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Deformation Obtained from Acceleration Data using Wireless Sensor Motes

L. Sebastian Bryson[1], April Barnes[1], and Thomas Lutz[1]

[1] Department of Civil Engineering, University of Kentucky, Lexington, KY, 40506, USA

ABSTRACT: Real-time deformation monitoring of geotechnical-based infrastructure during construction or during the service life can provide forward predictions of system response. These predictions can later be used to provide warnings if the system response exceeds systems limits. Unfortunately, the majority of the current real-time deformation monitoring technology typically consists of very expensive and bulky systems. In addition, the systems rely on long cable runs to connect the sensor arrays to the data acquisition systems. Wireless systems utilizing micro-electromechanical systems (MEMS) technology will provide an important solution to the real-time monitoring problem. MEMS technology facilitates a reduction in size and cost of the monitoring system while maintaining accuracy.

This paper presents the results of experiments that evaluated the ability of MEMS accelerometers to accurately measure the deformation of a structure. To determine the accuracy of the accelerometers, the MEMS were mounted on a planar surface which was rotated to simulate deformation. The actual measured deformations of the planar surface were compared to those obtained from the MEMS accelerometer measurements. From the experimentation, it can be concluded that this technology can be reliably used to measure deformation in a structure.

1 INTRODUCTION

Each year, the U.S. and countries around the world experience failures of critical geotechnical-based infrastructure as a result of natural or manmade changes to the static equilibrium state of the systems. This infrastructure includes systems such as earth retention structures, tunnels, and foundation systems. This infrastructure also includes earth structures such as embankments, dykes, levees, and dams. Failure of these systems can result in casualty and significant economic loss. In many cases, failure of these systems can result in loss of life. Real-time deformation monitoring of geotechnical infrastructure during construction and service life will protect lives and property, and will greatly reduce risk.

Wired sensor technology already exists to monitor geotechnical structures (Baise and Glaser, 2000; Dowding and Connor, 2000; Ding et al., 2002; Manetti et al., 2002). However, these systems are typically bulky and very expensive. Newer technology now exists for wireless sensors based on micro-electromechanical systems (MEMS) technology. The MEMS-based

systems are less expensive and smaller than traditional systems. The reduced size of these systems allows the physical footprint of the monitoring equipment to be greatly reduced. This reduction translates to a reduced possibility of tampering or service disruption from accidental onsite damage. The wireless MEMS-based systems are also able to remotely monitor system response and transmit that information back to a central information center, which can be far away from the site. The remote monitoring capabilities translate into lower costs and labor efforts associated with onsite monitoring.

This paper presents the results of research that evaluated the performance of wireless sensor motes that utilized onboard MEMS accelerometer sensors. In particular, this paper examines the ability of the onboard MEMS accelerometers to accurately measure tilt and then calculate deformation for a semi-rigid planar surface. The planar surface was intended to represent a typical surface of any geotechnical-based infrastructure. The hardware and software of the MEMS-based motes will be discussed as well as the experimentation procedures.

2 DESCRIPTION OF TEST MOTES

A mote is a tiny computer with a power supply, multiple sensors, and a communication system. The motes used in this study were the commercially-available MICA2 motes developed by Crossbow Technology, Inc. of San Jose, CA. The MICA2 (Crossbow, 2005) is rectangular in shape with dimensions of 57.1 mm by 31.7 mm and 6.3 mm thick. The motes are powered by two AA-sized alkaline batteries and communicate with other motes via a stubby monopole antenna. The radio embedded in the mote consists of a Texas Instruments Chipcon CC1000 RF transceiver with frequency range of 300-1000 MHz that can operate at speeds up to 76.8 K baud. The 915 MHz model MICA2 motes were used for this research. However, it is noted that the actual transmission frequency used in this study was 916 MHz. The MICA2 mote sensor board incorporates a two degree of freedom Analog Devices ADXL 202JE MEMS accelerometer. The accelerometer is a surface micro-machined 2-axis, ± 2 g device. It features very low current draw (< 1mA) and 10-bit resolution. The sensor can be used for tilt detection, movement, vibration, and/or seismic measurement (Kurata et al., 2005).

The mote is designed such that within a network of motes, each mote alternates between functioning as a “sender” mote (i.e. transmit the data received from the sensors) and a “receiver” mote. Once sensor readings are taken, the MICA2 motes send the data to the gateway mote. The gateway allows the aggregation of sensor network data onto a PC or other computer platform. Any MICA2 mote can function as a gateway when it is connected to a standard PC interface or gateway board. For this research, the gateway was directly connected to a dedicated laptop via a serial cable. The gateway also provides programming and data communications functions from the computer to the motes using the TinyOS (TOS) Distributed Software Operating System. This operating system is specifically designed to support large scale, self-configuring sensor networks.

3 TILT AND DEFORMATION FROM ACCELERATION MEASUREMENTS

Tilt (i.e. angles of inclination relative to orthogonal axes) of a planar surface can be obtained from the vector components of the acceleration due to gravity. Angles can be obtained from accelerometer data using the following expression (Analog Devices, 2000),

$$\Theta_{x,y} = \sin^{-1}\left(\frac{a_{x,y}}{1g}\right) \tag{1}$$

where $\Theta_{x,y}$ = angle from the horizontal axis; $a_{x,y}$ = acceleration data from the mote in the x and y directions, respectively, in units of g. The deformation of a planar surface can then be easily calculated from trigonometry. Using the angle calculated in Equation 1 and the distance the mote is from the base, deformation is determined from,

$$\Delta_{x,y} = \sin(\Theta_{x,y}) \cdot L \tag{2}$$

where $\Delta_{x,y}$ = deformation of the planar surface in the x and y direction, respectively; and L = the distance of the mote from the base.

4 TEST BOARD CONFIGURATION

The primary focus of this research was to evaluate the capability of the MEMS accelerometers for providing measures of deformation. This was facilitated by attaching five motes to a planar surface. The planar surface consisted of a 19 mm-thick section of plywood with dimensions of 1.88 m x 1.22 m. Figure 1 shows the layout of the motes on the board. The motes were placed in a configuration of two parallel horizontal lines. The first line of motes was placed a distance of 0.930 m from the base of the test board (i.e. planar surface). The second line of motes was placed a distance of 0.676 m from the base. The placement of the motes was selected to best capture the assumed inflection points of the test board. Points of know deflection are simply points on the top and bottom of the board where deflection could be physically measured using a tape measure.

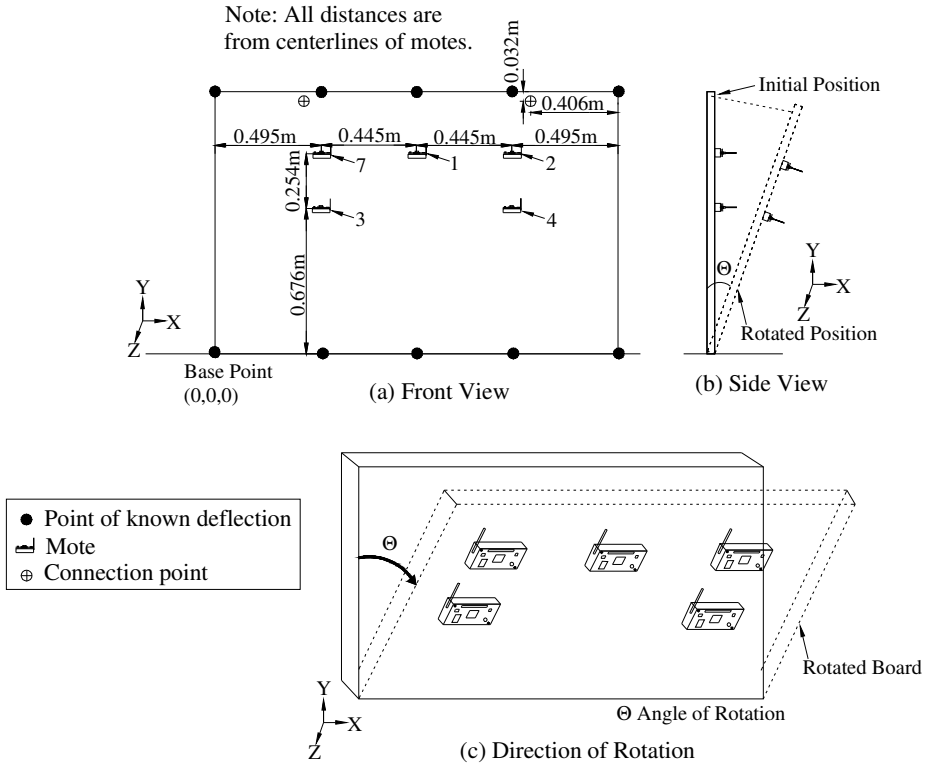

Figure 1. (a) Front view of test board with positioning of motes (b) side view of test board with positioning of motes (c) rotated view of test board.

The motes were oriented and attached to the test board with adhesive such that rotation would be about the x-axis. The vertical position was chosen as the initial reference position. Connection points were established on the test board at the locations shown in Figure 1(a). These points were small holes drilled 406 mm from the side and 32 mm from the top of the board on both sides. One lag thread eye bolt was placed in each hole and secured with a nut and a spooled cord was attached to each eye bolt. Rotation of the test board was achieved by fixing the base of the board and either spooling or unspooling the cord. This allowed exact tilt angles to be achieved. Using the measured distance along with the length of the planar surface, the actual tilt of the surface was determined. At each angle, the motes transmitted data for 30 seconds.

5 INFLUENCE OF ANTENNA ORIENTATION

The antennas on the motes are capable of 360 degrees of rotation. Thus, there are many different orientation combinations that the antennas can have when transmitting data. It was suggested that antenna configuration may play a role in the data transmission due to the quality of low radio frequency power used by the motes (Glaser et al., 2007). Therefore, extensive testing was performed to investigate the influence of antenna orientation. Multiple tests were performed with the motes and the antennas in various configurations. Figure 2 shows the configuration of the mote antennas in comparison to the gateway antennas for both the x-axis and the y-axis of the accelerometer. There were six antenna configurations for each accelerometer axis. The figure also shows a plan view of the mote to orient the reader to the layout of the local accelerometer axes.

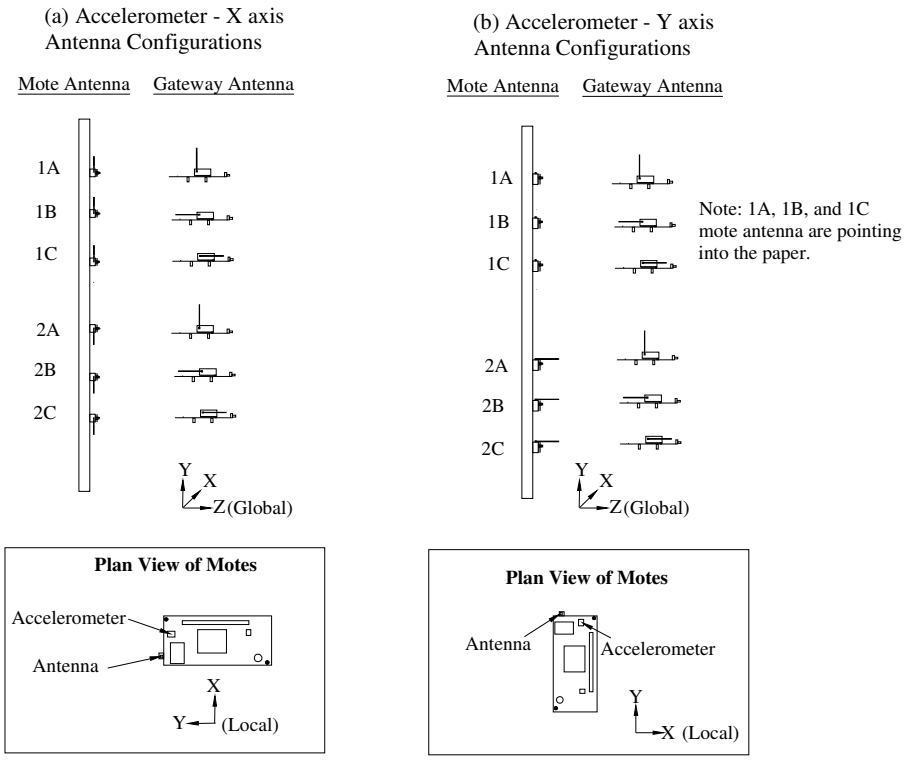

Figure 2. Antenna location and direction for the mote and the gateway relative to; (a) the x-axis of the accelerometer; (b) the y-axis of the accelerometer.

The results of the antenna and mote configuration testing are presented in Figure 3. The figure shows deflections of the test board at an inclination of 37 degrees from the vertical. Only this inclination is presented in that it represents a severe tilt. For this series of tests, only data from Mote 1 was recorded (see Figure 1 for mote location relative to testing board).

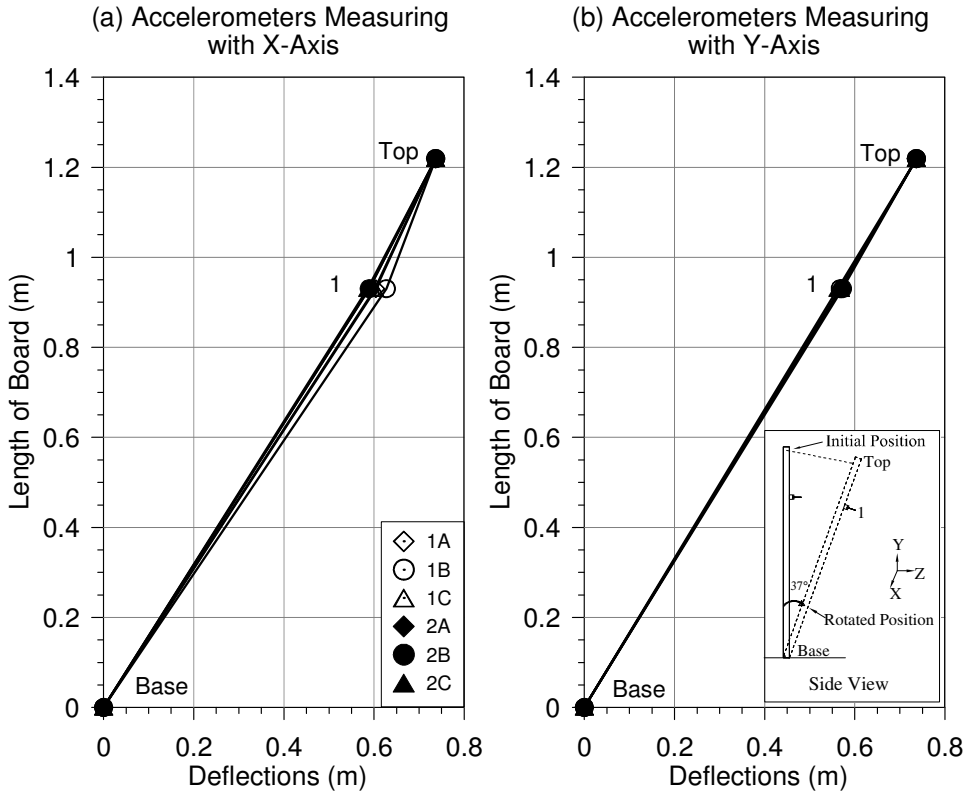

Figure 3. Deformations measured with varying antenna orientations: (a) accelerometers measuring with the x-axis; (b) accelerometers measuring with the y-axis.

When comparing the antenna configurations, it is seen that there is no significant difference in the deflections when the y-axis was being tested. For these sets of tests, the mote antennas were oriented perpendicular to the direction of gravity and orthogonal (i.e. perpendicular) to the accelerometer y-axis (the local y-axis). These antennas were oriented in the positive direction in the plane of the accelerometer (the global X-axis) and in the positive direction out of the plane of the accelerometer (the global Z-axis). However, when the x-axis of the accelerometer was used to determine the deflections, there was a slight variance within the readings. The antennas of the motes for these tests were oriented parallel with the direction of gravity. In addition, it is noted that the accelerometer axes were no longer coincident (i.e. same orientation and same direction) with the global axes. The variability within the deflections is detected when the mote antenna is oriented opposite to the direction of gravity. This is in the positive direction of the accelerometer y-axis. In particular, the variability is maximum when the gateway antenna is oriented perpendicular to gravity.

The gateway behavior is consistent with similar findings reported by Stoyanova et al. (2007) and, Yang and Cha (2007) who suggested that a vertical orientation of the receiving antenna performs best. However, they also recommend that the transmitting antenna be oriented vertically as well. Whereas the behavior observed for this study would suggest that the transmitting antenna yields the best performance when it is oriented horizontally. Nevertheless, the data does support a recommendation that is more consistent with Stoyanova et al. (2007) and, Yang and Cha (2007). The best performance is achieved when the transmitting antenna is

coincident with the receiving antenna. An additional recommendation from this study is that the best performance is achieved when the principal axes of the accelerometer is coincident with the principal axes of the planar surface.

6 THREE-DIMENSIONAL REPRESENTATION OF DEFORMATIONS FOR THE TEST BOARD

Using all of the accelerometer data from the deformation testing and the known points of deflections, it was possible to create a wireframe and contour map based on deformation of the test board. The wireframe and contour map create a three-dimensional representation of deformations. The wireframe and the contour map were created using the Radial Basis Function to interpolate between the known points. The Radial Basis Function is a standard data interpolation method and is found in most contouring software.

Figure 4 shows the planar surface as described by the mote deflections obtained from the y-axis accelerometer test data. The data represents the condition in which the test board was at an angle of 37 degrees from the vertical. Note that although test data was collected for both x-axis and y-axis accelerometer measurements, only the y-axis data is presented for brevity.

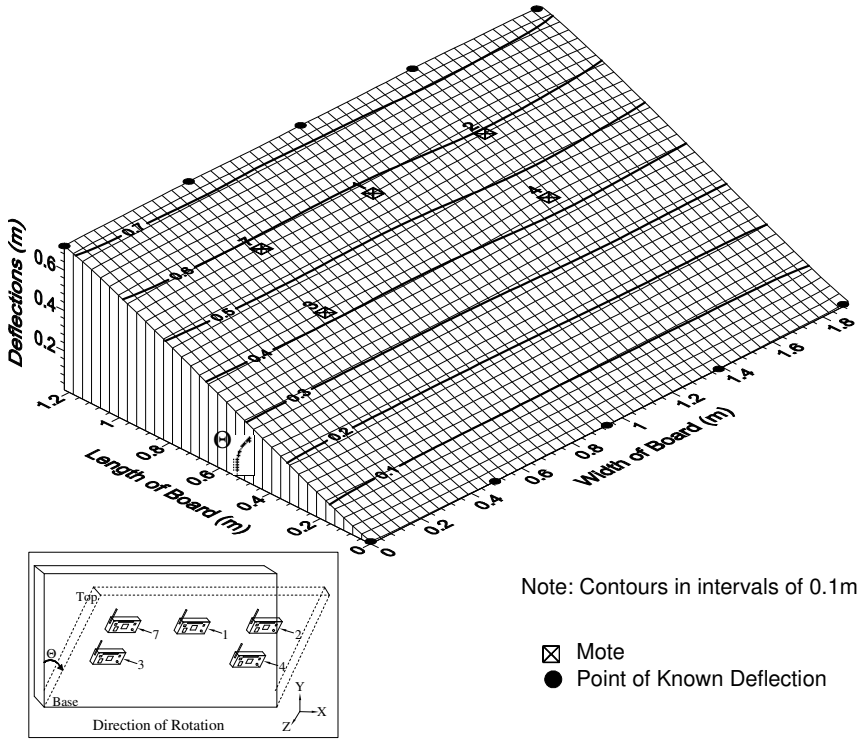

Figure 4. Contour map and wireframe developed from y-axis accelerometer measurements with the test board at 37 degrees from the vertical.

It is observed that the figure possibly shows the self-weight deformation of the test board or a natural deformation such as a bow or hump around Motes 2 and 4. Though for the most part, the figure simply shows the three-dimensional tilt of the board. The importance of the three-dimensional representation is that it allows the observer to predict deformations at locations other than the actual sensor locations. It also allows the geotechnical system to be evaluated in terms of true system behavior as opposed to just the behavior at discrete locations. However,

this evaluation capability is predicated on the ability of the data interpolation method to adequately predict data.

The validity of using the Radial Basis Function to develop the contours was verified by taking sections through the contour map and comparing them to measured data. Figure 5 presents a vertical section cut through the location corresponding to Motes 3 and 7. The figure shows that the interpolated data are a perfect match to the measured deformations in the upper half of the board. There appears to be a very slight variation in the deformations in the lower half of the board. Although it is remembered that the line representing the "actual" deformations is in fact just straight line segments connecting the measured deformations, the variation does seem to indicate a slight discrepancy between the interpolated data and the measured data. This is because the interpolated data indicates the deformation as being concaved up. Whereas the physics of the system would imply that the deformations are either linear or concaved down.

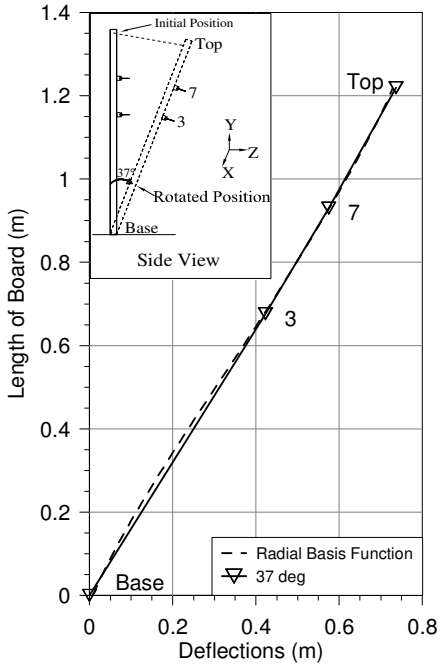

Figure 5. Comparison of radial basis function with measured data from the y-axis accelerometer measurements through a vertical section of the test board.

Figure 6 presents a horizontal section cut through the location corresponding to Motes 7, 1, and 2. The figure shows that the interpolated data are an excellent match to the measured deformations. The results of this series of tests would tend to suggest that Radial Basis Function is quite adequate for depicting three-dimensional deformation. However, this conclusion must be tempered with the knowledge that the (i) the test board did not experience any significant out of plane bending (i.e. bowing); (ii) the motes were not distributed uniformly over the surface of the board; and (iii) test were not performed to ascertain optimum spacing of the motes. Nonetheless, three-dimensional representations of deformations are possible using MEMS accelerometers attached to a planar surface.

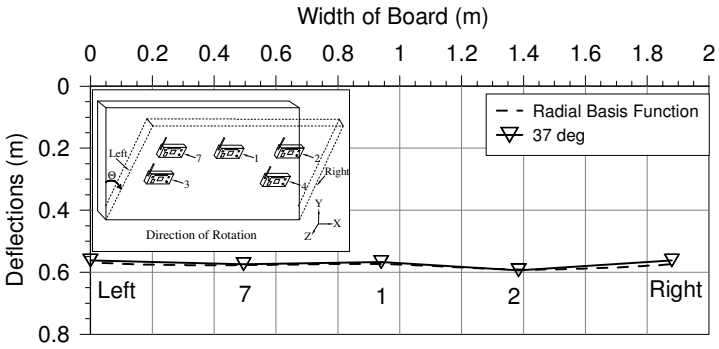

Figure 6. Comparison of radial basis function with measured data from the y-axis accelerometer measurements through a horizontal section of the test board.

7 CONCLUSIONS

This paper presented the results of testing that showed the viability of MEMS accelerometers for determining deformation at discrete locations. This study also showed that when spatial deformation measurements are aggregated together, three-dimensional visualizations are possible which allow true system behavior to be evaluated. This behavior can be used to develop early warning systems of critical geotechnical-based infrastructure.

More specific conclusions from the experimentation include:

1. The best performance is achieved when the transmitting antenna is coincident with the receiving antenna. Also, performance can be further improved when the principal axes of the accelerometer is coincident with the principal axes of the planar surface.
2. MEMS accelerometers can be used to accurately determine deformation of a geotechnical system.
3. Three-dimensional representations of deformations are possible using MEMS accelerometers attached to a planar surface.
4. The Radial Basis Function appears to be an adequate interpolation method.

8 ACKNOWLEDGEMENTS

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