Multi-Hop Wireless Crack Measurement For Control Of Construction Vibrations

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ABSTRACT

Miniaturized, multiple position, multi-hop, wireless instrumentation is now a reality and this paper describes development and testing of such a system to monitor crack response. These wireless systems will facilitate measurement of crack width changes in structures in order to assess structural health of critical infrastructure components such as fracture critical bridges or structures near construction. A low power consumption potentiometer displacement transducer and multi-hop communication algorithm allow this system to operate up to a year with 2 AA size batteries. The system described herein is capable of measuring long-term crack displacement along with temperature and humidity. A field test of the system is described that includes operation of multiple, remote data motes as well as back casting communication necessary to autonomously display crack response in a graphical format over the Internet. This system in another form won third place honors in the 2005 Crossbow Smart Dust Challenge, which represented the best executable ideas for wireless sensor networks that demonstrate how it is used, programmed and deployed to positively impact society.

INTRODUCTION

The overall objective of Internet-enabled remote monitoring is to provide timely information to parties interested in the structural health of critical infrastructure components such as cracks in the bridges or houses near construction activity. Sensors on a structure are polled regularly so that responses may be compared graphically with past responses to identify trends and automatically alert authorities of impending problems. Deploying

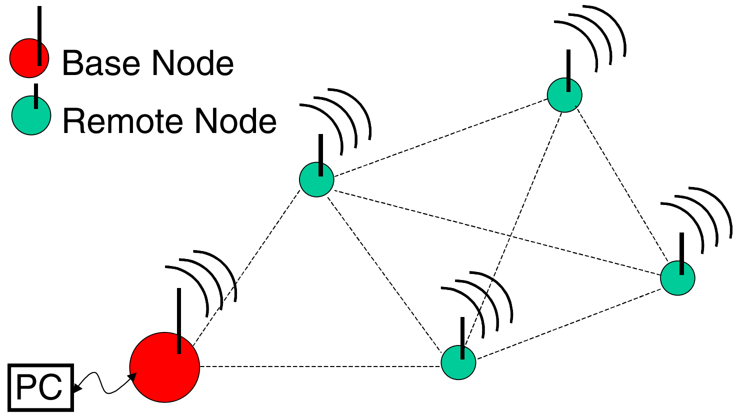


FIG. 1: Sensor nodes scattered in the sensor field communicate wirelessly with the base node through multiple node paths. In other words each node operates as both a sensing as well as a data transmission node.

sensors without the necessity to hard wire them in place would greatly enhance the capabilities or these structural health monitoring systems. One of the critical aspects of wireless deployment is the consumption of power. The only viable systems will be those that can operate for months without the need for battery replacement. At this time multi-hop communication is a critical component of wireless low power consuming systems. To date these systems have been designed to replicate wired systems to monitor long-term micro-inch response of cracks in structures near vibratory construction environments (McKenna and Dowding, 2005). Recently development has begun on systems to monitor the extension of cracks on fracture critical bridges.

An example multi-hop, wireless mesh network is shown in Figure 1 with its components; sensor nodes of a multi-hop network where each of the sensor node is capable of collecting the data and routing it back to the base node. The base node then stores data from the sensor nodes for autonomous back casting to the central computer for processing and graphical display on the Internet. Multi-hop radio communication between the nodes is a self-healing process where a continuous flow of data is maintained even if some of nodes are blocked due to lack of power, physical damage or interference. Multi-hop networks also increase the total spatial coverage and operate with the lowest energy consumption.

A sensor node is the key element of the network. It is comprised of four major components: a sensing unit, a processing unit, a transceiver and a power unit. Sensing units are also composed of two subunits: analog-to-digital converters (ADC) and the sensor transducers. Analog signals produced by a sensor's response to the physical phenomenon (eg crack opening and closing) are converted to digital signals by ADC's and sent to the processing unit of the sensor node. The processing unit manages the procedures that alert the sensor node to respond and perform assigned sensing tasks, and collaborate with the other nodes. These units are responsible for pre-processing (encoding, decoding etc.) the data for transmission. The transceiver unit connects the node to the sensor network via a wireless radio link. Finally, the power unit provides power for all activities on a sensor node including communication, data processing and sensing. Thus determination of long-term battery behavior requires testing in the field where power is consumed by both communication and sensing.

Further information on miniaturized wireless systems can be found in the literature and product manual of Crossbow Incorporation (Crossbow, 2005) and TinyOS tutorials (TinyOS, 2005). Culler (2002) introduces the mica platforms for embedded networks for habitat monitoring. Glaser (2004) presents real-world experience with wireless networks. Asis et al (2005) describe use of wireless systems in the laboratory. Background for wireless instrumentaion can be found in Ozer (2005), a copy of which, along with other papers is available on the autonomous crack monitoring web site, www.iti.northwestern.edu/acm.

HARDWARE

As shown by the photographs in Figure 2, each sensor node consists of one Mica2 radio module (upper left) that houses low power microcontroller and a radio transceiver operating at 433 MhZ., and an MDA300 sensor board (lower left) a general measurement

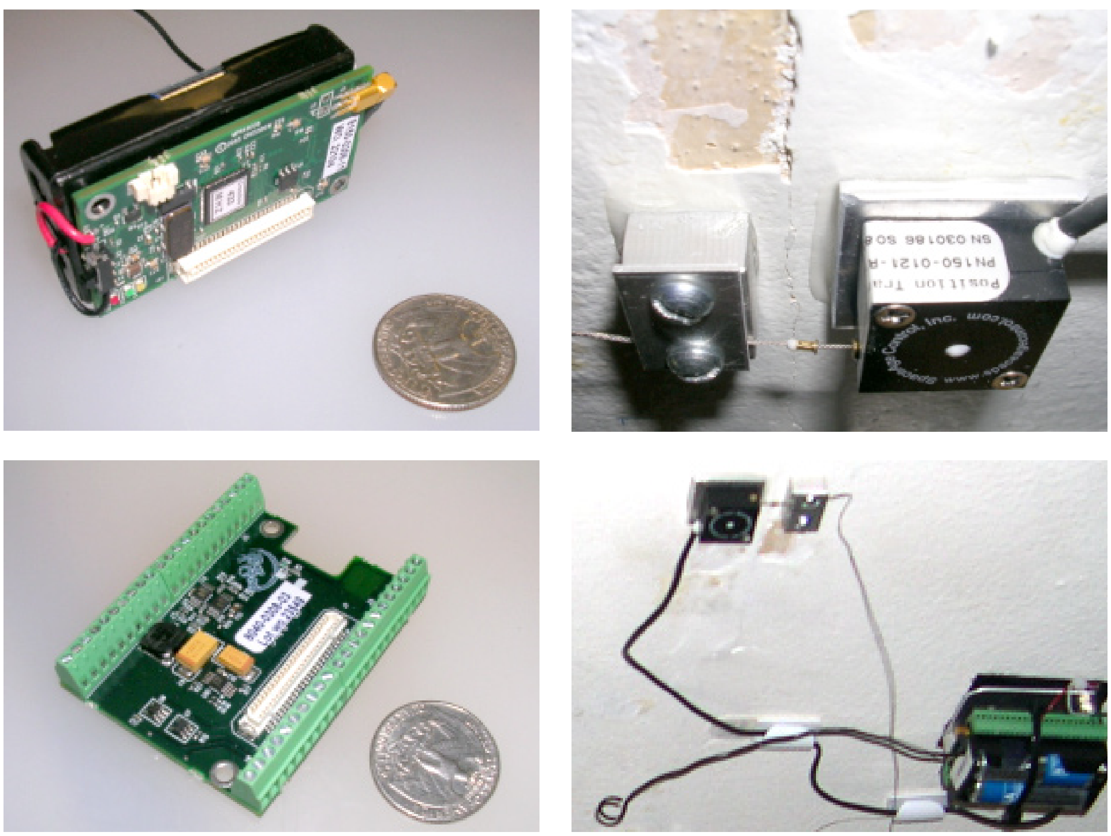


FIG. 2: Assembled wireless remote node with displacement sensor across a ceiling crack (lower right), potentiometric displacement sensor (upper right), Mica2 radio module (upper left), and MDA 300 sensor board (lower left).

platform for Mica2. It provides 12 bits analog-to-digital conversion for analog sensors. MDA300 also has temperature and humidity sensors onboard. A Ratiometric string displacement potentiometer (lower right) is employed to measure micro-meter changes in the crack width and is connected to the screw terminals of the MDA300. Potentiometers are attractive for wireless systems because of their low power consumption and to ability to operate without warm-up time. A potentiometer spanning a crack is shown in place with its mote in the upper right The base station (not shown) an MIB510 or Stargate can be employed depending on the mode of radio communication (single-hop or multi-hop configurations respectively). In this case Stargate was used as the base station node to store the data transmitted from the sensor nodes.

SOFTWARE PROTOCOL (TINYOS)

This system is based upon the TinyOS operating system, which is an open-source operating system designed for wireless embedded sensor networks. It is designed to meet the requirements of a self-assembling sensor network, which are low power consumption, small size, diversity in design, usage, and concurrent-intensive operations (where data flows from one mote to another continuously).

As described in (Ozer, 2005), two different applications of TinyOS were configured in order to measure crack displacements produced by environmental factors. The first of those applications, a single-hop wireless communication, was customized from a sense-light-to-log application. The second was a built-in multi-hop application that provides a more power efficient operation and thus a more robust long-term operation of the sensor network. Accuracy and long-term robustness of the wireless system described herein configured by single and multi-hop customizations were validated by several field tests. (Dowding, Ozer and Kotowsky, 2006).

The multi-hop configuration employed for this study employed XMesh software. It is an open-architecture, flexible, embedded wireless networking and control platform built on top of the TinyOS operating system. Some of the features of Xmesh include: 1.) self-forming and self-healing communication routing in the case of loss of communication between the motes 2.) extendable coverage area with the addition of motes to the mesh 3.) Low power consumption listening, which turns on the radio periodically to transmit data and to maintain the mesh network 4.) Multi-month operation with reporting intervals of 60 minutes.

OPERATION OF THE SYSTEM

The Xmesh multi-hop protocol with the Stargate base provides a more efficient and built-in power saving model than TinyOS by itself, which allows individual mote operation for 4 months to a year with two AA batteries. In this mode of communication routing data and/or analog actual data flow from one mote to another and finally reach the base station where they will be stored. Based on the algorithm written for dynamic mesh networks, the motes search continuously for the most convenient path of propagation to the base.

Figure 3 illustrates details of the communication between the motes via a power con-

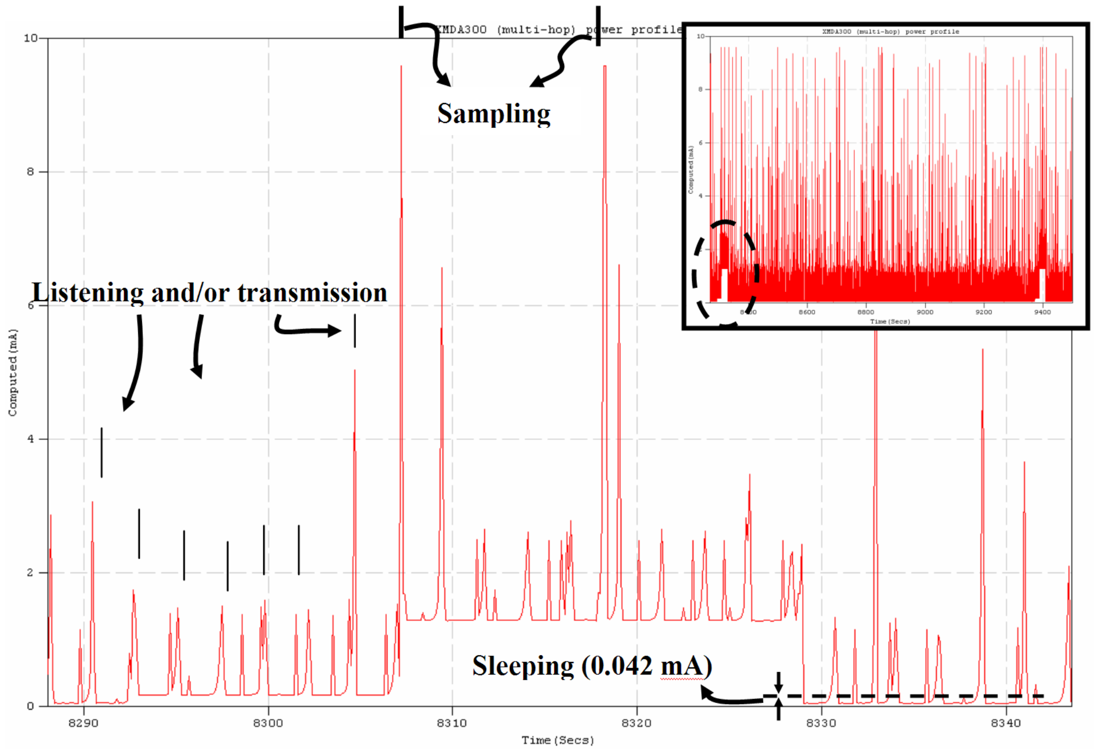


FIG. 3: Power consumption profile of one of the low power modes in Xmesh. The sampling window is shown within the dashed oval in the inserted figure, which demonstrates its intermittent operation and short duration compared to ongoing operation.

sumption profile obtained by one of the low power modes available in the Xmesh multi-hop customization. Sampling activity, shown in the center of the main figure occurs every 18 minutes, as shown by the encircled zone in the inset. As shown by the amperage spikes on either side of the sampling time (labeled "Sampling"), the motes wake up 1 or 2 times in one second to listen for RF and for transmission. But in this case transmission does not necessarily mean that the motes are transmitting the analog sensor data. Those transmitted packets shown with spikes several seconds apart and magnitudes of 8-10 miliamps include the routing information between the motes in order to locate the sensor in the network or re-form the network. In this manner, the motes can calculate the propagation path that will minimize the cost of transmission. During the non sampling period, the base amperage draw is 0.042 milli amps (mA) as shown on the right side of the figure. With the sampling interval of 18 minutes between each sample, the overall hourly average current draw is approximately 0.31 mA and battery lifetime can estimated to be about 380 days. However, this calculation remained to be proven as described in the field trial described below.

FIELD INSTALLATION OF THE WIRELESS SENSOR NETWORK

A four node multi hop system was field tested in a house in Evanston near Northwestern

University shown in plan views and photograph in Figure 4. Four nodes were deployed in the garage, basement, third floor apartment and on the second floor sun porch. Each node measured temperature, humidity, and battery voltage.

The sun porch node was also fitted with a potentiometer displacement sensor placed across a plastic donut as shown in the center photograph in Figure 5. Figure 5 is a colage of photographs of the four nodes in place. The central photo is of the sun porch mote and its power supply with a displacement sensor in the lower left of the container.

The white plastic donut between the sensor and the anchor block (denoted in the photograph by the two screws) expands and contracts with changes in temperature. This expansion and contraction mimics the action of a crack (Ozer, 2005) and is used for calibration and qualification of micro meter displacement sensors. An enlarged view of the sensor and anchor block is shown in the upper right in Figure 2.

Figure 6 compares the long term temperature time history with the battery voltage time history to illustrate the long term viability of the multi hop operation over the 9 month operational period. These graphs were obtained from the ITI web site, which autonomously displays the field measurements. (www.iti.northwestern.edu/acm - press Evanston, Historic Wood Framed House). Three of the 4 lithium ion battery pairs displayed sufficient voltage to operate including the batteries that operated the system with the potentiometer displacement sensor. Only one battery pair failed; #2 in the basement. After failure, the lithium batteries were replaced with alkaline batteries, which lose voltage much more rapidly and failed again after only several months.

As shown in Figure 3, radio operations are clearly the most taxing on the battery. Therefore, minimizing the amount of time during which the radio is in operation is key to reducing the power consumption and thereby increasing the amount of time that a set

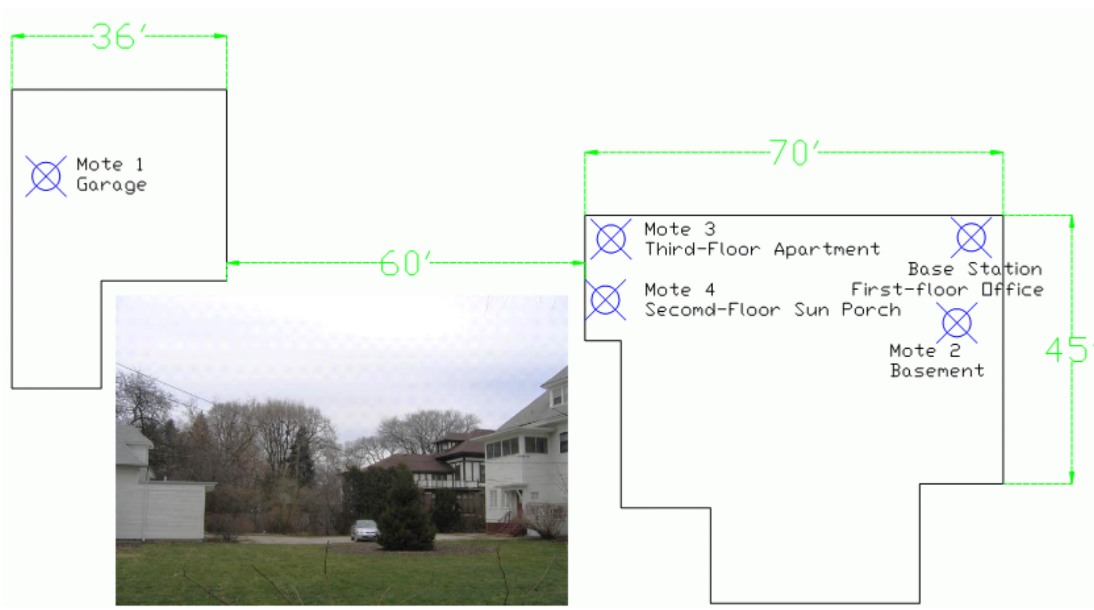


FIG. 4: Structure wirelessly instrumented with four multi-hop nodes and Stargate back casting of data over a cable modem to the central computer for graphical presentation on the internet.

FIG. 5: Collage of photographs of the mote nodes in place that demonstrates their small size and multiple modes of placement. Clockwise from upper left: Sun porch, garage, basement, and apartment. Center photograph is that of the node with the same potentiometric displacement sensor shown in Fig. 2.

of batteries can power the system before they are depleted. The XMesh protocol strictly limits the amount of time that the radio is in use, allowing for a significant reduction in power consumption over the standard TinyOS networking protocols.

Figure 7 compares the expansion and cotraction of the white plastic donut insert (shown in the lower left of the center photograph in Figure 5) with variation of the temperature. Its response was measured by the potentiometer shown in Figure 2 by placing it between the sensor and anchor block (denoted by the two screws) The plastic donut insert has been employed for qualification of micro-meter displacement seinsor (Ozer, 2005) because a 10 mm length expands as much as typical cracks and thus provides known control for evaluating performatnce of sensors. Comparison of time histories of the response of the plastic (top graph) to the variation in temperature (bottom graph) shows almost perfect correleation. This high degree of correlation is expected since the temperature was measured by the moted in the same container.

Potentiometer micro-meter displacement measurement systems are an important com-

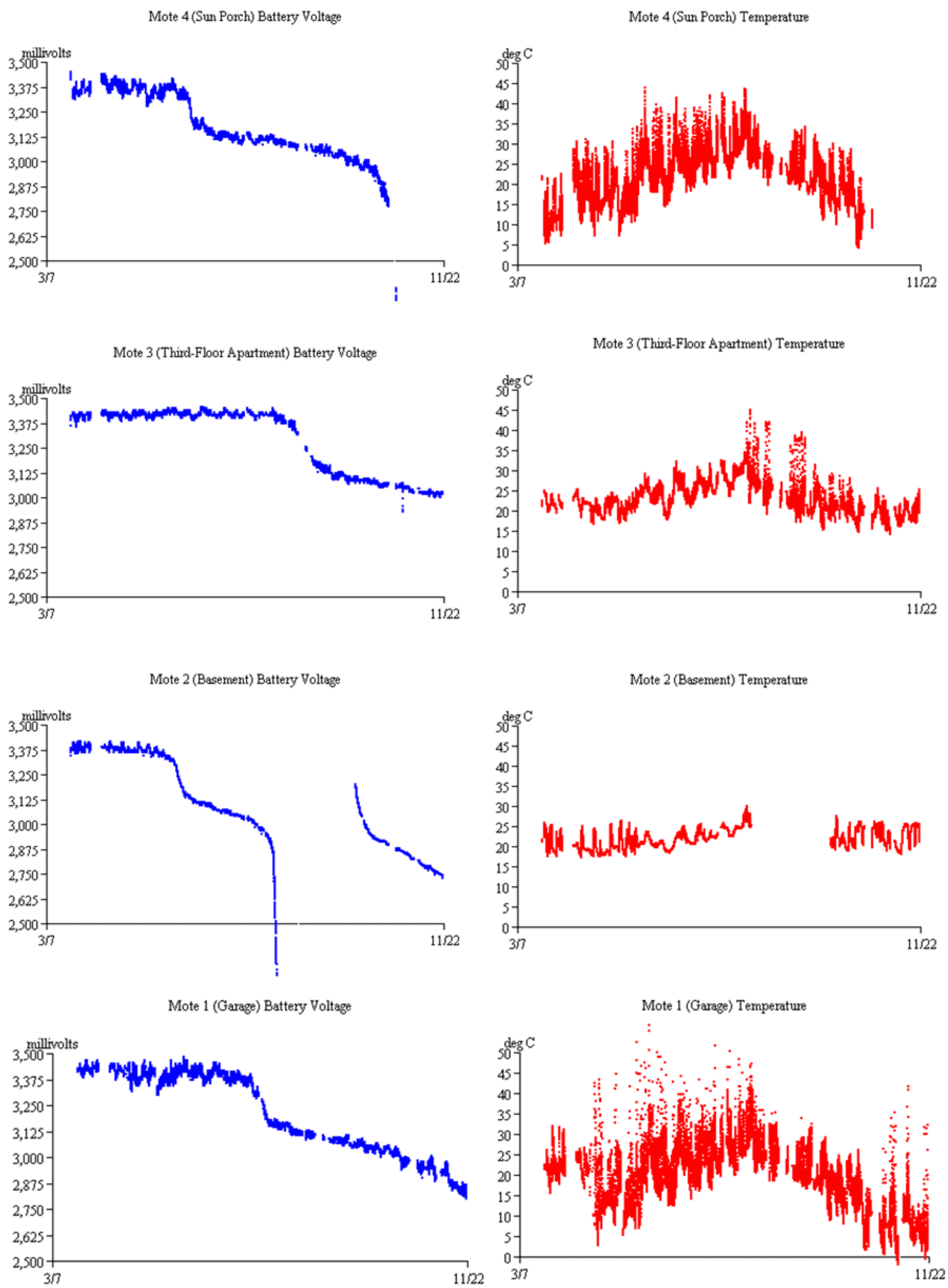
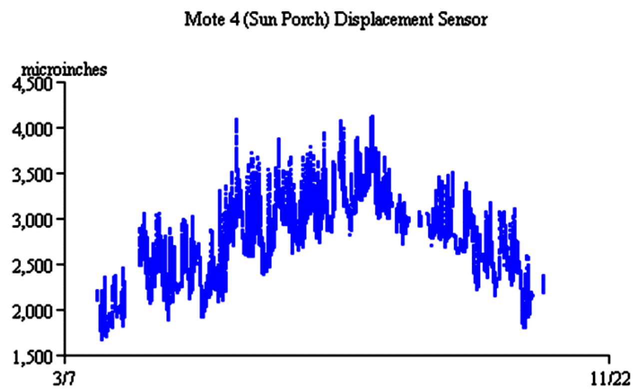


FIG. 6: Time histories of the variation of battery voltage (left) and temperature (right) measured by the motes (from the top) in sun porch, third floor, basement, and garage. Battery voltage remained above the 2.85 Vt floor for all 9 months of continuous surveillance for all but the basement mote.



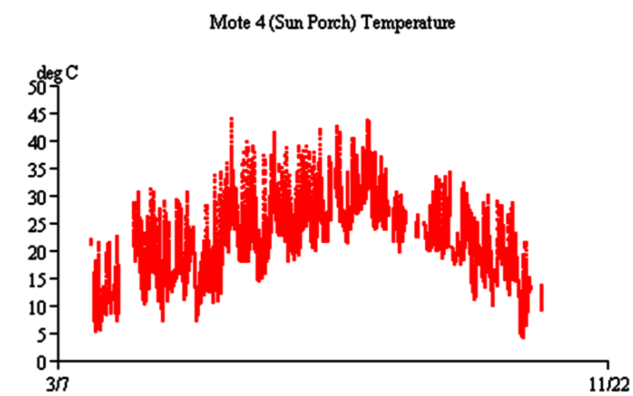


FIG. 7: Time history of the response the sun porch potentiometric sensor (top) compared to the variation of temperature (bottom) showing the ability to precisely track the temperature induced changes to the thickness of the white plastic insert shown in the center photograph in Fig. 5.

ponent of any wireless system to monitor displacement because they require no power to warm up. Other micro-meter systems, such as the Kaman edy current sensor or LVDT require auxiliary power and must be on constantly even when measurements are only made hourly. This requirement for continual operation is costly for battery life.

Other studies (Ozer, 2005) have shown that the potentiometers are able to replicate the long term crack response measured by the edy current and LVDT sensors. Figure 8 compares time histories of a crack response measured by both LVD and potentiometer systems. Both were subjected to blast induced motions, at the three times indicated by the cloud symbol, which failed to produce any change in long term crack response. The wired LVDT and wireless potentiometric senors (lower two graphs) responded proportionally to changes in temperature (top graph) Comparison with the changes in temperture (top graph) shows that the crack response followed the variation in temperature.

Timing of blast events shown in Figure 8 demonstrates that patterns of crack displace-

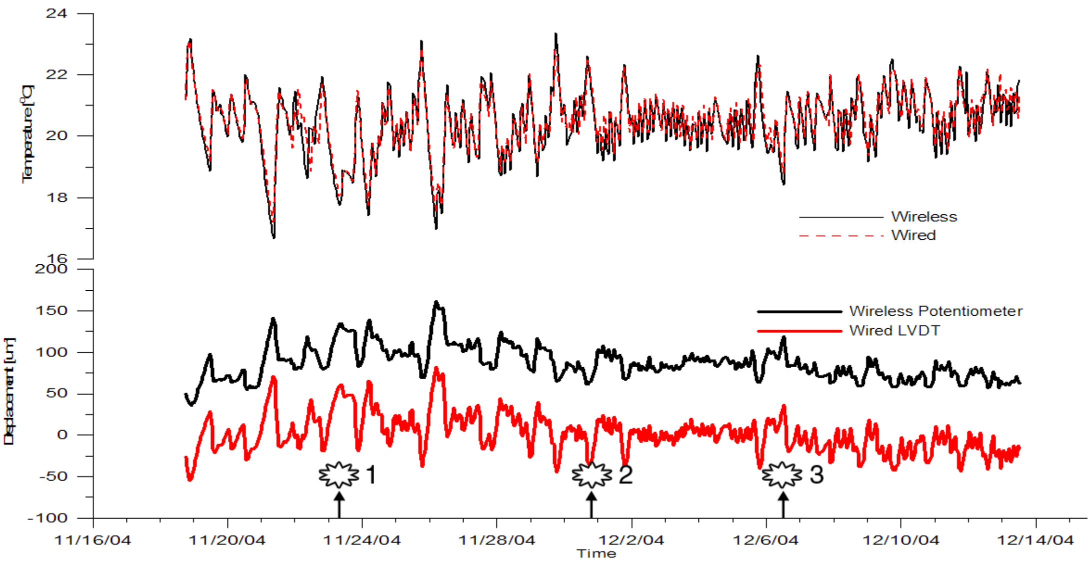


FIG. 8: Comparison of ceiling crack displacements measured by wireless and wired systems (lower two graphs) and temperature variation shows that the wireless system responds in the same manner as the wired and that they both show that blast induced event events (the clouds) do not change the long tem response. (Dowding et al, 2006)

ment were not altered from those observed during non-blasting periods. During these non-blasting periods environmental factors were the only driving force inducing crack opening and closing. This measurement of only long term response is Level I operation of ACM systems. Level II operation, which requires sampling at high sample rates and a triggering system to capture dynamic crack response, requires further research and development for wireless deployment.

CONCLUSIONS

Wireless sensor networks allow for the monitoring of structures without the inconvenience and cost associated with running wires through the structure. As wireless sensor network technology advances, wireless systems for the autonomous Internet-based monitoring of structural health will be as practical and robust as their wired counterparts. This project demonstrates the long-term viability of such systems to measure changes in crack widths with respect to changes in climatological conditions. This multi-hop configuration will allow continuous operation of such a system for 6-12 months with two AA lithium batteries per node. This performance is achieved by use of a low-power string potentiometer and Crossbow Mica2 motes equipped with TinyOS and the XMesh low-power multi-hop networking protocol.

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