Wireless crack measurement for control of construction vibrations

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Abstract
Miniaturized, wireless instrumentation is now a reality and this paper describes development of such a system to monitor crack response. Comparison of environmental (long-term) and blast-induced (dynamic) crack width changes in residential structures has lead to a new approach to monitoring and controlling construction vibrations. A low power consumption potentiometer displacement transducer and a short communication duty cycle allow this system to operate up to a year with AA size batteries. The system described won third place honors in the 2005 Crossbow Smart Dust Challenge, which represented the best executable ideas for wireless sensor networks. (Kotowsky and Ozer, 2005)

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 nearby a quarry. Sensors on a structure are polled regularly so that responses may be compared graphically with past readings to identify trends and automatically alert authorities of impending problems. Work has already begun on development of these systems to monitor the extension of cracks in fracture critical steel bridges. Others are designing systems for yet other purposes. (Glaser, 2004)

A typical wireless mesh node is shown in Figure 1 with its components during the measurements of a ceiling crack response in a test house. A sensor mesh of several such nodes forms a multi-hop network where each of the sensor nodes is capable of collecting the data and routing it back to the base station. An off-site PC polls the data autonomously via Internet. Back casting communication is also available to autonomously display response in a graphical format over the Internet.

Components of the wireless system network

Hardware

A wireless data acquisition system consists of a network comprised of one "base node" and any number of "sensor nodes." As shown by the inserted pictures of Figure 1, each sensor node consists of one Mica2 mote logger radio module (low left thumbnail), one MDA300 sensor board (low middle thumbnail), and one ratiometric string displacement potentiometer (low right thumbnail) connected to the screw terminals of the MDA300. The base station (not shown) MIB510 and Stargate were employed depending on the mode of radio communication (single-hop or multi-hop configurations respectively). The mote with its attached sensor board is mounted a few inches away from the sensor. Though only one "sensor node" is pictured, any number of "sensor nodes" may be attached within radio range of any of the node to form mesh. They relay back to the base station, which is connected to the Internet to back cast the collected information.

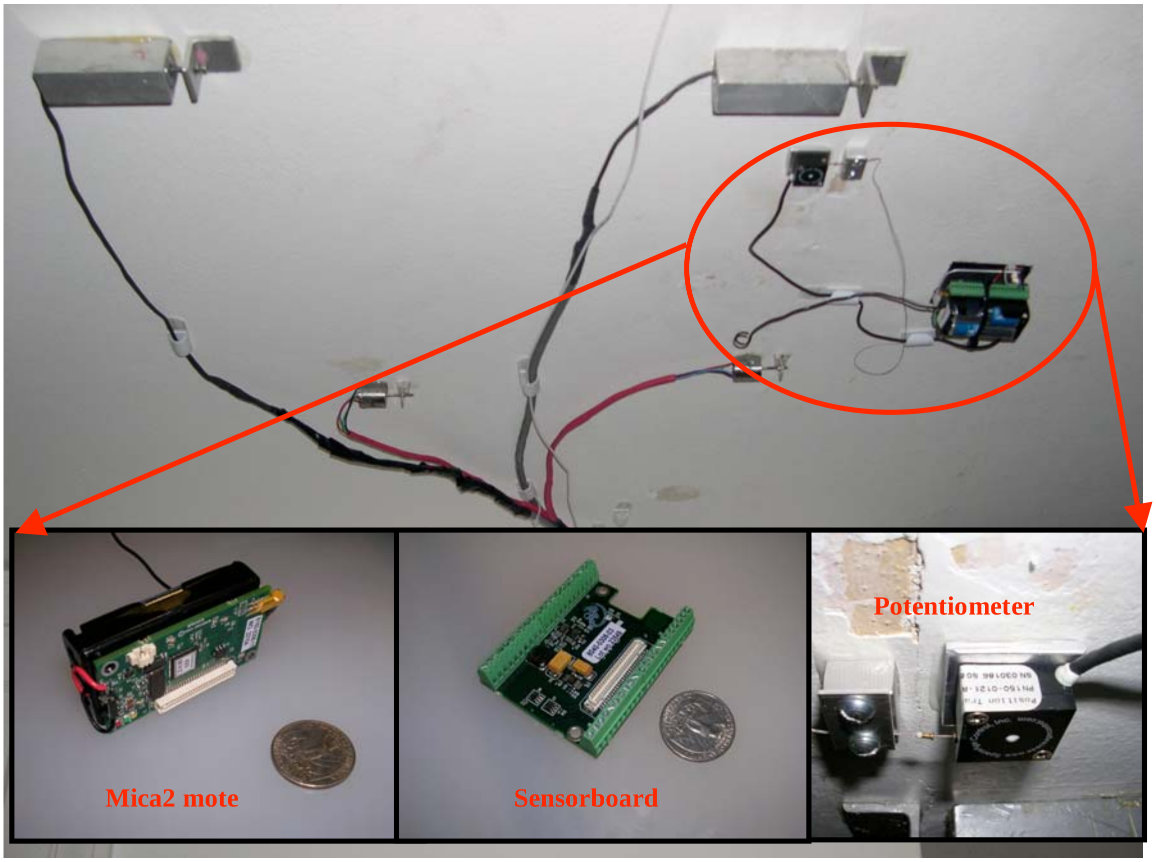

Figure 1: Wireless remote node on a ceiling crack along with the sensors of the wired system

Software Protocol (TinyOS)

This system is based upon TinyOS, is an open-source operating system designed for wireless embedded sensor networks. It is designed in such a way that it can 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 from 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.

Structural health monitoring applications

Single-hop Customization

The single-hop customization is essentially designed to collect readings at predetermined times over long periods of time, write them to the EEPROM, and transmit the sensor readings over the radio to the base station. This application functions as a single hop network. The wireless remote nodes are individual data loggers and they only transmit their data to the base station when READ_LOG command is given. In this application, MIB510 and Moxa Nport form the base station and served as an interface between the motes and an off-site PC. Battery lifetime for 2 AA batteries is between 27 to 50 days in this configuration and mode of operation.

Field operability of this system was established by measuring the micrometer change in width of cosmetic cracks in a house subjected to blasting at a nearby quarry. The ceiling crack, shown in Figure 1, is in a concrete block-house (with wood interior frames) located some 1500 to 2000 feet away from quarry blasting. Data have been collected in this house on experimental basis since August 2000 by a wired system. (Louis 2000 and McKenna 2002) Figure 2 presents the micrometer changes in crack width obtained by wireless and wired benchmark systems. As can be seen, the long-term response measured by the two data acquisition systems is remarkably similar. Timing of blast events shown in Figure 2 demonstrate that patterns of crack displacement were not altered from those observed during non-blasting periods, where environmental factors are the only driving force inducing crack opening and closing. This is a Level-I of the Autonomous Crack Monitoring (ACM) systems, which includes installing an operable remote controlled data acquisition system, measuring and collecting data (temperature, humidity and displacement or velocity) at regular intervals. Level-II, which requires sampling at high data rates for random events via a triggering mechanism, requires more research and development for wireless deployment.

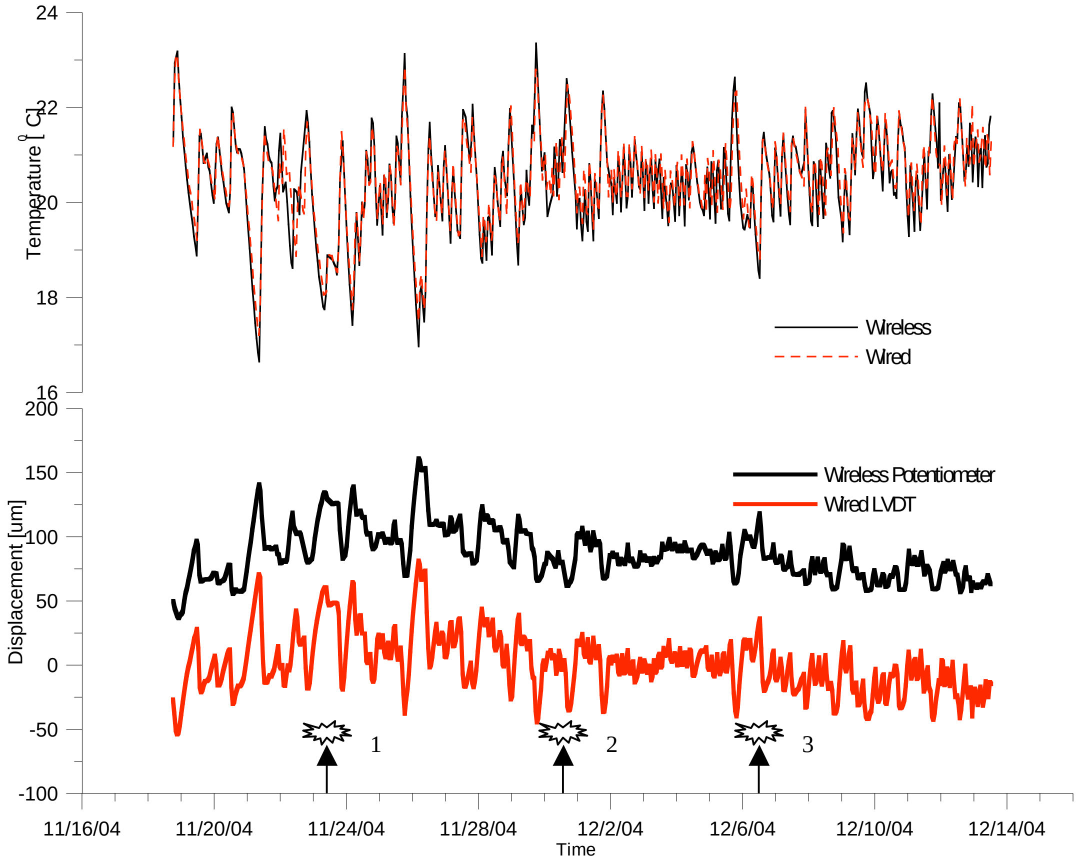

Figure 2: Crack displacement measurements by wireless and wired data acquisition system in Milwaukee test house (only first half of the measurements are shown due to space limitations)

Multi-hop Customization

This configuration provides a sophisticated method of multi-hop data propagation through the XMesh software protocol stack. It is an open-architecture, flexible, and powerful embedded wireless networking and control platform built on top of the TinyOS operating system. Some of the features of Xmesh include: 1.) True mesh (self-forming and self-healing in the case of loss of communication between the motes) 2.) Coverage area is extended as the motes are added to the mesh 3.) Low power listening (wake up X times per second to listen to RF if there is any data ready to be transmitted). 4.)More than year of AA battery life with reporting intervals of 5 to 60 minutes is made possible. As opposed to the single-hop configuration, multihopping employs remote motes only as sensing units, where the base station is the only data logger. Stargate stores the data and provides communication with an off-site PC.

Figure 3 compares the power consumption profiles obtained by single-hop and multi-hop customizations. The motes wake up only for sampling in single-hop customization as shown with the spikes in the bottom figure whereas multi-hop customization causes the motes wake for several reasons: listening, transmission of either the data or routing health information, which are shown by the spikes in the zoomed figure inserted in Figure 3. Power consumption is decreased considerably by multi-hop customization so that the network can operate more than a year without any human intervention. Overall hourly average of current draw with single-hop and multi-hop configurations are 4.6 and 0.31 miliamps respectively.

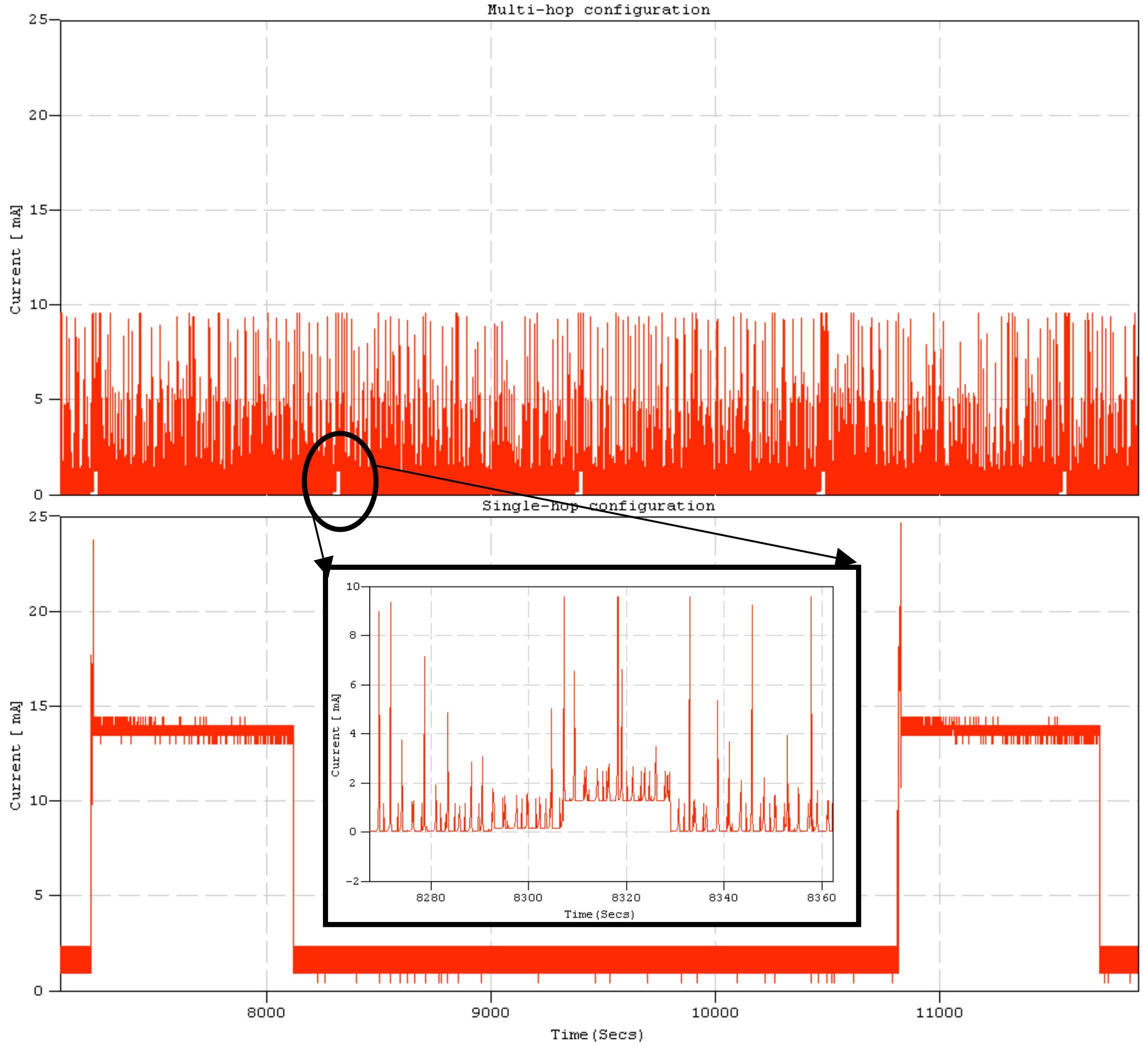

Figure 3: Power draw during single and multi-hop configurations of wireless system

The multi-hop system has been field tested on the roof of the building housing the Infrastructure Institute of Technology laboratories as shown in Figure 4. There the motes were exposed to high intensity electromagnetic radiation from other communication devices. Despite the high E-M environment, the motes operated well. Two potentiometers were attached to two different remote nodes. Each outside remote node (ID2 and ID3), which consists of sensorboard (MDA300), radio module (mica2) and an outboard sensor (potentiometer), sampled the temperature, humidity, battery voltage and displacement sensor data every 18 minutes. One remote (ID1) inside the elevator penthouse measured only temperature, humidity and battery voltage. Data propagated to the base through the most efficient path network. Efficiency (cost) is a measure of distance and is calculated by wireless routing algorithms, which will not be discussed in detail. Data sampled every 18 minutes were stored in the base (Stargate) and retrieved via Internet autonomously every night.

Figure 4: Remote nodes deployed on the roof of a downtown building

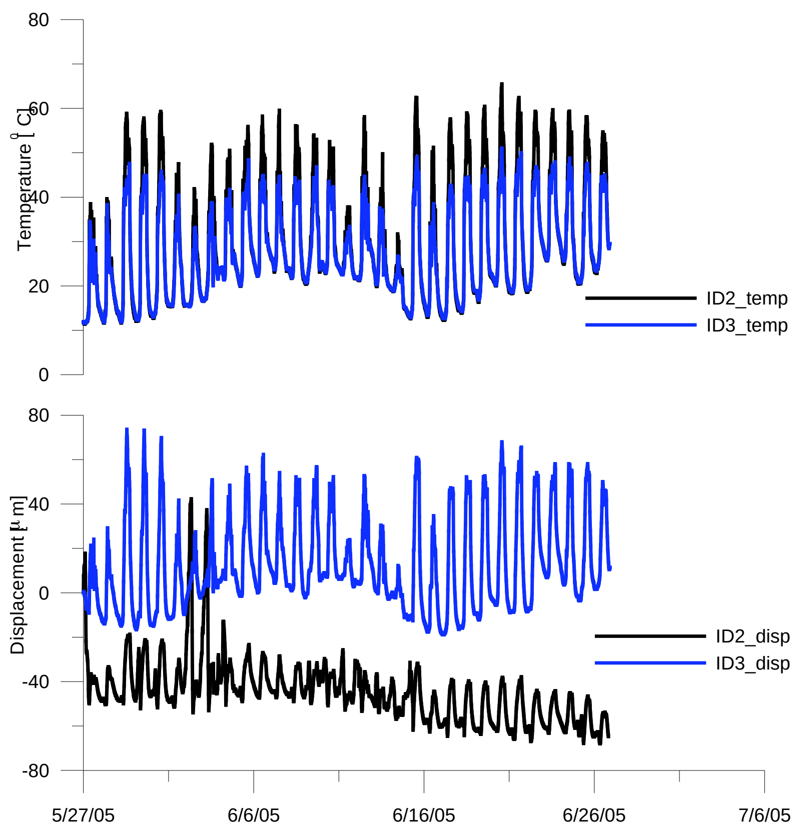

Figure 5: Displacement and temperature variation measured by the wireless remote nodes due to cyclically changing temperature variations on the roof

Figure 5 shows the results obtained from the test performed to validate the performance of the motes programmed with multi-hop configuration. Two remote nodes measured the expansion and contraction of aluminum and plastic materials respectively via potentiometer. The mote ID2 and ID3 denote the nodes with the potentiometers on the aluminum plate and with the plastic donut respectively. Although the temperature was not directly measured on the plate or donut, the cyclic temperature variations in the box that housed the motes clearly reflects the daily expansion and contraction cycles of aluminum plate and plastic materials. During the monitoring period of more than a month, no data were lost in transmission and the mesh operated without any stoppage, while changing data transmission pathways.

Conclusions

Wireless networks for monitoring long-term crack response obtained the same results as a wired system without the need to snake wires through a structure. The measured patterns of crack expansion and contraction were the same. The multi-hop configuration will allow operation to up to a year with 2 AA batteries. This low power of power consumption was made possible by use of string pot potentiometer, which do not require continuous power as do LVDT's, and the special low power listening mode. Successful operation of this system opens the door for its use to measure fracture extension in fracture critical bridges.

Acknowledgements

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