Research on wireless sensor network system for structural damage monitoring

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Abstract. In recent years, the application of wireless sensor networks in the field of structural monitoring has been widely concerned by experts and scholars in various countries. The throughput and real-time performance of the wireless sensor network should be considered when the structure health monitoring wireless sensor network is deployed. According to the characteristics and requirements of wireless structure damage monitoring, this paper analyzes the system from three aspects: monitoring system process, node design and damage diagnosis algorithm.

1. Introduction
With the development of economy, there are many large-scale projects, such as large bridge, space flight. These projects are bulky, which occupy a wide area, and have a long service life. After a long time of use, some structures will be damaged. Through the wireless communication organization distributed nodes to monitor the target structure intensively, and transmit the sensing information to the end user for diagnosis and processing, the damage source and its extension can be displayed, and the health status of the structure can be judged from a long distance.

2. Wireless structural damage monitoring

2.1. system composition
Wireless sensor networks have a wide range of deployment, and are often used to collect samples from objects in a certain environment. Usually, they are designed according to the basic principles of distributed collection and terminal processing [1]. In this paper, the wireless structure damage system is divided into three layers: sensor monitoring layer, wireless network framework layer and data monitoring and diagnosis layer. Each layer contains sensor nodes, base station nodes and computer terminals. As shown in Figure 1.
The sensor monitoring layer is composed of a number of micro embedded sensor nodes for signal excitation, acquisition and transmission. The wireless network framework layer is composed of network topology and communication control protocol[2], and each node is organized according to its specified way, and the sensor node is directly controlled by the base station node in the area where it is located and obtains user instructions. The data monitoring and diagnosis layer is mainly composed of computer terminals. After the sensor nodes independently complete the collection and transmission of signals, the damage diagnosis algorithm will be used to analyze the data. This paper chooses the wireless communication technology based on ZigBee, which can meet the requirements of remote monitoring distance, large throughput, changes of network scale, synchronization of node time transmission and node robustness.

2.2. Wireless structure damage monitoring process
In general, the structural damage monitoring usually divides the structural parts into several sub regions, and arranges the sensor nodes in the monitoring area, and implements the wireless structure damage monitoring schematic diagram as shown in Figure 2.

3. Design and implementation of node
The sensor node used for structural damage monitoring mainly completes the active excitation of guided wave signal, the acquisition of damage response signal and wireless communication. According to different functions, it can be divided into excitation and acquisition module, FPGA data processing
module, cc2630 ZigBee wireless communication module and power supply module. Using Xilinx Spartan-3 FPGA as the core logic processor, it can realize multi task fast parallel processing, and provide hardware support for the real-time requirements of the system.

4. Wireless structure damage monitoring network

4.1. Network architecture

Wireless sensor networks adopt multi-channel hierarchical clustering topology. As shown in Figure 3.

![Network Architecture Diagram]

In the data acquisition layer, the data acquisition sub node collects the data, transmits it to the parent node of the base station, and transmits to the upper layer through the channel. In the monitoring network layer, the cluster head node composed of the parent node and the monitoring network composed of other child nodes. The cluster head node is responsible for collecting monitoring data and forwarding it up in the same channel. Finally, the monitoring data is transmitted to the computer through the serial port through the sink node.

4.2. Synchronous acquisition

Time synchronization plays an important role in structural damage monitoring of wireless sensor networks. In this paper, DMTS[3] algorithm is used to estimate the relative frequency deviation between nodes by broadcasting two synchronous messages containing clock information to the channel to correct the local time of wireless damage monitoring node.

The base station records the sending time $T_1$ and stores it in the synchronization message. When the wireless damage monitoring node receives the synchronous message, it records the receiving time $T_2$. Ten seconds later, the base station sends the message again. At this time, the sending time $T_3$ is recorded, and the node records the arrival time of synchronous message is $T_4$. The relative frequency deviation between the base station and the wireless damage monitoring node is estimated to be $\Delta$.

$$\Delta = \frac{T_3 - T_1}{T_4 - T_2}$$  \hspace{1cm} (1)

At time of $T_5$, the node calls the local time as

$$T_5 + \Delta(nt + (T_5 - T_4))$$  \hspace{1cm} (2)
5. Damage diagnosis method

In wireless structural health monitoring system, it is usually necessary to process the damage information. The common methods are ellipse positioning, four point circular arc positioning, four point hyperbola method and probability based imaging positioning method[4]. In this paper, the damage location method and damage imaging technology are used to complete the damage diagnosis.

As shown in Figure 4, the nodes are arranged in two elements. \( R_{ij} \) represents the distance between the damage and the monitoring node.

![Figure 4. Schematic diagram of imaging algorithm.](image)  

As shown in the figure above, it is assumed that the approximate coordinate point is \((x_n, y_n)\). The monitoring structure can be divided into \(N \times N\) unit areas. Each cell corresponds to a micro pixel, and \(f_v\) represents the resolution of the image. The virtual path distance on any unit area is

\[
R_{ij} = \sqrt{(i \cdot f_v - x_n)^2 + (j \cdot f_v - y_n)^2}
\]

(3)

We can set the velocity of guided wave to \(v\). The time interval between the reflected signal and the sensor node is

\[
T_{ij} = \frac{R_{ij}}{v}
\]

(4)

The time from the beginning of excitation to receiving the reflected signal is \(2T_{ij}\). On the node monitoring path, the extracted envelope amplitude points are used to assign values to the pixel matrix points in the pixel matrix. The assignment parameters of each unit area can be obtained as follows:

\[
A_{ij} = \sum_{n=1}^{N} a_n f_n \left( \frac{2R_{in}}{v} + t_{in} \right)
\]

(5)

Among them, \(N\) is the number of node monitoring, \(f_n(t)\) is the envelope function of the damage reflection signal collected by the nth node after preprocessing, \(t_{in}\) is the initial excitation time of the nth node, \(a_n\) is the normalized scattering coefficient.

It is assumed that the number of working wheels of sensor node is \(n\). Finally, the focus matrix of the damage can be obtained by scanning \(n\) times. Focus matrix of damage is
\[ A_{n \times N}^n = \sum_{i=1}^{n} A_{n \times N}^i \]  

The systematic errors in the joints are often random, and the results of single round diagnosis cannot accurately show the specific location of structural damage. Multiple scanning eliminates the influence of randomness, which increases the accuracy of damage identification. The overall flow of the algorithm is shown in Figure 5.

6. Experiment

In the test, 500 mm x 500 mm aluminum sheet was used for structural damage diagnosis test. There is damage in the specimen. In order to monitor the damage better, through the previous experimental experience, the sensor nodes are arranged around the damage.

As shown in Figure 6, the specific location coordinate of perforation damage is (220,200). The PZT piezoelectric plates were pasted on four different positions of the structure and marked as 1, 2, 3 and 4. The specific locations of sensor nodes are shown in Table 1.

| number        | excitation coordinates | receiving coordinates |
|---------------|------------------------|-----------------------|
| first node    | 1(120,50)              | 11(120,55)            |
| Second node   | 2(420,50)              | 22(420,55)            |
| Third node    | 3(420,350)             | 33(420,355)           |
| Fourth node   | 4(120,350)             | 44(120,355)           |
In the experiment, the nodes start four rounds of collaborative scanning. Each round of scanning will use the standard excitation signal with peak value of 2V and frequency of 200kHz. The sampling frequency of each round of nodes is 2Msps. Finally, through wireless transmission, the signal is uploaded to the computer terminal for storage. The method of fusion imaging is used to stack the pixel matrix detected by four rounds. Although the interference in each path is random, it will not have a significant impact on the focus of damage location. Therefore, the aluminum plate is divided into 1 mm × 1 mm micro element area by algorithm. After MATLAB software processing, the focus imaging effect picture with damage can be obtained, as shown in Figure 7.

![Figure 7. Imaging results.](image)

It can be seen from Figure 7, there is a very obvious focusing position informed after the fusion imaging algorithm processing, and the damage obtained by focusing is marked by yellow. After comparing with the actual structure, it is found that there are still several suspected damages caused by random errors or interference in the diagnosis result image. These locations are more obvious than the surrounding blue undamaged part, but obviously lighter than the yellow marking position after focusing, indicating the requirements of symbol monitoring.

7. Conclusion
Wireless structural damage monitoring technology uses distributed nodes to replace the traditional centralized system, wireless communication replaces multi-channel cable transmission, so that the overall monitoring area of the structure is discretized into multiple local areas. Through the cooperation between nodes and imaging algorithm, it can achieve a larger monitoring range.

Acknowledgments
The Projects is supported by National Natural Science Foundation of China (Grant No.51105209) and Aviation Science Foundation (Grant No.20161959001).

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