High-Frequency Distributed Sensing for Structure Monitoring

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ABSTRACT

Structural health monitoring (SHM) involves continuous monitoring of a structure's condition with near real-time analysis of sensed data. The emerging wireless sensor network (WSN) technology enables distributed data acquisition and processing for structure monitoring applications, which currently adopt a centralized solution, using a network of intelligent sensors. We design a robust WSN-based distributed sensing system for high-frequency data acquisition in structure monitoring. The system emulates the functionality of a centralized sensing system employing analog sensors, achieving comparable performance. The resulting compatibility with existing centralized SHM algorithms will facilitate the adoption of sensor network technology for structure monitoring. The networking and sensing services comprising the system also enable *in situ* data processing in WSNs, providing a seamless transition from centralized to fully distributed structural health monitoring applications.

Keywords: wireless sensor network, structural health monitoring, high-frequency sensing

INTRODUCTION

The goal of structural health monitoring (SHM) is to determine the condition of the monitored structure and identify potential problems at an early stage, by examining the output of sensors attached to the structure. This may involve measuring strain values or vibration characteristics at different points in a building. Most existing SHM applications have taken an approach employing centralized data processing, with a small number of analog sensors wired to the central controller [2]. In these systems, data acquisition and processing capacity of the central node places limits on scalability. Wiring sensors to a central node in a large structure is expensive and cumbersome (the wires may cost more than the sensors!); it may also be detrimental to system reliability as wires may be damaged and severed.

Recent advances in sensing and networking technologies have led to the emergence of wireless sensor networks (WSNs). Composed of a large number of small, intelligent sensor nodes, WSNs have started replacing centralized sensing and control systems with a distributed alternative [7]. WSNs are attractive because they offer increased robustness through decentralization. For example, a distributed sensor network would continue to function, at diminished capacity, even when it sustains the failure of a large fraction of the sensors. WSNs do not suffer from wire breaks in catastrophic events such as earthquakes. Moreover, some of the data processing may occur locally at the sensors, reducing the control turnaround time and improving overall system responsiveness.

We develop a high-frequency distributed sensing system for structure monitoring applications on a WSN platform consisting of Mica-2 motes and Mica sensor boards [1]. A Mica-2 mote is equipped with a 433 MHz RF transceiver for wireless communication, with maximum raw data rate of 19.2Kbps (*i.e.*, network bandwidth is very limited). For storing measurement data, 512KB of serial flash memory are available. The WSN-based sensing system enables bringing data processing and control into the network itself. It is designed to be highly customizable; the system provides options for local data processing, data aggregation and different sensing modalities.

In this paper, we describe our experience with the distributed sensing system with centralized data processing on a wireless sensor platform. The objective of building such a system is to facilitate the transition to fully distributed SHM applications. We present the evaluation results and discuss the limitations of current WSN platforms for use in SHM applications. We examine future research directions and conclude the paper with a brief summary.

STRUCTURAL HEALTH MONITORING WITH WIRELESS SENSOR NETWORKS

In traditional centralized sensing systems, sensors continuously generate data that are sampled by a central data acquisition unit. SHM computations are performed after the desired amount of data is collected. We develop a WSN-based system that emulates the functionality of centralized sensing systems, with added benefits of increased robustness and lower cost.

Requirements

With the current WSN technology, it is not possible to sample sensors at a sufficient frequency while sending data over the network. In order to sample sensors accurately at a high rate, we must disable other sources of high priority interrupts in the sensor node, *e.g.*, the radio. For this reason, we first store sensor data in the flash memory to be retrieved later. Thus, the size of the flash memory limits the maximum duration of uninterrupted sensing. On Mica-2 motes, which have 512KB of flash memory, we are able to record approximately 90 seconds of continuous data at 250Hz.

Second, we need a way to deliver sensor data to the processing station reliably, since current SHM algorithms require that no sensor readings are lost to work properly. We develop an adaptive self-healing tree routing service for establishing a mesh network among the sensors to transport the data efficiently and reliably. *Path length* is the primary criterion for establishing the tree structure, with *link quality* being the secondary. To maintain connectivity within the network, each node periodically sends out heartbeat messages. The advantages of this method include: *1)* optimal bandwidth utilization for sensor-to-gateway communication, which is dominant in this scenario, *2)* memory efficiency: only constant amount of storage space per node is used, *3)* simple and fast fault recovery: the tree can quickly adapt to node failure without causing global topology changes.

Finally, it is important for the sensors' clocks to be synchronized within a tight error bound. Distributed sensor readings are meaningless, unless they can be correlated on a global time scale. We adapt the FTSP time synchronization service [4] to maintain clock synchrony. By piggybacking time synchronization messages on the heartbeat messages, we are able to establish synchronization without consuming any additional bandwidth. The time synchronization service can maintain better than 1ms synchronization for a long period of time (Figure 1). This is sufficient to ensure proper synchronization for our target application.

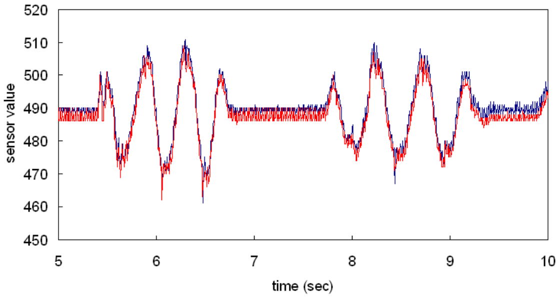

Figure 1: Accelerometer data from two sensors showing tight synchronization.

Distributed Sensing and Control

When put together, these services form a basis for building a distributed sensing and control platform. Distributed sensing enables application of SHM techniques to large-scale structures. Local actuation is useful for control applications as it decreases reaction time and improves overall responsiveness. We use these services to emulate a centralized sensing system that features sensing frequencies and synchronization precision similar to its centralized counterparts, and improved reliability. Its purpose is to facilitate transition to truly distributed sensing and control.

EVALUATION

We study the performance of the distributed sensing system using two sets of experiments: accelerometer and strain gage sensor measurements to verify precision, and networking tests to examine time synchronization and scalability. The objective of the experiments is to demonstrate the viability of this system for real-world SHM applications.

We use Mica-2 motes from Crossbow, Inc. [1], equipped with a mix of standard sensor boards, an improved accelerometer sensor board, and a strain gage sensor board. All measurements are made on 3- and a 18-story building models (Figure 2) placed on a shaking table that produces white noises at frequencies of 1 to 100Hz. Sensing is performed at 250Hz for 60 seconds. Sensors are located on each floor of the model, spaced approximately 30cm apart. Radio power is reduced in order to induce multi-hop communication.

Figure 2: Experimental setup: sensors are attached to an 18-story building model on a shaking table.

For comparison, a typical tower building where an SHM application may be deployed is 100 to 300m tall and contain one sensor per one to five floors. More advanced SHM applications may require multiple sensors per floor. Sensing must be performed at frequencies of at least 100Hz, for an indefinite duration.

Sensor Precision

The Mica sensor board has an accelerometer (model ADXL202E), which has insufficient precision for the kind of measurements required for typical SHM applications. We use sensor boards customized with an accelerometer (Silicon Designs model 1221 [9]), which is suitable for low noise applications [8]. Its performance is comparable to that of analog accelerometers (*e.g.*, PCB Piezotronics model 393B04 [6]) used for SHM (Figure 3). We also use a strain sensor developed specifically for use in SHM applications with Mica-2 motes [5], capable of achieving the sufficient precision (Figure 4).

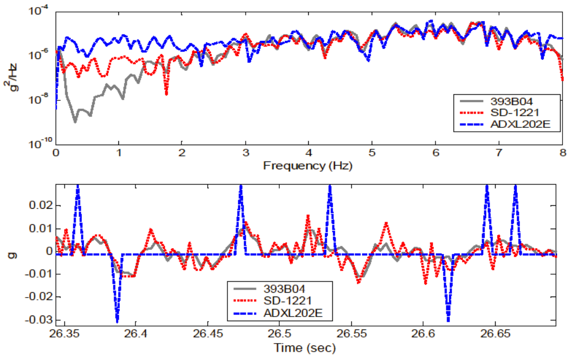

Figure 3: The improved Mica accelerometer (393B04) exhibits precision comparable to that of an analog one (SD-1221) for SHM [8]. ADXL202E shows data from the standard Mica sensor board.

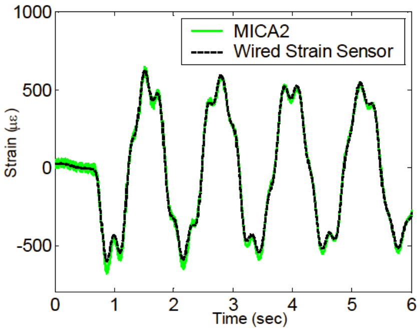

Figure 4: A Mica-2 strain gage we used shows precision comparable to that of a wired strain sensor [5].

Data Aggregation

As we discussed earlier, for centralized sensing in a Mica-2 sensor network, sensors store measurements in local memory and later send them to the processing node. Data from different sensors are aggregated on the way to the central node. The efficiency of data aggregation is critical to the scalability of the distributed sensing system. A fully distributed sensing system would still need data aggregation, though on a smaller scale. We evaluate the performance of this data aggregation phase in our system.

Table 1 shows the time it takes to transfer all of the sensor data recorded at 250Hz for 60 seconds and the ratio of aggregation time to sensing time, for varying numbers of sensors. The data aggregation phase is very long even with a relatively small number of sensors, which was expected, since even two sensors can saturate the bandwidth of the data acquisition node. (Recall that a Mica-2 mote has the maximum raw data rate of only 19.2Kbps.) Additional sensors competing for the bandwidth only increase congestion and exacerbate the sensing/aggregation imbalance.

Table 1: Aggregation time and aggregation-to-sensing ratio for 60s of sensor data.

Sensors	1	2	4	8	16
Time	288s	491s	818s	2136s	6287s
Ratio	4.80	8.18	13.63	35.60	104.78

DISCUSSION

Data compression may help alleviate the sensing/aggregation imbalance to some extent, although only by a constant factor. Another way to tackle the bandwidth limitation is to employ *in situ* processing: letting sensors perform local processing on the raw data and transfer only the summary results would keep the network from being saturated. In the Mica-2 platform, one microprocessor controls both sensing and communication on a node. Having separate controllers would enable concurrent sensing and communication, further reducing the extent of the imbalance. Such an architecture would also open up the possibility of new communication controller designs optimized for power usage [3].

In principle, the problem stems from the low-rate design of communication protocols in emerging WSNs (*e.g.*, the Mica-2 protocol and ZigBee/IEEE 802.15.4 [10]). Given the fact that sensors on WSNs operate on a limited power supply, the choice of “low-rate” is uncompromisable. Thus, these low-bandwidth wireless networks cannot perform well with high-volume data transfer, which is unavoidable in any centralized SHM applications. Our experiment results have confirmed this. Exactly for this reason, we argue that structure monitoring and control applications built on WSNs should be fully distributed. Our communication and synchronization services will facilitate the transition.

CONCLUSION

We present a high-frequency distributed sensing system for structure monitoring. Within limits of the wireless network, we adapted the system to emulate a traditional centralized sensing system by gathering data and returning it to a central location for processing. Through the experiments using realistic building models we were able to show that we could achieve time synchronization precision and sensing resolution comparable to those observed in wired SHM systems employing analog sensors. We believe that the system’s high adaptability makes it suitable for fully distributed sensing and control, which we view as a future direction for structural health monitoring and control applications.

ACKNOWLEDGMENTS

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