Design of Wireless Sensor Node to Measure Vibration and Environment Parameter for Structural Health Monitoring Application

Sen Siddheswar, Swarnakar Biplab and Datta Uma

Abstract The paper presents the design of sensor node for wireless sensor network (WSN) dedicated for structural health monitoring (SHM) application. The sensor node, based on Cortex M3 ARM controller, integrates software and hardware for measuring vibration, temperature and humidity data in a compact miniaturized unit. The sensor node is designed for acquiring low frequency vibration with 50 Hz bandwidth. It uses ZigBee protocol based wireless transceiver. A Laptop works as base station to receive information from sensor node. Performance of the sensor node is evaluated by measuring vibration of a 3 phase AC motor and its frequency response is compared with standard vibration data logger Slams Stick^{TM} and a single axis mobile industrial accelerometer.

Keywords Wireless sensor network · Structural health monitoring · MEMS · Accelerometer · Temperature and humidity sensor

1 Introduction

Due to prolonged load, fatigue, environment effect and material aging, civil engineering structures such as Bridges, High rise buildings undergo structural deterioration. To avoid the structural collapse, which leads to loss of life as well as monitory loss, the structural health monitoring has become an inevitable preventive measure. SHM systems are capable to estimate the state of structural health and its

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condition. The most effective way to find out the structural defects is the analysis of vibration data [1]. However Temperature and humidity are also two important environmental parameters which changes structural vibration properties [2]. For the purpose of data communication in SHM system, traditional wired network has been replaced by wireless sensor network (WSN), as the former one experience drawbacks like expensive installation and maintenance [3, 4]. WSN is comparatively new and promising technology which can be implemented in a flexible manner. Reductions of cost, physical size and power consumption are important challenges of WSN system on its path to prosperity. Another challenge related with SHM is small amplitude, low frequency vibration characteristic of structures [5]. With the development of micro-electro-mechanical-systems (MEMS) technology, solution of these challenges has become feasible. 'Smart Dust' or Motes are the outcome of the Smart sensing applications development program funded by US Defense Advanced Research Projects Agency under Network Embedded Software Technology program [6]. 'Rene' is the first modular construction of mote which was developed in 1999 by CrossBow Technologies [6–8]. The latest available sensor node LOTUS is a product of MEMSIC Inc. It includes two separate boards. The mote board is built around LPC1758 processor and integrates an 802.15.4 compliant radio. To provide flexibility from application point of view, it incorporates a 51 pin connector for attaching application specific sensor board. The results are viewed in Moteview platform. Accelerometer data displayed in the MoteView, represents the instantaneous tilting angle of the mote and does not carry any frequency information [9]. A sensor node named 'S-Mote', as described in Yin et al. [4], is developed for Structural Health Monitoring of bridges. Accelerometer, SD1221L having noise density of 5 $\mu g/\sqrt{Hz}$ at 5 V, is used in 'S-Mote'. However the sensor draws 8 mA current. Herranen et al. [10] developed a system to acquire and process the acceleration data. The solution includes a sensor board based on MEMS based sensor ADXL326 or ADXL377 and NI data acquisition box USB-6259. The noise density of ADXL326 and ADXL377 are 300 and 250 $\mu g/\sqrt{Hz}$ respectively. Acquired data is processed on Labview platform on a PC

In the present paper, the design of a miniaturized wireless sensor node on a single board, based on LPC1768 Cortex M3 CPU, dedicated for SHM application is described. The node includes accelerometer sensor, temperature and humidity sensor, with a ZigBee firmware loaded wireless transceiver. Vibration, temperature and humidity data are acquired through high speed sampling and sent to the base station through reliable wireless communication. Vibration data is analyzed at the base station using Fast Fourier Transform. Design of a wireless intelligent sensor node for measuring the vibration of structures along with the environment parameters, and processing of signals from sensors for measurement are briefly described in Sect. 2. The efficiency of the developed sensor node for SHM application is verified in Sect. 3. Finally we conclude in Sect. 4.

2 Design of a Wireless Sensor Node and Processing of Signals

The wireless intelligent sensor node is designed by integrating suitable modules/components as shown in Fig. 1. Selection of components is an important part from design perspective. Important features of modules/components to suit design objectives are described in Table 1. The developed sensor node consists of LPC1768 ARM Cortex-M3 based microcontroller [11], Accelerometer ADXL203 [12], humidity and temperature sensor SHT11 [13], a ZigBee protocol based wireless transceiver XBee [14] and a power unit with two AAA battery. System integration is accomplished by the embedded software running on the microcontroller LPC1768, developed on Keil platform. An In-system programming facility of the micro-controller is incorporated through USB interface with proper hardware. The size of the developed sensor node, including battery compartment, is 3 inch × 1 inch × 2 inch.

ADXL203, a dual axis accelerometer, provides ratio metric (560 mV/g for 3 V power supply) analog output signal correspond to acceleration [12]. Outputs of ADXL203 are connected with two 12 bit ADC channels of LPC1768. The voltage reference levels of ADC are set at 3 and 0 V for VREFP and VREFN respectively resulting in a resolution of 1.3 mg (approx). To secure 50 Hz bandwidth, 0.1 uF capacitor is connected at the output of ADXL203 [12]. Temperature and Relative humidity (RH) sensor (SHT11) provide two wire serial interfaces and is connected with LPC1768 through General Purpose I/O pin. The serial clock (SCK) pin and tri state DATA pin of SHT11 are used for synchronization during data communication and bi-directional data transfer respectively. Resolution of the temperature and RH data generated by SHT11 are 14 and 12 bit respectively. Digital readout of

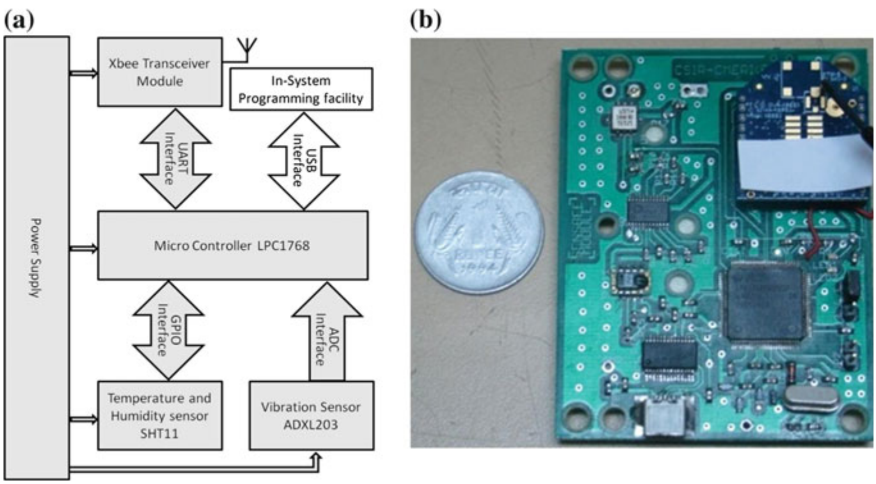

Fig. 1 **a** Block diagram **b** developed hardware of wireless sensor node

Table 1 Components/modules used in the design with their important features

Component/ module	Feature of interest	Selection criteria
LPC1768 Microcontroller	512 kB flash memory	Eliminate the need of external memory; reduced sensor node size
	64 kB data memory	
	Inbuilt 12-bit ADC	Eliminate the need of external ADC; reduced sensor node size
		Higher bit ADC; increased system resolution
	Integrated power management unit	Reduced power consumption
ADXL203	Low current consumption (450 uA at 3 V)	Reduced power consumption
	Low noise density (190 μg/√Hz rms at 3 Volt)	Enhanced system accuracy
SHT11	Digital output	Interface with microcontroller through general purpose I/O of microcontroller; eliminate the need of external ADC; reduced sensor node size
	Includes sleep mode	Reduced power consumption
XBee	ZigBee protocol	Meets open global standard
	Includes sleep mode	Reduced power consumption

temperature and RH data are converted to physical value using suitable equation and its coefficients as provided in the datasheet [13]. XBEE is an 802.15.4 compliant radio transceiver. Microcontroller interfaces with the XBEE through DOUT and DIN pins for bi-directional data communication. Microcontroller also uses CTS pin of the XBEE for flow control of the data packet send from the microcontroller. The transceiver can be operated as End Device/Router/Coordinator. XBee mounted on the developed wireless sensor node, is configured as ‘End Device’ [14]. The sensor node runs on 3 V power supply, supplied by two AAA size batteries.

The data acquisition from sensors is initiated by data request generated from the base station. On receive the request, the microcontroller of the sensor board acquire temperature and humidity data by issuing suitable command [12], followed by acquiring of vibration data for 4 s, at a sampling rate of 1,250 samples/s. The system requires 20 kB memory for storing dual axis vibration data samples. Vibration data is stored in 250 packets with proper format, each containing 80 byte data appended by 1 byte CRC, and sent to base station through XBee transceiver. Temperature and humidity values are also sent to base station. Flow diagram of sensor data acquisition and successful transmission to the base station is shown in Fig. 2. A laptop is used as the base station. An XBee transceiver, configured as ‘Coordinator’ is connected with the laptop through USB port for communication with sensor nodes. Received data from sensor node is stored and analyzed on

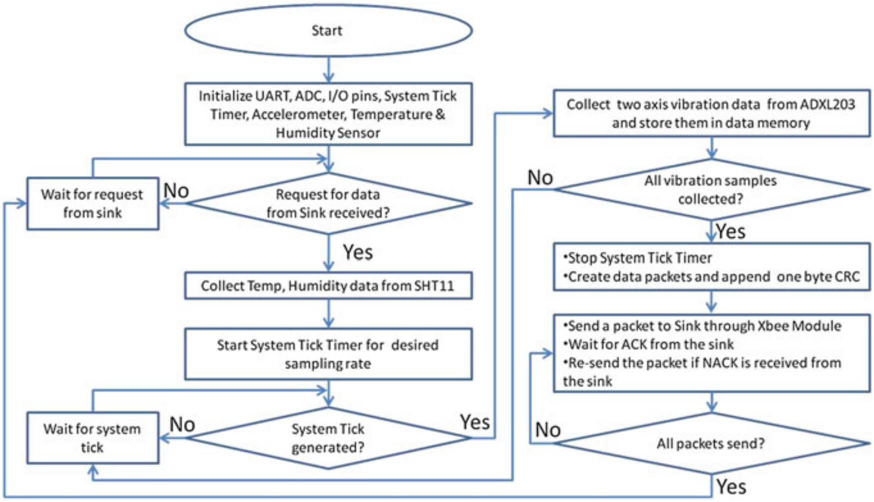

Fig. 2 Flow diagram of data acquisition and transmission from sensor node

MATLAB platform at the base station. Vibration data is plotted in frequency domain after performing FFT on data samples. Temperature and RH values are also displayed.

3 Test Results on 3 Phase AC Motor

Testing of the developed sensor node is performed at the Condition monitoring Laboratory of CSIR-CMERI, by measuring the vibration level of an AC motor excited at 15 Hz (Fig. 3). The speed of the motor is controlled by a Motor controller unit. Complete set of data samples, consisting of vibration, temperature and RH data are received at the base station from the wireless sensor node placed on the shell of the motor structure. Fourier analysis of vibration data is executed using MATLAB FFT function. Amplitudes are further scaled into physical level in the form of 'g' by using suitable weight factor (1.3 mg/LSB) and plotted against frequency. This result is validated by the FFT from a vibration data logger (model: Slam Stick^{TM} VR-001, make: Mide Technology) [15], acts as reference system and further by using a standard mobile industrial accelerometer having single axis data logging capability (model: VIB 6.142, make: PRÜFTECHNIK Condition Monitoring Germany). Both the reference units are placed on the same structure. Figure 4 shows FFT vibration signal as obtained by the developed system, Slam Stick^{TM} and the standard mobile industrial accelerometer (single axis). All responses are showing higher peak response at 30 Hz compared to 15 Hz along with other harmonics. These figures verify the efficacy of the developed system to measure

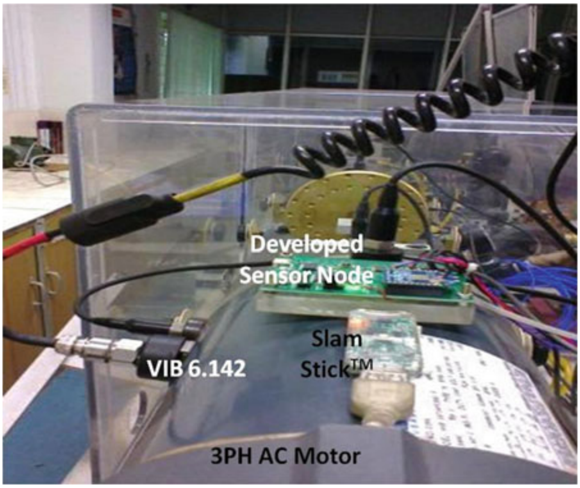

Fig. 3 Test setup for vibration measurement of 3 phase AC motor using developed sensor node, slam stick™ VR-001 and PRÜFTECHNIK VIB 6.142

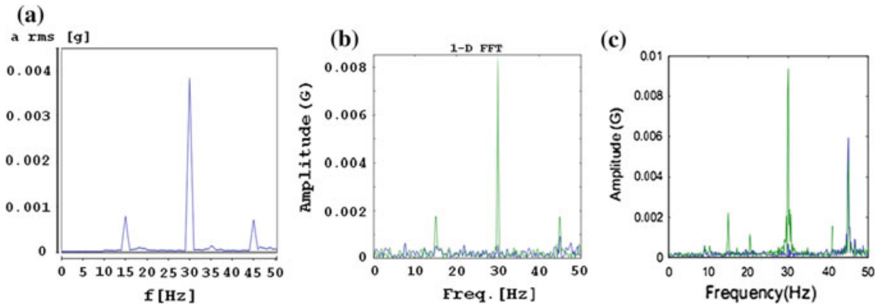

Fig. 4 FFT of vibration data acquired by **a** PRÜFTECHNIK VIB 6.142 **b** slam stick™ VR-001 and **c** developed sensor node

very low level vibration (~2 mg). Differences in the value of 'g', measured by the systems are observed. It is due to different points of placement as well as different system bandwidth. The temperature and humidity of the environment are also received at the base station and validated by the temperature and humidity meter (Metravi HT-3005).

4 Conclusion

A wireless intelligent sensor node, to detect vibration, temperature and humidity parameters for the SHM of civil engineering structures, is designed. The wireless sensor node will be intelligent in the sense that it preprocesses the complete set of data by suitable algorithm to enhance reliability in communication. Satisfactory results in terms of frequency response of vibration signals are revealed by the experiments and subsequent comparison with the standard data loggers. Temperature and humidity measurements are validated by a standard meter. More tests need to be carried out on actual structure with energy optimal code before practical use in network system.

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