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An Overview of a Wireless Sensor Network for Structural Health Monitoring Using X-Bee Pro Module

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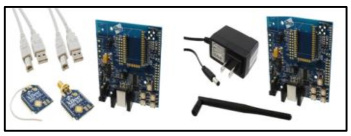
Graphical abstract



Abstract

This paper proposes a new design for structural health monitoring devices system by integrating the strain gauge in digital sensor signal and embedded wireless communication system. X-Bee Pro modules are proposed to be integrated with the system to provide long range wireless connectivity to the devices. This system is designed to enhance the efficiency of structural health monitoring by obtaining real time data remotely from a different place. In order to achieve objectives and to develop a smart wireless system for structural health monitoring, the methodology of this study includes hardware designing and interfacing of a prototype according to the model system. Smart wireless sensor networks for structure health monitoring have the potential to facilitate more economical management in structure monitoring.

Keywords: Wireless sensor network; structural health monitoring; strain gauge; X-Bee Pro

Abstrak

Kajian ini mencadangkan sebuah reka bentuk baharu untuk sistem peranti pemantauan keutuhan struktur dengan mengintegrasikan tolok terikan dalam signal sensor digital dan sistem komunikasi wayarles terbenam. Module X-Bee Pro disyorkan untuk pengintegrasian dengan sistem bagi memberikan ketersambungan wayarles jarak jauh kepada peranti. Sistem ini direka bentuk bagi meningkatkan keberkesanan pemantauan keutuhan struktur dengan mendapatkan data masa nyata secara jauh dari tempat lain. Bagi mencapai objektif dan membina sebuah sistem wayarles pintar untuk pemantauan keutuhan struktur, metodologi yang digunakan dalam kajian ini adalah termasuk reka bentuk perkakasan dan pengantaramukaan sebuah prototaip mengikut sistem model. Rangkaian sensor wayarles pintar untuk pemantauan keutuhan struktur berpotensi membuatkan pengurusan pemantauan struktur lebih menjimatkan.

Kata kunci: Rangkaian sensor tanpa wayar; pemantauan kesihatan struktur; tolok terikan; X-Bee Pro

1.0 INTRODUCTION

Structural health monitoring (SHM) strategies have been developed by many researchers in support of efficient operation and maintenance of civil infrastructure to ensure structure safety. Structural health monitoring diagnoses material condition during the life of a structure. The structure must maintain its original specified design and condition although it can be affected by wear and tear, the environment and mishaps due to human error. The conventional SHM uses visual inspection method or cable-based sensor technology. In the conventional SHM system, high cost for the purchase and installation of SHM system components, such as sensors, data loggers, computers, and connecting cables, is a major obstacle.[17] It was reported that a SHM system installed in a tall building generally costs an excess of USD5000 per sensing channel.[3] In recent years, structural health monitoring is done using wireless sensor network to substitute the conventional manual inspection as well as cable-based monitoring system. Wireless sensor networks are capable in that they have the potential to dramatically improve structural health monitoring. By eliminating the cable, it will definitely reduce the cost of sensor installation. Wireless Sensor Network (WSN) technology has attracted increasing interest in recent years.[8,11&20] Furthermore, with the advent of wireless technology, data from the sensors applied to the structure can be obtained in real time without damaging the structure. In this wireless sensor network, sharing information and sending the data to the monitoring centre is the most important and challenging matter. The data must remain accurate for the long range transmission.

2.0 OVERVIEW OF STRUCTURAL HEALTH MONITORING SYSTEM

The advancement in information technologies and the multipurpose application of microcontroller has created an advantage for the SHM to be more reliable. In SHM, researchers are looking for a low cost method that does not damage the structure. The implementation of wireless sensor network in SHM involves integration of sensors, microcontroller, wireless communication and a dependable source of power. Smart wireless sensor is an emerging sensor with on-board microprocessor, with sensing capability, wireless communication, battery powered, and is low cost.[16] The first proposed design of a wireless sensor network for civil structure is a low cost wireless modular monitoring system (WiMMS) that integrated a microcontroller with a wireless radio.[18] The design, then, was improved by enhancing the power of the computational core.[15] The WiMMS platform has been improved further with implementing a software which allows multiple threads (e.g. processing or transmitting data while collecting data) to be executed simultaneously to fully utilize the computational power of the wireless sensor.[19] In the era of 21st century, the development of wireless sensor network for SHM is getting wider with many researchers introducing their own developed wireless sensor network for SHM, such as remote intelligent monitoring system (RIMS),[2] a wireless sensor platform DuraNode for monitoring bridges and buildings,[4] a smart wireless sensor platform called Husky[7] and Mote, which is initially developed at the University of California-Berkeley and subsequently commercialized.[21] Since the world today globally communicate using the internet, a cost effective wireless structural health monitoring system (wSHMs) is presented, which can be implemented in Wide Area Network mode to cover many remote structures and buildings, on a metropolitan scale.[6] Using X-Bee Pro Module provides a radio frequency communication up to 40 kilometres in the line of sight range with high-gain antennas and the implementation of mesh networking protocol. Therefore, we are able to have a long range wireless sensor network for SHM and the implementation of a wide area network.

Structural Health Monitoring (SHM) begins by the diagnosis of data to estimate new improved ways to evaluate the SHM. But the SHM is not just the diagnosis. It involves the combination of sensors, data processing, communication system and data management system. It makes the monitoring and management of the design structure a part of a broader system. This is schematically presented in Figure 1.

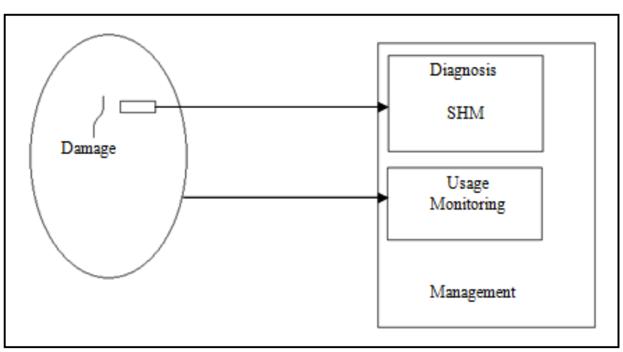


Figure 1 Principle of a SHM

By focusing on the monitoring system in Figure 1, knowing the reliability of structure on a continuous real time basis is important to the monitoring teams. The SHM must allow an optimal use of the structure physically, a minimized downtime in data collection and to avoid disastrous failures. This will drastically change on broader systems, that is by focusing on the method of acquiring the data, reducing the time taken and minimizing human involvement and consequently, reducing labour, human error and improving safety. The improvement on safety is an important aspect, in particular, after several accidents occurred during onsite inspection.

2.1 Sensor

The application of SHM involves many methods that enable immediate assessment of the safety of a structure. In civil engineering, visual inspection is the most common method but it involves labour costing and is time consuming. Thus, alternative methods are used, such as integrated sensor networks. Using sensors allow an advantage of discovering damage at a much earlier stage, and enable continuous tracking of its development. The common sensors normally used in SHM application are listed below[5]:

a) Vibration based techniques
b) Fibre optic sensors
c) Piezoelectric Sensors
d) Electrical Resistance
e) Electromagnetic techniques
f) Capacitive methods

2.2 Data Collection

Data collecting from sensors depends on the method and the type of sensor used. In a conventional system that only requires a measurement at infrequent intervals, the supplier normally provides a portable or handheld indicator used to collect and store data.

2.3 Communication System

Data transmission from sensors to the monitoring station commonly uses wire communication and wireless communication. In the wire communication system, sensors are placed at critical points of the structure and are connected to a central data acquisition system with cables. These wired application result in high installation and maintenance costs in SHM. Currently, wired measuring methods are being used prevalently to collect structural vibration information of a building in practical SHM systems[9&10], while the wireless communication system can be divided into two parts. The first part contains the sensors and the second part is the receiver or base station that processes and monitors the data received. By using wireless communication system, multiple sensor types can also be interconnected; thereby reducing the number and length of wires, and changes to the SHM system can easily be implemented by simply adding more connections.

3.0 COMPARISON ON WIRELESS SHM

Since the inspiring study by Straser, a number of researchers have proposed the use of wireless sensors for structural health monitoring. Those researchers have either designed their own wireless sensor prototype or have elected to adopt a commercial wireless sensor platform. In this review, a comparison based on basic performances of the proposed and the previous wireless

SHMs are made. Most of the SHMs use accelerometer for the sensor to detect the health of the structure. The internal architecture of the accelerometer uses balanced differential capacitors to measure acceleration. By using accelerometer, they are able to monitor the vibration of the structure and compute the acceleration versus time for the data. The higher acceleration received means the more risk for damage to occur on structural health. For the local behaviour of the structure, it is more suitable to use strain measurement for the SHM. Strain sensors are normally placed at the critical points of a structure where high amount of strains are expected. Strain is the amount of deformation that the body/structure undergoes when subject to an applied load. Due to the need of the critical points being monitored in term of damage rather than the whole behaviour of a structure, the strain measurement techniques are selected.

The researchers designed the wireless SHMs explicitly for monitoring from a certain distance. As shown in Table 1, each researcher used different types of commercial wireless communication platform. Each platform had limitation on their range of communication. Early research by Straser utilized the Proxim Proxlink MSU2 platform that came with a range of 30m indoor and 300m outdoor. This is due to the limitations of technology at that time compared today's technology of the proposed X-Bee Pro 900HP, which can achieve up to 610m indoor and 45km with high gain antennas.

By comparing the range with the transmission power and data rate from Table 1, the proposed model is still in the acceptable low power consumption communication protocol and nominal data transfer rate of 200 kbps, which is sufficient to transmit data.

Table 1 (a) Comparison data on Wireless SHMs performances

Researcher	Sensor	Wireless Communication	Range
Straser 1998 [18]	Transduction Mechanism for MEMS Accelerometer	Proxim Proxlink MSU2	- 30m (indoor) - 300m (outdoor)
Lynch 2001 [15]	Analog Device's ADXL210 accelerometer is a low cost, low power accelerometer that can measure acceleration on two axes.	Proxim Proxlink MSU2	- 30m (indoor) - 300m (outdoor)
Wang 2005 [19]	Capacitive Piezotronics PCB3801 accelerometers	MaxStream 9XCite	- 90m (indoor) - 300m (outdoor)
Pentaris 2014 [6]	Accelerometer in Waspmote platform manufactured by the Spanish company Libelium	Waspmote	700 m (indoor)
Kamrul 2011	Strain Transducer BDI ST-350	Telos Wireless Module	50m (indoor) 125m (outdoor)
Proposed model	Omega Precision Strain Gages	X-Bee Pro 900HP	- 610m (indoor) - Up to 9 miles (14km) w/ dipole antenna - Up to 28 miles (45km) w/ high-gain antenna

Table 1 (b) Comparison data on Wireless SHMs performances

Researcher	Transmission Power	Data rate	Voltage Supply
Straser 1998 [18]	300mW	19.2 Kbps	9V
Lynch 2001 [15]	300mW	19.2kbps	9V
Wang 2005 [19]	385mW	38.4 kbps	5V
Pentaris 2014 [6]	117 mW	250 kbps	3.6V
Kamrul 2011	41mW	250 kbps	3.6V
Proposed model	250mW	200kbps	3.6V

4.0 WIRELESS SENSOR NETWORK FOR SHM

The wireless sensors are composed of four components: a processing unit, a transceiver unit, a battery unit and a sensor unit.[13] In this research, the same architecture is applied for the sensor system. The process and flow of the structure is done as shown in Figure 2 and the data that will be collected from the sensors is to be transmitted from one wireless module to another wireless module, and finally to the computer for monitoring.

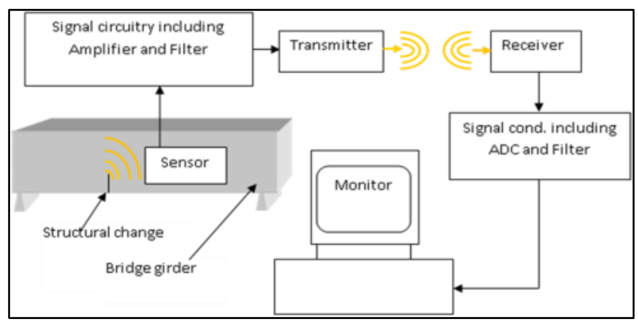


Figure 2 Block diagram of wireless application on structural health monitoring system

In this research, the strain gauges sensor will be used for the structural health monitoring. The strain-based technique is one of the methods to detect crack on the structure. It is more suitable for continuous performance monitoring purposes. The strain measurement is the most reliable and available structural response including acceleration and displacement. However, displacement is usually hard to measure with appropriate accuracy without fixed reference point.[12] Using strain-based technique to evaluate the crack behaviour of a structure can solve this problem because strain sensors and corresponding data acquisition systems are usually much cheaper than those for displacement and acceleration measurements.[12]

Strain is defined as the amount of deformation per unit length of an object when a load is applied. Strain is calculated by dividing the total deformation of the original length by the original length (L):

$$Strain(\varepsilon) = (\Delta L)/L \tag{1}$$

Fundamentally, all strain gauges are intended to convert mechanical motion into an electronic signal. A change in capacitance, inductance, or resistance is proportional to the strain experienced by the sensor. When the wire in the sensor is put under tension, it gets changed in length and its cross-sectional area is reduced. This changes its resistance (R) in proportion to the strain sensitivity (S) of the wire's resistance. When a strain is introduced, the strain sensitivity, which is called the gauge factor (GF), is given by:

$$GF = (\Delta R/R)/(\Delta L/L) = (\Delta R/R)/Strain \quad (2)$$

The ideal strain gauge would change resistance only due to the deformations of the surface to which the sensor is attached. The variations in the electrical resistance of the grid are measured as an indication of strain. Bonded resistance strain gauges have a good reputation. They are low-priced, have small physical size and low mass, and are highly sensitive. Bonded resistance strain gauges can be used to measure both static and dynamic strain.

In order to measure strain with a bonded resistance strain gage, it must be connected to an electric circuit that is capable of measuring changes in resistance corresponding to strain. Strain gauge transducers electrically connected to form a Wheatstone bridge circuit as shown in Figure 3. A Wheatstone bridge is a divided bridge circuit used for the measurement of static or dynamic electrical resistance. The output voltage of the Wheatstone bridge is expressed in millivolts output per volt input.

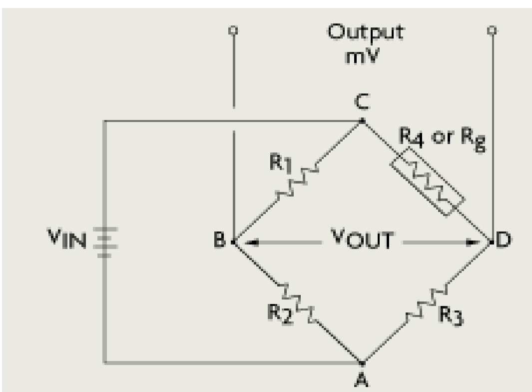


Figure 3 Wheatstone bridge circuit

$$Vout = Vin \left[\frac{R3}{R3+Rg} - \frac{R2}{R1+R2}\right] \quad (3)$$

In Figure 3, if R1, R2, R3, and R4 are equal, and a voltage, VIN, is applied between points A and C, then the output between points B and D will show no potential difference. However, if R4 is changed to some value which does not equal R1, R2, and R3, the bridge will become unbalanced and a voltage will exist at the output terminals. The variable strain sensor now has resistance, Rg, while the other resistors are fixed value resistors. The sensor, however, can occupy more than one at the bridge, depending on the application. The output voltage of the circuit (VOUT) is equivalent to the difference between the voltage change across R1 and R4, or Rg. This can also be written as:

$$VOUT = VCD – VCB \quad (4)$$

For more detail, see Figure 3. The bridge is considered balanced when R1/R2 = Rg/R3 and, therefore, VOUT equals zero. Any small change in the resistance of the sensing grid will throw the bridge out of balance, making it suitable for the detection of strain. When the bridge is set up so that Rg is the only active strain gage, a small change in Rg will result in an output voltage from the bridge. If the gage factor is GF, the strain measurement is related to the change in Rg as follows:

$$Strain = (\Delta Rg/Rg)/GF \quad (5)$$

The number of active strain gages that should be connected to the bridge depends on the application. The block diagram for the sensor is shown in Figure 4. The sensor will show the data in digital output for accuracy in transmission using X-Bee Pro embedded modules and for easy data analysis at the sensor.

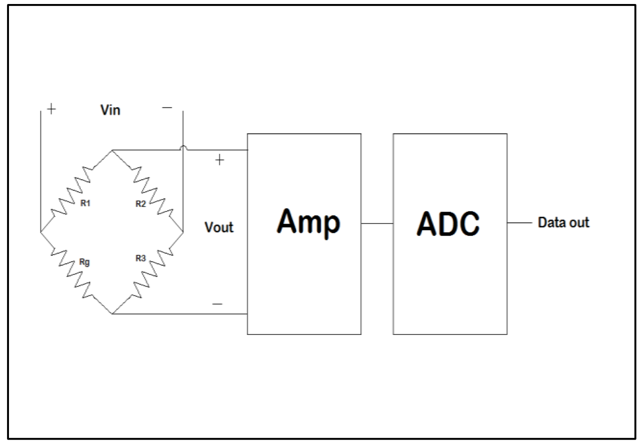


Figure 4 Sensor diagram

5.0 X-BEE PRO MODULE

X-Bee Pro 900HP embedded modules provide best in class range wireless connectivity to devices. They take advantage of the mesh networking protocol, featuring dense network operation and support for sleeping routers, and are also available in a proprietary point to multipoint configuration. The X-Bee Pro 900HP development kit contains X-Bee interface board, X-Bee modules S3B, antennas, USB cables and power supply. Figure 5 show the contents of an X-Bee Pro 900HP kit.

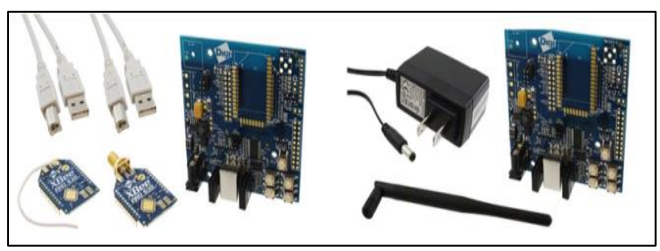


Figure 5 X-Bee Pro 900HP development kit

The X-Bee Pro 900HP is suitable for a long range application since it can be setup up to 24dBm (250mW) for the transmitting power output by software selectable. The X-Bee Pro 900HP consists of firmware loaded onto S3B hardware module. The modules with the programmable option have a secondary processor with 32 k of flash and 2 k of RAM. This allows module integrators to put custom code on the S3B module to fit their own unique needs. The DIN, DOUT, RTS, CTS, and RESET lines are intercepted by the secondary processor to allow it to be in control of the data transmitted and received. All other lines are in parallel and can be controlled by the internal microcontroller. The internal microcontroller by default has control of certain lines. These lines can be released by the internal microcontroller by sending the proper command to disable the desired DIO line.

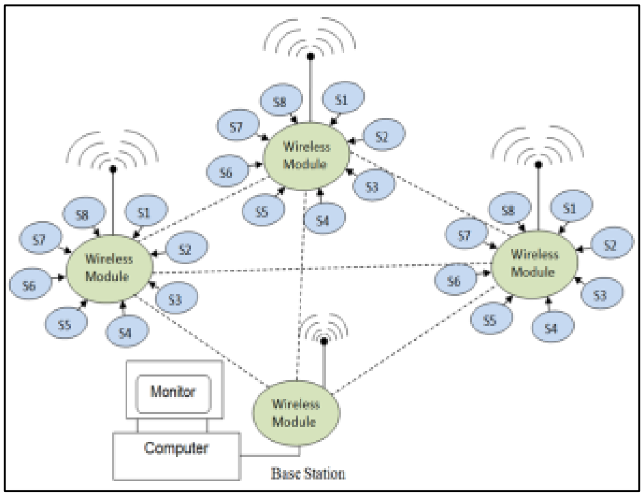


Figure 6 Mesh network using X-Bee-Pro 900HP

These modules are ideal for extending the range of communication and also can reach up to 15.5km using high gain antennas with line of sight. Ideally, for this communication, the mesh network topology was selected. Initially, the sensors sense the physical data and convert into electrical signal. Transmitter then sends the packet data to its neighbour sensor. The neighbour sensor may be a gateway or other type of sensor. Then the gateway decides the optimum path based on routing algorithm to send the data to the base station. Base station processes and analyses the received signal to define the status of the respective signal as shown in Figure 6. The detail specifications on the X-Bee Pro 900HP are shown in Table 2.

Table 2 X-Bee Pro 900HP module specifications

Specification	X-Bee Pro Module (S3B)
Performance	
Indoor/Urban Range	10kbps: up to 610m 200kbps: up to 305m
Outdoor line-of-sight Range	10kbps: up to 15.5km 200kbps: up to 6.5km (with 2.1dB dipole antennas)
RF Data Rate	10kbps or 20kbps
Transmit Power Output	Up to 24dBm (250mW) software selectable
Receiver Sensitivity	-101 dBm, high data rate, -110 dBm, low data rate
Power Requirements	
Supply Voltage	2.1 to 3.6VDC
Receive Current	29mA typical
Transmit Current	215mA at 24dBm
Power Down Current	2.5uA typical @3.3v
General	
Frequency Range	902-928MHz (software selectable channels)
Operating Temperature	-40º to 85º C
Network Topology	Point-to-Point, Peer-to-Peer, Point-to-Multipoint
Digital I/O	15 I/O lines
Board-level Serial Data Interface (S3B)	3V CMOS UART

6.0 CONCLUSIONS

Wireless sensor network system using X-Bee Pro Module is an effective way for structural health monitoring. From the overview presented in this paper, it can be seen that wireless communication capabilities are more than mere low cost alternative to traditional cable-based sensors. By using strain sensors, it is more ideal to monitor the critical points of a structure rather than using accelerometers as sensors, which provide global data on the structure. The programmable microcontroller that comes together with the X-Bee Pro module makes it more manageable and allows the user to programme for immediate warning in the case of possible damage to the structure. The long range capability of data transmission in continuous real time can provide early information and reduce the risk of any unwanted incident that could involve human lives. Furthermore, the down time for structure monitoring is reduced because of not involving technicians for onsite data collection.

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