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（第4分册）

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第四分册

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航空宇航学院2007年学术论文清单（0134）

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A wireless sensor network node designed for exploring a structural health monitoring application

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Abstract

This paper presents a wireless sensor network node designed for building a structural health monitoring (SHM) application. To develop a low-cost, low-power, dedicated wireless sensor node for a composite SHM system, a modular approach is taken in the design of the wireless sensor node. Three functional modules are adopted, including a sensor input unit, processing core and wireless communication. Different from existing wireless sensor nodes, the signal conditioning circuit is designed on this developed node for two typical SHM sensors, the piezoelectric sensor and the strain gauge. The developed wireless sensor nodes can be expediently used to deploy the dedicated wireless sensor network for SHM application. A two-tier wireless sensor network is deployed adopting the designed wireless sensor nodes to verify the efficacy of developing SHM systems. An embedding pattern matching method and a directed diffusion routing algorithm are developed to monitor the strain distribution or the bolt loosening position successfully.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Structural health monitoring (SHM) is an active area of research and practice in recent years. The SHM process involves the observation of a system over time using periodically sampled response measurements from an array of sensors. The extraction of damage-sensitive features from these measurements and the statistical analysis of these features are then used to determine the current state of the system's health. The key point of health monitoring is damage detection, damage localization and damage severity estimation. There are several advantages to using a SHM system over traditional nondestructive testing, such as reduced down time, elimination of component tear down inspections and the potential prevention of failure during operation. Marine, aerospace, ground and civil structures can receive unexpected damage that may compromise integrity during their lifetime. Therefore, the development of the SHM system can save revenue and lives depending upon the application. A lot of developments have been made to prove that the structural health monitoring technology is a promising one [1–4].

When implementing a cable-based SHM system for large engineering structures, there are two practical problems. Firstly, sensors embedded in the structure have no means to locally process their data, and the centralized data servers become overburdened with computational tasks if the system is comprised of a large number of sensors. Secondly, massive interconnections from the sensors to the centralized data server require complex configurations of hardware systems. To deal with these problems, wireless communication technologies have been explored in recent years. Straser and Kiremidjian proposed a civil infrastructure SHM system based on wireless data transfer technology [5]. The authors used wireless communications to transfer sensor measurements to a centralized data acquisition server. Mitchell *et al* [6] proposed the use of distributed computing and sensing to detect damage in critical locations. Their systems made use of wireless communication technologies, either radio-frequency (RF) communication links or commercial wireless cellular phone networks. Many benefits can be gained from wireless SHM systems, such as local computational ability, low cost of deployment and wireless networking functionality.

Therefore, increasingly researchers in both academia and industry focus on developing wireless sensor networks for SHM applications [7–13].

A number of wireless sensor nodes have been built by several research institutes and some in the private sector. Jason Hill *et al* [14] proposed a wireless network sensor node architecture. Based on this architecture, Mote is designed by UC Berkeley. Henri Dubois-Ferriere *et al* [15] proposed a versatile lowest-power sensor node with an array of extension hardware offering a wide set of connectivity, storage, energy and interfacing options. The above wireless nodes are both supported by the TinyOS software platform [16]. The Intel Mote project team designed a wireless platform that consisted of an ARM7TDMI core running at 12 MHz, a Bluetooth 1.1 radio, 64 kB RAM and 512 kB FLASH memory [17]. Lynch *et al* [18] designed a low-cost wireless sensing unit for deployment as the wireless structural monitoring system on the Alamosa Canyon Bridge. Shunzo Yamashita *et al* [19] developed an ultra-small, low-power sensor-net module called ZN1, which had been used for food sanitation and home healthcare. However, except for the node designed by Lynch, most of the sensor nodes developed are not specially designed for SHM applications. They do not meet the requirements of SHM applications. For example, Mote, ZN1 and the Intel Mote all do not include sensor signal conditioning circuits dedicated for SHM. The wireless sensing unit designed by Lynch is only suitable to be used to monitor civil engineering structures, since the form size of the node is too big.

The research in this paper aims to develop a low-cost, low-power, dedicated wireless sensor node to develop for the SHM system, which is functionally comparable to current cable-based SHM systems. Including two typical sensing elements' signal conditioning circuits, the wireless sensor node can be directly connected to the piezoelectric elements and the strain gauges. The wireless sensor node also has an on-chip analog-to-digital converter, with 15 kSPS sampling rate. A low-power eight-bit microcontroller is chosen to control the data acquisition operation of the wireless sensor node. Specifically, the Atmel ATMEGA128 microcontroller is chosen. The whole wireless node draws less than 10 mA of current in active mode and 300 μA in sleep mode. The transmission range of the node can be extended to 100 m in the outdoor environment with 0 dBm output power. To validate the capability of the wireless sensor node, a small-scale sensor network system is deployed to monitor the strain distribution and bolt loosening of a composite structure. In the top tier of the experimental network, the optimization path for network data delivery is formed using the directed diffusion routing algorithm.

2. The wireless sensor node design

A wireless sensor network is defined as a large-scale, multi-hop, unpartitioned network of tiny, resource-constrained, mostly immobile sensor nodes that would be randomly deployed in the area of interest. Hence a wireless sensor network device must meet strict power consumption and size requirements. The key design requirements for the wireless sensor nodes are cost, size, power, heterogeneity and robustness.

The physical size and cost of the wireless sensor nodes have a significant and direct impact on the ease and cost of the SHM system network deployment. A reduction in per-node cost will result in the ability to purchase more nodes, deploy a collection network with higher density, and collect more data. Physical size also impacts the ease of sensor network deployment. Smaller nodes can be placed in more locations of the engineering structures. To meet the long-term monitoring requirements, an individual sensor node must be incredibly low power. The average power consumption of wireless sensor nodes should be in microamperes. This ultra-low-power operation can only be achieved by combining both low-power hardware components and low duty-cycle operation techniques. The degree of heterogeneity for wireless sensor nodes is another important factor since it affects the complexity of the software executed on the sensor nodes and also the management of the whole SHM system. In a large-scale deployment for engineering structures, hundreds of nodes should work in harmony for years. To achieve this, each node must be designed to be as robust as possible.

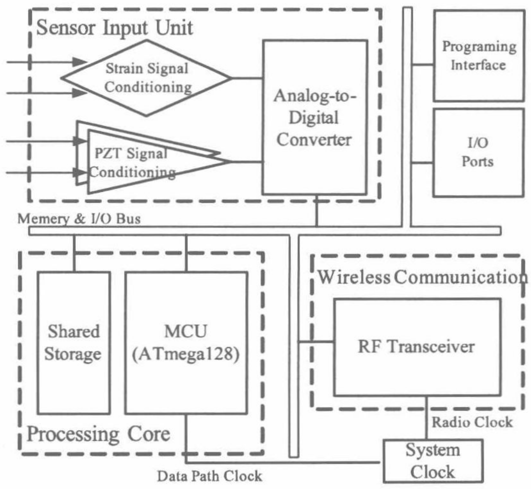

Figure 1. The schematic diagram for the wireless sensor node.

Wireless sensor nodes require an unusual degree of hardware and software modularity while simultaneously maintaining efficiency. System modularity is a powerful tool that can be used to develop a robust hardware system. By dividing system functionality into isolated sub-pieces, each function can be fully tested in isolation prior to combining them into a complete application. Therefore, a modular approach is taken in the design of the wireless sensor node. Based on the generalized wireless sensor node architecture [20], the design of the wireless sensor node can mainly be divided into three functional modules: sensor input unit, processing core and wireless communication. The wireless sensor node can easily be upgraded as advanced IC technologies continue to be improved. The schematic diagram for the wireless sensor node is shown in figure 1.

2.1. Sensor input unit

In the SHM research area, piezoelectric elements and strain gauges are two typical sensing elements usually adopted. Considering this, two signal conditioning circuits are designed for these two sensing elements on the node.

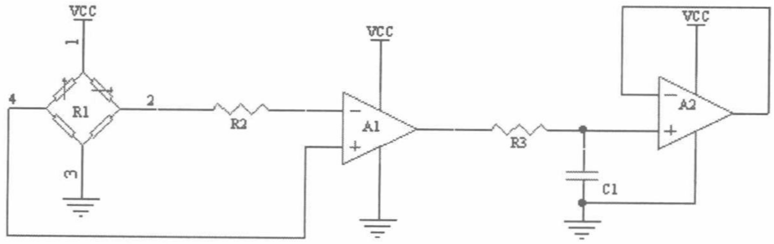

Figure 2. The schematic circuit diagram for strain gauge signal conditioning.

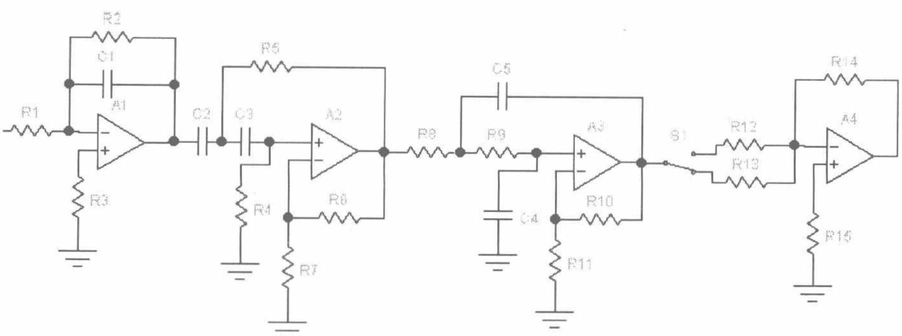

Figure 3. The schematic circuit diagram of the charge amplifier and filter circuit.

Figure 2 is the schematic circuit diagram for conditioning the strain gauge sensor signal. The circuit is composed of three parts: the bridge circuit, the amplifier and the output circuit. The conditioning circuit provides a 3 V power supply for the bridge circuit. The bridge circuit output corresponds to the structural strain monitored. Since the sensitivity of the strain gauge is low, the instrumentation amplifier INA118 is adopted to amplifier the bridge circuit output. The INA118 is a low-power instrumentation amplifier offering excellent accuracy from Burr-Brown Company. Its versatile 3-op amp design and small size make it ideal for a wide range of applications. The strain gauges are usually adopted to monitor a static signal; thus a low-pass filter is designed to eliminate the high frequency noise. The voltage follower is adopted to output the filtered voltage signal.

Figure 3 is the schematic circuit diagram of the charge amplifier and filter circuit which is designed for the piezoelectric elements. The LF412 is a low-cost, high-speed, FET input operational amplifier with very low input offset voltage and guaranteed input offset voltage drift. It can be used in many circuits requiring low input offset voltage and drift, low input bias current, high input impedance, high slew rate and wide bandwidth. The leftmost operational amplifiers circuit, A1, is to transform charge signals to voltages. The other amplifier circuits are to amplify the voltage signals and filter disturbance noises. The A3 operational amplifier is made up of an active second-order high-pass filter, whose cutoff frequency is 160 Hz. The A4 operational amplifier composes a first-order low-pass filter with cutoff frequency up to 500 kHz, whose function is to filter high frequency noises and output the conditioning signals.

The main hardware component of the sensor input unit is an analog-to-digital (A/D) converter that is chosen to accommodate external sensors with analog outputs. With the sampling rate of 15 kSPS, the 10-bit successive approximation A/D converter integrated into the Atmel Mega128 MCU has eight multiplexed single-ended input channels. The ADC features a noise canceler that enables conversion during sleep mode to reduce the noise induced from the CPU core and other I/O peripherals. At the maximum sampling rate of 15 kSPS, the converter draws 300 μA of current.

2.2. *Processing core*

The most important component of the proposed wireless sensor node is the processing core. The central processing engine is timeshared across applications and protocol processing. Only a single processing core is included because it allows the allocation of all processing resources to a single task when necessary. Multiple register sets can be included in the CPU so that each context switch does not require the registers to be written out to memory. Instead, the operating system simply switches to a free register set.

A low-power eight-bit microcontroller is selected to control the data acquisition operation of the wireless sensor node. Specifically, the Atmel ATMEGA128 microcontroller is chosen. The main microcontroller runs at 8 MHz and delivers about eight million instructions per second (MIPS). This 8-bit microcontroller has: 128 kB flash program memory, 4 kB static RAM, internal 8-channel 10-bit analog-to-digital converter, three hardware timers, 48 general-purpose I/O lines, one external universal asynchronous receiver transmitter (UART) and one serial peripheral interface (SPI) port. Normally, programming of these embedded microcontrollers occurs during manufacture with a firmware upload or during field maintenance. A 4-Mbit Atmel AT45DB041B serial flash chip

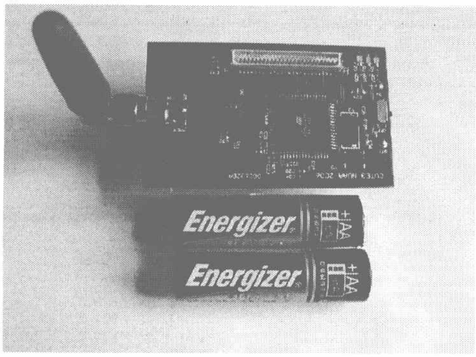

Figure 4. The picture of the wireless sensor node.

is added to the computational core to hold long time-history records.

2.3. Wireless communication

For size and power requirements of the wireless node design, a single-chip UHF transceiver is chosen. Specifically, the TI CC1000 RF transceiver is chosen. CC1000 is a true single-chip UHF transceiver designed for very low-power and very low voltage wireless applications. The circuit is mainly intended for the ISM (industrial, scientific and medical) and SRD (short range device) frequency bands at 315, 433, 868 and 915 MHz, but can easily be programmed for operation at other frequencies in the 300–1000 MHz range. The main operating parameters of the CC1000 can be programmed via an easy-to-interface serial bus, thus making the CC1000 very flexible to use. In the wireless sensor node, the CC1000 is used together with the Atmega128 and a few external passive components. At 433 MHz RF frequency and −20 dBm output power, the wireless transceiver only draws 5.3 mA of current while actively receiving and transmitting, guaranteeing the low-power character of the designed wireless node.

2.4. Wireless sensor node development and validation

After the choice of circuit components, a four-layer printed circuit board is designed and fabricated. The circuit board is designed to have a small size. The dimension is 7.5 cm × 4.0 cm which is almost the same size as a pair of AA batteries. The reason to adopt the four-layer circuit is to sufficiently separate analog and digital circuit components. The power to supply the wireless sensor node is designed to use 3 V direct current (DC) power since all the components are low power. Thus, two normal 1.5 V batteries can power the complete wireless sensor node. Figure 4 shows the picture of the developed wireless sensor node.

After the fabrication of the sensor node, the node performance tests were completed in the indoor, office environment. The first test for the node service lifetime is to confirm the node's low-power character. The test wireless sensor node, which is supplied by two AA batteries, transmits a data packet once every 4 s with the radio channel set to 433.02 MHz and transmission power set to 0 dBm. End-of-service life was determined when data packets could not be received by another reference node that was 15 m away from the test node and supplied by 3 V DC power. Table 1 shows the different service lifetime tests with corresponding AA battery capacity. Power supply load for the whole test wireless node was about 10 mA in this test configuration. It can be calculated by summing up the operation currents of three functional modules. The node total current consumption in sleep mode is about 200 μA, so a conservative estimation for the anticipated life of the wireless sensor node using two batteries (each 1700 mA h) is approximately of the order of a year.

Table 1. Different lifetimes to corresponding AA battery capacity.

Batteries (mA h)	Lifetime (h)
1000	98
1700	170
3000	291

Table 2. The different transmission ranges corresponding to the transmission power.

	Test1	Test2	Test3	Test4
Power (dBm)	−20	−10	0	5
Range (m)	7.5	11	27.5	33

The transmission range is the second test item for the wireless sensor node. The test wireless sensor node also transmits a data packet once every 4 s with the radio channel set to 433.02 MHz. The end point of transmission was determined when data packets could not be received by another immobile reference node. Table 2 shows the different transmission ranges corresponding to different transmission powers. The transmission range of the wireless system is controlled by several factors. The most intuitive factor is the transmission power. The more energy put into the signal, the farther it can travel. The relationship between power output and distance traveled is a polynomial with an exponent between 3 and 4 (non-line of sight propagation) [21].

The final performance test of the wireless sensor node is data acquisition. The function generator is used to simulate the sensor input signal, and is connected directly to the ADC input channel of the wireless sensor node. The sine wave with 250 mV peak value is generated for the test input signal. The test wireless sensor node collects the wave signal and transmits a data packet per second with the radio channel set to 433.02 MHz. Figure 5 shows two received signals by another immobile node connected to the monitor server by the serial 232 port when the sine wave frequency is set to 1 and 2 kHz separately. From the received signal, it can be found that data can be collected and transmitted correctly.

3. Exploring a composite health monitoring application

In order to verify the possibility to develop structural health monitoring systems based on the designed wireless sensor nodes, in this paper a wireless sensor network system is deployed to monitor strain distribution and bolt loosening of composite structures.

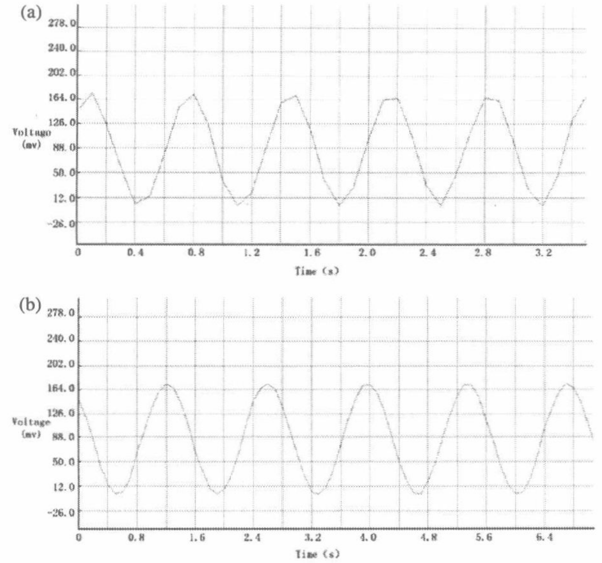

Figure 5. The received signals when the sine wave frequency is 2 kHz (a) and 1 kHz (b).

3.1. Experiment system set-up

The set-up of the composite health monitoring system based on the wireless sensor nodes is shown in figure 6. Fifteen wireless sensor nodes make up a two-tier wireless network, which includes two clusters monitoring the applied concentrated strain distribution and bolt loosening, respectively, named the cluster of *loading localization* and *bolt loosening monitoring*. Two glass-fiber epoxy composite plates with the dimensions of 800 × 800 mm and 5 mm thick are fastened to separate steel frames by 20 bolts. Four strain gauges are arranged on the surface of one plate to monitor the strain distribution in the structure. The wireless sensor node connected to the strain gauge is called the *strain gauge node*, in which the strain gauge signal conditioning circuit is only enabled. Four piezoelectric ceramic sensors and one piezoelectric ceramic actuator are incorporated into another plate and adapted to monitor the bolt loosening of the composite plate. In the *PZT sensor node*, the charge amplifier and filter circuit is only enabled. In the wireless SHM application systems, multi-hop technology is very important for the sensor network usability, since the monitored structures are usually located far away from the centralized server. In order to validate the monitoring capability of the wireless sensor network, in this paper some multi-hop nodes and the base station node are deployed to make up the top tier of the sensor network, in which the processed result data are transmitted to the monitoring server connected to the base station node.

3.2. Cluster of 'loading localization' and 'bolt loosening monitoring'

The measurements taken from changes of strain distribution of the composite structure are used to illustrate the successful execution of concentrated loading localizations using the wireless sensor network node. Four strain gauges with 80 mm length each are incorporated in the composite and adapted to monitor the strain distribution changes caused by applying a

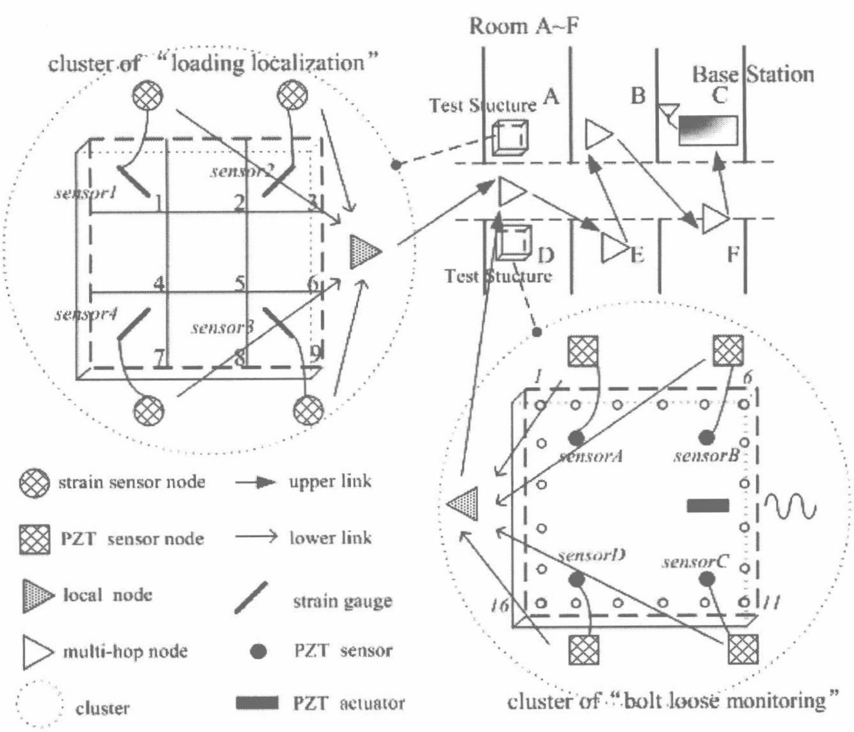

Figure 6. The set-up of the network system.

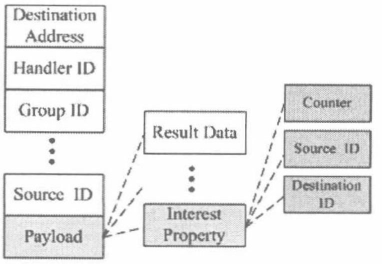

Figure 7. The definition of the communication packages.

concentrated load at different positions on the structure. There are a total of nine areas at which the load may be applied. The strain gauges are incorporated in area 1, area 3, area 7 and area 9, respectively. Each strain gauge is connected to a wireless strain gauge node.

The load position monitoring is based on the strain distribution change monitored by the wireless sensor nodes. The four outputs of the wireless strain gauge nodes form a mode to represent the strain distribution of the composite structure. When there is a concentrated load applied on the composite or the applied position changes, the strain distribution changes correspondingly and the output mode of the strain gauge nodes changes too. The pattern recognition method is adopted to classify the different modes to decide different load positions [22]. In this paper, the embedding pattern matching method is developed to process the structural responding information and decide the structural health status. Since the Euclidean distance measure is simple and easy to implement, it is chosen to run in the local master nodes for pattern recognition. In the experiment, the centralized load is 5 kg. The differences between the real-time loading output voltage values and the no-loading voltage values of the strain gauges compose the input vector $x(\theta_1, \theta_2, \theta_3, \theta_4)$, and the trained differences between nine areas' load output and the no-loading output compose the standard difference $\alpha(\alpha_{i1}, \alpha_{i2}, \alpha_{i3}, \alpha_{i4})$, $i \in [0, 9]$. By the squared Euclidean distance formula, $A_i = \sum_{j=1}^{4} (\alpha_{ij} - \theta_j)^2$, $i \in [0, 9]$, the result vector, $[A_0, A_1, \ldots, A_9]$, is achieved. The minimum of $[A_0, A_1, \ldots, A_9]$ implicates the corresponding centralized loading pattern. The local master sensor nodes in the cluster of *loading localization* transmit the load position result to the base station by multi-hop nodes.

The bolt loosening monitoring is based on the structural vibration response [23]. A piezoelectric ceramic is adopted here to give a sine wave excitation signal to the structure at 1.7 kHz. One reason to choose 1.7 kHz excitation here is because this excitation is acceptable for the wireless sensor node to sample data and transmit data. Another reason is because the vibration response of the structure under this excitation is sensitive to the loose bolt. The test glass-fiber epoxy plate composite is fastened to a steel frame by 20 bolts 5 mm thick. Four piezoelectric ceramic sensors with 10 mm diameter and one piezoelectric ceramic actuator with a rectangular shape of 20 × 5 mm are incorporated in the composite. The piezoelectric ceramic sensors and the piezoelectric ceramic actuator are adopted to monitor the bolt loosening. The PZT sensor nodes monitor the response of the structure under excitation and extract the peak values of voltage signals to form a signature mode. When there is one bolt loose in the structure, the vibration response changes, causing the signature mode to change. Using the Euclidean distance measure, the mode can correspond to a certain bolt loosening situation by the local master sensor node in the cluster of *bolt loosening monitoring*.

Table 3. The sensors' output of 10 patterns in the '*loading localization*' cluster.

Load applied area	Sensor 1 (mV)	Sensor 2 (mV)	Sensor 3 (mV)	Sensor 4 (mV)
No load	492	20	94	140
Area No. 1	511	27	95	144
Area No. 2	494	38	92	140
Area No. 3	489	52	93	144
Area No. 4	488	25	98	145
Area No. 5	492	27	100	149
Area No. 6	490	24	96	145
Area No. 7	485	21	98	164
Area No. 8	484	23	116	158
Area No. 9	483	21	162	144

Table 4. The trained 10 difference patterns in the '*loading localization*' cluster.

Load applied area	Difference 1 (mV)	Difference 2 (mV)	Difference 3 (mV)	Difference 4 (mV)
No load	0	0	0	0
Area No. 1	19	7	0	3
Area No. 2	2	18	2	0
Area No. 3	3	32	1	4
Area No. 4	4	5	4	4
Area No. 5	0	7	6	9
Area No. 6	2	4	2	5
Area No. 7	7	1	4	24
Area No. 8	8	3	22	18
Area No. 9	9	1	68	4

3.3. Wireless sensor network design

In deployment and development of the wireless monitoring network, the clustering of sensor nodes is decided according to the proximity, in the communication sense, of the wireless transceivers to each node. Thus the transmission range requirement of the local sensor nodes is greatly reduced, as they have to transmit only up to the local master node that is located within the cluster. Also, all wireless nodes (including sensor nodes, the local master node and the multi-hop node) operate on battery power. The cluster of sensor nodes communicating with the corresponding local master node forms the bottom tier of the whole network system, and the network of master nodes and the multi-hop nodes forms the top tier. The local master nodes receive the data from the corresponding sensor nodes and process the structural responding information, then route the monitoring results to the base station node over the top network, in room C.

In the top tier, a directed diffusion algorithm is used for transmitting the useful result data in the optimization path from the master nodes to the multi-hop nodes and base station. The interest property is defined to count the number of links with other nodes, added to the communication package. Figure 7

Table 5. The statistical data for the recognition accuracy of '*loading localization*'.

Patterns	Sample size	Recognition accuracy	Sample size for patterns Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Area 7	Area 8	Area 9
Area 1	50	100	50	0	0	0	0	0	0	0	0
Area 2	50	96	0	48	0	0	0	0	0	2	0
Area 3	50	80	0	0	40	0	5	0	5	0	0
Area 4	50	92	0	0	0	46	1	1	0	2	0
Area 5	50	84	0	3	0	2	42	0	0	3	0
Area 6	50	100	0	0	0	0	0	50	0	0	0
Area 7	50	90	0	2	0	2	0	0	45	1	0
Area 8	50	94	1	1	0	0	1	0	0	47	0
Area 9	50	100	0	0	0	0	0	0	0	0	50
Total recognition accuracy = 92.9%											

Table 6. The sensor output voltage peaks of 21 patterns when a different bolt is loose.

Mode	Sensor A (mV)	Sensor B (mV)	Sensor C (mV)	Sensor D (mV)
System normal	1248	262	131	112
Bolt No. 1 loose	1127	770	639	801
Bolt No. 2 loose	692	689	440	614
Bolt No. 3 loose	1202	265	559	546
Bolt No. 4 loose	1670	888	462	770
Bolt No. 5 loose	1056	916	449	492
Bolt No. 6 loose	856	326	970	1168
Bolt No. 7 loose	659	354	1626	208
Bolt No. 8 loose	1301	526	537	638
Bolt No. 9 loose	1186	384	644	1054
Bolt No. 10 loose	1063	182	610	588
Bolt No. 11 loose	1033	314	840	652
Bolt No. 12 loose	1111	590	183	304
Bolt No. 13 loose	956	516	912	876
Bolt No. 14 loose	1058	420	1538	1152
Bolt No. 15 loose	509	186	824	946
Bolt No. 16 loose	857	632	994	787
Bolt No. 17 loose	1318	1413	1283	987
Bolt No. 18 loose	572	372	722	819
Bolt No. 19 loose	466	428	809	1251
Bolt No. 20 loose	627	542	717	813

shows the definition of the communication packages for the routing algorithm. The first step of the routing is the interest broadcasting in the top tier of the network. Then through comparison of the interest property, some of the multi-hop nodes have been selected to form the optimization path for data delivery. Finally the optimization routing will be reinforced.

3.4. Experimental results

Table 3 presents the sensor output of 10 patterns when the 5 kg concentrated load is applied to different areas on the plate monitored by the *loading localization* cluster. In order to eliminate the influence from the sensor's temperature drift, the trained 10 difference patterns composed one input vector $\alpha(\alpha_{i1}, \alpha_{i2}, \alpha_{i3}, \alpha_{i4})\quad i \in [0, 9]$. Table 4 presents the trained 10 difference patterns in the *loading localization* cluster. For example, when the 5 kg weight was put in area No. 7, four measured sensor differences were 6, 1, 4 and 26 mV. The differences between the measured values and the trained values result from the environmental influences, such as temperature change. The four values composed another input vector $x(\theta_1, \theta_2, \theta_3, \theta_4) = x(6, 1, 4, 26)$. By the squared Euclidean distance formula, $A_i = \sum_{j=1}^{4} (\alpha_{ij} - \theta_j)^2$, $i \in [0, 9]$, A_7 is the minimum of the result vector $[A_0, A_1, \ldots, A_9]$. The experimental result implicated the centralized loading was in area No. 7. Table 5 presents the statistical data for the recognition accuracy of *loading localization*. The total recognition accuracy for *loading localization* achieved 92.9%.

Table 6 presents the sensor output voltage peaks of 21 patterns when a different bolt is monitored for loosening by the *bolt loosening monitoring* cluster. The differences between 21 sensor outputs and no bolt loosening output compose the standard difference vector $\alpha(\alpha_{i1}, \alpha_{i2}, \alpha_{i3}, \alpha_{i4})\quad i \in [0, 20]$, as one input to the Euclidean distance measure. For example, when the No.1 bolt was loose, four measured sensor differences were 119, 506, 507 and 688 mV. The four values composed another input vector $x(\theta_1, \theta_2, \theta_3, \theta_4) = x(119, 506, 507, 688)$. By the squared Euclidean distance formula, $A_i = \sum_{j=1}^{4} (\alpha_{ij} - \theta_j)^2$, $i \in [0, 20]$, A_1 is the minimum of the result vector $[A_0, A_1, \ldots, A_{20}]$. The experimental result implicated the No.1 bolt was loose. The total recognition accuracy for *bolt loosening monitoring* achieved 91.3%. After initialization of the network using the directed diffusion algorithm, the multi-hop nodes in room B were removed from the top tier, because the interest property value is the minimum. The routing mechanism and result of the algorithm are shown in figure 8.

Experiments show the developed two-tier network system can successfully monitor the position of the applied load and the position of the loose bolt. The advantage of the developed network system is to give guidance for developing a large-scale structural health monitoring system for composite engineering structures by adopting the embedding pattern matching method based on the wireless sensor network. Since the data transferred to the base station is reduced, the power consumed can be greatly saved.

4. Conclusions

Though the demonstration presented in this paper is successful, there are some important issues to be addressed further and more widely for future large-scale structural monitoring applications. Firstly, the computational power of the master nodes should be improved if more detailed and burdensome

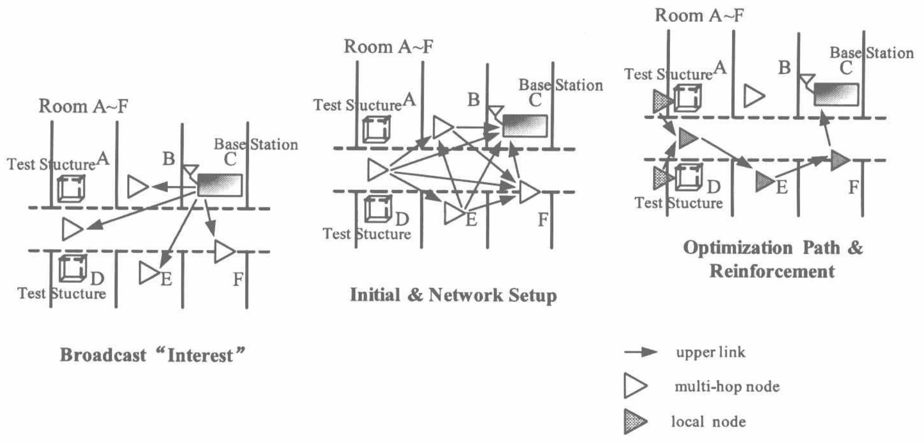

Figure 8. The routing mechanism of the algorithm.

tasks are waiting to be accomplished. Secondly, the sensor unit should have higher sampling rate and more sensor signal conditioners for extensive applications. Finally, with the increasing larger structural monitoring networks, some other problems, such as data fusion, time synchronization and energy efficiency will appear. Networking and routing protocols should be studied further for the solutions to these problems.

Acknowledgments

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esign and implementation of wireless sensor network node

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RACT: The wireless sensor networks are the hotspot research of current sensor technology.These net- ise small, low-power embedded devices for a wide range of applications and do not rely on any pre-existing ucture. In this paper, a novel design method is presented for building a new architecture for the wireless network node. The architecture is based on the premise that shared pools of resources should be used ossible to exploit the benefits of dynamic allocation, that buffering needs be used to decouple the gen- irpose data path and the radio, and that protocol flexibility is essential. Based on this design idea, the pment of a wireless sensor node has been completed. It consists of a microcontroller with internal flash m memory, data SRAM and data EEPROM, connected to a set of actuator and sensor devices, including , a low-power radio transceiver, a serial port, and a small coprocessor unit and an I/O connector that allows : of sensors to be attached. The software platform of the designed node is based on the TinyOS platform, is an operating system designed explicitly for the wireless sensor networks. Based on this platform, per- ince tests are conducted for the designed wireless sensor node, including power consumption, transmis- ange and data rate. The test results are satisfied, demonstrating that the presented design method can raise ficiency for wireless sensor network node design and implementation. Additionally, with external sensor l, the nodes have been used to deploy a wireless sensor network to SHM (Structure Health Monitoring) sys- . In our research, we develop it to implement the material's loading location.

INTRODUCTION

concept of wireless sensor networks (WSNs) is d on a simple equation: Sensing + CPU + io = Thousands of potential applications. The er of wireless sensor networks lies in the ability to oy large numbers of tiny nodes that assemble and igure themselves. Usage scenarios for these ces range from national defence and military affairs ner 2001), to behavior observation of animals inwaring et al. 2002), to monitoring of the health ructures and materials (NIST's SHIELD Project 2), to traffic controls (Shih 2001), to medical ment and sanitation (Noury 2000), to monitoring sasters (Bonnet 2000). Wireless sensor networks ot need supports of stationary networks, but moni- remote environments for low frequency data ls. The network could be incrementally extended mply adding more devices – no rework or com- configuration. Unlike traditional wired systems, oyment costs would be minimal. Instead of thou- s of feet of wire routed through protective con- the network just needs a small-sized node device ch sensing point.

Unlike traditional wireless devices, wireless sensor nodes do not need to communicate directly with the nearest high-power control tower or base station, but only with their local peers. Instead of relying on a pre-deployed infrastructure, each individual sensor or actuator becomes part of the overall infrastructure. Peer-to-peer networking protocols provide a mesh-like interconnect to shuttle data between the thousands of tiny embedded devices in a multi-hop fashion. The flexible mesh architectures envisioned dynamically adapt to support introduction of new nodes or expand to cover a larger geographic region. Additionally, the system can automatically adapt to compensate for node failures.

Initial research into wireless sensor networks was mainly motivated by military applications, with DARPA continuing to fund a number of prominent research projects (e.g., Smart Dust, NEST) that are commonly regarded as the cradle of sensor network research. National Science Foundation (NSF) established wireless sensor networks project in 2003, funded $34 million for basic research about WSNs. Then many academic institutions (e.g. University of California, MIT, Cornell University etc) started the research for the basic theory and key technology about WSNs. Other countries, such as Britain, Japan, Italy etc, also developed the research for WSNs and have some research outcome. However, today the research about WSNs in China just is in laboratory. Some Chinese academic institutions, such as Tsinghua University, Shenyang Institute of Automation Chinese Academy of Science and Hefei Institute of Intelligent Machines Chinese Academy of Sciences, have started on research for this line (Feng-yuan et al. 2003) (Zu-chang et al. 2004).

More recently, civilian application domains of wireless sensor networks have been considered, such as environmental and structural health monitoring, in Harbin Institute of Technology and Nanjing University of Aeronautics and Astronautics (Jinpin & Hui 2004) (Xiaosong & Shenfang 2004). At the same time, civilian applications were all based on the MOTE platform, and had no own wireless sensor networks node. In this paper, a novel design method is presented for building a new architecture for the wireless sensor network node, and performance tests are conducted for the designed wireless sensor node. Then with external sensor board, the nodes have been used to deploy a wireless sensor network to SHM (Structure Health Monitoring) systems. In our research, we develop it to implement the material's loading location.

2 WIRELESS SENSOR NODE ARCHITECTURE

2.1 *Key design requirements for wireless sensor nodes*

In the past, a number of early, mostly USbased research projects established a de facto definition of a wireless sensor network as a large-scale ad hoc, multihop, unpartitioned network of largely homogeneous, tiny, resource-constrained, mostly immobile sensor nodes that would be randomly deployed in the area of interest. Hence a wireless sensor network device must meet strict power consumption and size requirements. The key design requirements for wireless sensor networks nodes are cost, size, power, heterogeneity, and robustness.

2.1.1 *Cost, size, and power*

The physical size and cost of each individual sensor node has a significant and direct impact on the ease and cost of deployment. Total cost of ownership and initial deployment cost are two key factors that will drive the adoption of wireless sensor network technologies. In data collection networks, researchers will often be operating off of a fixed budget. Their primary goal will be to collect data from as many locations as possible without exceeding their fixed budget. A reduction in per-node cost will result in the ability to purchase more nodes, deploy a collection network with higher density, and collect more data.

Physical size also impacts the ease of network deployment. Smaller nodes can be placed in more locations and used in more scenarios. In the node tracking scenario, smaller, lower cost nodes will result in the ability to track more objects.

To meet the multi-year application requirements individual sensor nodes must be incredibly low power. Unlike cell phones, with average power consumption measured in hundreds of milliamps and multi-day lifetimes, the average power consumption of wireless sensor network nodes must be measured in micro amps. This ultra-low-power operation can only be achieved by combining both low-power hardware components and low duty-cycle operation techniques.

2.1.2 *Heterogeneity*

Early sensor network visions anticipated that sensor networks would typically consist of homogeneous devices that were mostly identical from a hardware and software point of view. However, each application scenario will demand a slightly different mix of lifetime, sample rate, response time and in-network processing. Additionally, for cost reasons each device will have only the hardware and software it actually needs for a given the application. The architecture must make it easy to assemble just the right set of software and hardware components. Thus, these devices require an unusual degree of hardware and software modularity while simultaneously maintaining efficiency. The degree of heterogeneity in a sensor network is an important factor since it affects the complexity of the software executed on the sensor nodes and also the management of the whole system.

2.1.3 *Robustness*

In order to support the network lifetime requirements demanded, each node must be constructed to be as robust as possible. In a typical deployment, hundreds of nodes will have to work in harmony for years. To achieve this, the system must be constructed so that it can tolerate and adapt to individual node failure. Additionally, each node must be designed to be as robust as possible.

System modularity is a powerful tool that can be used to develop a robust system. By dividing system functionality into isolated sub-pieces, each function can be fully tested in isolation prior to combining them into a complete application. To facilitate this, system components should be as independent as possible and have interfaces that are narrow, in order to prevent unexpected interactions.

In addition to increasing the system's robustness to node failure, a wireless sensor network must also be robust to external interference. As these networks will often coexist with other wireless systems, they need