Title: **Demonstration of Damage Detection with a Wireless Sensor Network**

Author(s): Neal A. Tanner, Charles R. Farrar

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Demonstration of Damage Detection with a Wireless Sensor Network

Neal A. Tanner[1], Charles R. Farrar[2]

[1]Dept. of Mechanical Engineering, Stanford University. Palo Alto, CA 47907
[2]Engineering Analysis Group, Los Alamos National Laboratory. Los Alamos, NM 87545

ABSTRACT

A damage detection system was developed with commercially available wireless sensors. Statistical process control methods were used to monitor the correlation of vibration data from two accelerometers mounted across a joint. Changes in correlation were used to detect damage to the joint. All data processing was done remotely on a microprocessor integrated with the wireless sensors to allow for the transmission of a simple damaged or undamaged status for each monitored joint. Additionally, a portable demonstration structure was developed to showcase the capabilities of the damage detection system to monitor joint failure in real time.

NOMENCLATURE

x	acceleration, position x
y	acceleration, position y
XCC	cross correlation coefficient
i	sample index
n	number of samples
F	data feature
μ	mean value
σ^2	variance
S	outlier statistic
T	binary outlier indicator

1.   INTRODUCTION

Structural health monitoring is the implementation of a damage detection strategy for aerospace, civil and mechanical engineering infrastructure. Typical damage experienced by this infrastructure might be the development of fatigue cracks, degradation of structural connections, or bearing wear in rotating machinery. However, with the exception of applications to rotating machinery, a review of the literature [1] shows that there are no examples of reliable strategies for SHM that are robust enough to be of practical use. The authors feel that this lack of success is, in part, due to the common approach taken where the monitoring is accomplished with a limited number of sensors dispersed over a relatively large area of the structure. Therefore, the goal of this research effort is to develop a robust and cost-effective *local* structural health monitoring solution where the engineer must take greater care to more precisely define the damage that is to be detected. Such definitions allow the sensors to be better placed to capture changes in the system's dynamic response that are indicative of damage.

This local monitoring system approach is based on integrating and extending various engineering and information technology disciplines. This structural health monitoring approach couples structural dynamics and statistical pattern recognition with wireless micro-electromechanical systems (MEMS) being developed at the University of California, Berkeley [2]. The authors believe this coupled approach is key to developing a robust local structural health monitoring system.

Because each structural health monitoring solution must be developed for a specific application, this effort will focus on monitoring bolted joints, as they are pervasive to many engineering systems. However, a significant portion of this technology development, particularly that associated with the development of LANL's data interrogation schemes, has generic application to a wide range of structural health monitoring applications.

Off-the-shelf wireless sensing hardware with local processing capability was utilized for this project. Basic statistical outlier detection algorithms were programmed onto the local processors. This system was then used to monitor

the loss of preload in a bolted connection. A demonstration structure was developed where preload in a joint could be released without adding additional inputs to the structure. This paper concludes by summarizing issues that must be addressed from the hardware and software perspectives if this system is to be deployed on an actual structure.

2 SENSING HARDWARE

2.1 General Description

For this project, emphasis was placed on adapting the structural health monitoring system to the limitations of off-the-shelf wireless sensing and data processing hardware because of the focus towards a proof of concept rather than designing a field installable product. A wireless sensing system of "motes" developed at UC Berkeley and running UC Berkeley's TinyOS operating system was chosen because of their ready-made wireless communication capabilities. A mote consists of modular circuit boards integrating a sensor, microprocessor, analog to digital converter (ADC), and wireless transmitter. A significant reduction in power consumption can be achieved by processing the data locally and only transmitting the results.

2.2 Accelerometers

Two sensor boards were obtained from UC Berkeley that contained ADXL202 accelerometers. The ADXL202 is a dual axis, +/- 2g MEMS accelerometer available commercially from Analog Devices. The sensors board's original configuration only allowed for a bandwidth of 50 Hz, but was modified by changing capacitors to increase the bandwidth of the accelerometer to 1 kHz. The accelerometer mounted on the circuit board is shown in Fig. 1
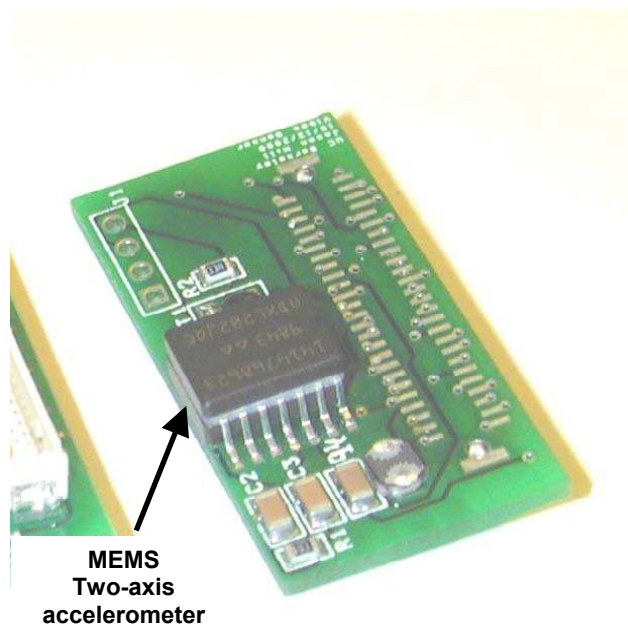

**MEMS
Two-axis
accelerometer**

Figure 1: Two-axis accelerometer mounted on a circuit board.

2.3 Processing Boards

Four processor boards were obtained from UC Berkeley that mate directly with the sensor boards. The core of the processor board is a 4 MHz ATMEL AVR 90LS8535 microprocessor with 8 KB of flash program memory and 512 bytes of RAM. A 10-bit ADC is included in the microprocessor. The ADC is capable of sampling 8 channels but only by sequentially multiplexing them. The processor board also contains three LEDs and a short range 916 MHz radio. The processor board is shown in Fig. 2
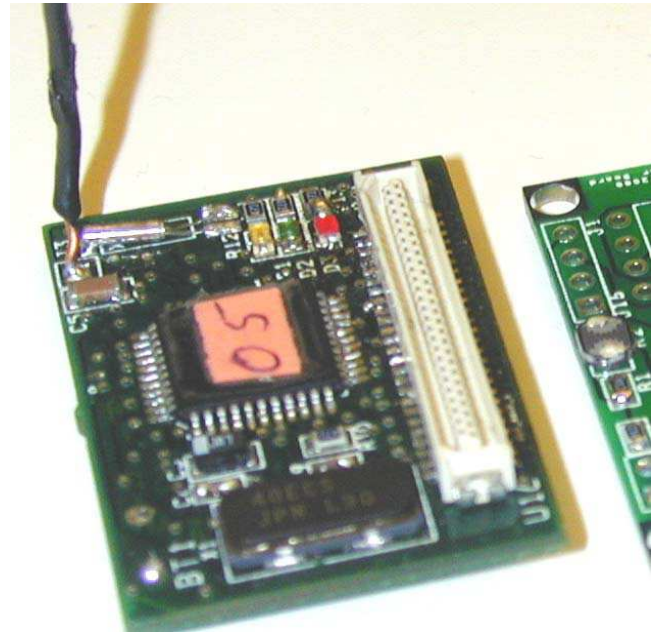

Figure 2: Processing board with wireless transmitter.

2.4 Programming Bay

Programs were written on a PC and compiled into a binary image file that was downloaded into the flash program memory on the processing board. This software download was accomplished by placing the processing board in a programming bay connected through the PC's parallel port. The programming bay also connected to the PC's serial port to allow for data transfer from the processing board back to the PC. The programming bay is shown in Fig. 3.
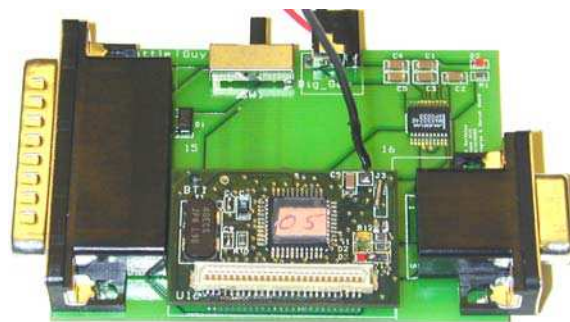

Figure 3: Processing board mounted in programming bay.

2.5   Putting it all Together

Custom cables were made to connect two independent accelerometers to a single processing board and isolate them from the dynamics of the original cantilever connection between boards. A simple crossover in one of the cables allowed the two accelerometers to be accessed through separate channels on the ADC. In this manner, a single processing board could collect data from a pair of accelerometers (for up to a total of 4 channels), perform basic digital signal processing on the measured time histories, and broadcast the processed data over the radio. A second processing board situated in the programming bay received broadcast data and relayed it to the PC.

2.6   System Performance Properties

The ADC itself can handle sampling rates of up to 4 kHz, but the achievable sampling rates were dictated by either the radio bandwidth (when transmitting raw data) or the processing power of the microprocessor and typically ranged between 256 Hz and 1 kHz. Because the ADC multiplexes 8 channels onto a single actual converter, two channels cannot be sampled simultaneously. The minimum time offset between samples from two channels was on the order of 30 microseconds. The system had a full-scale range of +/- 2g with a resolution of 17 mg.   Both accelerometers and ADCs showed considerable DC bias and required calibration for each combination of a particular accelerometer and ADC.

3   DEMONSTRATION STRUCTURE

3.1   Concept

The demonstration structure was to develop for use both as a laboratory test bed for studying damage in bolted joints as well as a portable demonstration platform for both the wireless and traditional structural health monitoring systems. The goal was to be able to introduce damage to a joint without disturbing the structure. This design would allow for continuous monitoring during the introduction of damage rather than looking only at discrete data sets taken before and after damage.

3.2   Design

The demonstration structure is a 56 cm x 30.5 cm bolted frame. The beams are 5 cm x 0.6 cm aluminum bar stock bolted together with 5 cm long pieces of 6 cm angle iron and mounted to a 1.3 cm aluminum base plate. Each beam to angle joint uses a single 13 mm steel bolt.   All mating surfaces were sanded to provide a smoother contact area. The first bending mode of the structure was measured as approximately 37 Hz.

3.3   Modifying the Preload

Three piezoelectric ring actuators were purchased from Peizomechanik. These actuators have a 25 mm OD, a 15 mm ID, a 23 mm length, a maximum force of 10 kN, and a maximum stroke of 15 micrometers. By placing one of these actuators underneath the head of one of the 13 mm bolts, a predicted change in bolt tension of 4 kN could be achieved by varying the input to the actuator from –200 V to +1000 V.

This change in preload was used to simulate damage in the form of a loosening bolt while monitoring the structure in real time.

Figure 4:   PZT washer stack used to vary preload in the bolted connection.

3.4   Excitation

For the purpose of portability, a small electromagnetic shaker was used to excite the structure. The shaker could be positioned to excite the structure either vertically or horizontally at several different locations. To avoid having to transport large amplifiers and signal generators with the structure, a virtual signal generator was written in MATLAB that outputs the signal to a standard set of computer speakers. The left computer speaker was replaced with the shaker that was powered by the small stereo amplifier built into the right computer speaker. By performing the signal generation and amplification on the laptop along with the sensor programming and data collection, the entire demo can be transported in a moderate sized suitcase.   The demonstration structure is shown in Fig. 5 and 6.
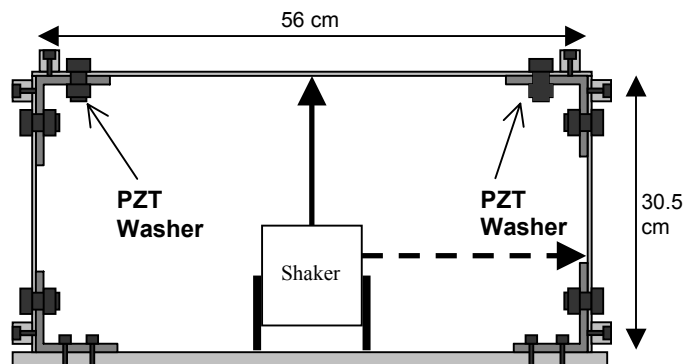

Figure 5:   Schematic diagram of the demonstration structure.

Figure 5: Actual demonstration structure.

4 DATA INTERROGATION SOFTWARE

4.1 TinyOS

TinyOS is an operating system developed at UC Berkeley for small remote sensors like the ones used for this project. It is built on top of the C programming language and provides the programmer with pre-packaged functionality for interfacing with hardware components such as the radio and ADC. TinyOS also allows for configuring a group of sensors into a network for mote-to-mote communication and message relaying back to the base station. The data processing can basically be written in C with minor modifications to incorporate it within TinyOS. All sensor programming for this project was done within the confines of TinyOS.

4.2 General Approach

The general approach for the data interrogation software was to track the statistical distribution of some feature extracted from the accelerometer signal or signals. For the first approach, the features used were the maximum and minimum values of each packet of 100 data points from a single sensor. The implementation of this approach could be run at a sampling rate of 1 kHz. For the second approach, the feature used was the cross correlation coefficient between data from two sensors mounted across a joint. This approach utilized two accelerometers (x and y), positioned across a joint and that measured response in the same direction. The cross correlation coefficient, XCC, was calculated as

$$XCC_n = \frac{\sum_{i=1}^{n} x_i \times y_i}{n},$$

(1)

which corresponds to a non-normalized, discretized, special case (τ=0) of the cross correlation function. The packet size, n, was typically 32. This approach could only be implemented at a sampling rate of 256 Hz. The lack of sufficient memory to log an entire packet's worth of data forced the use of "on-the-fly" algorithms that significantly decreased the attainable sampling rates.

4.3 Training Phase

Once a feature, F, had been calculated for a packet of data, it was passed on to a training algorithm that continuously tracked the feature mean, μ, and variance, σ^2, as

$$\mu_{n+1} = \mu_n \times \left(\frac{n}{n+1}\right) + \frac{F_{n+1}}{n+1},$$

(2)

$$\sigma_{n+1}^2 = \sigma_n^2 \times \left(\frac{n-1}{n}\right) + \mu_n^2 + \frac{F_{n+1}^2}{n} - \mu_{n+1}^2 \times \left(\frac{n+1}{n}\right).$$

(3)

This training was performed with the structure in a known "healthy" condition and used to establish statistical process control bounds on the features. Bounds were typically set at $\mu \pm 2.5\sigma$. This processing was originally done on the main processing board, but due to time, memory, and processing constraints in calculating the variance, it was temporarily offloaded onto the laptop. This processing shift was accomplished by broadcasting the values of the feature back to the base station for processing in MATLAB. After the bounds were calculated in MATLAB, they were hard-coded back into a monitoring program on the processing board. It should be possible to refine the calculation of the variance such that setting the bounds for the feature can be moved back onto the processing board, thus allowing for the consolidation of separate training and monitoring programs into different phases of a single self-training monitoring program.

4.4 Monitoring Phase

In the monitoring phase the features are calculated in exactly the same manner as in the training phase, but are then checked against the bounds set on their distribution. When an outlier is detected, it's occurrence is signaled either through the lighting of the yellow LED or the transmission of a message back to the base station. In addition, a statistic is continuously maintained which gives an indication of the frequency of outliers within an exponentially weighted time window. This statistic is calculated as

$$S_n = S_{(n-1)} \times \left(\frac{24}{25}\right) + T \times 40$$

(4)

$$T \in \{0,1\}$$

(5)

where S is the statistic and T is a binary variable representing the existence or absence of an outlier. This statistic has a range from 0 to 1000 and oscillates around a value 10 times the percentage of outliers for evenly spaced outliers. The value of this statistic will also show a high valued spike for a quick succession of several outliers. In the current monitoring program, the red LED signals joint damage when this statistic exceeds 100. Due to the oscillatory nature of this statistic, this represents an evenly spaced occurrence of about 6% outliers or 3 or more outliers in a tight cluster. In addition to signaling joint damage with the red LED, a message can also be transmitted back to the base station.

5   EXPERIMENTAL RESULTS

5.1   *Damage Detection on Demonstration Structure*

Using the cross correlation coefficient approach, remote structural health monitoring was successfully demonstrated on the portable demonstration structure. The structure was excited horizontally near the base with a 100 Hz sin wave and accelerometers were located across the actuated joint. With the actuator in the fully contracted position, the bolt was hand tightened. The actuator was then set to its fully expanded position, thus providing a nominal tension in the bolt. All other bolts were tightened to 120 in-lbs. In this configuration, the training program indicated that the cross correlation coefficient across the actuated joint had a mean of 1.5 and a standard deviation of 3.0. The resulting bounds of –6 and +9 were programmed into the monitoring program. The monitoring program was started with the actuator at full voltage, representing the healthy structure, and correctly showed no damage. When the voltage to the actuator was removed the monitoring program detected the newly introduced damage and signaled it accordingly. The yellow LED flashed repeatedly as outliers were detected and after a few seconds the red LED came on, signifying that the onboard statistical process control had successfully detected the simulated failure of the joint. Upon reapplication of the voltage to the actuator, the monitoring program displayed the return to the healthy condition of the joint. Further analysis of the cross correlation coefficient time histories showed that in the damaged condition, the cross correlation coefficient had a mean of –3.5 and a standard deviation of 5.0. As further runs were completed, the specific values of the cross correlation coefficient changed with changing excitation, but the shift between damaged and healthy conditions remained detectable. A sample time history showing both healthy and damaged conditions as well as the thresholds used for detection is shown in Figure 7.
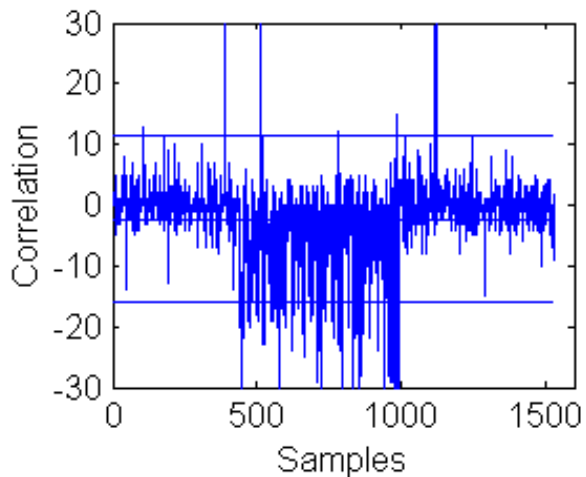
Figure 7: Change is correlation values caused by reducing and then increasing the preload in the bolted connection on the demonstration structure.

5.2   *Vehicle Detection on Highway Bridge*

During a field test of a separate hard wired system on a highway bridge, an early version of the monitoring program utilizing the maximum/minimum approach was installed on one of the piers underneath the bridge as shown in Fig. 8. Using the no-traffic condition to simulate the healthy or normal situation, the remote sensor easily detected and signaled the passing of vehicles on the bridge above.

Figure 8: Accelerometers and processing board mounted on bearing plate under a bridge girder at a pier.

6   HARDWARE AND SOFTWARE ISSUES

Due to the approach of using off the shelf hardware, several very serious issues arose that greatly complicated or impeded the development of the remote structural health monitoring system.

6.1   *Sensing System*

The first of these limitations arose out of the very limited range and resolution of the sensing system itself. The range was limited by the accelerometer itself while the resolution was limited by only having a 10 bit ADC. All 10 bits were not even usable because the voltage range of the sensors and the ADC did not match. This mismatch resulted in a very narrow excitation range where enough resolution was maintained without overloading the sensors. Additionally, this range of excitation had to be made to coincide with the level of excitation required to generate relative motion at the joint in the loosened condition. A final limitation of the actual sensing system was the inability to simultaneously sample multiple channels for calculating the cross correlation coefficient. Sampling the two sensors sequentially causes the correlation to break down if there is any high frequency content in the signals. All of these issues could be easily remedied by selecting sensors and an ADC that were better suited to this application.

6.2 Memory

Because of the small size of the flash program memory, any programs that contained floating-point calculations would not fit into the flash. Having to perform all processing in integer format led to some very harsh tradeoffs between range and precision of calculations. This problem was the source of difficulty with calculating the variance of the features on the processing board that resulted in temporarily having to calculate the statistical process control bounds in MATLAB. Similar but less drastic complications and inaccuracies are found throughout the programs. The extremely small amount of RAM available on the processing board prevented the storing of buffers of data for lumped processing. This was dealt with by working entirely with "on-the-fly" algorithms but at the cost of consuming additional processing time and ruling out many options such as data normalization. The lack of any data normalization means that features such as the cross correlation coefficient are not independent of excitation and therefore the monitoring program must be retrained for any changes in excitation or environmental conditions.

6.3 Processing Power

Processing power is almost always the limiting factor in attainable sampling rate for the application of this hardware to structural health monitoring. Much of the expected change in a structure from the introduction of damage is expected to be at much higher frequencies than this system can currently resolve. For this demonstration, the frequency content of the signal was kept very low through the design of the structure and its excitation. The ability to run at much higher sampling rates would allow for the application of this approach to much more generalized structures and excitations. Additional processing power would also enable the incorporation of far more sophisticated methods of feature extraction and statistical analysis of the data. The processing limitations encountered were specific to the current hardware and are not inherent for other hardware of similar size and cost.

7 SUMMARY

The purpose of this study was to develop and demonstrate a wireless structural health monitoring system for structural joints. The system was applied to a demonstration structure specifically designed such that preload in the bolted connections could be modified without introducing extraneous inputs such as those caused by the impact of a wrench applied to the joint. The health monitoring system was developed from commercially available wireless sensing technology that was integrated with a local processing capability.

Within the hardware limitations of this off-the-shelf system the monitoring system was shown to successfully identify changes in the preload of a bolted connection. This damage was detected by implementing simplified statistical pattern recognition algorithms onto the local processor. And applying these algorithms to acceleration-time histories measured with the system.

Now that it has been shown that structural health monitoring can be implemented using onboard processing of data from remote sensors, the logical next step is to develop a set of hardware tailored to fit the needs of an "real-world" structural health monitoring application. The technology is readily available to design a remote sensing system with significantly greater capabilities in data acquisition, processing, and storage. Removing the barriers created by the limited hardware capabilities of the current system will open up tremendous room for further development of wireless structural health monitoring systems.

To this end, current work is focusing on using detailed finite element analysis of a candidate structural joint to establish the parameters of such a wireless structural health monitoring sensing system. These parameters include the required bandwidth and sensitivity of the measurement hardware, optimal locations for the sensors at the joint, and appropriate features that will be indicative of a particular damage phenomena such a cracking of weld or loosening of a bolt.

REFERENCES

[1] Doebling, S. W., et al., (1998) "A Review of Damage Identification Methods that Examine Changes in Dynamic Properties," *Shock and Vibration Digest* **30** (2), pp. 91-105.

[2] See http://www.xbow.com/