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Structural Health Monitoring using Wireless Sensor Networks

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Abstract— Conventional Structural Health monitoring systems use traditional wired sensor technologies and several other devices that are time consuming to install and require extensive lengths of cables to transmit recorded data from multiple sensors to a centralized data repository. Wired Structural Health Monitoring (SHM) systems poses constraints like high installation and maintenance cost, trained skilled personnel and data corruption due to noise issues. The technology advancement in wireless communication and microelectronics provides scope for wireless monitoring systems to eradicate the extensive lengths of wires associated with wired systems. Structural Health Monitoring systems equipped with MEMS sensors and wireless communication can reduce the costs to significant percentage of conventional monitoring systems, and will increase its field of application. In this paper an innovative approach based structural health monitoring system developed using wireless sensor nodes called Intelligent Structural Intelligent Health Monitoring (ISHM) has been presented. Wireless Sensor Networks allows for a pervasive observation over the sites of interest in order to minimize the potential damages caused to structures and increasing safety of the people. Moreover, the system provides real-time feedback to the civil engineer that promptly steer the functioning of the monitoring network.

Index Terms— MEMS, Motes, SHM, Wavelets, WSN.

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1 INTRODUCTION

WIRELESS Sensor Networks (WSNs) have emerged as a class of information technology infrastructure where computation is embedded into the physical world .WSN consists of a large number of spatially distributed devices called Motes or Smart Sensors with computing and sensing capabilities. Applications of WSNs include building control [1,2], environmental monitoring, traffic control, manufacturing and plant automation.

1.1 System Overview

Wireless sensor networks consist of distributed, wirelessly enabled embedded devices capable of employing a variety of electronic sensors. Each node in a wireless sensor network is equipped with one or more sensors in addition to a microcontroller, wireless transceiver, and energy source. The microcontroller functions with the electronic sensors as well as the transceiver to form an efficient system for relaying small amounts of important data with minimal power consumption. When deployed in the field, the microcontroller automatically initializes communication with every other node in range, creating an ad hoc mesh network for relaying information to and from the gateway node. This eliminates the need for costly and complex wiring between systems and also provides flexibility of mesh networking algorithms to transport information from node to node.

This allows nodes to be deployed in almost any location and offers flexibility of monitoring large number of structures much potential for Structural health Monitoring solutions. [3-5]

2.1 Advantages

- Low power and relatively inexpensive microcontrollers and transceivers, the sensor nodes used in wireless sensor networks are often less cost compared to Wired system in structural health monitoring
- Wide coverage of an area with minimal effort involved in positioning the individual nodes compared to centralized wired layout sensing technology and reduces the manual intervention.
- Mesh networking in SHM application can potentially deploy more sensors using a wireless sensor and simultaneously monitor a network of structures than they could use more traditional technology.

2.0 INTELLIGENT STRUCTURAL HEALTH MONITORING (ISHM)

Recently researchers [6,7] have been developing and testing wireless sensor networks as part of a Structural Health Monitoring (SHM) applications, where distributed sensors track the of vibrations induced in the structures .Accordingly, potential damage can be localized and its extent can be estimated in almost real time. WSN has been developed to address the limitations of existing SHM techniques which rely on either periodic visual inspections or expensive wired data acquisition systems. Unique Features of WSN suitable for Structural Health Monitoring are

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- The sensor nodes can be placed in areas that are inaccessible to wired and bulky devices.
- Deploying large number of nodes will provide correlation between different measurements. This facilitates localizing damage.
- The deployment as well as the management (maintenance) of the sensor network does not require disruption of the normal operation of the structure.

When many sensor nodes cooperatively monitor health of large physical environments like Bridge structures can be termed as Intelligent Structural health Monitoring Networks **.** This involves wide variety of research fields including structural engineering, wireless communication, networking and software engineering.

The factors that influence the design of ISHM are

- Hardware/Sensor modules
- Fault tolerance
- Scalability
- Sensor network topology
- Transmission media
- Structural characteristics/parameters

The integration of the solutions for these factors is still a major challenge because of the interdisciplinary nature of this research area. In this paper an innovative approach based structural health monitoring system developed using wireless sensor nodes called Intelligent Structural Intelligent Health Monitoring (ISHM) has been presented. The WSN has Analog to Digital converters, processors andTranceiver. Usually analog signals are obtained from the sensors; an A/D converter in WSN will convert the signal to digital format to enable long distance data transmission before transmitting it to the monitoring station. In addition to data transmission WSN also performs some computational tasks (hence called Intelligent) that will reduce the computational load of the processor at the monitoring station. But the prime advantage of incorporating computational capability at local site processor is that it will reduce the data transmission load between the node and the monitoring station. The Intelleigeience embedded inside wirlesess sesnor node for computational tasks can be determination of Fast Fourier Transforms or damage detection algorithms, which will refine the voluminous raw data in to meaningful information and provide real time Intelligent Structural Health Monitring system.

2.1 Wireless Sensor Network- Overview

A wireless sensor network (Fig. 1 & 2) consists of three main components:

- Sensor nodes
- Gateways
- Network Manager.

The spatially distributed measurement nodes interface with sensors to monitor structures or their environment. The acquired data wirelessly transmits to the gateway, which can operate independently or connect to a host system (Manager) which will collect, process, analyze, and present measurement data using software.

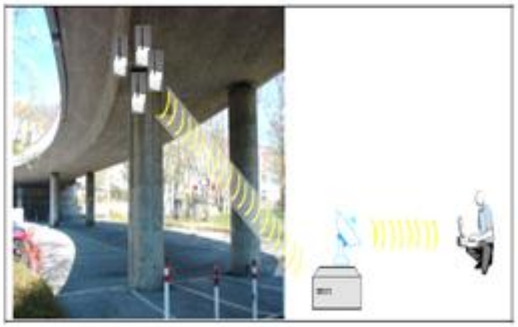


Fig. 1 Wireless Sensors Networks Scheme Implementation in a bridge structure

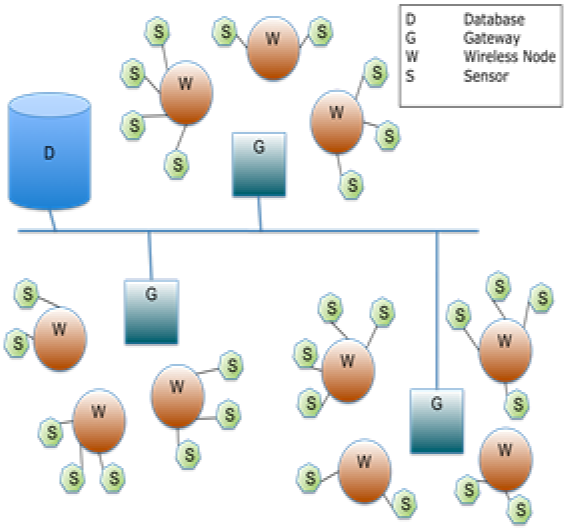


Fig.2 Typical Wireless Sensor Network architecture

2.1.1 Motes /Sensor Nodes

Wireless modules or Motes are the key components of the Wireless Sensor Network (WSN) as they possess the communication capabilities and the programmable memory where the application code resides. A wide variety of platforms have been developed in recent years including Mica2, SunSPOT, Imote2, Waspmote etc.

Motes basically has the following key hardware components (Fig. 3)

- Microprocessors/Microcontrollers
- Sensor modules with Micro-Electro-Mechanical Systems (MEMS)
- Low-power radios (also called transceivers).

Sensor Modules collects the measurement data with on board MEMS based sensors followed by data processing performed by microprocessors using various algorithms .The communication modules transmits data to the gateway or uses other wireless sensor nodes to forward data to the gateway. The radios enable the sensor nodes to wirelessly transmit their sensor readings throughout the network. A programming board known as the gateway board provides multiple interfaces including Ethernet, Wi-Fi, USB or serial ports for connecting different motes to an industrial network or locally to a PC/laptop. Routers are a special type of measurement node that you can use to extend WSN distance and reliability.

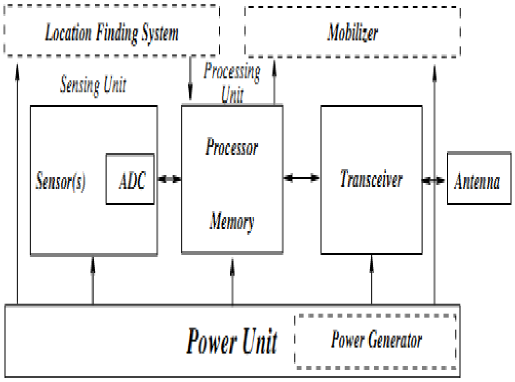


Fig.3 WSN Hardware Scheme

2.1.2 Wireless Networking Protocols and Standards

Typical Wireless Sensor Architecture is as shown in figure3. The IEEE 802.15.4 standard defines both the physical and Media Access layer protocols for remote monitoring and control as well as sensor network applications. ZigBee is an industry consortium with the goal of promoting the IEEE 802.15.4 standard. ZigBee ensures interoperability by defining higher network layers and application interfaces. The low-cost, low-power features of 802.15.4 are intended to enable the broad-based deployment of wireless networks able to run for years on standard batteries for a typical structural health monitoring application. Fig. 4 shows a simple WSN scheme for structural health monitoring.

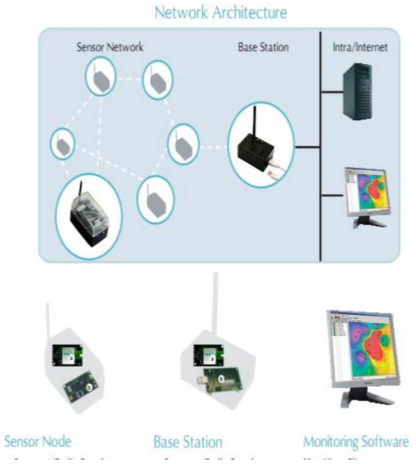


Fig.4 Scheme of WSN Framework

2.2 Wireless Monitoring System based on Imote2

Many studies have utilized Mica mote based wireless sensor to develop individual wireless monitoring applications [8]. However, the Mica mote has limitations such as limited sampling rate, processing ability, storage, and transmission ability. Therefore, the .NET-based advanced wireless sensor platform, Imote2, is considered an appropriate choice for efficiently developing and deploying customized wireless sensor networks (WSNs). The Imote2 sensor node architecture is a multipurpose architecture that consists of a power management subsystem, a processor subsystem, a sensing subsystem, a communication subsystem and an interfacing subsystem. The elements of the platform associated with wireless communication are described briefly (Fig. 5).

The features of Imote2 are as follows:

- PXA271 XScale® processor @ [13–416] MHz
- Wireless MMX coprocessor
- 256kB SRAM, 32MB FLASH, 32MB SDRAM
- Integrated 802.15.4 radio, support for external
- AC97, USB host, Camera I/F, GPIO
- Mini-USB port for direct PC connection

2.2.1 Radio

The radio chip used on the Imote2 is the Chipcon CC2420 2.4 GHz IEEE 802.15.4 RF transmitter. The radio supports multiple transmission options that can be tailored to the application to optimize network performance.

2.2.2 Antenna

The Imote2's onboard antenna is a 2.4 GHz SMD type onboard antenna is designed to use the printed circuit board on which it is mounted as a ground plane

2.2.3 Power supply

To supply the processor with all the required voltage domains, the Intel Mote 2 includes a Power Management IC. This PMIC supplies 9 voltage domains to the processor in addition to the Dynamic Voltage Scaling capability. It also includes a battery charging option. Two of the PMIC voltage regulators (1.8 V & 3.0 V) are used to supply the sensor boards with the desired regulated supplies at a maximum current of 200 mA. The processor communicates with the PMIC over a dedicated I2C bus (PWRI2C). The Intel Mote 2 platform was designed to support primary and rechargeable battery options, in addition to being powered via USB. The Intel Mote 2 platform can be powered using primary batteries with a voltage range of 3.2 - 4.5 V (e.g. 3 AAA alkaline batteries). A battery board with a basic or advanced set of connectors can be connected to the Vbat pins of the connector. As shown in the figure below, a diode and fuse should be connected between the battery and mote board to protect the battery and the PMIC. A rechargeable battery can be used to supply power to the Intel Mote 2 platform by connecting it directly to the Vbat pin on the connector. In this case, the PMIC battery charger can be used to recharge the batteries. The battery board should drive the nCHARGE_EN pin low to connect the USB input to the PMIC charger pin, hence allowing to recharge the battery using USB. The PMIC supports single cell Li-Ion and Li-Polymer pack.

The mote can be powered directly from USB, by routing the USB power to the Vbat input of the PMIC. This is the default state when either a battery is not connected, or when a battery board drives the nCHARGE_EN input high (as the case with all primary battery boards). If a battery board pulls nCHARGE_EN low, the USB input gets routed to the Vchg pin of the PMIC, which would be the case for rechargeable batteries as mentioned above.

2.2.4 Sensors

Mote has MEMS based sensors that incorporate signal conditioning circuitry A/D-converters. Hybrid motes combining sensor systems using different measuring concepts can be designed to optimize the data acquisition and to best fit the in-situ requirements. Some physical properties to be measured in-situ are the vibrations of the structure and temperature outside and inside the structure. The sensor board has multiple sensors like temperature, light and accelerometer sensors which are used for wireless sensor network applications. The sensor subsystem provides an extensible platform to connect multiple sensor boards. One realization of the sensor board contains ADC, temperature/humidity sensor and a light sensor. These devices are interfaced to the processing subsystem through the SPI buses. The ITS400 module design includes

- Tri-axial ±2g accelerometer,
- High accuracy (±0.3°C) temperature
- Humidity sensors, a light sensor,
- 12-bit Four-channel A/D convertor.

The architecture of Imote is given in Fig.5. In the computation core processor is selected to coordinate the hardware components of the wireless unit. The processor together with internal and external memories provides the capability of onboard data interrogation at the sensor level. This processor can operate in a low voltage (0.85V) and a low frequency (13 MHz) mode, hence enabling low power operation. The wireless sensing unit is particularly designed to balance low power consumption while supporting high-data transfer rate and long communication range typically required for civil structural applications.

3.0 SOFTWARE CONSIDERATIONS IN WIRELESS COMMUNICATION

Unlike in wired sensor systems, where data is transmitted solely via hardware, wireless sensor data transmission requires the interaction of the software and radio hardware. Fig. 6 depicts a simplified framework for wireless communication that illustrates how these two elements interact Within the software application, the data to be communicated and its routing information are placed in packets and sent wirelessly over the network. A packet consists of four parts: preamble, header, data and footer. The portions of the packet formed by the application are the header, which contains the routing and packet information, and the data. This study considers only a fixed payload scheme where the number of bytes in a packet issued by the application does not change. Visual Studio .NET platform is used for the software development for the system. Layered Software Architecture is followed such that different modules can be ported depending upon application required. The wireless sensing unit is particularly designed to balance low power consumption while supporting high-data transfer rate and long communication range typically required for civil structural applications. The analysis of measured data and the knowledge of continuous changes of structural behaviour will improve the life time prognosis of civil structures, and reduce the overall maintenance costs of buildings and transport networks.

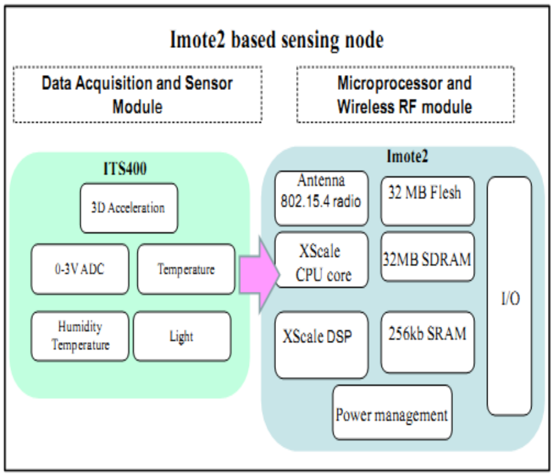


Fig 5 Imote2 Architecture

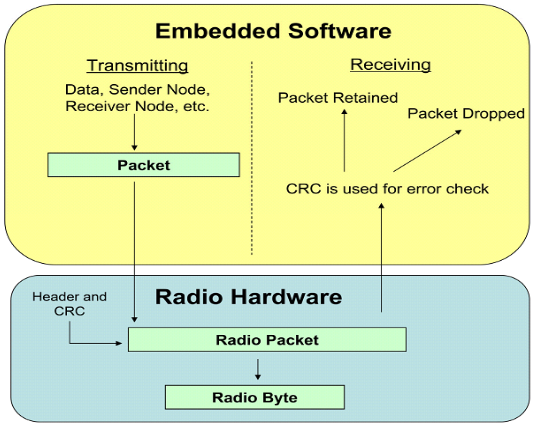


Fig 6 Framework for Wireless communication

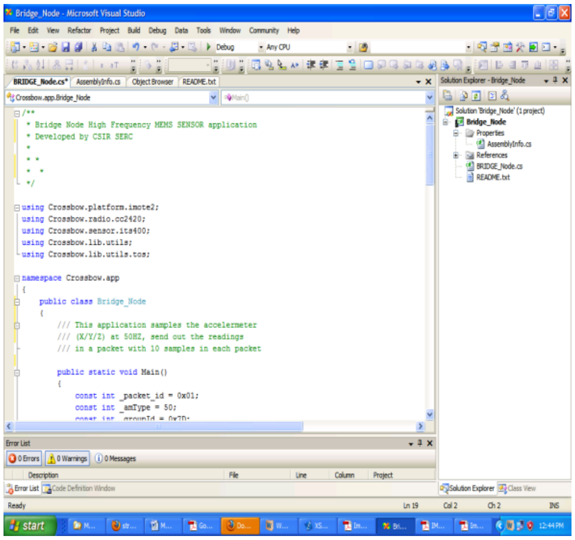
3.1 Software Architecture of Imote2

Software architecture for Imote2.NET-based wireless SHM system is based on three-layer architecture consists of a node tier, logging tier and processing tier. The node tier is on each sensor node. The logging tier is installed only on the base station node connected with the PC. The processing tier is on the PC and utilizes Labview/Matlab.

The node tier firmware embeds the application code, performs sensor management similar to high-frequency sampling on the 3-axis accelerometer, and ADC management and power management. The node tier is designed to be a complete developed environment for high performance wireless sensor network (WSN) applications based on the Microsoft .NET Framework. The .NET Micro Framework provides tools that simplify developing and deploying highly customized distributed sensing systems. Compared with the TinyOS system, the .Net Micro Framework has a "friendlier" developed environment and shorter learning cycle. Writing complex applications in the .Net Micro Framework is also easier than in the TinyOS. Highlights of the .NET Micro Framework include:

- A version of the .NET class library tailored to embedded applications, including GUI classes modeled on the Windows Presentation Foundation (WPF)
- A bootable CLR that can run directly on hardware without an operating system
- Support for common hardware and interconnects (nonvolatile memory, GPIO, I²C, RS232, SPI)

Data has to be continuously transmitted to the supervisor. Each sensor device (mote), which is itself a Complete, small measurement and communication system has to be powered and cost optimized. Using multi-hop techniques, the data of the sensor network can be transmitted over to a base station on site which will be collected and stored in a database for subsequent analysis. This data can then be accessed by a remote user. If the central unit detects a hazardous condition by analysing the data, it raises an alarm message. The central unit also allows for wireless administration, calibration and reprogramming of the sensor nodes in order to keep the whole system flexible.



```
/**
 * Bridge Node High Frequency MEMS SENSOR application
 * Developed by CSIR SERC
 *
 * *
 *  *
 */

using Crossbow.platform.imote2;
using Crossbow.radio.cc2420;
using Crossbow.sensor.its400;
using Crossbow.lib.utils;
using Crossbow.lib.utils.tos;

namespace Crossbow.app
{
    public class Bridge_Node
    {
        /// This application samples the accelermeter
        /// (X/Y/Z) at 50HZ, send out the readings
        /// in a packet with 10 samples in each packet

        public static void Main()
        {
            const int _packet_id = 0x01;
            const int _amType = 50;
```

Fig 5 Embedded Development Software

4.0 ACCELEROMETER ALGORITHM

In order to retrieve useful data from the accelerometer, it is necessary to process the output of the analog to digital converter. The first step in this algorithm is applying the resolution of the A/D converter to its output. Multiplying the V/bits resolution with the output of the A/D converter yields the voltage level of the A/D input. Each program begins with a startup sequence, initializing needed variables, the analog-to-digital converter, and user button functionality. The startup sequence for the accelerometer also incorporates an initial accelerometer reading to determine the starting orientation of the Imote. Following these startup procedures, each Imote begins monitoring their respective sensors; deciding if an event needs to be generated based upon the sensor readings it acquires. If no event is detected, the Imotes provide user feedback in the form of a blinking LED for easily verifiable functionality.

Table 1
Content of Message Header

Type	Field Name	Description
uint16_t	count	Incrementing sequence number for yield calculation
uint16_t	accel_x	Accelerometer reading of X axis
uint16_t	accel_y	Accelerometer reading of Y axis
uint16_t	accel_z	Accelerometer reading of Z axis
	...	
uint16_t	accel_x	Accelerometer reading of X axis
uint16_t	accel_y	Accelerometer reading of Y axis
uint16_t	accel_z	Accelerometer reading of Z axis

5.0 DATA ANALYSIS

Structural health monitoring (SHM) deals with the more or less continuous recording of data obtained from several parts of the structure. Based on the experience of the constructor, owner, or inspector the regions where data are obtained can be restricted. In many cases it is necessary to just detect a deviation of the "usual" behavior of the structure, i.e. an outlier in a time-series. It is obviously very helpful not to base this analysis on one physical quantity alone or on one sensor. The reliability of the monitoring system is fairly enhanced combining the information obtained at different sensor nodes.

5.1 Data Extraction Module

This module extracts the relevant signal information from the field measurement data with noise using wavelet based approach [9-11]. The Fast Fourier Transform (FFT) is a perfect tool for finding the frequency components in asignal. A disadvantage of the FFT is that frequency components can only be extracted from the complete duration of a signal. The frequency components are obtained from an average over the whole length of the signal. Therefore it is not a suitable tool for a non stationary signal such as the impulse response of cracked beams, vibration generated by faults in a gearbox, and structural response to wind storms. These types of problems associated with FFT can be resolved by using wavelet analysis.

5.2 Coefficients Extraction Phase

The Fourier transform is $\psi (x) \epsilon L2 (R)$ .When $\psi (\omega)$ meets conditions:

$$C_\psi = \int_{R^*} \frac{|\psi(\omega)|^2}{|\omega|} d\omega < \infty$$

It is called a basic wavelet or mother wavelet. By scaling and translation of mother wavelet, a group of wavelet sequence is obtained:

$$\psi_{a,b}(x) = \frac{1}{\sqrt{|a|}}\psi\left(\frac{x-b}{a}\right) \qquad a,b \in R; a \neq 0$$

where *a* for the stretch factor and *b* the translation factor.

In continuous wavelet transform, scaling factor *a* and translation factor *b* are continuously variable, that is: the time-frequency window is a continuous movement in the time-frequency plane. At the wavelet transform in the computer, Wavelet transform decomposes the signal into a set of basis functions called *wavelets.*

$$(W_\psi f)(a,b) = |a|^{-1/2}\int_{-\infty}^{\infty} f(x)\overline{\psi\left(\frac{x-b}{a}\right)}d_x \quad \left(a = a_0^m, b = nb_0a_0^m\right)$$

5.3 Daubechies Wavelet

Daubechies wavelets [12-15] are a family of orthogonal wavelets defining a discrete wavelet transform and characterized by a maximal number of vanishing moments for some given support. With each wavelet type of this class, there is a scaling function (also called father wavelet) which generates an orthogonal multiresolution analysis. In general the Daubechies wavelets are chosen to have the highest number *A* of vanishing moments, (this does not imply the best smoothness) for given support width $N=2A$, and among the 2^{A-1} possible solutions the one is chosen whose scaling filter has extremal phase. Daubechies wavelets are widely used in solving a broad range of problems, e.g. self-similarity properties of a signal or fractal problems, signal discontinuities, etc. Daubechies orthogonal wavelets D2-D20 are commonly used. The index number refers to the number *N* of coefficients. Each wavelet has a number of *zero moments* or *vanishing moments* equal to half the number of coefficients. For example, D2 (the Haar wavelet) has one vanishing moment, D4 has two, etc. A vanishing moment limits the wavelet's ability to represent polynomial behaviour or information in a signal. For example, D2, with one moment, easily encodes polynomials of one coefficient, or constant signal components. D4 encodes polynomials with two coefficients, i.e. constant and linear signal components; and D6 encodes 3-polynomials, i.e. constant, linear and quadratic signal components. This ability to encode signals is nonetheless subject to the phenomenon of *scale leakage*, and the lack of shift-invariance, which arise from the discrete shifting operation during application of the transform. Sub-sequences which represent linear, quadratic signal components are treated differently by the transform depending on whether the points align with even- or odd-numbered locations in the sequence.

Thresholding is a technique used for signal denoising. The discrete wavelet transform uses two types of filters: (1) averaging filters, and (2) detail filters. When a signal is decomposed using the wavelet transform, a set of wavelet coefficients that correlates to the high frequency subbands is obtained. These high frequency subbands consist of the details in the data set. If these details are small enough, they might be omitted without substantially affecting the main features of the data set. Additionally, these small details are often those associated with noise; therefore, by setting these coefficients to zero, the signal will be denoised. This becomes the basic concept behind thresholding-set all frequency subband coefficients that are less than a particular threshold to zero and use these coefficients in an inverse wavelet transformation to reconstruct the data set. Given a signal *s* of length *N*, the DWT consists of $\log_2 N$ stages at most. The first step produces, starting from *s*, two sets of coefficients: approximation coefficients CA_1, and detail coefficients CD_1. These vectors are obtained by convolving *s* with the low-pass filter Lo_D for approximation, and with the high-pass filter Hi_D for detail, followed by dyadic decimation (downsampling).The length of each filter is equal to 2*N*. If n = length(s), the signals *F* and *G* are of length $n + 2N - 1$ and the coefficients cA_1 and cD_1 are of length. The next step splits the approximation coefficients cA_1 in two parts using the same scheme, replacing *s* by cA_1, and producing cA_2 and cD_2, and so on.The wavelet decomposition of the signal *s* analyzed at level *j* has the following structure: [cA_j, cD_j, ..., cD_1]. If the signal is normalized in such a way that the data fit the model $x(t) = f(t) + e(t)$, where $e(t)$ is a Gaussian white noise with zero mean and unit variance.

6.0 LABORATORY TESTING OF WIRELESS SENSOR NODE

Wireless sensor node have been mounted on the test platform, and tested by applying a known vibration level of 0.5g (Fig. 6). The response of vibration testing measured by the sensor was processed and transmitted to the base station. The software for data acquisition and processing of sensor node was developed on Visual Studio .NET platform. The acceleration response measured from the Imote sensor is given in Fig. 7.

Fig. 6 Imote Sensor Mounted in the Vibration Test Bench

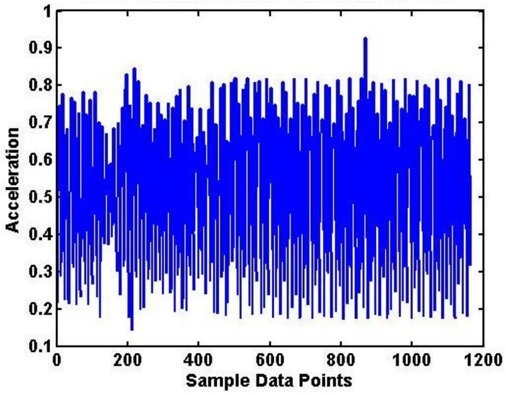


Fig. 7 Acceleration Response Measured from the Imote

7.0 FIELD TESTING OF WIRELESS SENSOR

Imote sensor was mounted on a structure and tested for acceleration measurement. In addition to the wireless sensor, conventional wired accelerometers were also placed on the structure for comparison of the performance. Responses from the structure were measured from both the sensors and plotted. The acceleration response measured from conventional accelerometer is shown in Fig. 8 and that from wireless sensor is shown in Fig. 9. Fig. 10 shows a comparison of the responses measured from wired and wireless sensors.

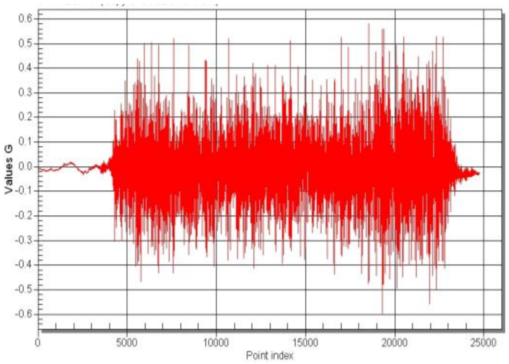


Fig. 8 Response Measured from Conventional Accelerometer

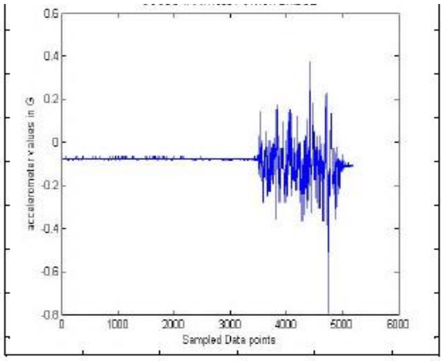


Fig. 9 Response Measured from Wireless Accelerometer

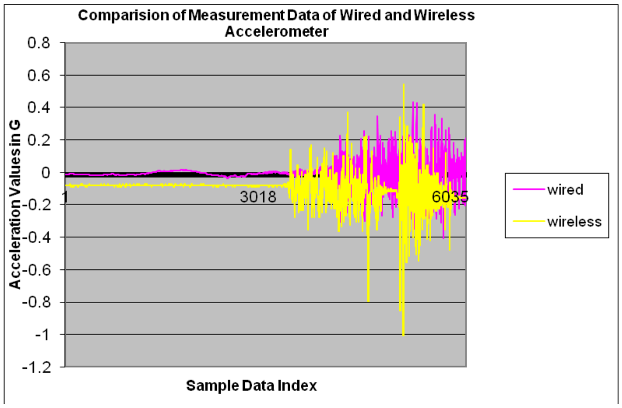


Fig. 10 Comparison of Responses Measured from Conventional Accelerometer and Wireless Sensor

8.0 CONCLUSION

This paper details about the evaluation of Imote2 wireless sensor platform developed for structural health monitoring experimentally. The selection of Wireless Sensor Node platform depends on specific and demanding requirements of structural monitoring. There are many challenges associated with SHM that can be managed or eliminated when appropriate measures are taken in the design of the network, the sensor node, and the algorithms. One challenge of SHM is that it requires high sample rates and the use of computationally intense algorithms. Vibration-based SHM schemes call for signals from the sensors within the network to be carefully synchronized to accurately assess the structural condition. Imote2 provides a commercially available wireless sensor platform that possesses the elements required for data intensive applications such as SHM. Although the Imote2 platform is well suited to high bit-rate applications but there are small drifts in the MEMS accelerometer due to signal quantization issues which can be compensated with proper signal conditioning circuits. Hence along with Signal conditioning circuits WSN provides an optimal solution for the deployment in SHM applications. From the above measurements it was found that wireless sensor nodes based accelerometer responses were found to be almost matching with the conventional accelerometer responses. However some fine tuning of offset is required initially as a part of initialization to get 100% accuracy. Thus WSN provides a wide area of challenges in application in the area structural health monitoring systems.

9.0 ACKNOWLEDGEMENT

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