MEMS-Based Wireless Real-Time Health Monitoring of Bridges

By

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Abstract

This paper introduces a solar and wind powered wireless sensor node called DuraNode. It is developed at UCI and its capability demonstrated for real-time structural monitoring in a field experiment on a steel bridge in the UCI Campus. The DuraNode design is inherently low cost and supports not only robust, high-speed wireless communication over standard internet protocols, but also provides sophisticated power circuitry for multiple power sources that perform load matching, power distribution, recharge scheduling, and dynamic power management. DuraNode utilizes the technology that lead two of the authors (Chou and Park) to an award for the low power design contest at the International Symposium on Low Power Electronic Design (ISLPED) 2003. This paper further introduces highly cost-effective sensor network systems with real-time wireless communication capability in practical ranges of transmission distance over several miles. This capability coupled with a neural network analysis tool enables remote and yet real-time diagnostics of bridge strength subjected to operational and other loads. The network systems are used for Caltrans’ bridges in Orange County, California and resulting diagnostic procedures are presented.

1. Introduction

Innovative scenario-based post-event response and crisis management, if coordinated with pre-event measures, plays a crucial role in cost-effectively mitigating the consequences of a sudden disaster. Given a scenario, the extent of damage, casualty and disruption can be rapidly assessed by real time acquisition of data from dense array of sensors, strategically placed advanced SCADA devices, remote sensing, human sensors and possible other instrumentations, through reliable and large capacity telecommunication capability. In the risk assessment context, this exercise provides conditional estimation of economic losses given the scenario, and somewhat simplistically put, the risk is then estimated as the sum of the products of conditional economic losses and occurrence probability of each scenario over the number of
scenarios envisioned for a particular system, or by extension, for a combination of systems in principle. From this and other points of view, real-time health monitoring technology is of great importance to the broader study of societal risk associated with civil infrastructure systems.

2. Real Time Visualization of Structural Response with Wireless Comunications

Feng et al. (2004) installed sensor systems including accelerometers, pressure sensors, displacement sensors, and embedded strain sensors, on two new highway bridges in Orange County, California. Taking advantage of these permanently instrumented bridges, a methodology has been developed by Feng et al. (2004) for long-term structural performance/integrity evaluation. In this methodology, response acceleration data are collected at the Jamboree Road Overcrossing (see Fig. 1) by distributed optical sensors, gathered by means of optical fibers, and transmitted by wireless through the line of sight by a pair of dish antennae (see Fig. 1) to the UCI Engineering Tower Building (see Fig. 1) at a distance 6.5 miles away from the bridge site (see Fig. 2). Fig. 3 shows a real-time record of acceleration time history at a column bottom of the bridge due to a passing vehicle.

The back propagation neural network technique (e.g., Feng and Bahng 1999; Masri et al. 2000; Yun et al. 2001) was applied to update the preliminary FE model to the baseline model based on the measured dynamic characteristics of the bridge. The neural network-based system identification method has several advantages compared with conventional system identification methods. The neural network approach is more capable to build a baseline FE model based on the partially and incompletely measured components of the modal information due to the limited sensor number, and on only a few lower modes extractable from the vibration signals. Furthermore, it is very convenient to use the neural network to parameterize any properties of the structures, such as the effective shear area, as the unknowns to be identified (see Fig. 4).
3. Real Time Visualization of Structural Response with Wireless MEMS Sensors

MEMS (Micro Electro Mechanical Systems)-type accelerometers for vibration monitoring of large-scale structures were developed (e.g., Chung et al., 2003 and Lynh et al., 2003). With wireless remote transmission capability, real-time visualization of structural response during earthquake and other events is more easily achieved. Currently, MEMS-based acceleration devices utilizing Analog Devices’ ADXL series are popular for health monitoring with wireless communication capability. These devices appear to have relatively high noise levels and may lack real-time visualization capability. As an alternative, MEMS-based accelerometer devices are built around Silicon Design’s chip and Analog Devices’ ADXL chip which result in a much lower level of noise (see Fig. 5). The devices are low-cost and capable for wireless communication equipped with transmitter chip. Receiver unit for data acquisition is connected to a laptop computer by serial cable allowing real-time visualization (Fig. 6). Traditional sensors have to be cabled giving rise to a cumbersome task for cabling and exposing the sensor system to electro-magnetic interference. The devise developed here can replace traditional sensors providing a low-cost modular type alternative with portable transceivers for wireless communication.

This study demonstrated first, through laboratory test, the accuracy of the MEMS-type accelerometers and associated instrumentation with the use of wireless communication. Second, field vibration test of a steel bridge in the campus of UCI (see Figs. 7 and 8) is carried out with a cable-based traditional accelerometer together with the MEMS devices in order to assess the reliability of wireless device and data acquisition systems. Agreement was excellent between visualization of the record transmitted in real time by wireless from this sensor (Fig. 9) and that obtained off-line from a traditional sensor used as a reference (piezoelectric based, Fig. 10). Figure 11 and 12 shows the corresponding Fourier amplitudes of these time histories. We are currently validating these results from 3D analysis performed on the bridge model.
Fig. 5. MEMS Sensors with Transmitters and Receiver

Fig. 6. Sensor and data acquisition system

Fig. 7. Bridge tested

Fig. 8. Instrumentation

Fig. 9. Real time visualization (Wireless)

Fig. 10. Time History of seismic piezoelectric accelerometer

A number of wireless nodes have been built by several research institutes and some private sectors (Hill et al., 2000, Horton et al., 2002, and see other references). However, even though they are low power, they do not necessarily meet the requirements for our purpose. Either the data rate is too low, transmission distance is too short, or they do not last. DuraNode is a highly enhanced version of the MEMS-based sensor developed at UCI and described in Section 3 above. As the name suggests, DuraNode is designed to be long lasting: it should operate for months, if not years, without any maintenance work. Although low power design is a major consideration, low power alone cannot achieve long operating life, because these nodes are designed to be at least 100 meters from each other or the nearest access point. Such distances impose a relatively high minimum power on communication. Our solution is to tap into renewable energy sources. In this case, we use solar power and wind power in combination with rechargeable battery. DuraNode also includes smart charging circuitry to prevent accelerated aging of the rechargeable battery.

DuraNode has a number of distinct features. As the first prototype, it is composed of three modular boards for power control, sensor and microcontroller, and wireless communication. The modular design enables experiments with alternatives without requiring an entire redesign. In addition to supporting standard dynamic voltage/frequency scaling and subsystem shutdown, DuraNode uses a novel multi-regulator topology: it maximizes the energy efficiency of the regulators by matching the dynamic range of the corresponding power consumers, while at the same time provides digital/analog separation for noise reduction. The firmware architecture by default supports deterministic, time-triggered operation and communication; it also includes hardware support for event-triggered operation as an alternative paradigm. The combination of these features makes DuraNode not only durable for extended operations, but more importantly the use of tried-and-true, industrial-strength WLAN interface is expected to keep DuraNode transmit data reliably even in a noisy environment.
The requirements specification of the DuraNode is adaptable to the need of users who process the sampled data for structural analysis. Their specification is then translated into system design parameters, and they include timing, power, and interface.

Each DuraNode contains accelerometers for sensing vibrations in the $x$, $y$, and $z$ axes. Two existing MEMS sensors (ADXL L202E and SD 1221) are used. Its design allows the use of more efficient MEMS of similar size as they are developed. Each axis has a 10-bit sampling resolution, and each complete sample should be tagged with a time stamp or a sequence number so it can be correlated with data from other sensor nodes. Each node should transmit the sampled data over a wireless link, possibly over the Internet, to the central server in the laboratory. It should also be possible for a researcher in the laboratory to query the status of each node, upload new configurations, and calibration remotely.

It may be desirable to suggest an event-triggered approach by suppressing transmission unless the vibration exceeds a certain threshold. It has the advantage of power management because it enables most of the system to sleep and eliminates most of the communication. However, for civil engineering applications, such thresholding would effectively filter out ultra low frequency components in the data, thereby making some types of damages undetectable. Therefore, by default we will use the time-triggered model, but we include threshold detection circuitry to support event-triggered model.

Additional considerations are made on timing, interface, power/energy constraints that eventually are integrated into the current hardware as shown in Fig. 13. The details of wireless communication board, micro controller and sensor board and power circuit board will be described elsewhere. The authors also paid special attention to software design, particularly the firmware stored in flash memory.

![Fig. 13. Dimensions of DuraNode](image)

5. Conclusions

For the purpose of health monitoring and emergency response, the real-time MEMS-based sensors and wireless communications is of absolute practical significance and can play a critical role when combined with the well-developed rapid visualization procedure and inverse analysis. This paper showed an evolution of the process of hardware and software development that has been taken place at University of California, Irvine.
Acknowledgement

The authors acknowledge the support and assistance by National Science Foundation, Center for embedded Computer Systems at UCI, California Institute for Telecommunications and Information Technology at UCI, Multidisciplinary Center for Earthquake Engineering, California Department of Transportation (Caltrans), Caltrans District 12, Tokyo Sokushin Co., FCI Constructors, and Silverado Constructors.

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