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WSNs for Structural Health Monitoring

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Abstract

WSN is an application specific network .There is no general solution for WSN problems. It depends upon application, budget (cost) & resource availability. Structural health monitoring (SHM) using wireless sensor networks has drawn considerable attention in recent years. It is an active area of research that can autonomously and proactively assess the structural integrity of buildings, bridges, coal mines, tunnels and turbines using Wireless Sensor Network. Recent technological advances promise the eventual ability to cover a large civil structure with low-cost wireless sensors that can continuously monitor a building's structural health.

Keywords: *Wireless Sensor Networks, Structural Health Monitoring, Design issues.*

I. Introduction

Wireless Sensor Network is the wireless network which is the combination of autonomous sensors to monitor or control environment conditions. Information that are to be collected or sensed are temperature, pressure , humidity, motion, heat, sound, light, electromagnetic field, vibration, images, pollutants etc.[1,2,3,4,5,6,7]. The popularity of WSN has increased due to growth in Micro-Electro-Mechanical Systems (MEMS) technology. The concept of wireless sensor networks is based on a simple equation: Sensing + CPU + Radio = Thousands of potential applications [8].WSN term can be broadly sensed as devices range from laptops, PDAs or mobile phones to very tiny and simple sensing devices. At present, most available wireless sensor devices are considerably constrained in terms of computational power, memory, efficiency and communication capabilities due to economic and technology reasons [1,2,3]. That's why most of the research on WSNs has concentrated on the design of energy and computationally efficient algorithms and protocols. RF design have enabled the development of relatively inexpensive and low-power wireless micro sensors [9,10,11]. These sensors are not as reliable as their expensive macro sensor counterparts, but their size and cost enable applications to network hundreds or thousands of these micro sensors in order to achieve high quality, fault tolerant sensing networks. Reliable environment monitoring is important in a variety of commercial and military applications.

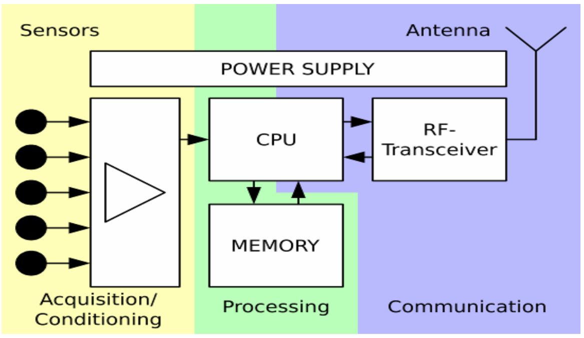

Figure 1: Hardware structure of a sensor node.

The hardware components of a sensor node are the sensors, a signal conditioning unit, an analog to digital conversion (ADC) module, a central processing unit (CPU) with random access memory (RAM), a radio transceiver and the power supply (see Figure 1). WSN suits the application requirements in comparison with wired sensing systems, since it is easily deployable and reconfigurable even in an inaccessible areas and reduces the system installation and condition monitoring cost in general. Wireless sensor network enables low-cost sensing of environment. Structure monitoring is one example of such applications. Wireless sensor networks are well suited for the structural health monitoring for buildings [16], wind turbines [15], coal mines [13], tunnels [14] and bridges [21, 18]. To monitor a structure, we measure behavior (e.g. vibration, displacement) of structure, and analyze health of the structure based on measured data. SHM is an emerging research area and is focused on the field of infrastructure mainly on the integration and application of sensors, signal processing, and communication technologies. It also focuses on complex engineering systems and infrastructure to prevent structural failure and disaster.

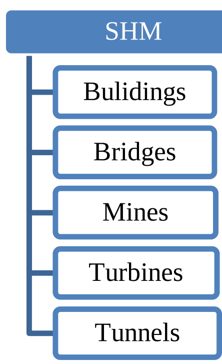

Figure 2: SHM for various applications

Large civil structures such as buildings and bridges form the backbone of our society and are critical to its daily operation. Inspectors typically assess them manually, but a networked computer system that could automatically assess structural integrity and pinpoint the existence and location of any damage could measurably lengthen a structure's lifetime, reduce its operational cost, and improve overall public safety[12].

II. Reasons for Performing Structural Health Monitoring

A. Damage Detection

Obviously damage detection is the most common reason. The main aim is continuously monitoring of a structure following an event, such as an earthquake, without requiring a dangerous and expensive manual inspection [19, 20].

B. Long Term Monitoring for Deterioration

Structure is detected over a long period of time. The aim here is to be assured of the structural performance and continued value of the asset under "normal" conditions.

III. Traditional Methods of Structural Health Monitoring

SHM projects can be divided into those undertaken over a short term for research purposes, and those performed over a long period for long term health monitoring. The short-term projects typically involve a relatively large number of sensors, many hundreds of meters of cable and a multi-channel recording system. This can take many days to set up. For long term monitoring projects, typically from one to three accelerometers are installed at key points within the structure and possibly cabled together [17, 22]. The reason for this small number of sensors is the cost of the equipment and its installation and operation.

Figure 3: Traditional method

Data from these sensors is usually collected manually, following an event of interest, and taken back to a laboratory for analysis. In some more recent installations a modem is connected to the recorder so that the data may be transmitted to the laboratory, thus removing one of the steps.

IV. Key Problems for SHM

The key problems for developing the SHM system in conjunction with WSN are summarized [23, 25, 26] as follows:

A. Compatibility between different sensors, their sampling frequencies and operational modes

In the field of SHM, various types of sensors are used like accelerometer, resistance strain, piezoelectric vibration, optical fiber strain, dip angle, acoustic emission, and stress measurement sensors. All these sensors have different physical mechanisms. Thus the choices of the sensor network sampling frequency, from several Hz to several hundreds of kHz, working mode, and compatibility must be considered when choosing each node.

B. Transmission Bandwidth

Generally WSNs are used for low-bandwidth applications. But in some applications, the data from vibration measurements as well as those resulting from image acquisition require a higher transmission bandwidth.

C. Synchronization

The signals must be sampled synchronously by the nodes; otherwise there will be incorrect information, due to samples grouped together coming from different times of the vibration phase, resulting in an incorrect vibration model judgment.

D. Energy Issues

Each function of a WSN, such as self-organize ability, adaptability, signal sampling, information fusion, signal processing and signal transmission requires energy consumption. Energy consumption issues various with application scenarios.

E. Topology and Data Fusion

WSNs need different topologies to meet the needs of different application characteristics in SHM. Typical topologies include star, cluster tree, and mesh networks.

V. Network Design Issues For Shm

WSN is an application specific network .There is no general solution for WSN problems. It depends upon application, budget & resource availability.

A. Network Model

Suppose we have a set S of densely employed N sensor nodes used to monitor the events in any SHM application. These nodes are deployed by some generic deployment strategy like uniform, random, or deterministic [33] at possible locations [34].
L= (L_1, L2,….L_n) where sensor i is placed at location L_i, and L_0 is a suitable location of the sink. Let R be the communication range, where the maximum and minimum communication ranges of a sensor are R_{max} and R_{min}, respectively. R_{max} is used to maintain local topology, where every pair of sensors within R_{min} are allowed to share and compare their decision with their neighbors.

B. Structural Model

After calibration and installation of all nodes in the structure the collected data is used to analyze the structural dynamic by estimating its modal properties, like frequencies, damping ratios and mode shapes. The collected data is then compared with theoretical models and previous studies of the structure. A change in modal properties is a result of a change in structural stiffness (assuming that the masses do not change significantly). These changes can be translated to a structural damage.
A structural system has mass, stiffness and damping elements. It can be modeled by the second order differential equation [24, 27, 30, 31]:

$$\mathrm{M}\ddot{\mathrm{X}}+\mathrm{C}\dot{\mathrm{X}}+\mathrm{KX}=\mathrm{u}$$

With block diagonal mass matrix
M=diag (M1, M2……, Mn)

$$\mathrm{K}=\begin{bmatrix} \mathrm{K}_1+\mathrm{K}_2 & \text{-}\mathrm{K}_2 & 0 & \cdots & \cdots & 0 \\ -\mathrm{K}_2 & \mathrm{K}_2+\mathrm{K}_3 & \ddots & & & \vdots \\ 0 & \ddots & \ddots & & & \vdots \\ \vdots & \ddots & & \mathrm{K}_{n-1}+\mathrm{K}_n & & \text{-}\mathrm{K}_n \\ 0 & \cdots & & & -\mathrm{K}_n & \mathrm{K}_n \end{bmatrix}$$

Where,
M: mass matrix, X: Displacement vector,
C: Damping Matrix, K: stiffness matrix,
u: external force/moment vector.

C. Network Lifetime or Lifetime of Sensor Network (LSN)

The main objective of any design is to extend the lifetime of the sensor network (LSN)[28].The lifetime of a wireless sensor network is an application-specific. The lifetime of a sensor network is defined as the time for the first node or a certain percentage of network nodes to run out of power. Lifetime of wireless sensor networks can be calculated as [29, 32]:

LFT=min i

$$i = \begin{bmatrix} \ell(i-1) > \ell(i) \,\&\, \ell(i+1) = \ell(i) & \text{Connectivity} \\ \mathrm{Cov}(i-1) > \theta \,\&\, \mathrm{cov}(i) \le \theta & \text{Coverage} \end{bmatrix}$$

Where,
ℓ = Remaining lifetime of whole sensor network
θ = Predefined threshold of the coverage of the sensor network based on application requirements
Cov = Coverage of sensor network

D. Energy Model

Energy consumption of different individual sensors shows the load balance feature.

In a simple way, Energy consumption of each sensor is defined as the normalized total amount of energy used in receiving or sending messages [36, 40].

$EC=E_c /E_o$

Where,
EC= Energy consumption, Ec = Total consumed energy, E_0 = Initial energy

The radio energy model is given below. For transmission of k bits message to a distance d, radio expends [37-39]:

$$E_{Tx\,(k,d)}=E_{Tx\text{-}\,elec(k)}+E_{Tx\text{-}\,amp(k,d)} \quad (1)$$

$$E_{Tx\,(k,d)}=E_{elec} *k+ E_{amp}*k*d^2 \quad (2)$$

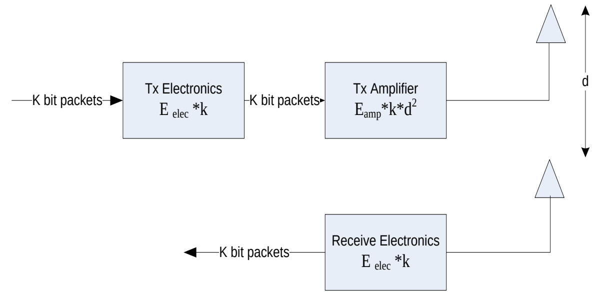

Figure4: Radio Model

Where,
$E_{Tx(k,d)}$ = energy dissipated to transmit a k-bit message over distance d
$E_{Tx\text{-}elec(k)}$= energy dissipated by transmitter electronics
$E_{Tx\text{-}amp(k,d)}$= energy dissipated by amplifier electronics
E_{elec} = constant energy of 50 nJ expended to run the amp and transmitter circuitry

For reception, radio expends [37-39]:

$$E_{Rx(k)} =E_{Rx\text{-}\,elec\,(k)} \quad (3)$$
$$E_{Rx(k)} =E_{elec} *k \quad (4)$$

Where,
$E_{Rx\text{-}elec}$=is the energy dissipated by receiver electronics

E. Data Aggregation Model

Since sensor nodes may generate significant redundant data, similar packets from multiple nodes can be aggregated so that the number of transmissions is reduced. Data aggregation technique has been used to achieve energy efficiency and data transfer optimization. Cluster based strategies are employed for Data Aggregation. First cluster heads are selected [41]

$$n_i = \frac{1}{P_1} = \frac{\bar{E}(r}{P_{opt} E_i(r)} = n_{Opt}\frac{\bar{E}(r)}{E_i(r)}$$

Then simple compression tech like random decrement (RD) is employed. Principal Component Analysis (PCA) is then performed in CH to cut down the data dimensions[41] by assuming n dimensions of data, then we can get n eigenvalues denoted by λ_i (i=1, 2, …, n).

$$\sum_{i=1}^{m} \lambda_i / S \ \ge R$$

Where, Sum of eigenvalues and proportion level is denoted by *S*, R respectively.

AR Model [42] is then employed to save energy consumed in transmitting the raw data.

$$Y_t = \sum_{i=1}^{p} b_i Y_{t-i} + r_t$$

Where, y_t is data obtained, b_i and residual error r_i are the coefficient corresponding to the AR Model.

VI. Conclusion

Wireless technologies are constantly improving and many different applications are already successfully implemented in different application scenarios. Structural health monitoring is a typical area amongst the many possible applications of wireless sensor networks. Recent advances in electronic components, MEMS sensors and wireless communications have created the opportunity to monitor structures in ways that were not previously possible.

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