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Wireless Sensing and Vibration Control With Increased Redundancy and Robustness Design

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***Abstract*—Control systems with long distance sensor and actuator wiring have the problem of high system cost and increased sensor noise. Wireless sensor network (WSN)-based control systems are an alternative solution involving lower setup and maintenance costs and reduced sensor noise. However, WSN-based control systems also encounter problems such as possible data loss, irregular sampling periods (due to the uncertainty of the wireless channel), and the possibility of sensor breakdown (due to the increased complexity of the overall control system). In this paper, a wireless microcontroller-based control system is designed and implemented to wirelessly perform vibration control. The wireless microcontroller-based system is quite different from regular control systems due to its limited speed and computational power. Hardware, software, and control algorithm design are described in detail to demonstrate this prototype. Model and system state compensation is used in the wireless control system to solve the problems of data loss and sensor breakdown. A positive position feedback controller is used as the control law for the task of active vibration suppression. Both wired and wireless controllers are implemented. The results show that the WSN-based control system can be successfully used to suppress the vibration and produces resilient results in the presence of sensor failure.**

***Index Terms*—Redundancy, robustness, vibration control, wireless sensor networks.**

I. Introduction

RECENT ADVANCES in sensing and networking technologies have led to the emergence of wireless sensor networks (WSNs). A WSN consists of spatially-distributed autonomous sensors which cooperatively monitor physical conditions, such as temperature, vibration, motion, etc. Although large-scaled implementation is still lacking, WSNs have gained increased popularity in various fields of life and they are being used in many applications, including industrial automation, office and home automation, and structural health monitoring. WSNs are designed to replace traditional wired sensor networks because installing a large-scale wired network data acquisition system can take several weeks and often turn out to be prohibitively expensive. Wiring sensors to a central node in a large structure is labor intensive and the wires may also cost more than the sensors and controllers themselves. The most prominent characteristics of wireless sensors are their low power consumption, low system costs, and compactness. These features endow WSNs with the ability and advantage of large-scale deployment and being battery powered. However, these features also determine that the WSN nodes can only have limited computational power and system complexity and must use applications that are not computationally intensive.

Over the last two decades, a large amount of research has been carried out on WSNs and their potential applications due to their increased flexibility and promise of lower costs compared with wired installations. A number of wireless sensor nodes have been built by several research institutes. The two commonly used architectures for low-power wireless sensor nodes involve: 1) an ATMEL AVR processor plus TinyOS [1] and 2) an MPS430 plus TinyOS [2]. Spencer *et al*. [3], [4] overviewed the hardware and software issues that should be addressed for using MICA (AVR + TinyOS) motes for structural health monitoring. Lynch and Loh [5] gave a summary review of WSN in structural health monitoring in civil engineering. Li *et al*. [6] presented a Piezoceramic-based WSNs platform for concrete structural health monitoring. Yu *et al*. [7], [8] introduced some recent advances on research, development and implementation of wireless sensors networks for the SHM of civil infrastructures in China, especially in Dalian University of Technology and Harbin Institute of Technology.

Although a lot of studies have shown the great potential of WSNs in monitoring systems, there has not been much effort directed toward using WSNs in real-time feedback control systems. As for wireless monitoring systems, the use of wireless networks in control systems allows for modular and flexible system design, simple and fast implementation, and reduced installation and maintenance costs. However, the use of communication networks in general, and a WSN in

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particular, is a challenging task due to the introduction of random delays and packet dropouts in the feedback loop of the control system that negatively affect the control performance. These effects are more pronounced in wireless networks due to time-varying channels, the limited spectrum, and interference. Research has been carried out to test the feasibility and performance of wireless control systems, without regard to the uncertainty in the wireless communication channels [9]–[11]. Wang *et al*. [12] introduced decentralized and partially-decentralized control strategies to mitigate the challenge of communication latency associated with WSNs. However, decentralized system architectures may only achieve suboptimal control performance compared with centralized counterparts. This is because each subsystem only has its own state data with which it must calculate control decisions. Taylor and Ibrahim [13] proposed an approach to find the acceptable sampling frequency and time delay for control system. Swartz and Lynch [14] used Kalman estimator to mitigate the effects of delayed or dropped packets in the wireless control system for seismically exited civil structures. Chamaken and Litz [15] analyzed the joined design of communication and control system and showed how different control algorithms in conjunction with dedicated communication protocols can be used to stabilize and optimize the control performance. An industrial wireless control communication network and protocol has been proposed by Tang *et al*. [16]. Service differentiating, resource reserving and cross-layer and cross-network schedule mapping mechanisms are used to provide real-time and reliable communications. Uchimura [17] described a wireless networked system with variable time delays in both input/output transmission paths. A synchronization function of IEEE 802.11 based wireless network was used to measure the time delay. Simulation studies were conducted to verify the effectiveness of the proposed identification and delay compensation methods. Bai *et al*. [18] proposed a discrete-time switched system with time-varying delay model for a wireless network control system with packet loss and time delay. The corresponding state feedback controller is designed via a set of linear matrix inequalities. Li *et al*. [19] developed a new stochastic switched linear model to describe the Zigbee-based wireless networked control system (WNCS) with both network-induced delay and packet dropout. By using the augmenting technique and multi-Lyapunov approach, a state feedback controller was designed. Although some workers have taken the network delay and sampling frequency problem into account in the system design, little effort has been made to deal with the worst case scenarios. A potential but critical problem for a wireless control system is the breakdown of wireless sensor nodes due to insufficient power, hardware failure, or software failure. Ignorance of this problem may sometimes lead to disastrous results.

Control and wireless communication systems are different kinds of systems with distinct design principles aimed at different goals. There are two special issues to be considered in order that the advantages of WSNs can be fully utilized in a control system. First, the advantages of WSNs such as low power consumption, low system cost, and mass deployment that originates from the simplicity of the wireless sensors themselves. These low-power microcontroller wireless systems have limited speed and hence limited computational power. Such a lack in computation power may cause control-induced or computational delays, which may lead to system instability [20]. This dictates that only simplified control algorithms are suitable for WSN systems. Secondly, the inherent problems of WSNs such as random delay and package dropout will influence the performance and even the stability of the control system. For a network control system, there are several approaches to addressing one or both of these issues [21]–[24]. Simplified time synchronization and other techniques must be carried out to guarantee control performance. Although complex algorithms may provide a solution and achieve even better results with these problems, they entail much higher computational power and hence greater hardware complexity, higher system cost, and larger power consumption. This disobeys the goals of using WSNs in the first place. By using those algorithms, the benefits of using WSNs themselves are tradedoff. Thus, in general, the design of a robust WSN based control system is a tradeoff between control system performance, system complexity, and cost.

Resilience of the WSN based feedback control systems is weakened by the inherent defects, such as possible data loss, sensor breakdown and irregular sampling periods, of the WSN system. This paper considers the design and implementation of a low-power 802.15.4 wireless control system, aiming at the improvement of the resilience and robustness of the wireless feedback system. A multinode wireless based control system which provides a good redundancy is presented. A time synchronization mechanism and a timing scheme that uses clock driven sensing and control is designed and implemented to verify the validity of the wireless data. Together with the timing scheme, model and system state compensation is used to solve the problem of data loss and sensor breakdown. Although time delay itself is also of great importance for wireless based control systems, the paper mainly focuses on the method and practical implementation for reaching a robust wireless feedback control system rather than time delay analysis. The rest of the paper is organized into five parts: the hardware system, the software system, the experimental setup, the control system design and experimental results, and lastly, some conclusions and future work.

II. Hardware System Design

Two kinds of device are used to perform wireless vibration control: wireless controllers and wireless sensors. A wireless controller performs the control algorithms. It is also the wireless network coordinator, which is responsible for organizing and controlling the behavior of the network. A wireless sensor, on the other hand, receives commands from the wireless controller and performs the wireless sensing tasks. Both of these components are battery powered, and both can gather and transmit vibration data to a PC for processing. The connection between the PC and the units is RS232 serial communication. Higher level decisions can be made on the PC and sent to the network through this serial connection.

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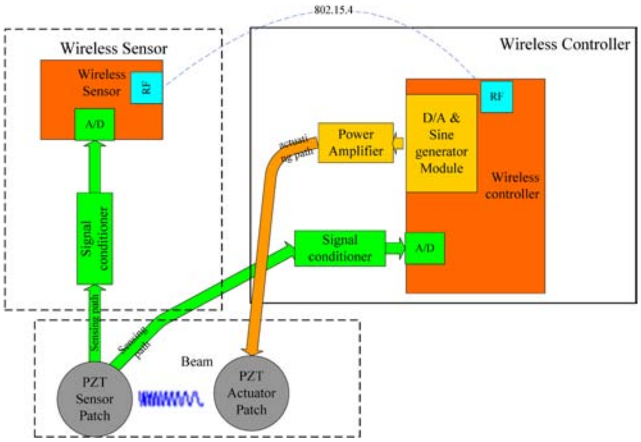

Fig. 1. System structure.

The hardware system design for the WSN can be separated into three parts: the wireless unit circuit design, the signal conditioning circuit design and the actuation circuit design. The wireless unit and signal conditioning circuit are used in both the wireless controller and the wireless sensor. The actuation circuit is used in the wireless controller only.

A. Wireless Controller Design

The wireless controller can perform both wireless and wired control tasks. The wireless controller is composed of four parts, as shown in Fig. 1: a wireless unit, a D/A converter with offset and amplifier circuit, a signal conditioning unit for A/D conversion, and a power amplifier for actuation.

1) *D/A circuit:* A MAX504 unit is chosen for the D/A converter in this project. It is a 10 bit D/A unit with a serial peripheral interface (SPI). The SPI is connected to the wireless controller as the communication bus and the output signal range is 0–2.048 V. As Lead zirconium titanate (PZT) based actuator requires bipolar signal for normal actuation, an offset and amplify circuit is designed to condition the driving voltage to a proper range. The offset circuit utilizes the D/A reference output (2.048 V) to set a negative 2.048 V offset on the output. Another amplifier is then used to amplify the output to –10 to 10 V range. The D/A circuit and the offset amplifier circuit are shown in Fig. 2.

2) *Signal conditioning:* The amount of charge generated by a PZT is proportional to the vibration in the structure but the current generated from the PZT sensor is usually very small (a few microamperes). Therefore proper amplification and signal conditioning is required before the signal can be sampled and processed by a microcontroller. An op-amp circuit is designed to convert the current to a voltage and to scale and offset the signal to a valid voltage range for A/D sampling by the controller. A low-pass filter is used to perform anti-aliasing tasks. The signal conditioning circuit is shown in Fig. 3.

3) *Wireless Unit:* The wireless controller is the core component of the overall system. A low-power 32-bit embedded platform based on the Jennic JN5139 was selected as the wireless unit for our network. The JN5139 is a low-power, low-cost wireless microcontroller which is suitable for IEEE 802.15.4 and ZigBee applications. It integrates a 32-bit RISC

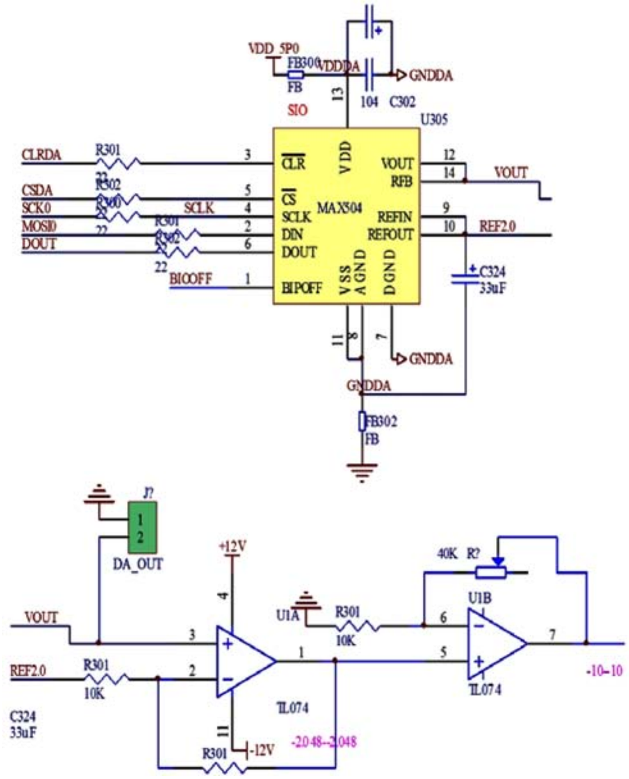

Fig. 2. D/A converter with offset and amplifier circuit design.

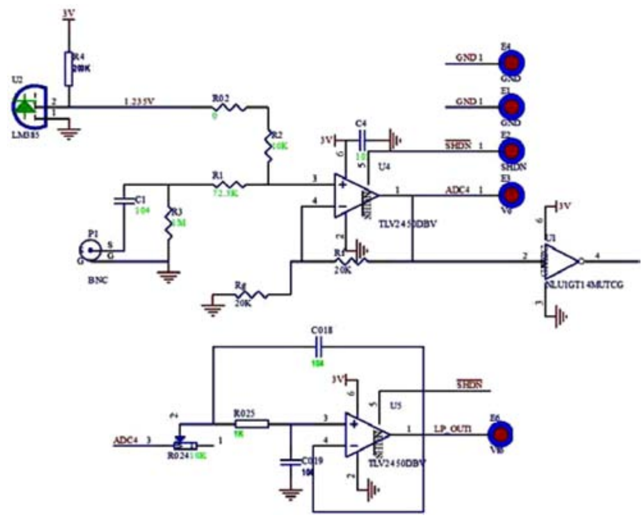

Fig. 3. Signal conditioning circuit.

processor, with a fully compliant 2.4 GHz IEEE 802.15.4 transceiver, 192 kB of ROM, 96 kB of RAM, and assorted analogue and digital peripherals. It also includes hardware medium access control (MAC) accelerators, power saving and timed sleep modes, and mechanisms for security key and program code encryption. These features all make for a highly efficient, low-power, single-chip wireless microcontroller for battery-powered applications. Fig. 4(a) is a system block diagram for the JN5139 and Fig. 4(b) is a picture of the wireless module itself.

The wireless control task is different from other control tasks as it requires relatively high computation density both

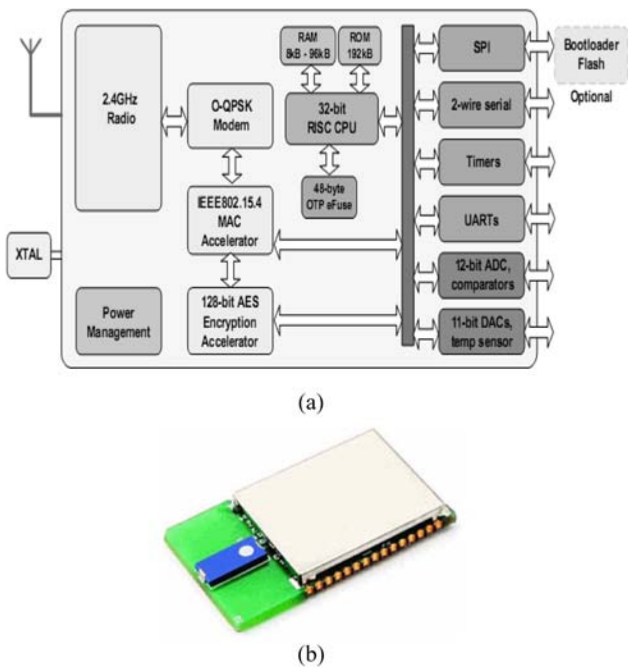

Fig. 4. Wireless microcontroller. (a) System block for JN5139. (b) Actual picture for the wireless module.

for the control algorithms and for processing the wireless communications. In the meantime, battery-based wireless systems require power efficient hardware and software design. Our study shows that JN5139 microcontrollers are suitable to address these problems. A JN5139 microcontroller can run at 32 MHz and delivers about 32 million instructions per second (MIPS). Three operating modes are provided in JN513x units that enable the system power consumption to be controlled efficiently to maximize the battery life. The Jennic JN5139 wireless microcontroller contains a 12-bit ADC which is used to perform the A/D sampling of the vibration. The wireless transceiver in the Jennic JN5139 comprises a 2.45 GHz radio, an O-QPSK modem, a baseband processor, a security coprocessor, and a PHY controller. The transceiver can operate in the unlicensed 2.4 GHz band. IEEE 802.15.4 wireless functionality is used with the transceiver and the protocol software.

4) *Power Amplifier:* The D/A circuit's output range is from –10 to 10 V. The signal is then sent to a power amplifier before application to the PZT actuators. The power amplifier has a gain of 20, and will generate a voltage in the range of –200 to 200 V [25]. This voltage signal is used to perform the excitation and vibration control of the beam.

B. Wireless Sensor Design

The wireless sensor hardware is basically the same as the wireless controller. The only difference is the removal of the D/A convertor and the power amplifier for lower power consumption.

With the hardware system described above, proper software needs to be designed to carry out the wireless control of the vibration of the beam.

III. Software System Design

The software system can be roughly divided into six layers: the driver layer, the interrupt service register (ISR) layer, the network interface layer, the shell layer, the system state machine layer, and the control algorithm layer. The software architecture is illustrated in Fig. 5.

Lower level layers provide services to upper level layers, and the upper level layers are designed based on the lower level layers. All the software is designed using the C programming language and implemented in the wireless units. The driver layer includes drivers for all the hardware peripherals in the system.

A. System Tasks Design

Proper system tasks must be designed to initialize the controller, realize the functions of the peripherals, and handle input and output events. Drivers for all the peripherals must also be designed. The system task performs the peripheral and database initializations after startup. The coordinator will build the network and start a state machine to process different events while the sensor nodes will search and join the coordinator and wait for commands from either the serial interface from the PC or the network interface from the coordinator.

A shell is designed on the coordinator, which uses serial input and output as a system console. Prebuilt commands can be sent from a PC via the RS232 and carried out on the coordinator. The shell is interrupt driven and command parsing is carried out after an enter is received from the UART.

Important tasks for this project are: adc to get A/D data, dac to output D/A values, sine to generate different frequencies of sine wave, control to perform different wired control algorithms, wcontrol to carry out different wireless control algorithms, sample to record sensor data, savedata to save all the sensor data to the PC, endinfo to printout all the node info in the WSN, and setkp, setck to tune the controller gain.

The wireless controller can generate sine wave excitation to the PZT patch to excite the vibration at specified frequency which is setup through the shell. The wireless controller can carry out both wired and wireless control algorithms. In this paper, a positive position feedback (PPF) controller is implemented in the system. Control results can be recorded and sent back to the PC.

ISRs are designed to handle various interrupts. Several timer ISRs are implemented to generate the sine wave, record the sensor data, and perform different control algorithms. The sampling frequency for recording data can also be specified through the shell.

B. Network Protocol

The JN5139 wireless unit has a wireless transceiver that is fully compliant with the 2.4 GHz IEEE 802.15.4 protocol. Consequently, the network protocol used in the project is just IEEE 802.15.4.

The IEEE 802.15.4 protocol features very low complexity, ultra low-power consumption, low data rate, a relatively short radio communication range (30 m), ability to use unlicensed radio bands, easy installation, and low cost. A central feature

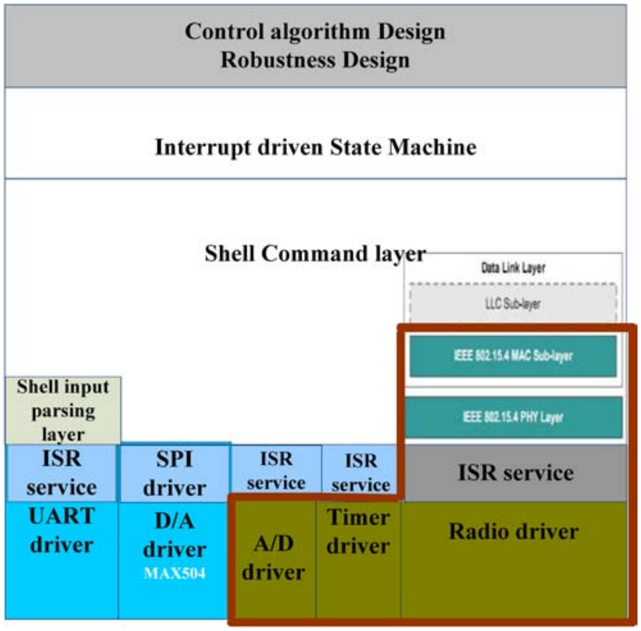

Fig. 5. Software architecture.

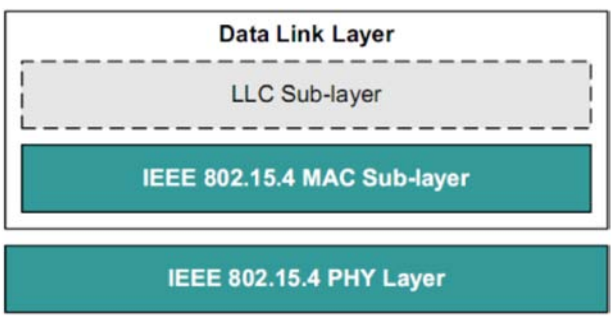

Fig. 6. Network architecture.

of the standard is the requirement for extremely low power consumption. The motivation for this strict power requirement is to enable the use of battery-powered network devices that are completely free of cabling (no network or power cables), allowing them to be installed easily and cheaply (no costly cable installation needed), possibly in locations where cables would be difficult or impossible to install. However, low power consumption necessitates short ranges.

The maximum data transfer rate with 2.4 GHz IEEE 802.15.4 is 250 kbps. This is enough to guarantee in-time wireless sensor data transfer for wireless control. A star network topology is adopted for this design, as there is only one controller in the network to perform the control tasks, and the sensors do not need to communicate with each other but with the wireless controller. The network protocol architecture is shown in Fig. 6. A standard 802.15.4 stack is provided by the Jennic manufacture, so most of the programming for the network protocol is in the data link layer. Software is designed to handle energy scanning, starting the network, node associating, and data transfer.

The WSN is configured as a nonbeaconed network. The network coordinator controls the behavior of the sensors nodes. After the network is built up and the network coordinator is asked to start vibration control from the PC serial interface, the coordinator will send out a control start command to the specified sensor node. The sensor nodes that receive the start command will perform initialization tasks for sensing the vibration data and give an acknowledgement to the controller when it starts. Only after receiving the correct acknowledgement will the controller start to work. When the controller is finished, the wireless controller will send out a STOP command to the wireless sensor, and the sensor will stop sensing to save power consumption.

IV. Experimental Setup

The experimental model is a cantilever beam with PZT patches as sensors and actuators. The size of beam is 17.5 in $\times$ 1.5 in. The size of the PZT actuator patch is 1.25 in $\times$ 1.75 in, and the size of the PZT sensor is 0.75 in $\times$ 1.25 in. One wireless controller and two wireless sensors are used in the experiment. A notebook is used for programming and debugging the wireless microcontrollers. A power amplifier is used to amplify the wireless controller to a range of 200 V. The experimental setup is illustrated in Fig. 7.

V. Control System Design and Experimental Results

The control system is designed and implemented on the hardware and software platform presented in Sections II and III. One difference between a computer based and microcontroller based control system is that a microcontroller has limited speed and computational power. Therefore, the control algorithm has to be designed to be as simple as possible so that it can be finished within one control step. Another point is the WSN has a complex network protocol running in the system. This network protocol usually consumes a considerable amount of the CPU's computational power. Complex control algorithms will not only increase the control loop time, but also jeopardize the network's response ability.

A simple and feasible control algorithm, PPF control, is used as the control law for the system. PPF control was first proposed for structural vibration control by Goh and Caughey [26]. In PPF control, structural position information is fed to a compensator. The output of the compensator, magnified by a scalar gain, is fed back directly to the structure. A block diagram of the PPF controller is shown in Fig. 8, where ξ is a coordinate describing strain of the structure, ζ is the damping ratio of the structure, ω is the natural frequency of the structure, G is a feedback gain, η is the compensator coordinate, ζ_c is the compensator damping ratio, and ω_c is the natural frequency of the compensator.

Another important issue that can affect a wireless feedback control systems is the irregular time delays that are inherent with any wireless systems. As for the wireless feedback control system, the time delays can be classified into three categories. 1) The time delay is less than one control step size. 2) The time delay randomly shows greater than one sampling period. 3) The sensor becomes dead and the time delay approaches

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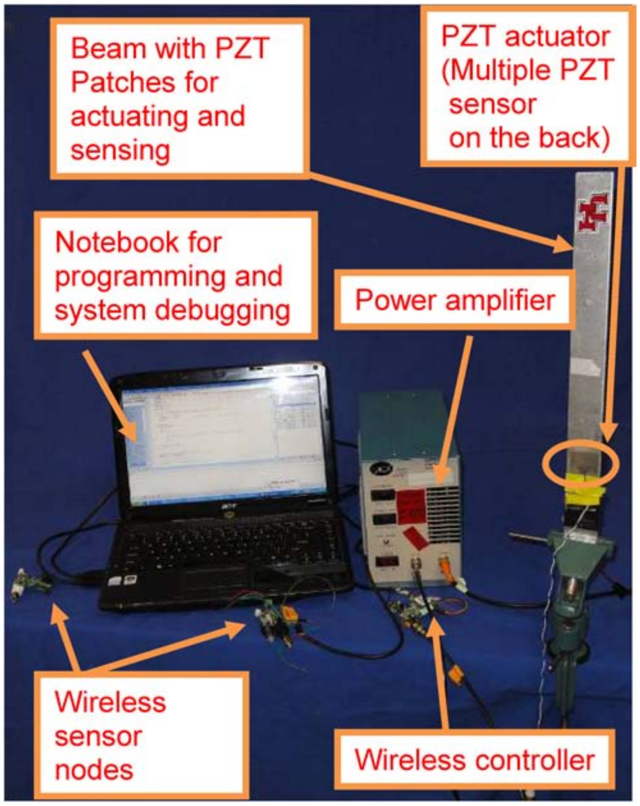


Fig. 7. Experimental setup.

infinity. Since this paper mainly concentrates on the design and implementation of a robust feedback control system with data recovery capability, sampled data under case one is considered as good data. For case 2 and case 3, model and system state based compensations are designed and analyzed, and as the experiment result will show, the method proposed in the paper provides a good solution for these kinds of time delays.

A. Wired Control System

Fig. 9 illustrates the configuration used in a regular wired microcontroller based control system. The signal flow in the control system is as follows. The D/A produces the control outputs as voltage signal, which is amplified by a power amplifier and applied to the PZT actuator. The PZT actuator then transforms the voltage signal into the form of a force, and generates vibration. The PZT sensor senses the vibration and generates a charge, which is transformed back to a voltage signal and sent back through A/D to the microcontroller.

To design the PPF controller, the system's natural frequency and damping ratio first has to be found. The designed system should have a similar natural frequency but a much larger damping ratio. The beam's natural frequency (11.875 Hz) and damping ratio (0.005) were calculated from experiments through the analysis of free vibrational data. A PPF feedback controller with a natural frequency of 11.875 Hz and damping ratio of 0.2 is designed to control the vibration. The controller designed in the continuous time domain is

$$C(s) = \frac{\omega_c^2}{s^2 + 2\omega_c\xi_c s + \omega_c^2} = \frac{5567}{s^2 + 29.85s + 5567}. \quad (1)$$

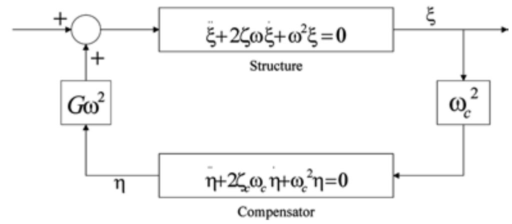


Fig. 8. Block diagram of the PPF controller.

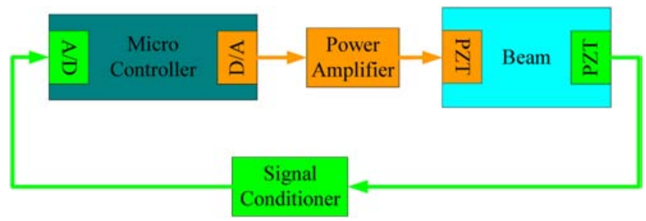


Fig. 9. Regular wired control system.

In order to carry out this control algorithm using a microcontroller system, the continuous controller is digitized and changed to the form of a difference equation. The sampling frequency is chosen to be 80 Hz, which is much greater than the system's natural frequency. The digitized system is

$$C(z) = \frac{0.3509z + 0.3093}{z^2 - 1.032z + 0.692}. \quad (2)$$

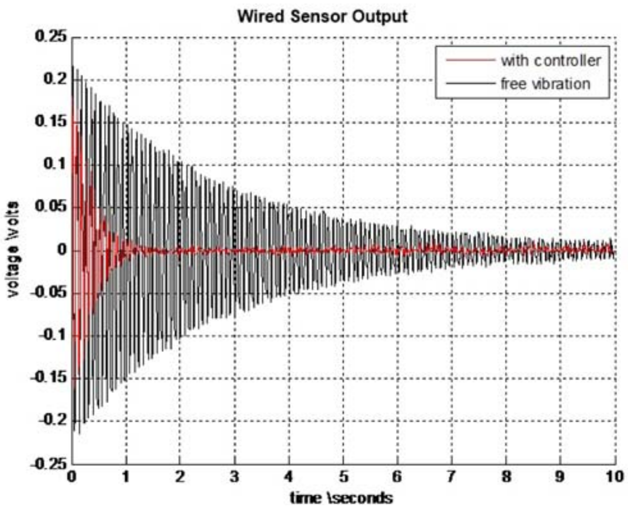
The system excites sinusoidal vibration at the beam's natural frequency for 10 s and switches output to the PPF controller. The controller output is shown in Fig. 10(a) and the control result in Fig. 10(b). From Fig. 10 it can be seen that the PPF controller is very effective in controlling the vibration.

B. Wireless Control System

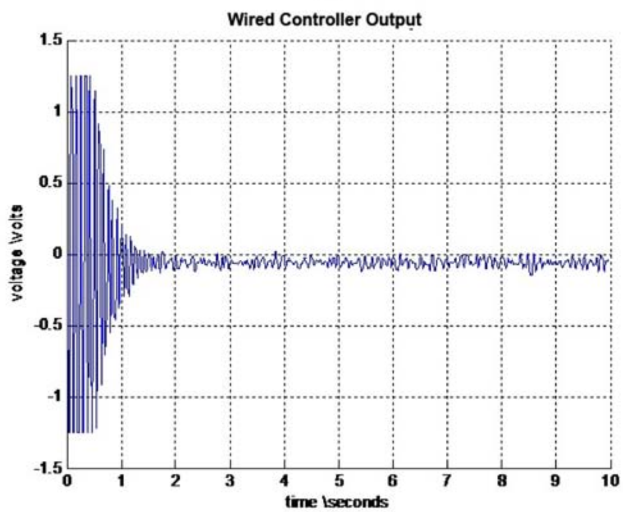
WSNs have certain advantages compared with wired control systems. First, although a greater number of wireless sensor nodes are needed in the system, WSNs can reduce the overall system cost. For systems which require long distance sensor wiring, wireless sensing saves a considerable amount due to reduced wiring labor and maintenance. Also, long distance wiring will usually induce problems with noise in the control system. In order to solve the noise problem, cables with good insulation (and high prices) are often used. Another way is to amplify the signal before transmission and signal condition it after it is received. Either way increases the system cost considerably. In addition, space costs will be saved once the wire is removed from the system. Secondly, for a rotational system such as a wind turbine blade, adding a wired sensor will increase the system complexity exponentially. In contrast, a wireless sensor based controller system can easily solve these problems.

The issues with the wireless control system are: possible data loss due to an unreliable wireless network, possible breakdown of the wireless sensor, and an irregular sampling period due to uncertainty in the wireless channel.

1) *Single-Node Wireless Control System:* The goal of this paper is to realize a wireless control system. The simplest



(a)



(b)

Fig. 10. Control result of the regular wired control system. (a) Control result. (b) Controller output.

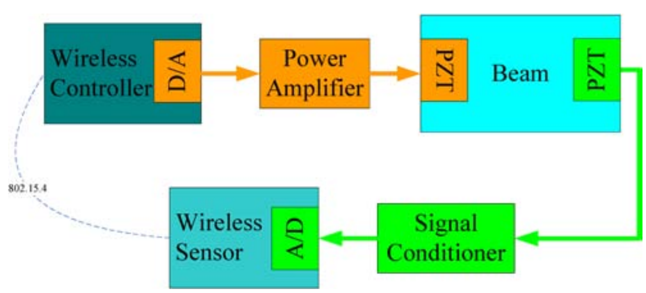
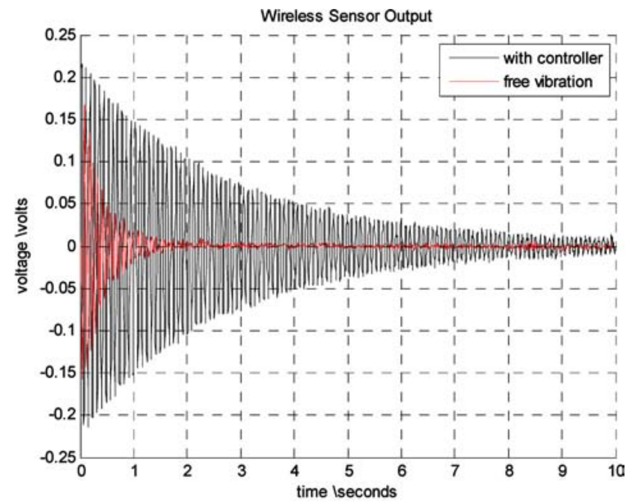


Fig. 11. Single node wireless control system.

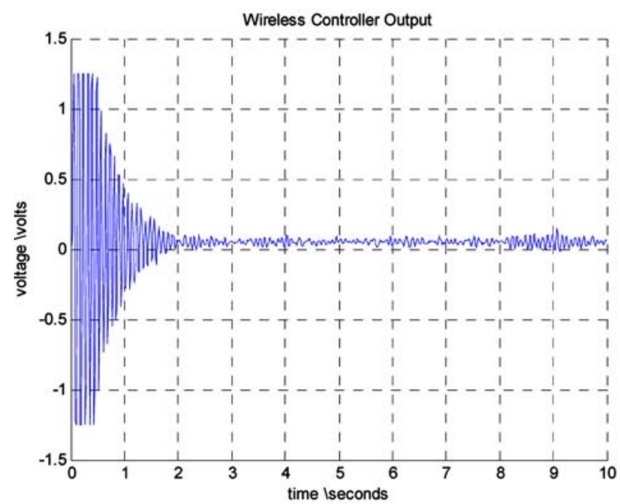
wireless control system that can be realized is based on a single-node start topology WSN. Fig. 11 illustrates the configuration for this control system.

The only difference between the wireless and the wired control system is the change in the sensor feedback path. If the uncertainty in the wireless channel is ignored, the control result is shown in Fig. 12(a) and (b).

It can be seen that, if the wireless channel is clear and the wireless sensor is in a good working condition, the control result is satisfactory. This is subject to the condition that the



(a)



(b)

Fig. 12. Control result of the single node wireless control system. (a) Control result. (b) Controller output.

sampling frequency of the control and sensing system is not too high and both the wireless controller and the wireless sensor can finish the sensing and control within one control step. However, there are times when the wireless channel is congested and data delay and loss happens more frequently. A time synchronization technique is utilized in the wireless controller wireless sensor in order to check the validity of the sensor feedback; this will be elaborated in details in the next section of the paper.

Another problem with a single-node wireless control system is that there is a chance the wireless sensor may run out of power and breakdown. Fig. 13(a) and (b) shows the results under the sensor-breakdown case. In Fig. 13(a), the red line is the actual sensor output and the blue line is the supposed sensor output. The sensor was powered off manually at about 0.65 s. It shows that the controller stops working after the sensor breaks down and the beam undergoes free vibration after that.

2) *Multinode Wireless Control System:* A multinode wireless control system is proposed to solve the problem experienced by the single-node WSN. Multinode wireless control

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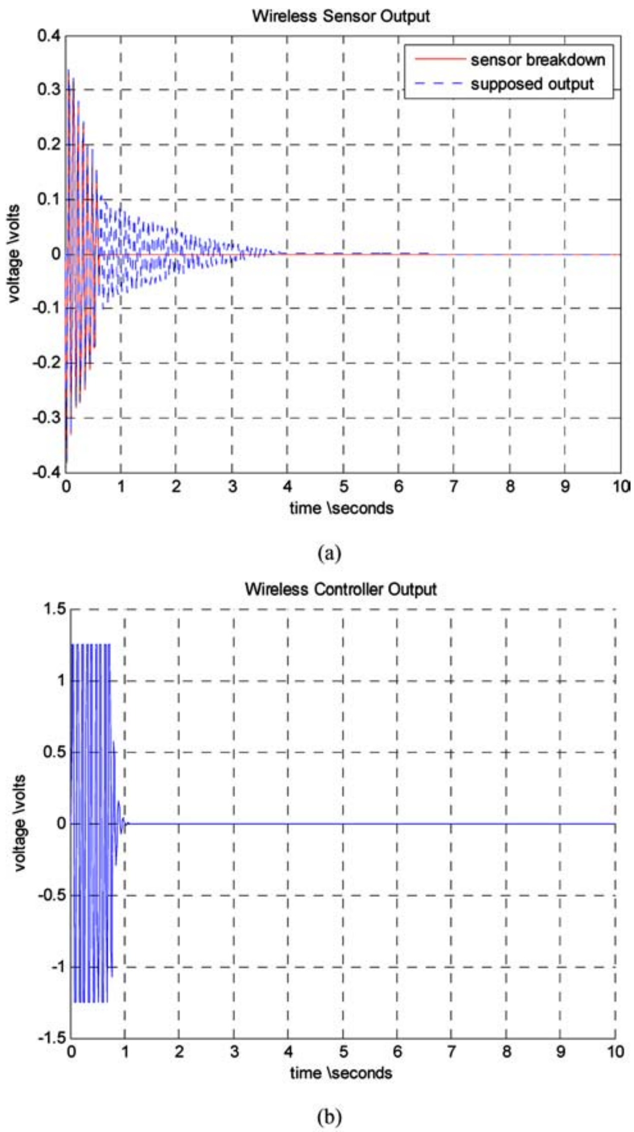

Fig. 13. Control result with sensor breakdown. (a) Control result. (b) Controller output.

will increase the system complexity and cost, but it also provides good redundancy to the system which is of critical importance in some applications. Fig. 14 illustrates the configuration used in the multinode wireless control system. In Fig. 14, both of the wireless sensors collect the sensor data but only one actually feeds data back to the wireless controller. If the wireless sensor feeding-back breaks, the wireless control will initiate and set up a data link with the other wireless sensor. It then switches to the other wireless sensor for data feedback.

In regular wired control systems, the control law is invoked by a timer with a fixed timeout period. This is because the sensor feedback and actuator output all have fixed timing. For the networked control system, however, the wireless sensor feedback timing is no longer fixed. The control law can have a different timing scheme that is invoked by the network event. Ploplys summarize different timing approaches in his paper [27]. Clock driven sensing and control with time synchronization is a good solution to this problem [28], [29].

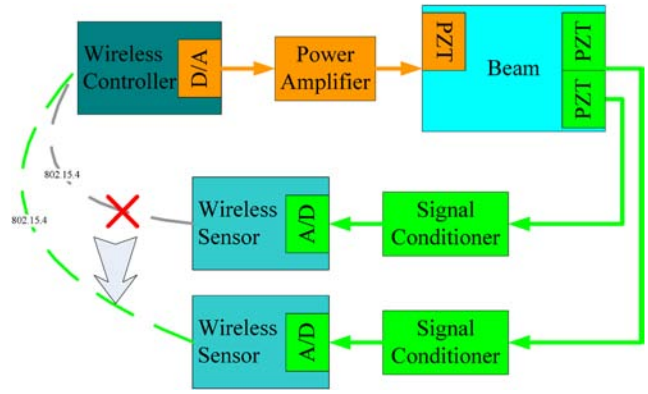

Fig. 14. Multinode wireless control system.

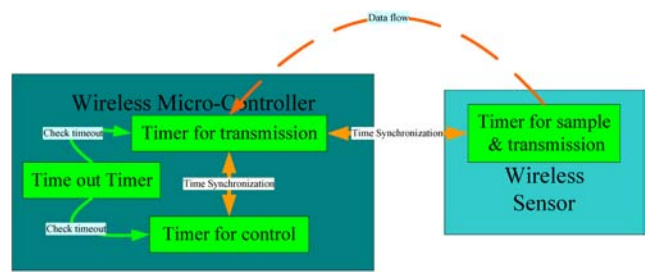

Fig. 15. Time synchronization scheme.

The failure of the sensor is detected by the time synchronization function. To realize exact time synchronization, complex synchronization algorithms which are not easy to implement on a microcontroller-based system, are usually needed. In this paper, a simple scheme is proposed to verify the validity of the wireless data. Three hardware timers are used on the wireless controller and one hardware timer on the wireless sensor. The wireless controller uses one timer to initiate wireless transmission. The wireless sensor starts its own timer after handshaking with the wireless controller. All the sampling and wireless transmission is realized based on those two timers in the wireless controller and wireless sensor. A timeout timer on the wireless controller monitors the data flow on the wireless channel and checks if the data of every sensor is sent back within one control step. The control algorithm, however, is running based on another hardware timer in the wireless controller. If the current sensor data is received within the current control step, it is defined as valid data. If not, this is considered as delayed data, and should be discarded. This simple time synchronization scheme guarantees the controller has valid sensor feedback. A predefined maximum sensor timeout is used to determine if a sensor stops working. Fig. 15 illustrates the time synchronization techniques used in the system.

The control algorithm is the same PPF control algorithm as used in the wired control system. Fig. 16 shows the control result with one sensor breakdown. Fig. 16(a) shows the sensor output seen by the wireless controller, and Fig. 16(b) shows the wireless controller output. At about 0.3 s, the first wireless sensor is powered down manually. The wireless controller identifies the breakdown and sets up a data link with the second wireless sensor. This happens at about 0.3–0.6 s, as can be verified from Fig. 19. Both the sensor and the controller

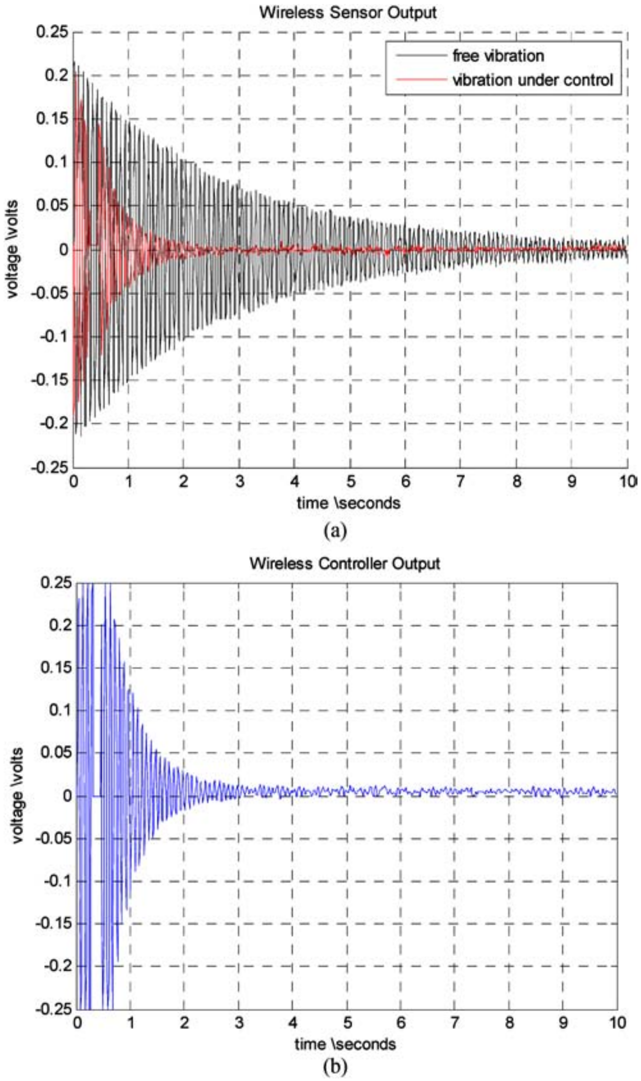

Fig. 16. Control result after one sensor breaks down. (a) Control result. (b) Controller output.

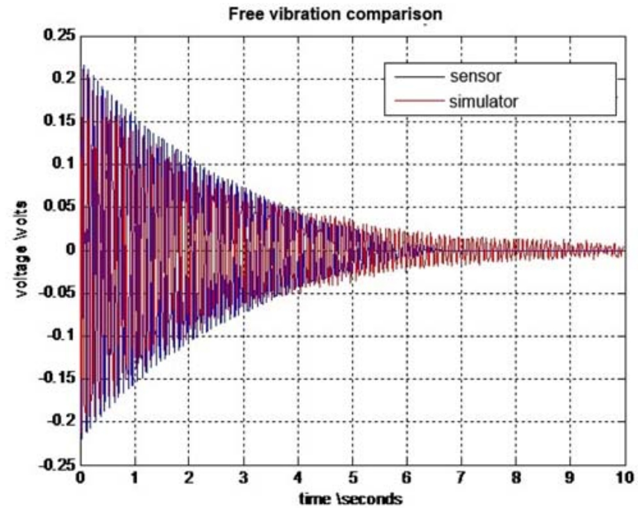

Fig. 17. Free vibration output by the simulator (blue line) and physical sensor (red line).

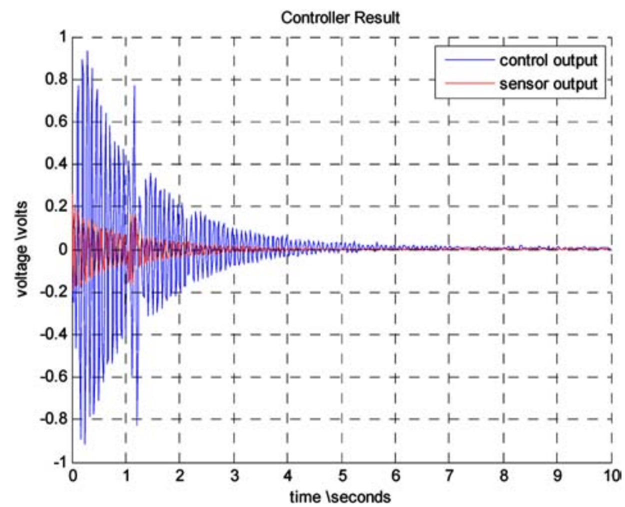

Fig. 18. Control result with beam simulator.

have zero output during this period. After 0.6 s, the second wireless sensor starts working and the controller works again.

Comparing this result with the single-node or wired control result, it can be seen that the sensor breakdown hinders the control performance since there is a period when control is absent due to sensor failure detection and wireless network reinitialization. Also, the earlier the breakdown happens, the worse the performance will be. This is because vibrations with large amplitude occur at earlier time when the period of control absence exists.

Although the multinode wireless control system endows the system with better redundancy, the control absence period due to switching is unwanted. To solve this problem, a multinode wireless control system with beam modeling and beam state compensation is proposed.

C. Multinode Wireless Control With Beam Modeling and System State Compensation

In order to solve the control absence problem, the system should have a sensor output prediction function. The prediction function is used to predict the sensor output in case of sensor failure and compensate the sensor output before the controller actually switches to the backup sensor. For a microcontroller based system, which requires a simple and easy way to implement algorithms, a feasible method is to put the known beam model into the microcontroller. The beam model acts like a simulator which constantly simulates the sensor output. The beam model itself is a complex system, but it can be simplified to a second-order system if only the first mode of vibration is considered. The second-order model is given as follows:

$$G(s) = \frac{\omega_n^2}{s^2 + 2\omega_n \xi s + \omega_n^2} = \frac{5567}{s^2 + 0.7219s + 5567}. \qquad (3)$$

If the simulator can predict an acceptable sensor output when there is a short period of sensor absence, then both the data loss and the sensor breakdown problem will be solved. After digitization at 598 Hz, we obtain

$$G(z) = \frac{0.007771z + 0.007768}{z^2 - 1.983z + 0.9988}. \qquad (4)$$

Note that the sampling frequency is increased from 80 to 598 Hz. The reason for this is because low sampling

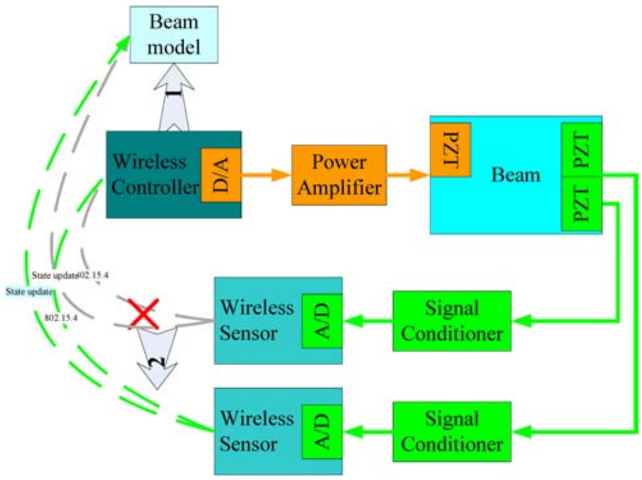

Fig. 19. Multinode wireless control with beam model and system state compensation.

frequency has limited precision and cannot achieve good simulation results on the microcontroller. Experiments show that 598 Hz fixed-point simulation can be afforded by the microcontroller and generates good results. To use the simulator, the system has to constantly track the simulator state and keep it updated with the beam. Otherwise, when it is in use, the simulator will have a different initial state to the beam and will generate a wrong output. Fig. 17 shows the free vibration output by the simulator and the real sensor.

In Fig. 17, except for some phase differences, the sensor and the simulator outputs match for the majority of the time. Toward the end of the vibration the difference becomes more prominent. Firstly, this is due to the inaccuracy of the beam model. The second-order beam system is just a simplified model of the beam system. Toward the end of the vibration, the first vibration mode dies out while other modes of vibration or some uncertain noises show up; hence, the simulation result is no longer accurate. Secondly, the simulation and sensing can never be exactly synchronized due to the limited computational power of the microcontroller. In addition, there are always some errors due to the limited simulation step size and rounding errors in the fixed-point calculations. The phase differences and inaccuracy mean that the simulator cannot be used directly by the controller. This is because the PPF controller relies heavily on the phase accuracy of the sensor output, and a phase inaccuracy will severely deteriorate the control performance. Fig. 18 shows a result of using the simulator output directly when sensor breakdown happens.

The first sensor breakdown happens at around 1 s. As the simulator output is phase distorted, the PPF controller cannot generate the correct output and the vibration actually becomes increased. In order to generate a good simulation result, the sensor states are used to adjust the simulator state. This control configuration is shown in Fig. 19.

The sensor output is fed back into both the PPF controller and the beam simulator. In addition, the state of the beam simulator is updated with the sensor output. In this way, whenever a sensor fails, the beam simulator itself runs on from the current state. Although the beam model is just an approximation of the real system, it can generate acceptable simulation output in a relatively short time with the initial state being set right. With the beam model and system state compensation, the experimental results are shown in Fig. 20(a) and (b). An enlarged sensor and simulator output is shown in Fig. 21.

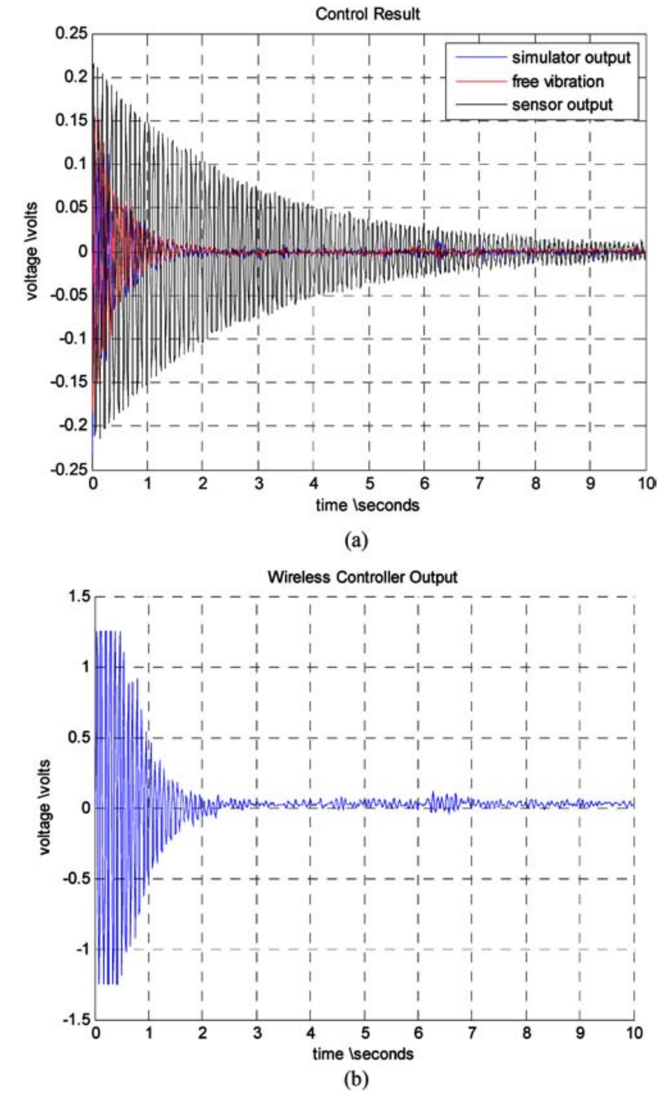

Fig. 20. Control result with the beam model and system state compensation. (a) Control results. (b) Controller output.

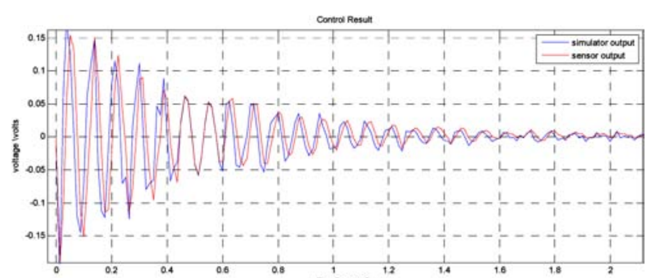

Fig. 21. Enlarged sensor and simulator output for the wireless control system with beam modeling and system state compensation.

With system state compensation, the simulator output almost matches the sensor output. One sampling unit phase difference is added to differentiate the two outputs. At about 0.4 s, the first sensor is powered down manually. The simulator continues to predict the sensor output until 0.6 s, when the backup wireless sensor connects to the wireless controller. From Fig. 20, it can be seen that good control results can be achieved and there is no longer a period where control is absent.

VI. Conclusion

This paper presents a WSN based control system with microcontrollers to increase the system's redundancy and robustness. All the control algorithms and robustness strategy are implemented in the wireless microcontroller and satisfactory control results are achieved. A multinode wireless control system provides the system with redundancy when a sensor node breaks down. A time synchronization scheme guarantees that the control algorithm uses valid wireless sensor data, and enables the controller to switch to a simulator to predict sensor output when no valid sensor data can be obtained. The simulator with sensor state compensation generates accurate system simulation results which can be treated as a sensor input when nodes break down.

In future work, we will attempt to include improved time synchronization algorithms and more sophisticated compensation methods.

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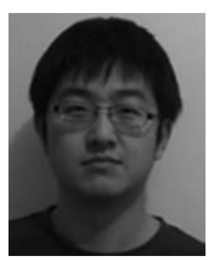

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