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Wireless Strain Sensor Development for Civil Infrastructure†

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Industrialized nations have made huge investments in civil infrastructure and attention must be given to its proper maintenance. Structural Health Monitoring (SHM) and Damage Detection (DD) strategies have been developed by many researchers in support of efficient operation and maintenance of civil infrastructure. Smart wireless sensor networks are promising in that they have the potential to dramatically improve SHM/DD. The Berkeley Mote smart sensor, with its embedded microprocessor and wireless communication capability, has emerged as an important new open hardware/software platform for SHM/DD. However, available sensors are limited and not necessarily optimized for civil infrastructure applications. Strain is one of the important physical quantities used to judge the health of a structure; strain sensors are currently unavailable for the Berkeley Mote platform. In this paper, a new strain sensor board for the Berkeley Mote platform is developed, and its performance is experimentally verified.

Key Words: strain sensor, wireless sensor, civil infrastructure, smart sensor, sensor network

1. Introduction

Industrialized nations have huge investments in civil infrastructure which needs proper ongoing maintenance. About 10-15 % of their GDP is typically spent for infrastructure every year [1),2)]. Our infrastructure is valuable asset, but without proper maintenance, can deteriorate and even become a liability. Indeed, poorly maintained buildings accommodating numerous people and bridges with heavy traffic may pose a significant hazard to both life and property.

SHM/DD strategies have been developed by many researchers in support of efficient operation and maintenance of civil infrastructure [3)]. Estimates of the health of a structure are sought through monitoring physical behavior and environmental condition, for example, acceleration, strain, and temperature. Current approaches collect measured responses at a centralized data acquisition and analysis system. Such approaches suffer from expensive sensor installation/wiring, signal degradation along lengthy cables, and data flooding.

Smart wireless sensors have recently been proposed to facilitate deployment of dense arrays of sensors on structures in support of more effective SHM/DD [4)]. Networked smart sensor nodes with embedded microprocessors and wireless communication capabilities offer many opportunities. For example, smart sensors can assess several structural quantities and/or environmental factors, combine these data from their own measurement and/or from neighboring sensor nodes, and process these data to extract important information about the structural system.

The Berkeley Mote smart sensor [5),6)] has emerged as an important new open hardware/software platform for SHM/DD. The Mote platform has a microprocessor and radio communication. Users can easily customize both the hardware and software. However, the available sensors are limited and are not necessarily optimized for civil infrastructure application. For instance, Ruiz-Sandoval et al [7] pointed out that the typical Mote accelerometer sensor board has low sensitivity and that its target frequency range was too high. They developed new accelerometer sensor board with high sensitivity and low noise. In addition to acceleration, strain is one of the important physical quantities to judge the health of a structure; currently, strain sensors are unavailable for the Berkeley Mote platform.

In this paper, a new strain sensor board for the Berkeley Mote platform is developed and its performance experimentally verified. The results are quite promising.

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2. Background

An open hardware/software platform for smart sensing applications has recently been developed with substantial funding from the US Defense Advanced Research Projects Agency (DARPA) under the Network Embedded Software Technology (NEST) program. The main idea behind this program is to develop smart dust, or Motes, in which the ultimate goal is to create a low-cost, fully autonomous system within a cubic millimeter volume [5], allowing for the realization of dense sensor arrays. The open hardware/software approach advocated in this project is necessary to effectively move technology forward, overcoming challenges inherent with previously developed proprietary solutions [7].

The first Motes were designed at the University of California at Berkeley by Prof. Kris Pister, followed by several generations, which include the latest Motes, MICA2 and MICA2DOT [5, 6]. The Mote system consists of four basic components: power, computation, sensors, and communication. With these components, the Mote is capable of autonomy and interconnection with other Motes. As for software, the Berkeley Mote platform utilizes TinyOS, which is a small event driven operating system with support for efficiency, modularity, and concurrency-intensive operation. Due to Mote's scalable design, user can customize the hardware and software, according to application needs.

3. Wireless strain sensor design

Several objectives were identified as desirable in a smart wireless strain sensor for civil infrastructure applications; they are realized as indicated in the following paragraphs.

First, low frequency responses (e.g., below 1Hz) typically found in tall and/or long civil infrastructure need to be measured; sensors with DC capacity are preferable. Foil strain gages, which have a wide frequency range, including DC, were chosen for this project. Polyvinylidene fluoride (PVDF) film sensors were also considered, because they have low power requirements, are rugged, and are low cost; however, their sensitivity in the low frequency range is poor. Some researchers are working to resolve this difficulty [8].

Low power consumption is important because the wireless sensor network frequently operates with on local battery power. For example, the MICA2 can operate for up to a year on two AA batteries in the power down mode, which shuts off everything but a watchdog and asynchronous interrupt logic necessary for wake up; however it operates for only 30 hours at peak load [6]. In the sensor design, power consumption was moderated by using a high resistance 4500 Ohm strain gage instead of the widely used 120/350 Ohm gage; power consumption in the sensor's Wheatstone bridge is inversely proportional to the resistance.

The measurement range was selected to be from 1 to 2000 micro strain. The lower limit was set based on the resolution of a commercial wireless strain sensor product, the SG-Link Wireless Strain Gauge System [9], and the upper limit was set based on the yielding strain of steel. To achieve a wide measurement range despite the MICA2's 10bit ADC restriction, a variable gain amplifier was implemented.

Finally, a target noise level is sought that is equal to the resolution, 1 micro strain. Significant high frequency noise was found to be present in the strain sensor board. An low-pass filter was designed to remove the high frequency noise as described in the following section. This filter also reduced the problem of aliasing. To have a larger signal to noise ratio and to mitigate problems with power fluctuation in the MICA2's two AA batteries, a voltage doubler/regulator is added which provides a constant 5V excitation for the strain bridge. Note that an amplifier with low noise was selected for this circuit (see **Fig. 1**).

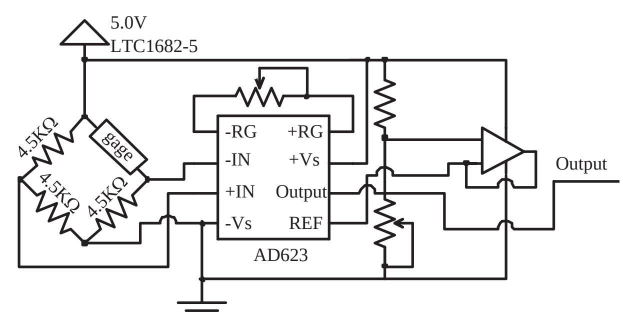

Fig. 1 Wireless strain sensor circuit schematic.

4. Anti-aliasing filter design

To eliminate high frequency noise and aliasing, a 4 pole Butterworth filter with a cutoff frequency of 50Hz was designed and implemented for the Berkeley Mote platform. To completely eliminate aliasing using this sensor board with the Mote platform, which has 10bit ADC, an attenuation of about 50dB is need at the Nyquist frequency, here 125Hz. On the other hand, filters with a fast roll off result in larger phase delays, which is undesirable for real time applications. Based on these tradeoffs, a Butterworth filter was designed (see **Fig. 2**) and experimentally verified as shown in **Fig. 3**. As in the case of the strain circuit, amplifiers with low power consumption were employed.

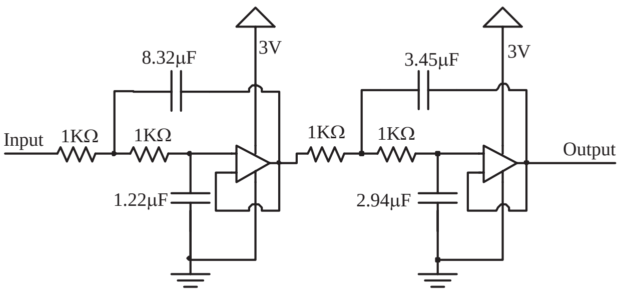

Fig. 2 Anti-aliasing filter circuit schematic.

5. Experiment

The strain sensor/anti-aliasing filter boards must be calibrated before use. These boards were stacked on a MICA2 node, and shunt calibration was conducted to determine the sensitivity of the strain sensor (see **Fig. 4**). The shunt calibration simulates a resistance change in the strain gage by shunting the Wheatstone bridge with a known resistor; the output can then be calibrated for the sensor system. For convenience of calibration, the strain sensor board is equipped with switches to shunt the bridge with 4 different resistors that are in parallel with the strain gage.

The sensor noise level must also be characterized. From the RMS of the measured signal, the working resolution of the strain gage is estimated to be 4 micro strain (see Fig. 4), which is slightly larger than the target noise level. By using a more precise amplifier, as well as electromagnetic shielding, further reduction in the noise level is considered possible.

The accuracy of the sensor boards was experimentally verified using a 3-story building structure model. A strain gage was installed on the first story wall of the structural model and connected to the strain sensor boards on the Mote platform (**Fig. 5**). A reference strain gage was attached on this structure, and the gage was wired to a conventional strain measurement system. The outputs of the wireless strain sensor and the reference strain sensor were compared for the case where the structure was responding under free vibration. As shown in **Fig. 6**, the two measurements showed good agreement.

To demonstrate the ability to acquire several physical quantities in a network, acceleration and the strain measurements were simultaneously collected using two different MICA2 nodes. The Tadeo Sensor board [7] was used, which was developed to have sensitivity and low frequency measurement capability (**Fig. 7**) that could meet the demands of civil engineering applications.

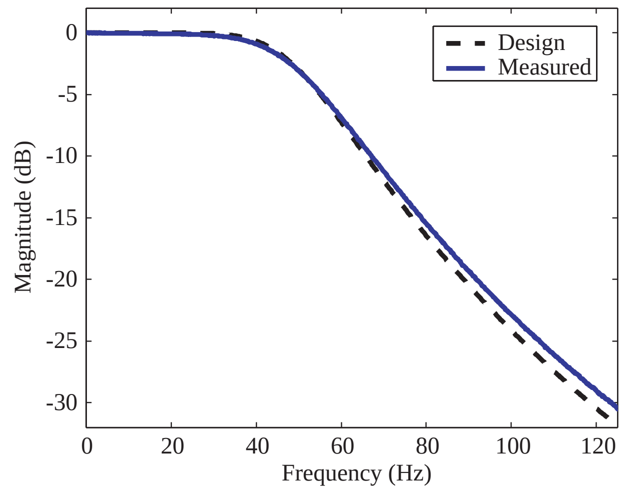

Fig. 3 Anti-aliasing filter transfer function.

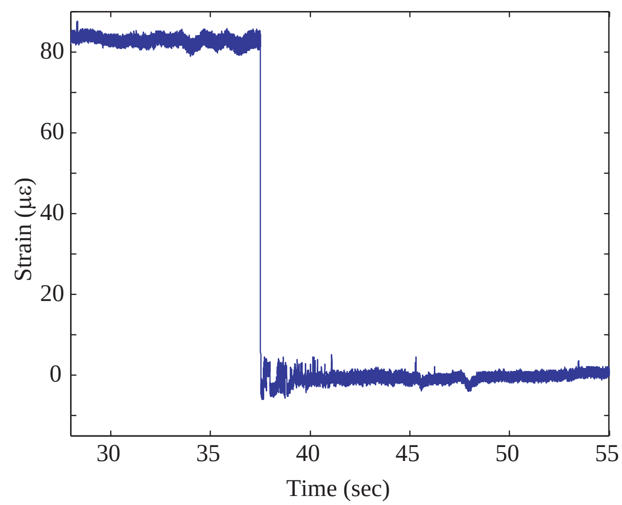

Fig. 4 Shunt calibration.

The strain and acceleration data measured by the Mote nodes were transmitted to a base station without data loss. The lossless transmission of data was made possible using a new communication program [10], which stores data on the Motes memory during measurement and subsequently send it to the base station through sensor network.

6. Conclusion

The strain sensor board for the Mote platform, which is considered an important component of future SHM/DD systems, was designed, fabricated, and tested using a structural model of a three-story building. The tests revealed that the wireless strain sensor has good resolution,

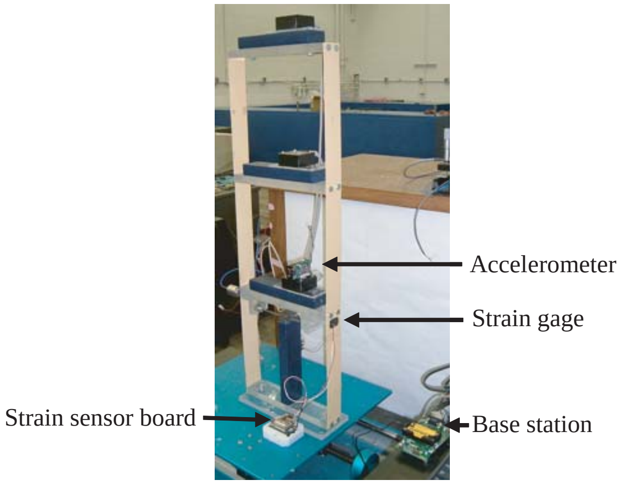

Fig. 5 Experiment setup.

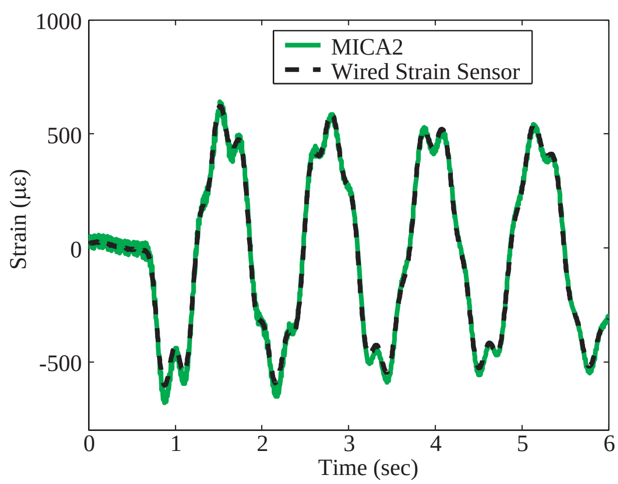

Fig. 6 Strain sensor reading.

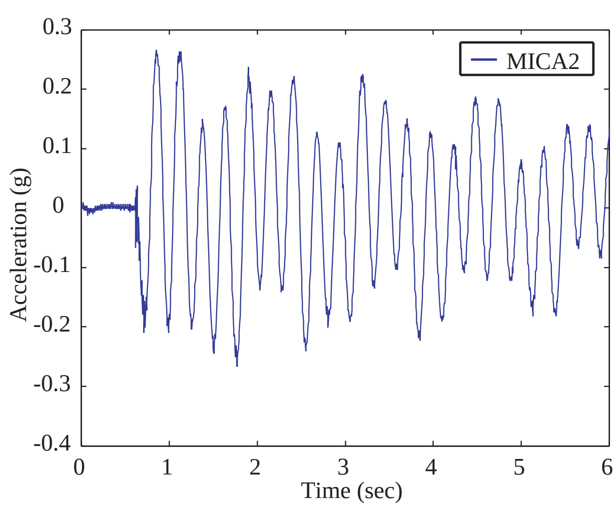

Fig. 7 Accelerometer reading.

and the output is comparable with conventional wired strain sensors.

Simultaneous measurement of both acceleration and strain were successfully demonstrated using the wireless sensor network, which is representative of future uses of these wireless sensors for advanced SHM/DD strategies. The fusing of the measurements from multiple physical responses is expected to provide more effective indications of structural condition.

This strain sensor, combined with the scalability of new communication programs [10], demonstrates the possibility of wireless strain monitoring with distributed Motes.

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