the area of building automation [100], [101], [102], [103].

7. CONCLUSIONS

This paper surveyed the area of sensor network applications in structures. Five major application areas of sensor networks in civil structures were identified, namely; structural health monitoring, structural damage detection, active control of structures, parameter identification and modeling of structures and building automation. Over one hundred research publications falling within the purview of the title of this paper have been referred and a broad range of sensing techniques as well as detection and estimation techniques have been summarized in the paper. In conclusion, it can be stated that the modern developments in sensor technology as well as networking technology has enhanced bringing up advanced sensor network solutions for civil structures which ensures their reliability and safety for users.

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