Design and Implementation of Wireless Identification and Sensing Platform in Structure Monitoring

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Abstract. In the process of structure monitoring, active wireless sensor devices are often used. In order to replace the energy limitation bottleneck of the power supply unit, the Wireless Identification and Sensing Platform (WISP) with real-time data transmission function is adopted to realize the collection of structural vibration acceleration data. Firstly, the various functional modules of the WISP with three-axis acceleration are introduced. Then, through software programming of the low-power MSPF430F2132 microprocessor on it, the drive and control of the external three-axis acceleration sensor ADXL330 is realized. Finally, it was tested through comparative experiments. The research results show that the acceleration data monitored by the WISP is accurate, effective and reliable. Compared with the active wireless Narada unit, the similarity is more than 83%. Compared with the OpenSEES system, the accuracy of the structure frequency monitored by the WISP is 99.07%. Therefore, it is feasible and reliable to use the WISPs to perform multi-point deployment control in structural dynamic monitoring.

1. Introduction

The service life of large-scale engineering structures such as large-span bridges and high-rise buildings is as long as decades or even hundreds of years. In order to make them operate safely, Structural Health Monitoring (SHM) should be performed regularly to repair the damaged parts of the structure. With the rapid development of wireless communication and sensing technology, wireless intelligent sensor network has been widely used in structural health monitoring[1]. Wireless sensor network node is composed of sensor unit, processing unit, communication unit and power unit. Power unit of which provides energy for each unit and decides the lifetime of the whole network. However, the power supply energy is limited. Due to the limited conditions, it is difficult to replace the battery for the node during use, which makes the energy limitation a bottleneck in the design of the entire wireless sensor network. In addition, with the miniaturization of sensor nodes, their computing and storage capabilities are relatively low, which poses a challenge for the development of wireless sensor networks.
For these reasons, this paper presents a Wireless Identification and Sensing Platform (WISP) for structural vibration monitoring. The WISP receives the Radio Frequency (RF) electromagnetic field emitted by the Radio Frequency Identification reader (RFID reader), converts it into power energy, drives and controls the operation of the components on the platform through the microprocessor on the platform, then collect the required data, and finally transmit the collected data back to the computer in real time through the RFID reader.

2. Function realization

2.1. Hardware design
The function module of the WISP is shown in Figure 1. After receiving the RF signal, the antenna first passes through the impedance matching, which can avoid the reflection of the signal, and then propagates along both paths, one of which is used to provide the required energy for the sensor platform, and the other is used for data transmission. The first part of the signal is transmitted to the voltage regulator and voltage controller via an energy storage circuit consisting of a capacitor and a rectifier, wherein the voltage regulator is used to prevent voltage overloads on the microprocessor, the voltage controller is used to monitor the capacity of the capacitor. After the voltage reaches the rated voltage required by the microprocessor MSPF430F2132, the microprocessor starts to run. The latter part of the signal demodulates the RF signal and transmits it to the microprocessor, so that the transmission information of the RFID reader can be interpreted. The microprocessor runs the software program on the compiler, and drives and controls the operation of the three-axis acceleration sensor ADXL330 through the built-in ADC10 with a precision of 10 bits. The microprocessor MSPF430F2132 transfers the data collected by the acceleration sensor through the modulation of the modulator, and transmits it back to the RFID reader via the antenna, and then transmits the data to the computer after the interpretation of the RFID reader.

![Figure 1. WISP functional module](image)

2.2. Realization of power supply energy
The WISP obtains energy and realizes data communication through Ultra-High Frequency Radio Frequency Identification reader (UHF RFID reader). RFID enables to identify specific targets and read and write related data through radio signals, without the need to establish mechanical or optical contact between the identification system and specific targets. The system adopts backscatter coupling to realize the communication between it and UHF radio frequency identification reader. The system encodes the collected dynamic data into the Electronic Product Code (EPC) in real time through the programmable ultra-low power microprocessor, and the required data can be obtained by decoding the EPC.

In this article, the Speedway UHF RFID reader produced by Impinj in the United States is used, and the EPCglobal Low Level Reader Protocol (LLRP) is adopted to realize the communication between it and the system. The working frequency range of Speedway UHF RFID reader is 865MHz-
956MHz. The connection diagram of RFID reader is shown in Figure 2. Using the RF electromagnetic field emitted by the antenna of Impinj reader, the radio power supply is constructed to supply the energy of the system and realize the data communication between it and the reader. Since the WISP is powered exclusively by the RF electromagnetic field emitted by the reader antenna, its distance from the reader antenna must not exceed 4.5 m[2].

![Figure 2. The connection diagram of RFID reader](image)

After the connection of the UHF RFID reader is completed, its parameters need to be set accordingly, the hyper terminal is used to obtain the IP address on the reader, and then the reader parameter settings are realized through this address. The reader parameter setting dialog box is shown in Figure 3. Figure 3(a) is the setting window of the reader. The working mode of the reader is set as: dense reader M=4; since the reader antenna is connected to the reader’s antenna port 1, the antenna channel used needs to be checked. Figure 3(b) is the interface of successfully obtaining the system label after the setting is successful.

![Figure 3. RFID reader parameter setting](image)

2.3. Software implementation
The WISP uses the MSPF430F2132 low-power microprocessor produced by TI in the United States as the control center of the entire platform. MSPF430F2132 is an ultra-low-power 16-bit simplified instruction structure microprocessor, with 5 low-power modes and 1 active mode. When no event occurs, the MSPF430F2132 enters a low-power mode. When an event occurs, the CPU is awakened by an interrupt. After the event is processed, the CPU enters a low-power state again. Since the CPU spends most of the time in low power consumption mode, the power consumption is greatly reduced. In this paper, the embedded platform IAR is used to realize the software programming of MSPF430F2132, and the three-axis ADXL330 is used to realize the data acquisition of the acceleration sensor. The x, y, and z channels of the ADXL330 are connected to the P2.0, P2.1, and P2.2 pins of the MSPF430F2132, respectively, and the power channel of the ADXL330 is connected to the P1.5 pin of the MSPF430F2132. The control flow of MSPF430F2132 on acceleration data acquisition is shown in Figure 4 below.
MSPF430F2132 is in the power-saving mode of LPM1, after realizing the setting of the corresponding registers such as sampling time and reference voltage of ADC10, MSPF430F2132 enters the power-saving mode of LPM4. When the capacitor is stored to the rated voltage of Adxl330, it drives ADXL330 through ADC10 to collect data. The collected analog voltage data is converted into digital data by ADC10 and stored in the 16-bit register of ADC10 on the lower 10 bits, and enter the interrupt program, and wake up MSPF430F2132, make it exit from the power-saving mode of LPM4, after the interrupt function runs, MSPF430F2132 continues in LPM1 power-down mode. If the collected data is reasonable, store the data in RAM, otherwise, discard the data collected this time and store the data collected last time in RAM.

3. Comparative experiment and result analysis

3.1. Experiment program
Figure 5 shows a schematic diagram of a 5-layer steel frame structure placed on a vibrating table. The total height of the steel frame is 125.92cm. The length of each layer of steel plate is 40.9575cm. The width of each layer of steel plate is 30.7975cm. The distance between each layer of steel plate is 30.48cm.

![Flow chart of MSPF430F2132's acceleration data collection](image)

![Schematic diagram of steel frame structure and vibrating table](image)
In the experiment, the WISP and the active wireless Narada unit were first placed on the second layer of the steel frame structure, and the accelerator applied external force to the steel frame structure. Under the action of the spring, the steel frame structure will reciprocate left and right. The WISP and the active wireless Narada unit are used to dynamically monitor the steel frame structure, and the acceleration data obtained by the WISP are compared with that obtained by the active wireless Narada unit, then, the accuracy and rationality of the data obtained by the WISP is proved. Then three WISPs were placed on the second, third and fourth floors of the five-story steel frame structure, and acceleration data were acquired at the same time. Comparing the calculated structure frequency with the structure frequency obtained by OpenSEEs simulation, it is further proved that the energy supply and data communication of multiple WISPs can be realized through a single reader antenna and reader, and the data obtained is accurate and reliable.

The active wireless Narada was developed by Swartz and Lynch of the University of Michigan[3]. Narada is connected to a single-axis Silicon Designs 2012-002 acceleration sensor (size: 25mm×25mm) to realize data collection[4]. In this paper, Narada and its acceleration sensor are named as active wireless Narada unit. The validity and rationality of the acquired data are verified[5–6].

Figure 6 is a visualization software written using Visual C# software, used for real-time display and storage of the EPC code acquired by the WISP.

![Figure 6. Visualization software](image)

The output of ADC10 is stored in the EPC, and the acceleration information can be obtained by decoding the EPC. The result of ADC10 is given by the following formula:

$$N_{ADC} = \frac{1023V_{out}}{V_{CC}}$$

(1)

Wherein, $V_{CC}=1.8V$ is the voltage supplied to ADC10 by the wireless power supply; $V_{OUT}$ is the analog voltage information collected by ADXL330; 1023 is the largest binary number that the 10-bit ADC10 can express.

3.2. Experimental comparison between a single WISP and a single active wireless Narada unit

Set the sampling frequency of the WISP and the active wireless Narada unit to 50 Hz and the sampling time to 25 seconds. The clock source of the MSPF430F2132 with the built in ADC10 is its inherent clock source ASC10ON, reference voltage $V_{REF}=V_{CC}$, the $V_{CC}$ is the operating voltage supplied to the ADC10 by a radio power supply. The range of the three-axis acceleration sensor ADXL330 is ±3g (360mv/g). Open the x-channel, y-channel and z-channel of the ADXL330 to obtain acceleration data, and compare the acceleration data with the acceleration data obtained by the active wireless Narada unit. The result is shown in Figure 7, where Figure 7(a), Figure 7(c) and Figure 7(e) show the acceleration data obtained by the active wireless Narada unit, and Figure 7(b), Figure 7(d) and Figure 7(f) show the acceleration data obtained by the WISP.
The similarity percentage results of the acceleration data monitored by the WISP and the active wireless Narada unit of the three experiments in 1 minute, 5 minutes, and 10 minutes are shown in Table 1.

As can be seen from Figure 7 and Table 1, the acceleration data obtained by the WISP can match the acceleration data obtained by the active wireless Narada unit, and the similarity can reach more than 83%. Therefore, the acceleration information obtained by the system is reasonable and accurate, and the stability of the acceleration data obtained by the x channel of the three-axis acceleration sensor ADXL330 is more stable. However, due to the volume limitation of ADXL330, its anti-noise ability is weaker than Silicon Designs 2012-002, which is shown that with the increased sampling time, the similarity is decreased, especially on the z channel of ADXL330, which can obtain more ideal acceleration data through later filtering processing.

Table 1. The similarity percentage results of the acceleration data monitored by the WISP and the Narada unit

| Sampling time | Channels   | x-channel (%) | y-channel (%) | z-channel (%) |
|--------------|-----------|---------------|---------------|---------------|
|              | Percentage|               |               |               |
| 1 min        | 1         | 97.15         | 95.28         | 92.56         |
|              | 2         | 94.32         | 92.18         | 90.04         |
|              | 3         | 96.98         | 93.62         | 91.59         |
| 5 min        | 1         | 92.28         | 91.34         | 89.15         |
|              | 2         | 93.36         | 91.92         | 89.27         |
|              | 3         | 91.67         | 91.05         | 88.67         |
| 10 min       | 1         | 87.13         | 86.59         | 83.66         |
|              | 2         | 85.51         | 83.15         | 83.10         |
|              | 3         | 86.72         | 84.16         | 83.47         |
3.3. Multiple WISPs experiments

The IDs of the three WISPs are set to 513, 514, and 515 through software programming, and they are placed on the second, third, and fourth floors of the five-story steel frame structure. After the external force is applied to the steel frame structure, the movement tendency of left and right oscillation is occurred. Therefore, after placing the WISP on it, the x-channel of ADXL330 is parallel to the direction of movement of the steel frame structure, and the above-mentioned experiments show that the x-channel of ADXL330 is more stable. Therefore, only the x-channel of ADXL330 on the three WISPs is opened for dynamic monitoring of the steel frame structure. Set the sampling frequency of the WISP and the active wireless Narada unit to 50hz, and set the sampling time to 40 seconds. The acquired acceleration data is subjected to Discrete Fourier Transform (DFT) in the form of the following formula (2), thereby drawing a frequency image.

\[ X(k) = \sum_{j=1}^{N} x(j)\omega^{-1}(j-1) \]

(2)

Wherein, \( \omega_N = e^{-2\pi j/N} \), \( N \) is the number of data collected in 40 seconds, and \( x(j) \) is the acceleration data.

The acceleration data obtained by the WISP and the frequency image calculated by equation (2) are shown in Figure 8 below.

![Figure 8. Acceleration and frequency](image)

Among them, Figures 8(a), 8(c), and 8(e) are the acceleration data obtained by the WISP with ID 513, ID 514 and ID 515. Figures 8(b), 8(d), and 8(f) are the structural frequency images drawn by the corresponding acceleration data using Matlab software. It can be seen from the figure that the fundamental frequencies of the steel frame structure actually monitored by the three WISPs are all 0.875hz.

In this paper, the finite element analysis system OpenSEES jointly developed by Pacific Earthquake Engineering Research Center (PEER) and the University of California at Berkeley is adopted and the structure is modeled. The mass matrix and stiffness matrix of the structure are programmed through Tcl language, and the eigenvalue analysis of the structure is completed to obtain the fundamental frequency and basic mode shape of the structure, as shown in Figure 9.

Figure 9 shows that the theoretical fundamental frequency of the structure is 0.8832hz, which is only 0.93% different from the fundamental frequency monitored by the WISP. It can be shown that the
acceleration data obtained by the WISP is accurate and effective, and can realize the dynamic monitoring of the steel frame structure. Moreover, it also shows that multiple WISPs can simultaneously obtain the RF signal emitted by a single antenna to drive their normal work, and can also successfully and completely transmit the collected data to the reader. Therefore, in SHM, it is feasible to use multiple WISPs to simultaneously perform multi-point deployment and control.

4. Conclusions
Through the experimental research and theoretical analysis of the WISP with three-axis acceleration, the following conclusions can be drawn:

1. The WISP realizes its power supply energy supply and information transmission through UHF RFID reader. It has completed the conversion from wireless active to wireless passive, overcoming the energy limitation, and at the same time, it also solves the shortcomings of the sensor's low computing and storage capabilities.

2. The WISP is capable of transmitting the monitored data back to the computer in real time and in full. By comparison with the active wireless Narada unit, it can be seen that the data monitored by the WISP and the active wireless Narada unit are similar to more than 83%, indicating that the acceleration data monitored by the WISP is accurate and effective.

3. Multiple WISPs are used for multi-point deployment at different positions of the structure, and the obtained structure fundamental frequency is only 0.93% different from the structure fundamental frequency obtained by OpenSEEs simulation, which shows that in SHM, it is feasible to use a single reader antenna and reader to provide energy and data transmission for multiple WISPs at the same time, and the data obtained is reliable and accurate. Therefore, it is feasible to use multiple WISPs for multi-point monitoring.

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