Research Article

Design of a Wireless Multi-Radio-Frequency Channels Inspection System for Bridges

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This paper presents a wireless multi-radio-frequency channels inspection system (WMCIS) based on wireless sensor networks (WSN) for the sake of bridge structural vibration inspection. The designed system consists of a wireless controller and eight wireless nodes with acceleration sensing units. The whole system has 64 collection channels, so every wireless node has eight 24-bit A/D channels. Integrated with acceleration sensing units, an embedded low-power microprocessing unit, a wireless transceiver unit, a large-capacity power unit, and a GPS time synchronization unit, the wireless node has the functions such as data collection, initial analysis, data storage, and wireless data transmission. The wireless controller, equipped with a high-performance computation unit, a wireless transceiver unit, a mobile power source, and an embedded data analysis software, can totally control multiple wireless nodes and receive and analyze data for parameter identification. To verify the performance of the WMCIS, experiments are made on the Caihong Bridge and Jinzhou Bridge in China for inspecting the bridge structural vibration. Experimental results show that the system has the advantages such as fast arrangement, high sampling rate, high resolution, capacity of low-frequency inspection, and GPS clock project for time synchronization and, thus, has good application prospects and practical value.

1. Introduction

With continuous development of the bridge-building technology, the bridge structure has become more and more complex and more attention has been paid to the quality and life of a modern bridge. After long-term use, the bridge structure will inevitably be damaged. It is necessary to inspect and monitor the bridge structure for the safety of a bridge. How to conduct a quality and safety test to the bridge structure has become a hot spot in domestic and international engineering field [1]. Bridge structural damage in the course of use can be found for many reasons, mainly, the improper design and maintenance, car accidents, man-made accidents, environmental factors, and so on. No matter ancient or modern, there are various examples of bridge collapse, causing great losses and huge disaster. Due to the design flaws which led to the actual carrying capacity of the bridge being much lower than the designed carrying capacity, the Quebec Bridge collapsed for the second time on September 11, 1916. Its first collapse was in 1907, resulting in the death of 95 people (Figure 1). At 7:00 on Nov. 7, 1940, Tacoma Narrows Bridge burst into sudden fluctuations and continued for more than three hours. Around 10:30 the bridge began to fracture into multiple pieces, at 11:00 the bridge collapsed. The main factor leading to the falling is the “stall flutter” phenomenon in aerodynamics which causes the sympathetic vibration of the structure. Although the crash of the bridge did not result in heavy casualties, it caused enormous economic loss of the country.

In recent years, China also has several examples of the bridge collapse, for example, the collapse of the Caihong Bridge and the Gaoping Bridge (Figure 2). Caihong Bridge in Chong Qing collapsed on January 4, 1999. One of the reasons resulted in the sudden collapse of the bridge is the poor engineering quality. The compressive strength of the concrete in steel tube was below the design standard by one-third
because of serious flaws. On August 27, 2000, Gaoping Bridge which is the important channel to connect Kaohsiung and Pingtung in Taiwan province suddenly broke down, causing traffic disruption and 16 vehicles falling into the river and 22 people injured. There was no information about whether lesions occurred in the body of the bridge or whether the aging structure was damaged before the tragedy happened. Many examples show that the health of the bridge must attract more attention.

Because of the occurrence of many accidents in recent years, many countries have paid more attention to the safety inspection of bridge structure, like the Faroe Bridge in Denmark, Tampico Bridge in Mexico, and Skamsundet Bridge in Norway. A lot of tests have been done on the bridge to collect the displacement, strain, acceleration, and other physical parameters and environmental factors of the whole structure and components. In China, for example, the Hong Kong Tsing Ma Bridge, Guangzhou Humen Bridge, Shanghai Xupu Bridge, Jiangyin Yangtze River Bridge, Nanjing Yangtze River Bridge, and Hunan Aizai Bridge, relevant monitoring equipment were installed during the construction period to conduct real-time inspection to the structure in operation. This work is done to ensure safe operation and extend the service life of the bridge and also to save maintenance costs and improve the effectiveness of the integrated use of the bridge through early inspection and monitoring [2–5]. Since new bridges are needed in many places and the functions of the bridges become versatile, it is further requested that the inspection system has the characteristics of quick installing and convenient detecting for ensuring safety.

One important element for inspection system is the transmission of the measurement data from the sensors to the processing terminal; conventionally, and most popularly, wired networks are used for this task. However, with a great number of sensors for a large structure, a huge amount of wires is needed. As a result, installation time and costs can be very high, and this may also affect the reliability of the data transmission. Moreover, there may be cases in which wires cannot be placed in certain locations of a structure. Fortunately, with the development of technologies in sensing, wireless communication, and microelectromechanical systems, wireless sensor network (WSN) technique has been developed rapidly and is being used gradually in structural health monitoring for civil engineering structures in an attempt to install quickly and inspect conveniently and lower the high capital costs associated with wire-based structural monitoring systems [6–10]. There exists a limit of power consumption for WSN working in some circumstances where there are no conditions of supplying power continually, so energy optimization is a basic problem for wireless sensor network [11]. For a wireless sensor, energy is usually provided by solar power [12], wind energy, structural vibration [13], chemical batteries, or lithium batteries. But the above energy methods cannot meet the requirement of long-term monitoring, so the WSN may be more suitable for rapid testing in short term. Otherwise, time synchronization of WSN is very important for further data analysis.

Based on the above information a system is developed for quickly inspecting the bridge in real-time and wireless way, the proposed wireless node may connected with not only the traditional high-resolution sensing units but also the MEMS chips with low resolution aroused by its machining technique. The paper includes system overview, hardware development, software design and on-site verification tests.

2. System Architecture

The system architecture of WMCIS is shown in Figure 3. The designed system consists of one wireless controller and eight wireless nodes. The whole system has 64 collection channels, that is, every wireless node has eight 24-bit A/D channels. Every wireless node have an individual data sensing frequency
channel and a common control frequency channel at 2.4 GHz wireless frequency band, so the wireless controller has nine frequency channels. Data is transmitted from wireless node to wireless controller at every data sensing channel; information orders of the wireless controller are sent to every wireless node by the same and stable frequency band.

3. Design of Wireless Node

Studies show that it is possible to get safety assessment of the bridge based on the modal information by making global dynamic inspection. Structural global inspection technology of bridges can overcome the limitations of local inspection. The global inspection technology can verify design assumptions, monitor construction quality, and make real-time safety status assessment; especially, it can work without external auxiliary excitation based on dynamic inspection. So the global inspection technology has great advantages. In this design, acceleration is selected as the global parameters, the structure of wireless node is shown in Figure 4. The wireless node which is modular designed consists of acceleration sensing units, a sensor interface unit, a microprocessing unit, wireless units, a storage unit and a power management unit [14].

3.1. Selection and Analysis of Sensing Unit. In the designed system, force-balance sensor is used for the low-frequency vibration sensing unit because bridges usually belong to low-frequency vibration structures. Force-balance acceleration sensor is a closed-loop one which converts data to force or moment of force firstly, then adjusts the balance system with feedback force. Force-balance acceleration sensor with huge dynamic range and high measurement precision is used in low-frequency and low-g measurement and is the crucial unit in inertial navigation system. With the good performance in ultralow frequency, force-balance acceleration sensor can meet the needs of low frequency vibration inspection. Also, the ICP sensing units, integrated with traditional piezoelectric acceleration sensor and charge amplifier, are considered to complete the acceleration measurement.

3.2. Sensor Interface. Wireless nodes support the acceleration sensing unit which needs ±12 V power supply, and outputs ±2.5 V or ±5 V analog voltage signal. In this design, multi-way switch chip MAX4051 is used to process 8 channels’ selection firstly, and then 24-bit high accurate ADC chip ADS1248 is selected to convert from analog signal to digital signal.

3.3. Microprocessor and Storage Unit. TI high performance 16bit MSP430F5438 is used for microprocessor. The series microprocessor has the lowest operating power consumption. The performance is up to 25 MIPS at 1.8 V–3.6 V operating voltage range and can meet the design needs of
wireless sensor in low power consumption and high rapid data processing. Storage unit uses NAND large capacity flash memory.

3.4. Wireless Units. Wireless units include wireless transceiver and GPS module.

Wireless transceiver unit for data wireless transmission consists of such Zigbee wireless chip as CC2520 RF chip and enlarge front CC2591. CC2520 RF chip is 2.4 GHz license-free ISM band Zigbee/IEEE 802.15.4 second generation RF transceiver of TI Company. CC2591 is 2.4 GHz RF front end unit for low power consumption and low voltage wireless application, can improve the transmission power and receiving sensitivity, and increases the wireless signal strength and transmission distance.

The GPS module is mainly designed to achieve the precise time synchronization for the wireless sensor nodes. Lassen IQ module uses the trimble’s breakthrough First-GPS technology. It can output reliable information about position, velocity, time (PVT) to the user in low power. Lassen IQ module uses three common standard protocols, but its volume is only equivalent to the size of the stamps. The adopted protocol is TSIP, TAIP (trimble standard interface protocol), and the NMEA0183. The module is placed inside a metal enclosure which plays the role of protection and shielding.

3.5. Power Management Unit. In the system, 24 V battery is selected as wireless node’s power source for rapid measurement and continued power supply. Because each unit in the system needs different power supply, such as ±15 V ±12 V, +3.3 V, and analog circuits require a higher voltage ripple, so energy design has two-stage transformation structure. The first stage uses DC/DC chips for the transformation from +24 V to ±15 V and +3.3 V. The second stage uses LDO chips 7812 and 7912 for the transformation from ±15 V to ±12 V.

The wireless node, shown in Figure 5, is integrated using the above units.

4. Integration of Wireless Controller

The main functions of wireless controller designed by module include the management of the wireless nodes, data collection, data storage, and data analysis. The wireless controller, shown in Figure 6, comprises computer units (PC), wireless modular (data channel, control channel), and serial server based on PCI bus. A detailed description about these modules is presented as follows.

4.1. Computer Unit. Computer unit is the center of wireless controller. In order to control the wireless nodes and analyze and process the measurement data, the intelligent controlling software is transplanted into computer units.

4.2. Serial Server. The serial server is a media used to connect computers with wireless modules. It is connected to a wireless module via serial port and connects to the PC through the PCI bus. The role of the serial server is to transmit the data received by the serial port to the PC through the PCI. The serial server used in this system is MOXA-C218 with cache settings function. And its serial cache can be set to overcome the problem of insufficient cache according to actual needs.

4.3. Wireless Modules. The wireless units are divided into eight receiving modules and a transmitting one, namely eight data channels and one control channel. The transmitting module (control channel) controlled by the embedded software on the PC is used to send commands to the WSNs nodes which can decide whether to sample data. The eight receiving modules (data channel) are used to receive the sampled data sent by the corresponding WSNs node.
respectively and to transmit it to the PC through the serial server.

The wireless module’s band should be matched with the wireless sensors’ band to realize two functions.

1. The embedded software of computer units sends the control orders to wireless vibration sensor nodes in order to control their behaviors.
2. Receiving the vibration data collected by wireless vibration sensor nodes and sends them to computer unit through serial server.

The integrated wireless terminal controller is shown in Figure 7.

5. Software Design

The software of wireless acquisition system consists of two parts: embedded program of wireless node and the wireless controller software.

5.1. Embedded Program of Wireless Node. The embedded program, integrated with ADC driver, storage driver, wireless driver, preliminary data analysis and diagnosis, and so on, can control circuits and receive command from the host for parameters setting, data acquisition, processing, storage, and transmission. Every wireless node’s workflow is as follows: the wireless node, powered up in the wireless receiving state, does not work until receiving the command from host. Among acquisition, host firstly finishes the parameters setting to all wireless nodes, then sends start or stop command to control data acquisition. The wireless nodes can collect the vibration data of the offshore platform for inspection.

5.2. Host Acquisition Software of Wireless Controller. The host acquisition software mainly completes the parameter setting of the wireless node, data collection, data export, data storage, and data analysis and process. The software consists of the basic setting, real-time waveform monitoring, history waveform playback, data export, help document, and other modules. The acquisition software’s modules are shown in Figure 8.

| Wireless node 1 | Channel 1 | Channel 2 | Channel 3 |
|-----------------|-----------|-----------|-----------|
| Sensor type     | ICP       | Servo     | ICP       |
|                 |           |           |           |
| Wireless node 2 | Channel 1 | Channel 2 | Channel 3 |
| Sensor type     | ICP       | ICP       | ICP       |

Table 1: Wireless nodes and sensor type.

Basic setting is used to set the state of wireless nodes, wireless transmission channels, sampling frequency, file storage path, and other parameters on demands. Real-time waveform monitoring can display the collected data’s real-time waveform and write the data in database. History waveform playback may show a playback of history waveform based on the data collected. Data export can export the data collected from a specific wireless node at certain channel and time to a certain file for further analysis and process. Help document provides some help information for the users who use this acquisition software.

6. Experiments

6.1. Natural Vibration Measurement on Caihong Bridge Using WMCIS. Caihong Bridge is a suspension bridge with the length of about 25 meters and located in the West Campus of Dalian University of Technology. In order to detect the vibration of the structure of the Caihong Bridge, the acceleration sensing units were placed on each suspension on one side of the bridge. Three acceleration sensing units were used to communicate and exchange data with wireless controller. While the bridge is closed to traffic, a rapid detection of the natural vibration of the bridge is carried out.

In the detection system, two wireless nodes, a wireless controller and six acceleration sensing units are used. The acceleration sensing units consist of a force balance sensing unit (servo) and five ICP sensing units. The sensing units configuration project as shown in Table 1. The system is laid close to the bottom location of the suspension, and the layout scheme was shown in Figure 9.

The sensing units are used to measure the acceleration of the vertical direction of the bridge, then the sampled data of the wireless nodes are sent to the wireless controller via wireless transmission for the user to observe and analyze (see Figure 10). In addition, a test about the wireless communication distance of the system is conducted in the west campus. In the case of no obstacles the communication distance of wireless nodes can reach 400 meters.

The typical vibration frequency spectrum is shown in Figure 11, by the analysis of the sampled data, the natural frequency of the bridge is about 3.964 Hz–3.986 Hz. The test result is very close to the theoretical values (4 Hz). All these show that the WMCIS can measure well the natural vibration of the bridge.

6.2. Vibration Test on Jinzhou Bridge Using WMCIS. Large bridge structure is an important part of the transport system which plays an important role in maintaining the sustained and stable economic development. Due to environmental
degradation, materials aging, and long-term effects of load and other factors together, the structural capability in resisting to natural disaster, or even normal environmental effects will inevitably decline. Therefore, the bridge structural health monitoring has practical significance and potential applications.

The monitoring object is the West Bridge (shown in Figure 12) in Jinzhou City, Liaoning province. The bridge was built in 1939 and completed in 1941. With the economic development and traffic volume demand, it was expanded in 2003. The total length is 1033.5 m, of which the main bridge is 501.9 meters long, 14 meters wide, and 7026.6 square meters area.

Cross-bridge vibration is possibly characterized by low frequency and large signal dynamic range. So the requirement to the sensing unit for inspecting the bridge’s vibration is relatively high. The wireless monitoring test selects a servo (force balance) acceleration sensing unit, five piezoelectric (ICP type) acceleration sensing units. The sensing units’ models and sensitivities used by the program are shown in Table 2.
According to the requirements of the on-site test, the cross-sections 1, 20, and 22 are chosen as a sample, respectively, to carry out experiments on the inspection of bridge vibration. The layout scheme of the 1st cross-section is shown in Figure 13.

The bridge span length is about 21 m, of which 5 sensing units were placed at equal interval location. And the sensing units layout of the other cross-section is the same as one of the first cross-section.

The test was carried out in the midnight on October 4, 2011 (see Figure 14). The inspection experiments included the natural vibration test and driving incentive vibration test. Typical experimental results are shown in Figures 15 and 16, and the corresponding vibration frequency of the bridge is shown in Table 3.

The above analysis and comparison show that (1) the bridge is a low-frequency vibration structure; (2) the bridge has a large dynamic range of vibration signal. While vehicles and other heavy objects are moving on the bridge, the vibration range becomes significantly larger.

### Table 2: Type and sensitivity of sensing units.

| Sensor | ICP | ICP | ICP | ICP | Servo |
|--------|-----|-----|-----|-----|-------|
| Model  | sno776 | snr168 | sno775 | snr165 | 2188 |
| Sensitivity (mv/g) | 2003 | 2017 | 2010 | 2016 | 2635 |

### Table 3: Vibration frequency.

| Cross-section 1 | Cross-section 20 | Cross-section 22 |
|-----------------|-----------------|-----------------|
| Natural frequency (Hz) | 5.865 | 5.848 | 5.895 |
| Incentive frequency (Hz) | 2.871 | 2.878 | 2.869 |

### Table 4: WMCIS’ performances.

| Specifications            | Details |
|---------------------------|---------|
| Wireless frequency band   | 2.4 GHz |
| Wireless distance         | 400 m   |
| Sensitivity               | 0.06 mg |
| Power (DC)                | 12–24 V |
| Wireless transmission     | 100 Kbps|
| Sample channels           | 64      |
| Measurement range         | ±2 g    |
| Frequency response        | DC-120 Hz|
| Working                   | −20°C to +70°C |
| A/D bits                  | 24 bits |

7. Conclusions

In this paper, based on the current energy methods of WSN not suitable for long-term monitoring, the WMCIS is proposed for rapid testing in short term. The WMCIS including wireless nodes, wireless controller and responding
The West Bridge of Jinzhou

![Experimental layout program.](image)

**Figure 13: Experimental layout program.**

![On-site layout program.](image)

**Figure 14: On-site layout program.**

![Time spectrum](image)

![Frequency spectrum](image)

(a) Time history  
(b) Frequency

**Figure 15: Experimental results of natural vibration of cross-section 20.**
software is designed for fast inspection of bridge structure’s global characteristics. The WMCIS’ performances are shown in Table 4. The experimental results show that the designed WMCIS with high reliability, no wiring, low-frequency vibration inspection, and GPS clock project for time synchronization is suitable for vibration inspection of bridges and has broad application prospects.

The design is preliminary and more tests need to be carried out before it can be of practical use.

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References

[1] O. U. Jinping, “Development present review on intelligent perception materials sensor and health monitoring system in civil engineering structure,” Functional Materials Information, vol. 2, no. 5, pp. 2–22, 2005.
[2] G. W. Housner, L. A. Bergman, T. K. Caughey et al., “Structural control: past, present, and future,” Journal of Engineering Mechanics, vol. 123, no. 9, pp. 897–971, 1997.
[3] J. P. Ou and X. C. Guan, “State-of-the-art of smart structural systems in civil engineering,” Journal of Earthquake Engineering and Engineering Vibration, vol. 19, no. 2, pp. 21–28, 1999.
[4] B. F. Spencer Jr. and S. Nagarajaiah, “State of the art of structural control,” Journal of Structural Engineering, vol. 129, no. 7, pp. 845–856, 2003.
[5] H. N. Li, D. W. Gao, and T. H. Yi, “Civil structural health system status and progress,” Mechanics, vol. 38, no. 2, pp. 151–166, 2008.
[6] B. F. Spencer Jr., “Opportunities and challenges for smart sensing technology,” in Proceedings of the 1st International Conference on Structural Health Monitoring and Intelligent Infrastructure, pp. 65–71, Tokyo, Japan, 2003.
[7] J. P. Ou and H. W. Li, “Wireless sensors information fusion for structural health monitoring,” in Multisensor, Multisource Information Fusion: Architectures, Algorithms, and Applications 2003, vol. 5099 of Proceedings of SPIE, pp. 356–362, Orlando, Fla, USA, April 2003.
[8] Y. Yu, J. Ou, and H. Li, “Design, calibration and application of wireless sensors for structural global and local monitoring of civil infrastructures,” Smart Structures and Systems, vol. 6, no. 5–6, pp. 641–659, 2010.
[9] S. D. Glaser, M. Li, M. L. Wang, J. Ou, and J. Lynch, “Sensor technology innovation for the advancement of structural health monitoring: a strategic program of US-China research for the next decade,” Smart Structures and Systems, vol. 3, no. 2, pp. 221–244, 2007.
[10] S. Jang, H. Jo, S. Cho et al., “Structural health monitoring of a cable-stayed bridge using smart sensor technology: deployment and evaluation,” Smart Structures and Systems, vol. 6, no. 5–6, pp. 439–459, 2010.
[11] C. Erin and H. H. Asada, “Energy optimal codes for wireless communications,” in Proceedings of the 38th IEEE Conference on Decision and Control (CDC ’99), pp. 4446–4453, December 1999.
[12] M. Kohvakka, M. Hannikainen, and T. D. Hamalainen, “Wireless sensor prototype platform,” in Proceedings of the 29th Annual Conference of the IEEE Industrial Electronics Society, pp. 1499–1504, November 2003.
[13] S. Meninger, J. O. Mur-Miranda, R. Amirtharajah, A. P. Chandrakasan, and J. H. Lang, “Vibration-to-electric energy conversion,” IEEE Transactions on Very Large Scale Integration (VLSI) Systems, vol. 9, no. 1, pp. 64–76, 2001.
[14] Y. Yu, J. Ou, J. Zhang, C. Zhang, and L. Li, “Development of wireless MEMS inclination sensor system for swing monitoring of large-scale hook structures,” IEEE Transactions on Industrial Electronics, vol. 56, no. 4, pp. 1072–1078, 2009.
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