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Concrete structural health monitoring using piezoceramic-based wireless sensor networks

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Abstract. Impact detection and health monitoring are very important tasks for civil infrastructures, such as bridges. Piezoceramic based transducers are widely researched for these tasks due to the piezoceramic material's inherent advantages of dual sensing and actuation ability, which enables the active sensing method for structural health monitoring with a network of piezoceramic transducers. Wireless sensor networks, which are easy for deployment, have great potential in health monitoring systems for large civil infrastructures to identify early-age damages. However, most commercial wireless sensor networks are general purpose and may not be optimized for a network of piezoceramic based transducers. Wireless networks of piezoceramic transducers for active sensing have special requirements, such as relatively high sampling rate (at a few-thousand Hz), incorporation of an amplifier for the piezoceramic element for actuation, and low energy consumption for actuation. In this paper, a wireless network is specially designed for piezoceramic transducers to implement impact detection and active sensing for structural health monitoring. A power efficient embedded system is designed to form the wireless sensor network that is capable of high sampling rate. A 32 bit RISC wireless microcontroller is chosen as the main processor. Detailed design of the hardware system and software system of the wireless sensor network is presented in this paper. To verify the functionality of the wireless sensor network, it is deployed on a two-story concrete frame with embedded piezoceramic transducers, and the active sensing property of piezoceramic material is used to detect the damage in the structure. Experimental results show that the wireless sensor network can effectively implement active sensing and impact detection with high sampling rate while maintaining low power consumption by performing offline data processing and minimizing wireless communication.

Keywords: wireless sensor network; impact detection; structural health monitoring; embedded system; piezoceramic sensor.

1. Introduction

Structural Health Monitoring (SHM) systems are important for structures, such as buildings and bridges, since they can diagnose the condition of structures and prevent the potential danger of collapse by detecting structural faults at early stages (Farrar and Worden 2007). Piezoelectric materials, due to their advantages of active sensing, low cost, quick response, availability in different shapes, and simplicity for implementation (Viscardi and Lecce 2002), have been successfully applied to structural health monitoring of concrete structures in either impedance-based methods (Bahel-el-din *et al.* 2003,

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Tseng and Wang 2004) or vibration-characteristic-based methods (Mevelet *et al.* 2000, Song *et al.* 2005, Song *et al.* 2008). Piezoceramic-based smart aggregate (SA) is a single transducer which can perform early-age strength monitoring (Gu *et al.* 2006), impact detection (Song *et al.* 2007c), and structural health monitoring for concrete structures (Song *et al.* 2007a, Song *et al.* 2008), especially for concrete infrastructures, such as concrete bridges. A smart aggregate (SA) is a one-cubic inch precast concrete block with a wired embedded PZT (Lead Zirconate Titanate, a type of piezoceramic) patch (Song *et al.* 2007b).

Most existing SHM implementations use wired data network systems to collect structural health information. A wired sensor network simplifies the hardware design of the system; however, it generates additional problems, such as wiring and maintenance of the network. Installing a large scale wired networked data acquisition system may sometimes take several weeks and often turns out to be prohibitively expensive (Pottie and Kaiser 2000). Wiring sensors to a central node in a large structure is cumbersome and sometimes the wires may cost more than the sensors and the controllers. Recent advances in sensing and networking technologies have led to the emergence of wireless sensor networks (WSNs). Composed of a large number of small, intelligent sensor nodes, WSNs have started replacing centralized sensing and control systems with a distributed alternative (Mechitov *et al.* 2004). Data acquisition systems based on WSNs promise enormous benefits, such as easy and flexible deployment in addition to low maintenance and deployment costs. WSNs are also attractive since they offer increased robustness through decentralization. For example, a distributed sensor network would continue to function at diminished capacity even when it experiences the failure of a large fraction of the sensors. Although WSNs bring much benefit, transferring data wirelessly tends to be more complex than that in wired systems. Wireless protocols have stringent demands on frequencies, data formats, timing of data transfers, security and other issues. Application development must consider the requirements of the wireless network in addition to product functionalities and user interfaces. The key design requirements for the wireless sensor nodes are cost, size, power, heterogeneity and robustness (Wu *et al.* 2007).

The goal of structural health monitoring (SHM) is to determine the condition of the monitored structure and identify potential problems at an early stage by examining the output of sensors attached to or embedded in the structure. In this paper, piezoelectric based smart aggregates (SAs) are used to form a distributed intelligent wireless sensor network (WSN) to address the important issues associated with concrete structures. Structural health monitoring is addressed via the active sensing approach where a swept sine signal is used to excite the SA as an actuator. Impact detection is performed by using the SA's passive sensing capacity, which is an inherent property of a piezoceramic material. Piezoceramic-based structural health monitoring systems have special requirement for the data acquisition systems, such as high sampling rate and high computational power for data processing, all of which require a relatively powerful processor. On the other hand, the battery powered wireless sensor network has strict limitation on power consumption to achieve longer life cycles. The design of the embedded wireless system for structural health monitoring must balance between the computational power and the power consumption to achieve optimal performances. In this paper, a wireless network is specially designed for piezoceramic transducers to implement impact detection and active sensing for structural health monitoring. A power efficient embedded system is designed to form the wireless sensor network that is capable of high sampling rate while maintaining low power consumption. Detailed design of the hardware system and software system of the wireless sensor network is presented in this paper. A two-story concrete frame with embedded SAs is used as the test structure to evaluate the developed wireless sensor network.

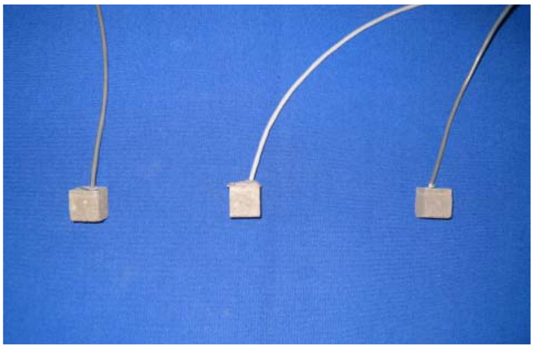


Fig. 1 Photos of piezoceramic-based smart aggregate

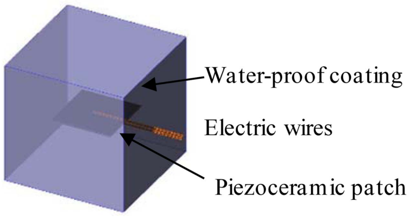


Fig. 2 Illustration of a smart aggregate

2. Basics about the piezoceramic-based smart aggregate

In this paper, the smart aggregates (SAs) shown in Fig. 1 were formed by embedding a water-proof piezoceramic patch with lead wires into a small concrete block before casting the smart aggregate into a larger concrete structure. Piezoceramic transducers are very fragile and can be easily damaged by the vibrator during the casting of concrete structures. In order to protect the fragile piezoelectric transducer, the piezoceramic patch is first coated with insulation to prevent water and moisture damage then embedded into a small concrete block to form a smart aggregate, as shown in Fig. 2. The piezoceramic material will generate electric charge when it is subjected to a stress or strain (the direct piezoelectric effect); the piezoceramic material will also produce a stress or strain when an electric field is applied to a piezoelectric material in its poled direction (the converse piezoelectric effect). Due to this special piezoelectric property, piezoelectric material can be utilized as both an actuator and a sensor. In this research, PZT (Lead Zirconate Titanate) type of piezoceramic material is used due to its advantage of high piezoelectric effect, high bandwidth and close-to-linear operation. The smart aggregate has been successfully used in the health monitoring of various concrete structures, such as concrete bridge bent-cap (Song *et al*. 2007b), shear wall (Yan *et al*. 2009), concrete column (Liao *et al*. 2008) and concrete frame (Laskar *et al.* 2009).

3. Principle for wireless SHM

The smart aggregate-based wireless active sensing system, as shown in Fig. 3, uses one smart aggregate as an actuator to generate excitation waves. The piezoceramic transducers in the other, distributed smart aggregates are used as sensors. The crack or damage inside the concrete structure

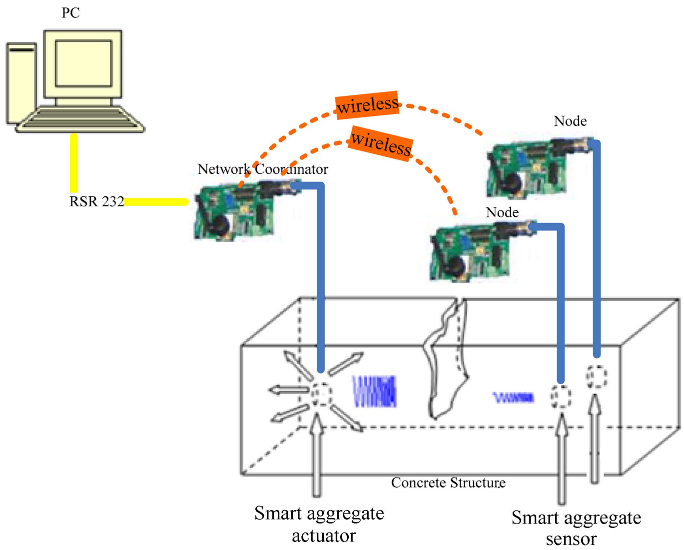


Fig. 3 Block diagram of piezoelectric-based active sensing system

acts as a stress relief in the wave propagation path. The amplitude of the wave and the transmission energy will decrease due to the existence of crack. The drop value of the transmission energy will be correlated with the degree of the damage inside (Song *et al.* 2008). The signal is captured by the smart aggregate sensors and sent back wirelessly to the network coordinator. Through the serial communication, the network coordinator sends the data to PC for post signal analysis. Wavelet packet analysis is used as the signal processing tool to capture the damage features. In the proposed health monitoring approach, a swept sine signal will be used as the excitation source for the smart aggregate actuator. The swept sine starts from 500 Hz and ends at 3 KHz with the period of 1.2 seconds. The swept sine response reveals the frequency response of the structure in a wide frequency range, which benefits the damage feature extraction through the wavelet packet analysis (Song *et al.* 2008, Laskar *et al.* 2009).

4. WSN hardware system design

In this project, two types of wireless devices, the wireless coordinator and the wireless nodes are designed and implemented for SHM and impact detection. The wireless coordinator is used to organize and manage the wireless network and it also controls the performance of all the nodes in the network. The function of the wireless nodes is to sense the impact, perform data acquisition and send data back to wireless coordinator wirelessly. The wireless coordinator is composed of three parts, the amplifier, the Swept Sine Module (SSM), and the wireless microcontroller. The wireless nodes are composed of the signal conditioner, the impact detector and the wireless microcontroller. The SA based wireless strength monitoring system is illustrated in Fig. 4.

4.1 Energy-efficient impact detection circuit

Impact detection is very important for civil structures since a large impact can possibly produce

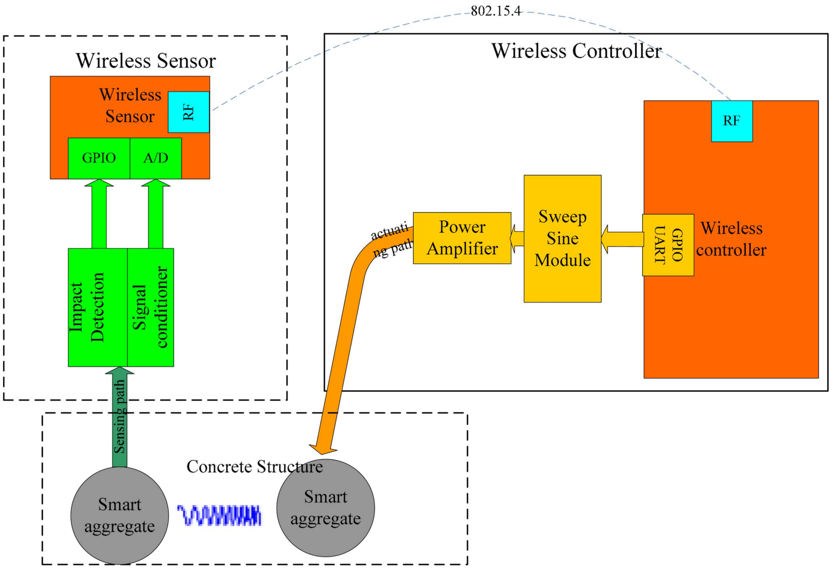


Fig. 4 The wireless system architecture

permanent damage and may result in the failure of the structure (Champaigne and Sumner 2007). Based on the measured physical variable, existing impact detection methods for structures can be classified into three major categories: the acceleration-based approach (Bernard *et al.* 1988), the impact force-based approach (Fujii and Fujimoto 1999, Song *et al.* 2007a), and the strain-based approach (Yang and Han 2002, Staszewski *et al.* 2000). Often piezoceramics (Staszewski *et al.* 2000, Song *et al.* 2007a) and fiber optic sensors (Yang and Han 2002) are employed for impact detection. The piezoelectric based method, which is used in this paper, has the advantage of low cost, quick response, near-linear response, simple implementation, and sensing and actuating functions. A piezoceramic sensor is suitable for either surface mount or embedment. PZT based SAs embedded in the structure are used to capture the vibration caused impacts, and the impact can be analyzed from the vibration signal it captured. PZTs can be used to evaluate the impact force since the open-circuit voltage yield by a PZT transducer is proportional to the compression force, as shown below

$$V = g_{33}Ft/A \tag{1}$$

where A is the area of the PZT patch, t is its thickness, and g_{33} is the piezoelectric voltage constant, which is defined as the electric field generated in a material per unit mechanical stress applied to it. Therefore, as long as the open circuit voltage is measured, the impact force on the structure can be determined. With PZT sensors, impact detection is not a difficult issue for continuously powered systems since the processor can remain powered to capture and record impact events. However, for a battery powered wireless network, where power consumption is a critical issue, the processor cannot be powered continuously. Actually the processor is placed in a sleep mode for most of the time to preserve energy. It only wakes up when necessary to perform certain tasks. Hence the onset of an impact must be detected and transformed into a wake up signal, which can trigger a system interrupt to the processor. An impact detection circuit is designed and fabricated for the PZT sensor to accomplish this task. Fig. 5 shows the impact detection circuit. In Fig. 5, the J1 is connected to the smart aggregate sensor, which sends out a charge signal to the impact detection circuit. The 1M ohm resister (R1) and the op-amp

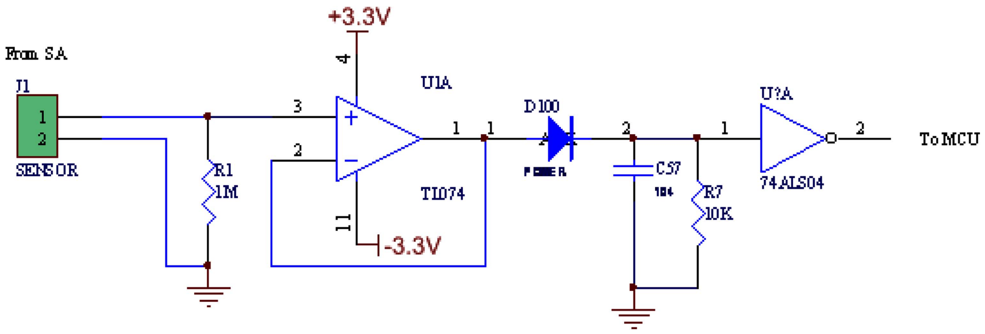


Fig. 5 Impact detection circuit

convert the charge signal to a voltage signal. The diode and the RC circuit is basically a peak detector, which convert the impact to a peak voltage signal. The inverter makes the analogue signal compatible with a digital interface so that when the input is large enough an interrupt can be generated to the microcontroller.

4.2 Signal conditioning

The amplitude of the charge and therefore the current generated by a PZT is proportional to the magnitude of the stress wave in the structure. The simplified model considers the PZT element as a high impedance current source. The current generated from the PZT sensor is usually very small (a few microamperes), therefore proper amplification and signal conditioning are necessary for later sampling and processing by a microcontroller. One resister with a large resistance is used to convert the current to a voltage signal. The PZT sensor here is used to measure dynamic signals: vibrations, not static signals, therefore this design does not require the PZT to hold the charge and the charge leakage will not be an issue. There are several ways to measure the charge signal. One common method is to use the so called integration circuit to convert charge into current, and then to a voltage signal. This method can solve the problem of the high-impedance feature of a PZT sensor. However, it causes another major problem: saturation of the capacitor in the circuit. This requires the circuit parameters to be tuned for certain range of inputs. If the amount of charge has dramatic changes, which fits our case, it is not suitable to use the integration circuit. Therefore, the method of using a large resistor to transform the charge signal to the voltage signal is adopted in this paper. Although the impedance of the PZT is large, it does not affect the charge to be converted to voltage on the large resistor. And with a proper selection of an Op-Amp, this circuit works much better than the integration circuit, as demonstrated by experiments. The tradeoff in this design is that a high-value resistor can produce a larger signal and small noises can be easily amplified through high-value resistors. Our experimental result shows that a 1M resistor is the best choice for our case. An Op-Amp circuit is used to scale and offset the signal to a valid voltage range for A/D sampling by the controller. The signal conditioning circuit is shown in Fig. 6. As shown in Fig. 6, the 1M ohm resistor (R4) and the first op-amp are used to convert the charge signal to a voltage signal. The second op-amp circuit offsets the bipolar voltage signal to a unipolar positive voltage signal. It also amplifies the signal so that the signal fits the range of the A/D converter. The third op-amp circuit is an anti-aliasing low pass filter for the A/D converter.

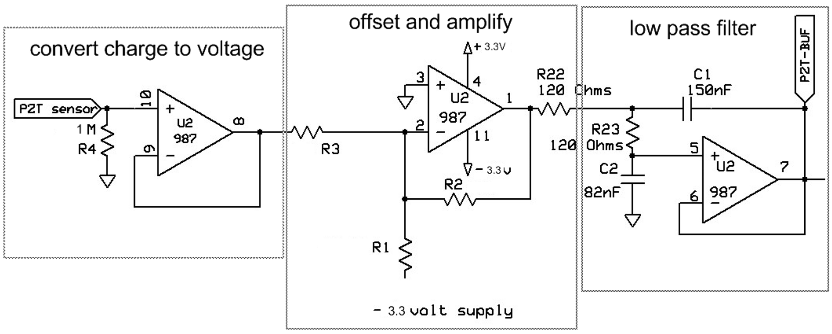


Fig. 6 Signal conditioning circuit

4.3 Swept sine module

A swept sine module is needed for the active sensing of the structure (Song *et al.* 2008). During active sensing, one SA is used as an actuator to generate the vibration that will propagate through the structure and the other SAs are used as sensors to detect the induced vibration. Damage on the wave propagation path will alter the signal strength for the sensing SAs. A swept sine wave is used as the excitation signal as its bandwidth can be set to the specified frequency range. The frequency response in a wide frequency range will be obtained by using a swept sine excitation. This is important to evaluate the damage development. Different frequency corresponds to different wave length which correlates with different resolution for the crack detection. A high frequency signal has a less wave length and it has higher resolution and sensitivity in crack detection.

The default swept sine is generated in the range from 500 Hz to 3k Hz over 1.2 seconds. The value of the swept sine is computed by the microcontroller and output to a D/A (digital to analog) converter, and a low pass filter is applied to smooth the swept sine signal after the D/A converter. Since the frequency of the swept sine signal is up to 3K Hz and the signal lasts for 1.2 seconds, it is impractical to store all the output sample points in a table and output upon request. On the other hand, computing the output values in real time is also problematic since most embedded processors have limited computational power and are not efficient with floating point arithmetic. A simple method is designed to approximate the swept sine signal. The table look up method is used to facilitate the generation of the swept sine signal. A 5000-point sine table is pre-stored in the system's flash memory, and a fixed point calculation is used to determine which value should be output from the sine table. The output value is updated every 14.4 microseconds. Although the swept sine signal generated using this method is not a perfect one, it is sufficient for the use as an excitation source for structural health monitoring.

The swept sine module is controlled by the wireless controller. Usually it is in a sleep mode to save system power. When there is a need for swept sine actuation, the wireless controller will generate an interrupt to the swept sine module through general purpose input/output (GPIO). If no parameter is changed, the swept sine will start to generate the default 500 Hz to 3 KHz swept sine signal. Optional hand shaking between the swept sine module and the wireless controller can be established through a serial communication.

4.4 Power amplifier

The signal from the D/A converter output from the swept sine module is -10V to +10 V, and it is

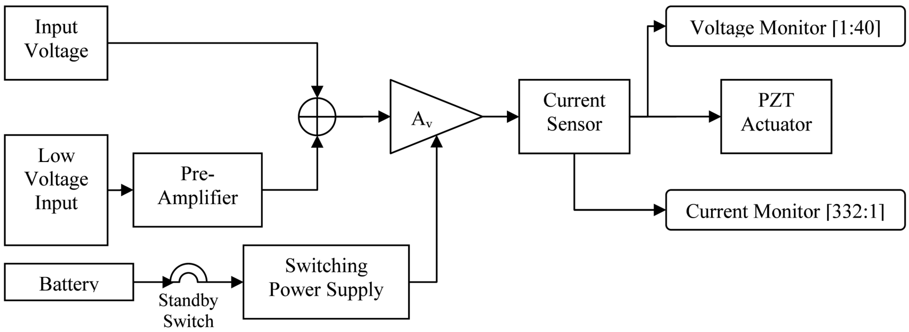


Fig. 7 Power amplifier for the PZT actuation

then sent to a power amplifier before it can be applied to the SA actuator. The power amplifier will generate a voltage in the range of -180 to 180 V. This voltage will enable the piezoceramic-based SA to generate stress waves strong enough to propagate through the concrete structure and detectable by other SAs. An EMCO switching power supply is used to convert the 12 Volts power supply to a +/-180 Volts high voltage power supply, which is capable to deliver 25 mA maximum current. Cirrus Logic PA15FLA operational amplifier, which is designed to drive a wide range of capacitive loads, is adopted to accomplish the amplification work. Fig. 7 shows the structure for the design of the power amplifier. A single, fully charged, 12 Volts 1.2 A/h battery is capable of powering on the circuitry and guaranteeing a bandwidth of around 8k Hz for as long as one hour of continuous use. Detailed description of this design can be found in Olmi *et al*. (2009).

4.5 Wireless controller

The wireless controller is the core component of the overall system. The network coordinator has an external power supply, and gathers and transmits the overall structural health information to a PC. The coordinator is connected to a PC via an RS232 connection. Higher level decisions can be made on the PC and sent to the network through the coordinator. The PC can also retrieve all the sensor data from the network. Offline data processing can then be carried out on the PC to determine the detailed health status of the structure.

A number of wireless sensor nodes have been built by several research institutes. Two commonly used architecture for wireless sensor nodes are ATMEL AVR processor plus TinyOS (Hill *et al.* 2000) and MPS430 plus TinyOS (Dubois-Ferriere *et al.* 2006). A low-power 32-bit embedded platform based on the Jennic JN5139 was selected as the wireless controller for the network in our work. The JN5139 is a low power, low cost wireless microcontroller which is suitable for IEEE802.15.4 and ZigBee applications. It integrates a 32-bit RISC processor, with a fully compliant 2.4 GHz IEEE802.15.4 transceiver, 192 kB of ROM, 96 kB of RAM, and assorted analogue and digital peripherals. It also includes hardware MAC (medium access control) accelerators, power saving and timed sleep modes, and mechanisms for security key and program code encryption. These features all make it suitable for a highly efficient, low power, single chip wireless microcontroller for battery-powered applications. Fig. 8 is a system block diagram of the JN5139.

The piezoceramic-based wireless sensor network is different from other wireless sensor networks as it requires relatively high sampling rate and computation for frequency analysis. Furthermore, the battery based wireless system requires power efficient hardware and software design. Our study shows

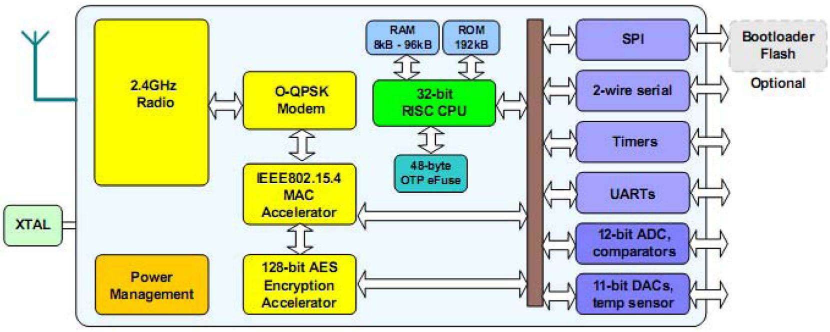
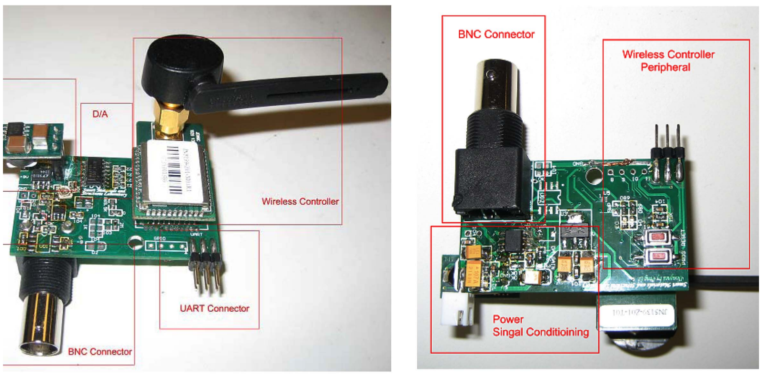


Fig. 8 System block diagram for JN5139

that JN5139 microcontrollers are suitable to address these problems. A JN5139 microcontroller can run at 32 MHz and delivers about 32 million instructions per second (MIPS). Three operating modes are provided in the JN513x microcontrollers that enable the system power consumption to be controlled efficiently to maximize the battery life. The wireless transceiver in the Jennic JN5139 comprises a 2.45 GHz radio, an O-QPSK modem, a baseband processor, a security coprocessor and a PHY controller. The transceiver can operate in the unlicensed 2.4 GHz band. IEEE802.15.4 wireless functionality is used with the transceiver and the protocol software.

4.6 Power

The wireless sensors require 3 Volts power supply only. The wireless MCU works under 3.3 Volts. A charge pump voltage regulator is used to convert the 3 Volts to -3 Volts, which provide bipolar power supply to the signal conditioning circuit. Since the wireless sensor consumes very little energy, two AA batteries are used to power the wireless sensor. The actuator system requires multiple power supply with different voltage rating. 3.3 Volts is needed by the wireless MCU, 5 Volts is needed by the D/A in the swept sine module, 12 Volts is required by the power amplifier, and +/-12 Volts is needed by the signal conditioning circuit from the swept sine module. Switching power regulators are used to reduce the power dissipation during the voltage regulating. 12 Volts lead-acid battery (1.3AH) is used to power the wireless actuator. The reason to use such kind of battery is its rechargeability. For active



(a) Top view (b) Bottom view

Fig. 9 Coordinator photo

sensing, although the voltage is large (180 Volts), the actuation period is short (only a few seconds) and the driving current is small (less than 10 mA). Therefore, the total power consumption is small. A lead acid battery is completely suitable for this task.

A photo of the wireless controller is shown in Fig. 9. Fig. 9(a) offers a top view, while Fig. 9(b) provides a bottom view.

5. Software system design

With the hardware system described in the previous section, proper software needs to be designed to carry out the wireless structural health monitoring and impact detection tasks. The software system is composed of two major parts, the embedded software design and the signal processing algorithm design.

5.1 Embedded software design

Since the embedded system has limited computational power, no operating system (OS) is used and all the programming is done using C language.

The software for the network coordinator is composed of five parts: the drivers for all peripherals, an interrupt driven shell, various interrupt service routines (ISRs), the network programming part, and the event driven state machine. The software architecture is illustrated in Fig. 10.

In Fig. 10, the right bottom blocks inside the border are provided as libraries by Jennic. The rest of the software has to be designed to realize the structural health monitoring and impact detection tasks. Since there is no OS, drivers are the most fundamental components in the software system. UART (Universal asynchronous receiver/transmitter) driver provides interfaces from basic functions as sending and receiving character to and from the PC to complex functions as *printf* to the upper level software. One important function of the UART is to print debug information to the PC, which is a very fundamental and useful method for debugging. A simple shell is designed and built on one of the UART in the system. The shell retrieves the input character from the serial register, and then either appends it to a buffer or performs a “backspace”, “delete” or “tab” operation to the end of the buffer,

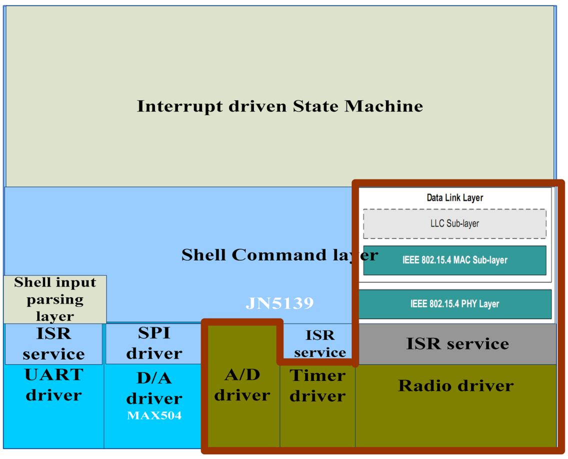


Fig. 10 Software architecture

depending on the character input. "Enter" is an indicator for the finishing of a command input, therefore a flag is set upon an "enter" input. Since all the system events are updated in ISRs, time spent in ISRs has to be kept to the minimum. The parsing of the shell input is performed in the system loop, where the "enter" input flag is checked. The shell input parsing layer is invoked if the "enter" input flag is set. The parser analyzes the input and finds out the entrance address of the command if this is a valid command input. A valid command input reaches the shell command layer, where the command function is actually executed. The shell implemented on the UART provides a means for a user to manage the network. All the tasks can be programmed as one of the shell commands and activated from the PC using any serial communication software, such as HyperTerminal or Putty.

Since the nodes are battery powered, the system software for the nodes is designed to minimize the power consumption over the network while realizing the function of impact detection and continuous health monitoring for the concrete structure (Avancha *et al.* 2004). Star topology is adopted to form the network. Normally all nodes are in sleep mode to save power. Three events can wake up a node, namely, when there is an impact to the structure, when its "heart beat" time is due, and when it receives commands from the network coordinator.

In presence of an impact to the structure, if the impact is above the threshold, the impact detection circuit will generate an interrupt to wake up the relevant nodes (nodes that are close to the impacted location) through their GPIO. These awakened nodes will start to record the impact immediately. The impact data is stored in RAM and analysis can be performed later. An impact message is transmitted to the network coordinator immediately. The network coordinator sends an acknowledgement to the node when it receives this message. If a node does not receive an acknowledgement, it will mark the impact as an unfinished event and transmit this event to the coordinator when its "heart beat" time is due. The node returns to sleep after this event. When the coordinator receives the impact message from the node, it will determine whether to retrieve the recorded impact data. The coordinator can send a command to the node in the acknowledgement, so that the node stays awake to send the data back to the coordinator.

Each node will also wake up when its "heart beat" time is due. This is the time for nodes to update events and to synchronize with the network coordinator. When the coordinator receives the "heart beat" from the nodes, it will update the system clock to the nodes and send out a preparation command to the nodes if a swept sine actuation is to be generated. The coordinator can also determine if there is any pending data stored in the nodes based on the nodes' heart beat messages. If there is an unfinished impact reported by some of the nodes, the coordinator will decide whether to retrieve the pending data wirelessly. If a swept sine actuation is needed, the coordinator will send a command in the acknowledgement to the nodes to keep the nodes to stay alive. The nodes will stay awake to capture the vibration from the swept sine and store all the data in its RAM. The data will be retrieved by the network coordinator afterwards. The coordinator can send commands to the nodes to request the sensing data stored by the node. The command is sent after the coordinator receives the node's "heart beat". An acknowledgement is sent by the coordinator after it receives the "heart beat". The coordinator will denote if it wants to send a command to the sensor node in the acknowledgement while time synchronization is performed at the same time. A sensor node will stay awake if it determines there is a command coming from the acknowledgement. Then the coordinator can send out the command and the sensor will return to sleep mode after it finishes the command. The software system is event driven. All interrupts will be processed, registered as an event and then return. The system will poll the event queues for updated events.

A flow chart for the main loop and the serial interrupt of the software system is shown in Fig. 11.

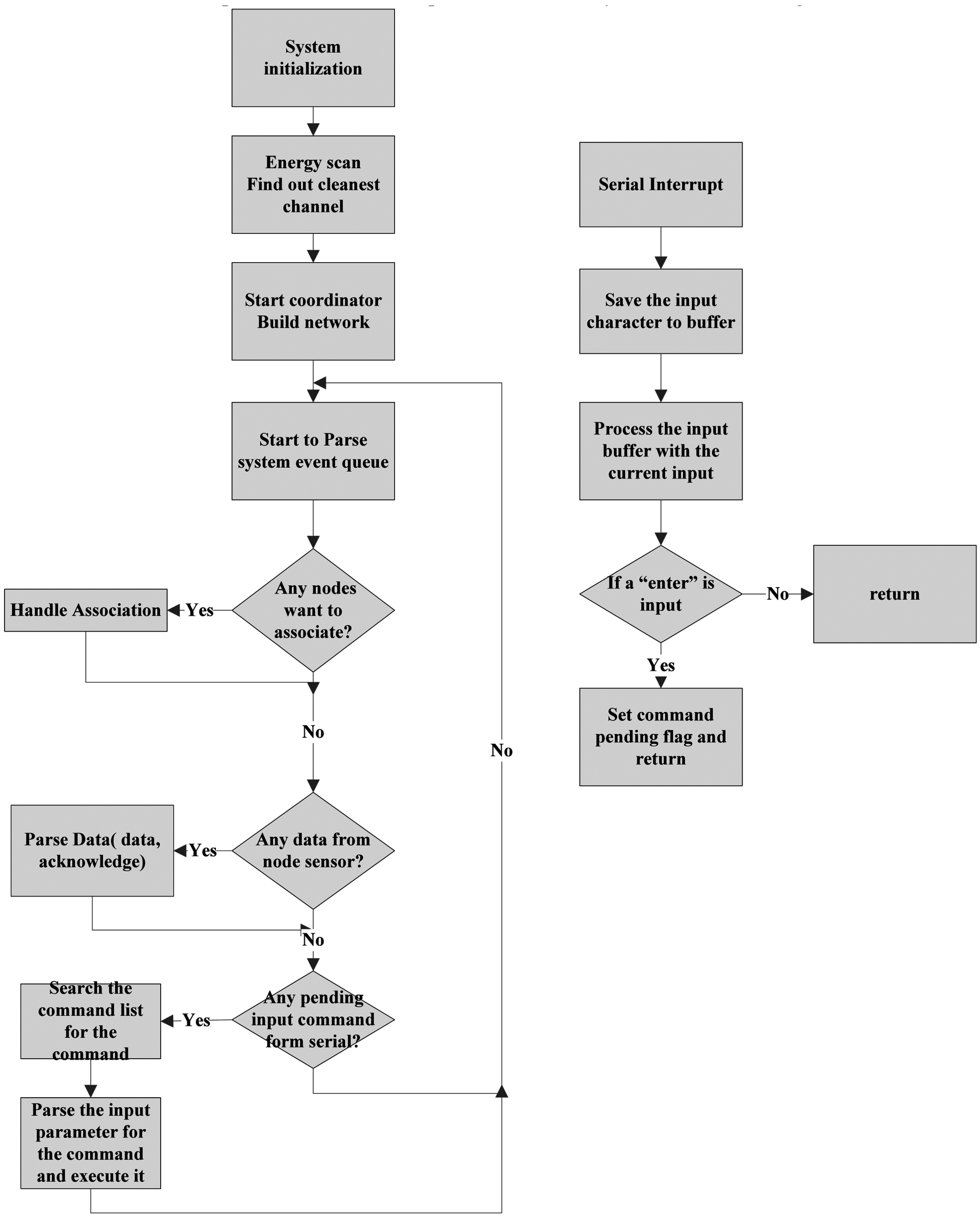


Fig. 11 System flowchart

5.2 Signal processing algorithm

In the proposed active sensing approach, wavelet packet analysis is utilized for signal analysis after data is retrieved from SAs wirelessly. Wavelet analysis can be viewed as an extension of the traditional Fourier transform. Fourier analysis consists of breaking up a signal into sine waves of various frequencies and phases. Similarly, wavelet analysis consists of a breaking up of a signal into shifted and scaled versions of the original (or mother) wavelet.

A wavelet is a waveform of effectively limited duration that has an average value of zero.

$$\int_{-\infty}^{+\infty} \Psi(t)dt = 0 \tag{2}$$

Using a selected analyzing or mother wavelet function $\Psi(t)$, the continuous wavelet transform (CWT) of a function f(t) is defined as

$$W_f(a, b) = \frac{1}{\sqrt{a}}\int_{-\infty}^{+\infty} f(t)\overline{\Psi}\left(\frac{t-b}{a}\right)dt \tag{3}$$

where $a > 0$ and $b \in R$ are the dilation and translation parameters, respectively. The bar over $\Psi(t)$ indicates its complex conjugate.

In wavelet analysis, a signal is split into an approximation and a detail. The approximation is then itself split into a second-level approximation and detail, and the process is repeated. The decomposition tree for wavelet analysis is shown in Fig. 12.

In wavelet packet analysis, the details as well as the approximations can be split. The decomposition tree of wavelet packet analysis is shown in Fig. 13. In this paper, the Daubechies wavelet base (db2) is used as the mother wavelet. The frequency band is not overlapped because of the orthogonality of the Daubechies wavelet base.

The wavelet packet analysis is an effective signal processing tool for damage feature extraction since it enables the inspection of relatively narrow frequency bands over a relatively short time window. In the proposed approach, the sensor signal S is decomposed by an n-level wavelet packet decomposition into 2^n signal sets $\{X_1, X_2, \cdots X_{2^n}\}$. The energy of the decomposed signal is represented by $E_{i,j}$, where i is the time index and j is the frequency band (j=1…2^n). $E_{i,j}$ can be expressed as

$$E_{i,j} = \|X_j\|_2^2 = x_{j,1}^2 + x_{j,2}^2 + \cdots + x_{j,m}^2 \tag{4}$$

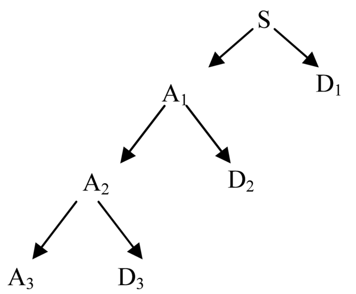


Fig. 12 The decomposition tree for wavelet analysis

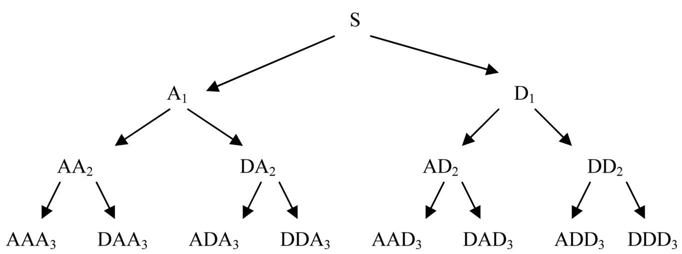


Fig. 13 The decomposition tree for wavelet packet analysis

where X_j is the decomposed signal in time domain using wavelet packet analysis at *jth* frequency band. X_j can be expressed as

$$X_j = [x_{j,1}, x_{j,2}, \cdots, x_{j,m}] \tag{5}$$

where m is the amount of sampling data. Additionally, the energy vector at time index i can be given as

$$E_i = [E_{i,1}, E_{i,2}, \cdots, E_{i,2^n}] \tag{6}$$

This energy vector is used in the experiment to analyze the health status of the structure in the experiment.

6. Experiment

The experiment was carried out on a two-story concrete frame with embedded piezoceramic-based smart aggregates. The dimension for PZT patch in SA is 10×10×0.267 mm^3, and its average capacitance is 5.07 nF. Sixteen SAs are embedded in different locations in the concrete frame and BNC connecters are left outside of the structure for connection to the wireless coordinator or nodes. The diagram of the structure is shown in Fig. 14, and the fabricated frame is shown in Fig. 15. The base of the structure is of 288 cm×150 cm×50 cm, and the two- story frame is of 218 cm×18 cm×194 cm. Fig. 14 also shows the locations of the PZT based SAs.

The two-story concrete frame was damaged by an early loading procedure (Song *et al* 2008). There are many cracks on the frame, especially near the beam-column connections and the two roots of the supporting columns. Only the base is intact. Each smart aggregate (SA) is designed as PZT*i*, where *i* is from 1 to 16.

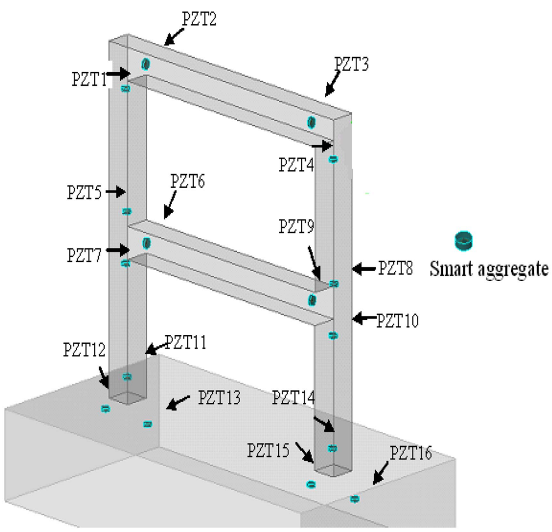


Fig. 14 Two-story concrete frame with embedded smart aggregates

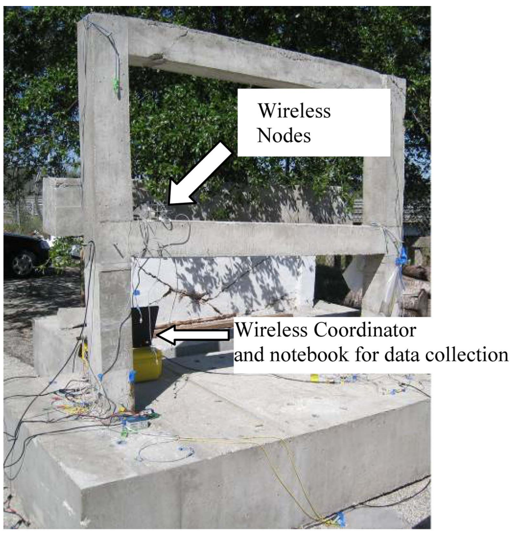


Fig. 15 Photo of the two-story concrete frame

6.1 Structure health monitoring with swept-sine excitation

The network coordinator generates swept-sine waves, and sends the amplified signal to one SA, which is in an actuation mode. This swept-sine actuation will generate stress wave that will propagate in the structure and wake up other nodes. The nodes will then collect the vibration data from the SAs and record it in RAM. A command is sent from the serial console to the coordinator to collect data wirelessly and retransmit to the PC. Data analysis can be carried out later to diagnose the health status of the structure.

Several actuator and sensor pairs are chosen to perform the structural health monitoring. Since the base is intact, the signal from PZT15 and PZT13 can be referenced as the data for a healthy structure. The structure segment between PZT 2 and PZT3 is damaged. PZT3 is used as an actuator and PZT2 as a sensor to capture the damage information. A portion of the actuator data is shown in Fig. 16; in which the swept-sine is from 500 Hz to 3 K Hz and lasts for 1.2 seconds.

The sensor signal is shown in Fig. 17. Power spectrum density for the sensor signal is computed and shown in Fig. 18.

It can be seen that the signal strength from PZT15 as an actuator to PZT13 as a sensor is much larger than that from PZT3 as an actuator to PZT2 as a sensor. This is because cracks between PZT3 and PZT2 absorb and attenuate the stress wave vibration. The frequency response comparison also shows that signals from PZT15 and PZT13 have much larger energy than that of the data from PZT3 and PZT2.

Wavelet packet analysis is used as the signal processing tool to evaluate the damage status of the concrete frame. The wavelet packet based energy vector described in section III is used to detect the existence of the damage and evaluate its severe degree. The comparison of the energy vector of a15s13 (PZT15 is used as an actuator and PZT13 is used as a sensor) and a3s2 (PZT3 is used as an actuator and PZT2 is used as a sensor) is shown in Fig. 19. From the visual inspection of the failed concrete frame, as shown in Fig. 15, there are severe cracks between PZT2 and PZT3. Since PZT13 and PZT15 are located in the base, there are almost no cracks between the propagation path between PZT13 and PZT15. The wave propagation distance between PZT2 and PZT3 is approximately the same as that of PZT13 and PZT15. From the energy vectors comparisons of these two actuator-sensor pairs (a15s13 and a3s2), it can be seen that the energy values at different frequency bands for the

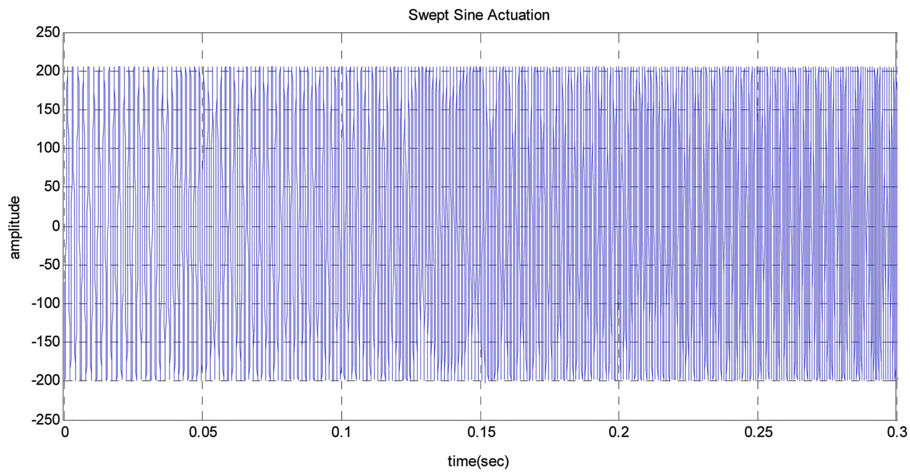


Fig. 16 Swept-sine actuation data

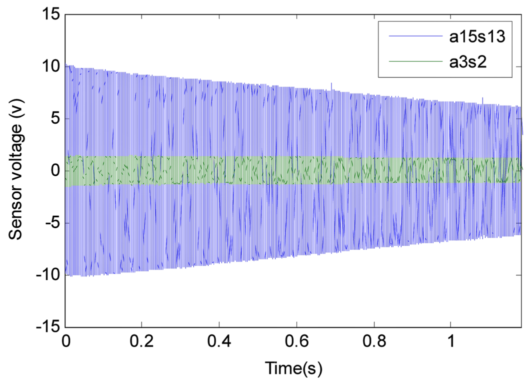


Fig. 17 Time domain sensor data

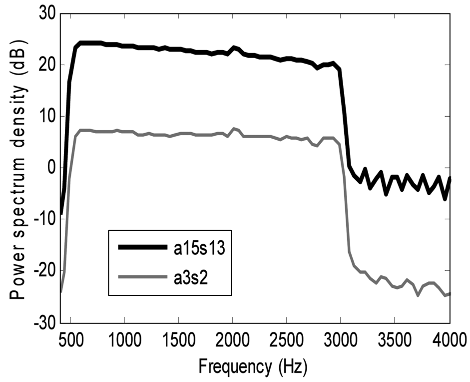


Fig. 18 Frequency domain power spectrum density of sensor data

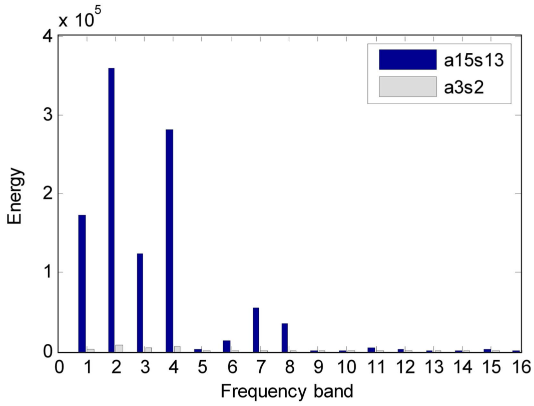


Fig. 19 Energy vector comparison for a3s2 and a15s13

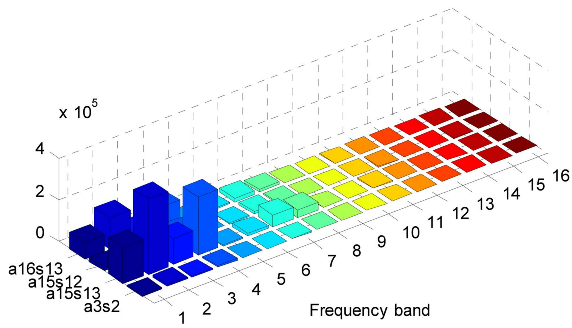


Fig. 20 Energy vector for other actuator-sensor

actuator-sensor pair a3s2 are much lower than those of the actuator-sensor pair a15s13. This experimental result has demonstrated that the existence of the damages in the propagation path has significantly attenuated the wave transmission energy and the drop value of transmission energy is correlated with the severe degree of damage. Therefore, the proposed energy vector can be used to detect the existence of the damage and evaluate the damage severity. From the energy vector comparison of actuator sensor pairs of a16s13, a15s12, a15s13 and a3s2 as shown in Fig. 20, it can be seen that the energy values at different frequency bands are much lower than those of a16s13, a15s12 and a15s13. The experimental results shown in Fig. 20 have further demonstrated that the damage status between PZT2 and PZT3 are much more severe than the damage status between actuator-sensors pairs of a16s13, a15s12 and a15s13. It is clear from the above analysis that structural health monitoring results based on the wireless smart aggregate is in consistence with results from visual inspection of the damage concrete structure.

6.2 Impact detection

Sensor nodes are in sleep modes most of the time. Nodes that are near to the impact will wake up and record the vibration upon an impact on the structure. Fig. 21 shows two sets of impact data

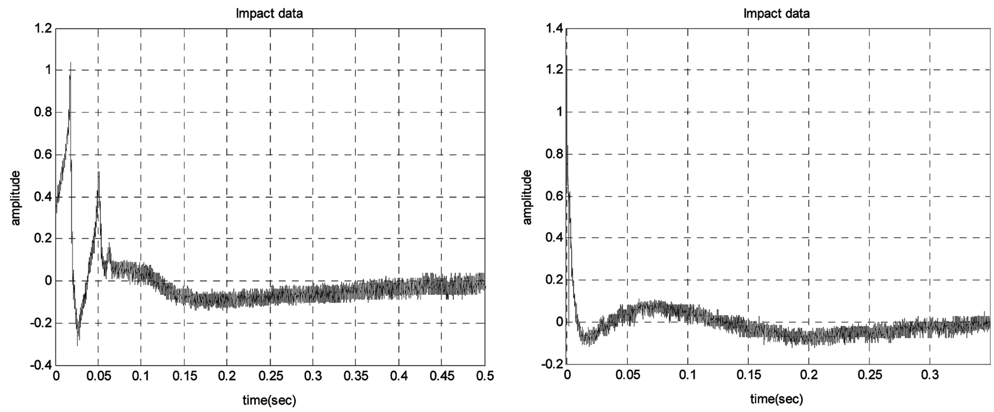


Fig. 21 Examples of impact data captured by the wireless nodes

captured by the sensor nodes. It can be seen that the designed system can capture details of impacts on the structure.

7. Conclusions

In this paper, a wireless embedded system for piezoceramic-based structural health monitoring has been designed and implemented on a two-story concrete frame with embedded SAs to perform impact detection and structural health monitoring. The damage status of the concrete frame is evaluated using the wavelet packet analysis method. The designed embedded system balanced the high sampling speed and high computational power requirement from the piezoceramic-based SHM and the low power consumption requirement from the battery powered wireless sensor network. The proposed piezoceramic-based WSN simplified the wiring and maintenance of the SHM system and can be used for large scale in filed applications. The experiment results show that the system presented in this paper achieves the necessary system performance while maintaining low power consumption by performing offline data processing and minimizing wireless communication.

Future work would include optimization of the network topology and routing algorithm so that the wireless sensor networks can maximize its performance for minimum power consumption. Early age strength monitoring of concrete structures using wireless smart aggregates will also be conducted.

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