Title: *Development of an Embedded Networked Sensing System for Structural Health Monitoring*

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ABSTRACT

An innovative networked embedded sensing system for structural health monitoring is currently being developed. This sensor network has been prototyped in the laboratory, and will be deployed in a series of forced-vibration tests involving a full-scale, four-story office building in the next coming months. The low-power wireless seismic sensor system enables the acquisition of 15-30 channels of 16-bit accelerometer data at 128 Hz over a wireless network. The advantage of such a system is its trivial deployability. This system contains several novel communication, data compression and time synchronization algorithms in order to deal with the low data rates and the lossy nature of low-power radios, as well as the inability to use GPS at each individual measurement. Our experiments indicate high-fidelity data acquisition, at the cost of slightly higher latency dictated by the radio data rates.

INTRODUCTION

Observations of the field performance of full-scale structures has been and continues to be a principal driving force behind advances in earthquake engineering [1]. However, previous studies of the field performance of full-scale structural systems have traditionally employed relatively sparse instrumentation that does not provide the *detailed* performance data that is needed to move the profession forward. For example, buildings permanently instrumented to record earthquakes typically have approximately 12 accelerometers. This level of instrumentation is sufficient to evaluate properties of low-order vibration modes, but is not sufficient to identify higher-order modal responses or component behavior. This is especially problematic for structures loaded into the nonlinear range, for which the data resolution is too low to aid in the development and verification of numerical models of nonlinear structural response, including damage localization and propagation effects.

Through the NSF-sponsored George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES) program, the University of California, Los Angeles

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Site (nees@UCLA) is currently in the process of developing a mobile field laboratory to substantially enhance the field testing capabilities of full-scale structural systems. The nees@UCLA Site was developed with the goal of addressing the following shortcomings which have limited the impact of field testing to date:

1. The inability of artificial (forced) vibration sources to test structures at large amplitudes, in particular, the nonlinear range.
2. The inability of traditional vibration sources to excite structures in a manner that emulates realistic broadband seismic excitation.
3. Practical difficulties associated with deploying a sufficiently dense sensor array such that detailed component behavior can be investigated.

Accordingly, the nees@UCLA equipment portfolio consists of large capacity harmonic eccentric mass shakers, a linear inertial shaker capable of producing broadband excitation and field data acquisition system with IP-based wireless telemetry (http://www.nees.ucla.edu). The development of the nees@UCLA Site is approaching completion and the full system will be deployed on a four-story office building, termed the Four Seasons project.

This paper focuses on the third issue identified above: the development of a wireless embedded networked sensing system for structural health monitoring and its role in the upcoming tests planned for the Four Seasons project.

THE FOUR SEASONS PROJECT

The Four Seasons building is a four-story reinforced concrete office building located in Sherman Oaks, California. This building was constructed in 1977 and the structural system includes a perimeter moment frame with an interior post-tensioned slab-column system with capitols, which represents a significant fraction of west coast reinforced concrete construction. The Four Seasons building was significantly damaged in the 1994 Northridge Earthquake, and post-earthquake studies of the building provide somewhat conflicting reasons for the observed damage. The building has since been yellow-tagged and is scheduled for demolition in approximately one year. We have secured access to this building from the site owner, and have planned a series of forced-vibration tests on the Four Seasons building.

The principal objective of this project is to collect a detailed dataset that will be used to improve on our understanding of the dynamic response of real buildings using the nees@UCLA equipment. The data archived through the proposed research could form the basis of detailed analytical studies for many years. Both earthquake-type and harmonic force histories will be applied to the building and the building responses to these force histories will be recorded with a dense array of instrumentation. The sensors used will monitor structural and non-structural responses (*e.g.*, partitions, suspended ceilings, sprinkler system), as well as foundation and soil responses through the use of accelerometers, displacement transducers, and strain gauges (concrete and rebar).

The instrumentation array will consist of the following three independent data acquisition systems:

1. 120 channels of Quanterra Q330 field data loggers from Kinemetrics, Inc. for vibration monitoring, with true 24-bit resolution and 145 dB dynamic

bandwidth replete with wireless data transmission and GPS time synchronization capabilities.

2. 96 channels of a National Instruments SCXI-based system for displacement measurements (i.e., strain gauges and LVDTs) with embedded GPS time synchronization.
3. a prototype 16-bit networked embedded sensor network, which is described in detail in the following section.

The Quanterra system represents the state-of-the-art in seismic instrumentation, providing the highest quality and most reliable vibration measurements. However, the cost of deploying such a system is considerable, which often precludes its use, even in much less dense arrays, in buildings. Accordingly, significant efforts are underway to develop wireless seismic sensors which have the potential for low-cost and easier deployments. The Four Seasons project presents an opportunity to evaluate this promising technology for structural monitoring systems.

WIRELESS SEISMIC ARRAY

Networked embedded systems are one class of emerging technologies that show great promise for collecting and processing vibration data from structures. Such systems consist of a collection of battery-powered nodes with wireless communication capabilities and on-board computation and sensing. A network of such nodes can be used to store vibration data in a distributed manner, and can be queried dynamically for the state of the structure or the history of its responses to ambient vibrations.

There are many challenges to designing networked embedded systems for structural applications. Since nodes are battery-powered and communication, sensing and computation all require energy and conserving energy for increasing the system lifetime is a primary design challenge. The vagaries of wireless communication and its limited bandwidth also pose a significant challenge, especially for structural applications. For example, in the embedded platform most widely used today, data transfer bandwidths rarely exceed 10 kbps and message loss of up to 30% is not uncommon [2]. Finally, synchronizing vibration data collected at different nodes in the system is a major challenge – using GPS for time synchronization is potentially a rather heavyweight solution.

In this paper, we describe a first step towards using networked embedded systems for structural applications – a wireless seismic data acquisition system. Our system, shown in Figure 1, consists of several motes [5] (wireless sensor nodes); each such device has a built-in low power radio, an 8-bit Atmel processor, 4K SRAM and about 512 KB of flash memory. We use an experimental vibration card under development by Crossbow Inc. that can collect up to four channels of 16-bit data at rates upwards of 100 Hz. This, together with an off-the-shelf accelerometer from Crossbow, will enable us to collect seismic structural response data.

Our goal is to build a wireless system that can collect tens of channels of vibration measurements in near real-time. Traditional data acquisition systems require several hundreds of feet of wiring from the sensors to a centralized data acquisition node. A wireless data acquisition system is much easier to deploy, not just because the placement of sensor is unconstrained by the availability of power and network connectivity, but also because a multi-hop wireless network (in which nodes can relay data towards one or more base stations) offers significant placement flexibility in not requiring nodes to be within radio range of a base station.

The design of the software subsystem for wireless data acquisition is quite challenging. In the rest of this section, we describe how we design a self-configuring wireless data acquisition system which allows rapid, reliable and time synchronized delivery of many channels of structural response to a base station. Our software subsystem is built on top of TinyOS, the operating system for the motes.

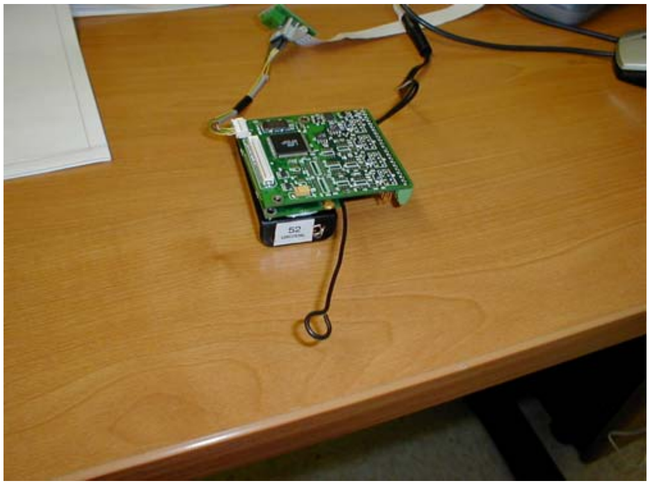

Figure 1. A mote with a vibration card

Self-configuration

A key requirement for a wireless seismic array is self-configuration – the ability to form, without manual intervention, a (possibly multi-hop) communication structure across all nodes for transporting data to the base station. For this purpose, we use a TinyOS software component that essentially creates a communication tree with the base station as the root. To create this structure, the base station periodically sends "heartbeat" messages throughout the network [3]; as the message traverses the network, nodes choose parents. A parent is the next hop from a node towards the base station.

An important aspect of this self-configuration is the ability to choose "reliable" parents. It is well-known that the quality of wireless links depends upon node placement and can vary with time. A node may have several parents and can thus choose one to which communication is likely to incur fewer data losses. Because the parent selection is repeated often, nodes will switch parents when the communication quality to its current parent degrades or when its current parent fails (*e.g.*, due to battery depletion). The multi-hop module incorporates this functionality, and it thereby improves the overall system performance.

Reliability

Selection of a reliable parent is not a guarantee for lossless communication. Thus, on top of this communication structure, we have built a simple mechanism for ensuring reliable transmissions. Such mechanisms have been extensively studied in the computer network literature, and involve signaling between nodes to detect and repair message loss.

Our mechanism recovers lost messages at every hop and works as follows. Nodes keep track of sequence numbers of messages they receive; a gap in the sequence number indicates message loss. Each node maintains a list of missing messages. When a loss is detected, the corresponding sequence number is inserted into this list. A node transmits this list in outgoing transmissions; the corresponding child picks up this transmission, infers that its parent has not received a particular message, and retransmits that message from its local memory (this requires, of course, that messages be cached in local storage). With sufficiently large buffering memory, our scheme enables reliable transmission of messages across the network, a fact which we have empirically verified.

Compression

Loss in packet transmission is just one of the challenges encountered while operating in a wireless environment. Another is limited data transfer bandwidth. In particular, the data transfer rate of the entire network is constrained by the radio receive bandwidth offered by a single radio (that at the base station).

We use two simple techniques to deal with this challenge. First for an N channel seismic array, we constrain each node to transmit at $^1/_N$ of the nominal radio bandwidth. More importantly, however, we use data compression to reduce the transfer rate requirements.

While lossy compression schemes can provide significant reduction in data rates, they are clearly not applicable given that we are designing a data acquisition system. Lossless compression schemes generally rely on detecting repeating patterns in the data. Our system uses a simple but effective silence suppression scheme for compressing vibration data. Essentially, it encodes a silence period (defined as a sequence of samples whose values lie within a small range) as a “run-length” (a sample value and a number of samples). This approach can reduce the volume of data transferred in situations where the duty-cycle of vibrations is expected to be small. The approach is also desirable since it reduces network communication (and therefore energy expenditure). Of course, other more sophisticated compression schemes exist; we have deferred an exploration of such schemes to future work.

These two techniques, transmission rate-limiting and compression, together ensure that if the long-term average duty cycle of vibrations is a fraction, f, then our system will provide near real-time data collection from $^1/_f$ channels. Short-term duty-cycle variations can be accommodated by buffering vibration data in node memory.

Time Synchronization

The final piece of our system is a technique to ensure that samples collected at the same time at different nodes can be temporally aligned at the sink. In Figure 2, suppose samples s_A and s_B are collected at the same time at nodes *A* and *B*, respectively. These samples, after compression and encapsulation into messages, are transmitted over multiple hops towards sink *S* and take two different paths. s_A passes through nodes *A1*, *A2* and *A3* while s_B passes through *B1* and *B2* before reaching *S*. The total transmission times *i.e.*, spent by samples T_A (for s_A) and T_B (for s_B) in the network will be different and hence these samples will reach *S* at different times. The challenge is to align s_A and s_B at *S* after it has received them.

One solution is to synchronize time in all the sensor nodes, this is also known as global time synchronization in sensor networks [4]. Mechanisms for global time synchronization have been proposed and implemented. However, global time synchronization incurs overhead in terms of periodic beaconing to compensate for the clock skew (difference in clock rates) that may be present in the clocks of different sensor nodes. In our implementation we take a different approach to avoid the overhead of global synchronization and at the same time enable synchronization of collected samples at the sink. Instead of attempting to synchronize time on all the sensor nodes we calculate the total time spent by the samples in the network and use this information to synchronize the samples.

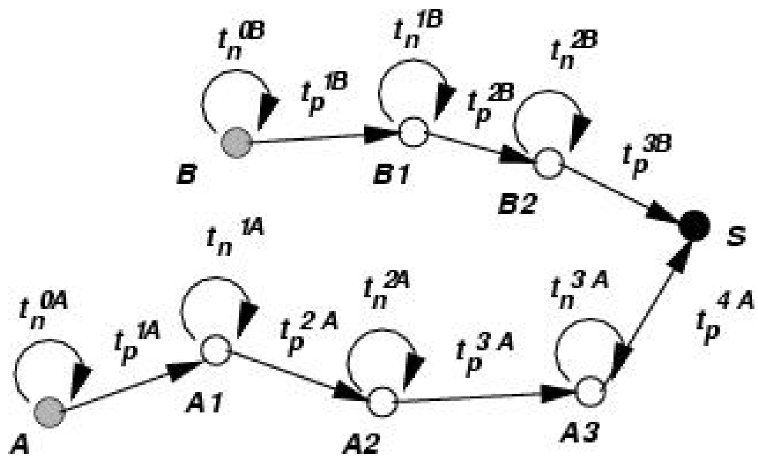

Figure 2. Time synchronization example

We explain our scheme through an example. In Figure 2, let t_n^{iA} be the time spent in at the i^{th} hop node and let t_p^{iA} be the propagation delay for the i^{th} hop. Then,

$$T_A = \sum_{i=0}^{i=2} t_n^{iA} + \sum_{i=1}^{i=3} t_p^{iA} \qquad (1)$$

Noting that propagation delay (of radio waves) incurred over several hundred meters (path distance to sink) is in the order of nanoseconds, we neglect the second summation in Equation 1. The time spent at a node is generally on the order of milliseconds and cannot be neglected. Under this assumption, T_A can be calculated by summing up the times spent at each node. In our implementation each transmitted packet has a header field which carries the summed times spent at all the encountered nodes. As this packet reaches the base station *S*, the sink notes the time (its own local time) at which it received this packet say t_A. Hence, the sample must have been generated at $t_A - T_A$ (T_A is obtained from the packet header) in the local time of the sink. The same procedure is applied for sample s_B. Now s_A and s_B can be aligned since $t_A - T_A = t_B - T_B$ and nodes do not require global time synchronization. We rely on the fact that while clock skews are not negligible of the scales of several tens of minutes, they are not significant over the time scales of multi-hop transmission delays.

Status and Discussion

We have prototyped these components into a working software system. To visualize the acquired data, we have written a GUI application in Java, which reads data at the base station, decompresses the data, and aligns the samples based on the timestamp information. Figure 3 depicts the collection of vibration signatures from several nodes.

We intend to deploy our array at the Four Seasons site. The goal of such a deployment would be to get some real-world experience on how well wireless arrays work --- whether they significantly simplify deployment, and whether they perform as well as wired acquisition systems. Longer-term, we intend to study how to make these arrays more energy efficient so that they can be deployed for extended periods of time in structures.

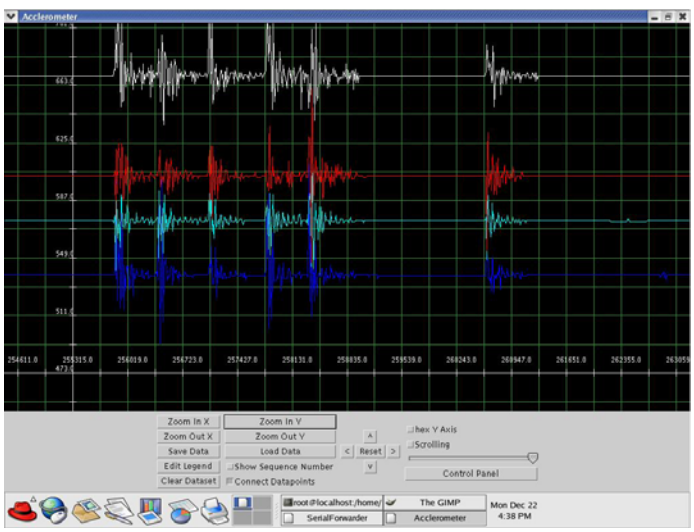

Figure 3. Screenshot of synchronized channels

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