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Field Qualification of Inexpensive Wireless System to Monitor Micro-Meter Crack Response for Structural Health Monitoring

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Abstract: This paper describes the details of installation and operation of a commercially-available, wireless system to measure response of interior cosmetic cracks in a residential structure over a period of a year. Wireless data loggers managed the response of low power draw potentiometers that measured micrometer changes in crack width. Systems like that described herein are useful to describe the performance of any component of a constructed facility that involves existing cracks such as bridges, building facades, etc. Four wireless nodes were deployed within and around a test home of frame construction to qualify the system for further field use. Considerations for qualification included: fidelity of the measured crack response, ease of installation, resolution of structural health measurement, length of operation under a variety of conditions without intervention, and ease of display and interpretation of data. The article first describes the components of the system and the measurement plan. It then closes with an evaluation of the considerations for field qualification.

Keywords: structural health, wireless, crack, monitoring, micrometer, weather, blasting, vibrations, construction

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Introduction

This paper substantiates the ability of wireless systems to measure remotely and autonomously the performance of any component of a constructed facility that involves existing cracks such as bridges, building facades, etc. over long periods of time. For some time, wireless systems have been on the verge of being usefully deployed in the field for structural health monitoring (SHM). These systems, such as that which serves as the example in this paper, have now matured to the point that the data logging and communication nodes can be sustainably deployed in the field at an affordable price in robust, weather proof enclosures with solar power supply and provision for external devices. In addition, the process of autonomous data logging and internet transmission have also matured to the point that storage and internet based graphical display of data can be accomplished by the average engineer.

Structural health is monitored in this example by the measurement of micro-meter opening and closing of cracks on the interior walls of structure. This response and the associated climatological data are transmitted via a secure Internet connection in an adjacent structure back to a central server where they are made available via the World Wide Web. While the nodes themselves are weather proof, the displacement sensors are not. Since there are other, more weather proof micro-meter displacement transducers, this interior case can also serve as an example for exterior deployment. Development of inexpensive, climatologically robust displacement transducers has lagged development of inexpensive wireless data logging nodes because these nodes have been developed for the larger agricultural market where the emphasis is on recording environmental and soil moisture conditions. The much smaller market for structural health monitoring through measurement of crack displacement, the basis of this comparison, is dependent upon larger markets other than the relatively small civil engineering market to drive development of accessory instruments for the nodes.

The article first describes the deployment of the wireless system for comparison with a typical research grade wired system. It then concludes with the results of the comparison. The deployment section describes the site, plan for qualification (comparison of performance with the wired system), installation details, and components of the wireless system. The results section then describes fidelity of the measured crack response, ease of installation, resolution of the measurements, length of operation under a variety of conditions without intervention, and ease of display and interpretation of data.

Instrumentation Deployment

Site

Figure 1: Instrumented house located just south of the quarry with aerial photograph of the quarry showing the location of the house. Map data © 2010 Google, USDA Farm Service Agency

The wireless system was installed in a test house adjacent to a limestone aggregate quarry near Sycamore, IL shown nestled in the trees immediately south of the quarry in Figure 1. The two-story house, an elevation view of which is shown in the inset to Figure 1, is typical of farm homes that have seen many additions. A visit to the basement shows that there are at least two additions to the house: one to the two-story frame structure and the most recent single story wrap around on the west side. The house consists of a wood frame with composite wood exterior siding and gypsum drywall for the interior wall covering.

Qualification plan and instrument locations

Four wireless nodes were deployed within and around the test structure to assess the wireless system's behavior by comparing its behavior under a variety of field conditions with that of research grade wired systems (Meissner, 2010). Assessment involves fidelity of the measured crack response, ease of installation, resolution of structural health measurement, length of operation under a variety of conditions without intervention, and ease of operation. The placement of nodes shown in Figure 2 was chosen to maximize the variety of operational conditions. Two interior nodes (3 and 2) were chosen to compare performance of the solar cells for an east and south facing window exposure as response of different cracks. Exterior nodes (4 and 5) were located at variable distances from the house, where the base station was deployed and the base station (0) in structure that housed the Internet connection. The objective of the variable distances of exterior nodes between the house and base station was to determine the occurrence and necessity of multi-hopping to reach the base station. Multi-hopping describes a process where nodes closer to the base station relay messages from other nodes that would not otherwise be able to communicate with the base station directly.

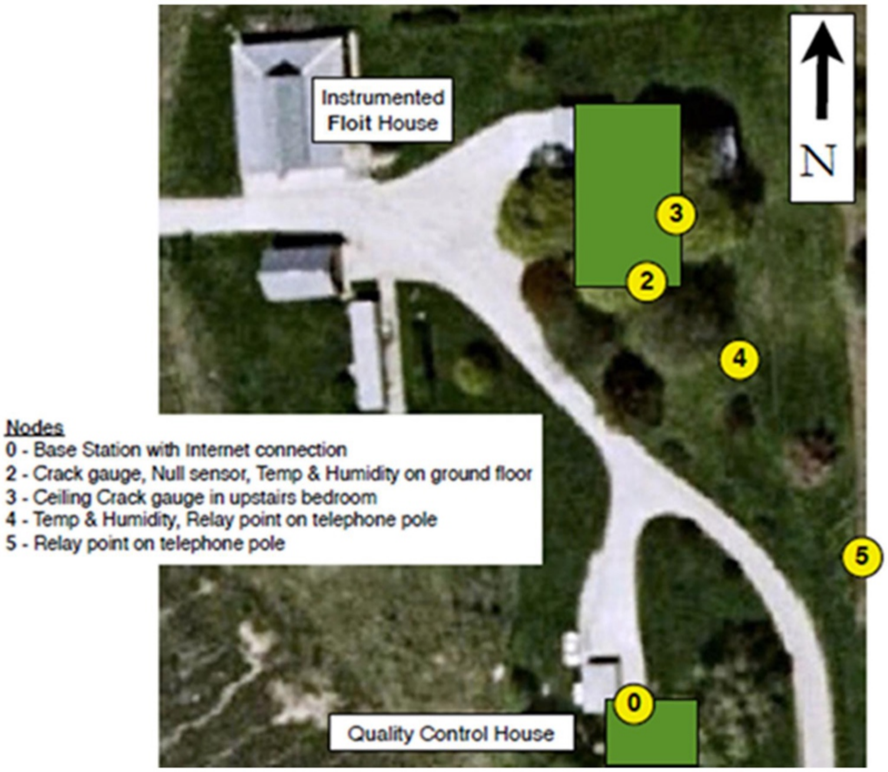

Figure 2: Location of the nodes showing the relation of the instrumented house (nodes, 2 & 3) outdoor nodes (nodes 4 and 5), and the location of the base station (node 0), and node 1 (not deployed). Map data © 2010 Google, USDA Farm Service Agency

Installation Details

Details and context of the nodal locations are shown in the close up photographs. External nodes 4 and 5, shown in Figure 3, were attached to poles and were faced to the south to maximize solar exposure. Nodes 2 and 4 were employed to measure internal and external temperature and humidity respectively. The manufacturer's temperature and humidity probes can be seen attached below node 4 and on the wall to the right of node 2 in Figure 5. Node 5 was located between node 4 and the base station, node 0, to provide a shorter path between node 4 and the base station. Node 5 employed no external measurement devices, and was positioned to facilitate transmission from the house to the base station. The need for 4 and 5 will be discussed later in the performance section.

Locations of the interior nodes 2 and 3 and the associated monitoring gages are shown in the building plan view in Figure 4. Nodes 2 and 4 were configured to monitor interior temperature and humidity as well as crack response of the large shear crack identified in the photograph in Figure 5. The node itself was mounted on the window frame of the south facing living room window such that its solar cells could achieve maximum solar exposure, while the temperature and humidity gage module as well as the crack and null displacement gages were mounted some 1.5meters away. Node 3 was responsible for monitoring response of the crack in the second floor bedroom ceiling some 2-2.5 meters away as shown in Figure 6. It was installed on the window frame of the east-facing window.

System Components

The example wireless system employed in this comparison with research grade wired system is designed for environmental and agricultural monitoring. Each node is water and dust resistant, capable of operating in wide temperature and humidity ranges, and is advertised to operate for over five years with sufficient sunlight. Its weatherproof design, shown in Figure 7 makes it an attractive platform for deployment in exterior as well as interior locations.

Nodes are the principal components of the Wireless Sensor Network (WSN). Its energy-efficient radio and sensors are designed for extended battery-life and performance, and integrates IRIS family processor/radio board and antenna that are powered by rechargeable batteries and a solar cell. Anode is capable of an outdoor radio range of 500ft to 1500ft depending on deployment. Since the nodes form a wireless mesh network, the range of coverage can be extended by simply adding additional nodes. The nodes come pre-programmed and configured with a low-power networking protocol.

The base station, which must be connected to 110 V AC power and a network connection, can transmit e-mail alerts when sensor readings cross programmable thresholds. Though the base station can be connected directly to the Internet, the test deployment described herein employed a secure virtual private networking system to traverse corporate firewalls and protect the system and the data. A point-to-point wireless Ethernet system was employed to connect the base station to an Internet connection located in an adjacent building.

The base station provides multiple methods for viewing and manipulating recorded data: One may use the base stations built-in web interface to perform simple plotting operations. One may also connect to the base station using FTP or SFTP to retrieve raw data for further, more sophisticated processing and Web display. The latter method was employed in the described test deployment.

A unique feature of this system is that the node end-user need not manually program the system to function properly, which is attractive to those with normal computer skills. The nodes record data every thirty seconds for the first hour after activation. Thereafter they record once every fifteen minutes. These data are automatically stored, retrieved once daily, processed, and graphically displayed on a secure Web site.

During every sampling cycle, each node records its internal temperature, battery voltage, and solar input voltage, along with data from up to four external sensors to which it is attached. For instance, external temperature and humidity, soil moisture, and other agriculturally interesting phenomenon can be recorded using sensors supplied by the manufacturer. Two nodes in this demonstration were fitted with temperature and humidity probes supplied by the manufacturer, as shown in the left photograph in Figure 3.

Figure 3: Installation of exterior nodes. Left installation includes temperature and humidity sensor module below the node.

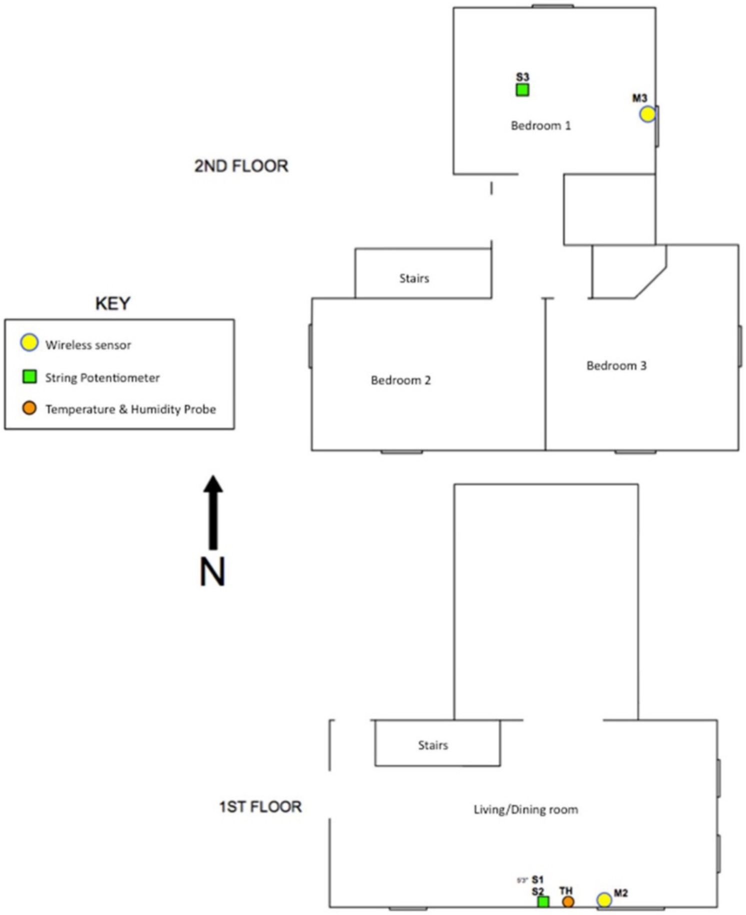

Figure 4: Plan view of the first and second floors of the test house showing the location of the interior nodes (circles) Temperature and humidity sensors (diamonds) and crack sensors (squares: 1 &2 on south wall and 3 on second floor ceiling).

Nodes that were deployed to measure crack response were supplemented with a signal conditioning board, available from the manufacturer, to amplify excitation voltage and sensor output voltage, effectively increasing the resolution of the system. As configured by the manufacturer, the signal conditioning board increases the resolution of the crack displacement sensor by approximately ten times. Unfortunately, the module is sold without a weatherproof enclosure and the black temporary housings shown dangling from the yellow node in the lower left of the lower photograph in Figure 5 was constructed using non-weatherproof components to facilitate indoor deployment.

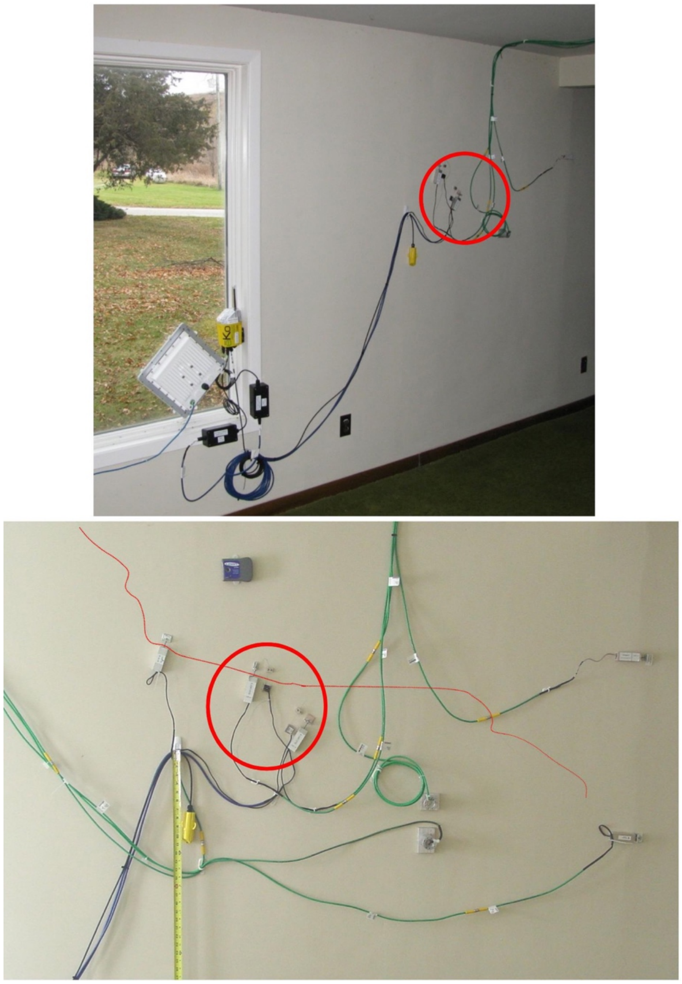

Figure 5: Context of south wall installation: wireless node on window frame, signal conditioners (boxes immediately below the node on window frame) on lines leading to sensors (temperature & humidity and crack sensors. The circle encircles the potentiometer crack sensors attached to wireless node. The crack, which transects the upper two displacement sensors in the inset circle, is underlined by the serpentine line from upper left to center right.

Figure 6: Context of node 3 and ceiling crack sensor. A close-up photograph of the ceiling crack and potentiometric proximity sensor is shown in Figure 8.

Figure 7 Wireless node weatherproof enclosure and access ports.

Crack response was determined by measuring the opening and closing of cracks with a miniature string potentiometer, shown in Figure 8. Potentiometer-based displacement sensors with their very low power consumption, no warm up time, and excitation voltage flexibility are prime candidates for wireless structural health monitoring. The batteries in typical nodes have limited energy density, which eliminates the usage of more power-hungry linear-variable differential transformer (LVDT) and eddy current sensors that have been used for many years in crack monitoring. As compared to these sensors, power consumption of the potentiometer is considerably smaller and thus prolongs the battery life of this system in periods of prolonged absence of sunlight.

Figure 8: Details of the potentiometric proximity sensor spanning the ceiling crack

The potentiometer chosen for wireless sensing is a subminiature position transducer. The sensor consists of a stainless steel extension cable wound on a threaded drum coupled to a rotary sensor, all of which is housed in a plastic block. The cable is anchored on the opposite side of the crack. Displacement of the crack extends the cable, which rotates the drum and changes the sensor output linearly between ground and the excitation voltage. This potentiometer is capable of measuring dynamic response (Ozer, 2005). However, as with all other wireless systems, there is insufficient battery life to maintain the 1000 samples per second operation necessary to capture dynamic events (Kotowsky, 2010).

As with the LVDTs, the more standard crack displacement sensor (Dowding, 2008) no additional electronics are required, which simplifies installation. While specifications indicate that this potentiometer's operational temperature range is –65 to +125° C, it has been qualified in an unmoderated garage with humidity's between 60 to 90% and temperatures between 10° and 30° C. As of the writing it has not been employed outside, where it can be exposed to rain.

As with other sensors, theoretical resolution can be calculated directly from sensor range and the specifications of the analog-to-digital converter employed in the sensor node. Full-scale range of the string potentiometer is 3.8 centimeters and the node utilizes a 10-bit analog-to-digital converter, rendering an effective resolution of .0038 centimeters. With the signal conditioner installed, the effective resolution is increased by a factor of approximately 10, for about 3.8μm, implying that the sensing system is approximately 38 times less sensitive than a system employing an LVDT.

Results

Results will be described in terms of field qualification, which, as introduced above, are 1) fidelity of the measured crack response, 2)ease of installation, 3) resolution of the SHM measurement, micro-meter opening and closing of cracks, and 4)duration of operation under a variety of conditions without intervention.

1) Fidelity of Crack Response

Fidelity of crack response will be determined by comparison of long-term response, e.g. response that is monitored with timed measurements at specific intervals. At this time wireless systems are capable of measuring responses as long as they only need to sense a few times every hour, which allows them to operate in a low-power mode for most of their deployment life. Because continuous sensing to record random dynamic response would cause the node to remain in a high-power-usage state, wireless systems are only capable of monitoring in this mode for periods no longer than a couple of hours.

In order to assess fidelity of the measurement of crack response by the wireless system, its measurements must be compared to those made by another system. During qualification of this system, two other systems were measuring response of the living room shear and bedroom ceiling cracks. These systems will be referred to as Wireless 1 (W1) and Wireless 2 (W2). The W2 is the standard system employed by the majority of past autonomous crack measurement (ACM) research (Dowding 2008). The W1 system is a newly developed, lower cost version of the ACM system based (Koegel, 2011). In this test house, one of each of these systems are deployed using LVDTs to measure micrometer response of cracks to both long term and dynamic phenomena. Space does not permit a detailed discussion of these systems, but they are described in detail in internal Infrastructure Technology Institute (ITI) reports (Koegel 2011).

Crack response measurements over a two-month period returned by these three systems are compared in Figure 9. Responses, in micrometers, measured by the three systems are plotted on top of each other for each crack with time along the horizontal axis. These long-term responses are the aggregation of measurements made autonomously every hour by the W1 and W2 and every 15 minutes by the wireless nodes.

The three systems return the same response over time for the crack in the interior, second floor ceiling. If the crack response is the same at all gage locations, the systems are expected to return the same measurement. This expectation is verified by previous work comparing response of LVDT and potentiometer gages (Ozer, 2005)

There is a difference in the responses of the three systems for the shear crack on the south facing exterior wall. The differences occur mainly at the beginning and end of the observation period. Over the two-month observation period, the gage attached to the wireless node responds less than the other two. The W1 LVDT is to the left of the red circle and the node potentiometer and W2 LVDT are in the circle.

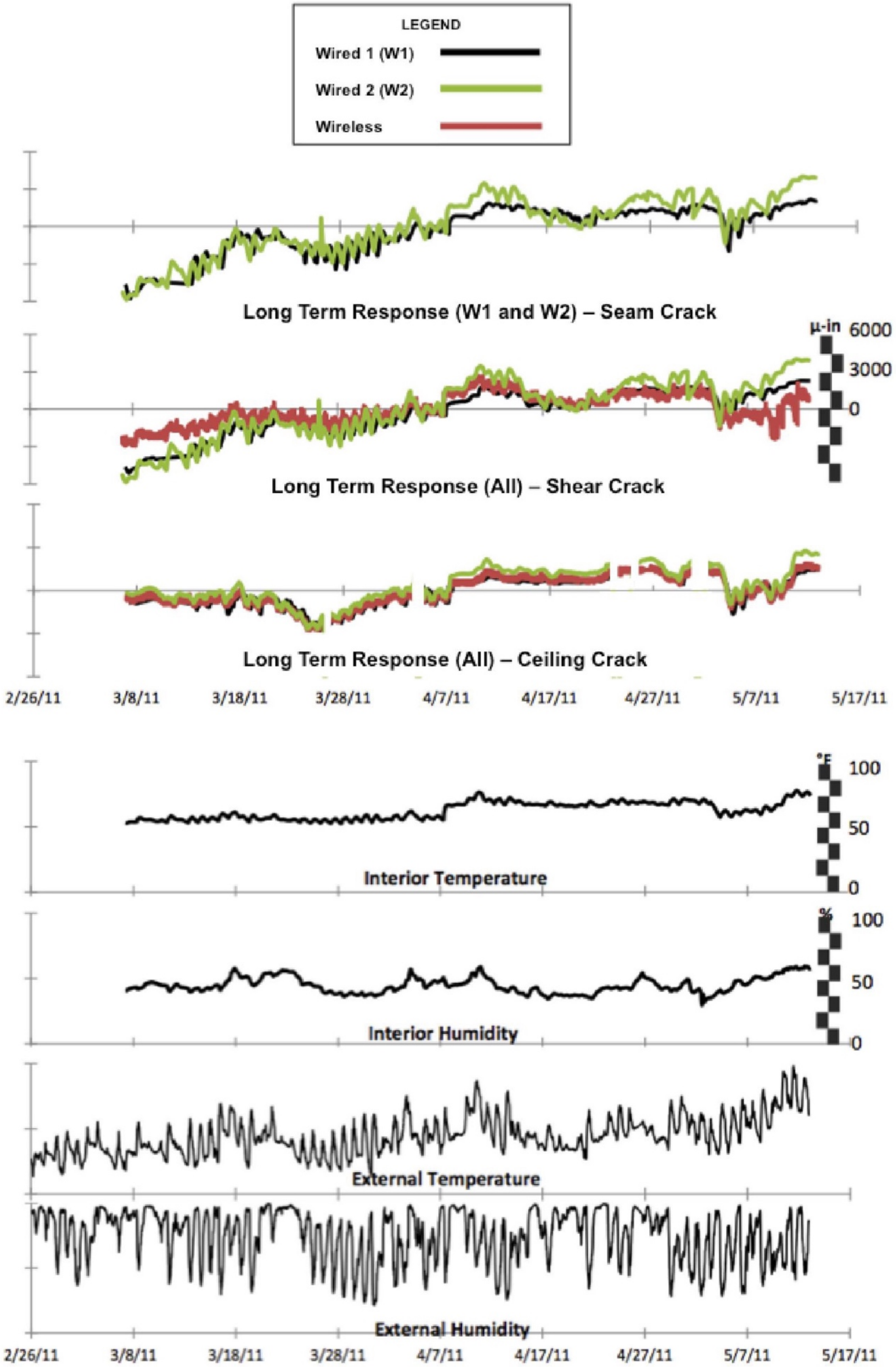

Figure 9: Comparison of long-term response of the three systems with temperature and humidity.

Detailed fidelity of the wireless system is good on a daily basis as shown by the comparison of the potentiometer response with that of the LVDT response in Figure 10 This figure displays the same information as in Figure 9 only separated and in more detail. In addition to the overall similarity, two regions demonstrate fidelity in both long term and daily responses. From 3/18 to 4/7 the similar daily responses for the wired (w1) and wireless systems are the oscillations with a return period of one day. Between 4/27 and 5/7 the similar longer lasting sharp drop for wired and wireless systems is the result of a longer-term climatological influence.

While the objective of this paper is not a study of crack response, a brief discussion places this study in context. In Figure 9 crack responses (at the top) are compared to the changes in exterior and interior temperature and humidity at the bottom. As can be seen, the rise in external temperature beginning in April induces a consistent change in both cracks. This rise in external temperature is accompanied by an increase in interior temperature and humidity. As discussed at length in Dowding (2008), this change in humidity causes the wood in the house to swell and shrink, which induces large changes in crack width. Over the course of these observations, the two cracks changed width by some 75 micrometers several times. In contrast, a quarry blast with peak particle velocities between 5 and 15millimeters per second (mmps) only produced dynamic crack displacements of 1.5 to 3.1 micrometers at the shear crack and 3.1 to 6.4 micrometers at the ceiling crack. This dynamic response is an order of magnitude less than that produced by climatological changes.

While this and most wireless system measure long term, climatological crack response well (1 to 4 samples per hour), they cannot measure short term, dynamic response (1000 samples per second) during long time intervals. This generic deficiency is the result of the lack of power provided by batteries small enough to be compatible with the small size of wireless systems. Dynamic events require continuous operation and thus quickly deplete battery power, whereas long term data can be captured by powering up only at selected times, say once an hour. In particular, dynamic events are captured by continuously recording at a high data rate and saving records that contain a data that exceed a threshold. Thus they must continuously record.

The long term data, which are measured once an hour, can provide dynamic response information by comparison of before and after blast crack width measures. For instance, a change in the long-term cyclical pattern of crack response after a dynamic event would indicate some change induced by the event. Only changes in pattern are diagnostic. Given the large change in crack response shown in Figures 9 & 10 produced by long-term environmental factors during an hour without a dynamic event, these changes would have to be large to be significant.

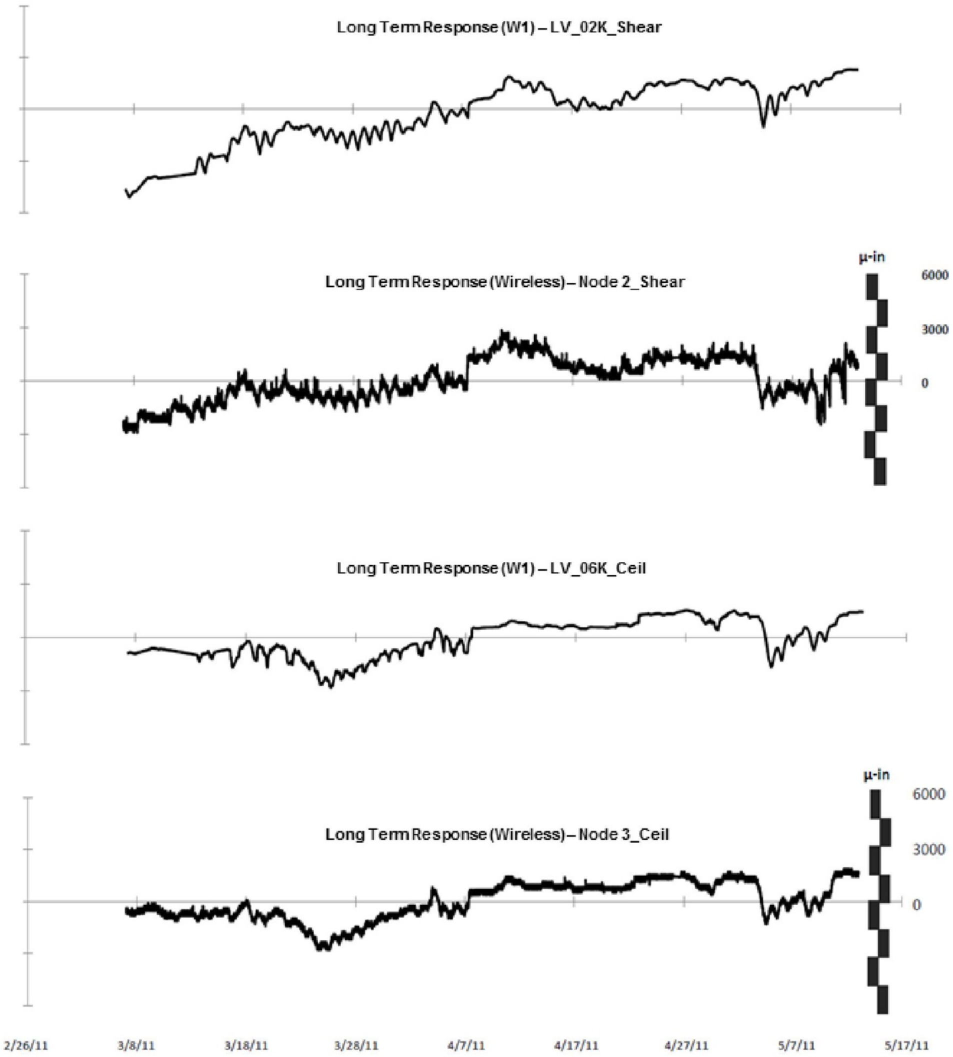

Figure 10: Comparison of the long-term responses of the shear and ceiling cracks as provided by the W1 and wireless node systems.

2) Installation

A discussion of the installation differences will be divided into three components: complexity, ease of installation, and cost. Comparison will be based on installation of two similar systems, which differ mainly in their wiring and power, and distribution of sensing activities; the wireless sensor system and the wired W1 and W2 .The wired systems will both monitor 3 crack and null sensors (for a total of 6) and 2 sets of indoor and outdoor temperature and humidity gages (for a total of 4 more) and a grand total of 10 channels of data. While the W2 has a greater capability, the comparison will be made on the basis of a need for only 10 channels. As described below the main differences are the lower node costs and lower wiring costs of the wireless system.

Complexity can be assessed by considering the sensors, their physical nature and the installation procedure, as well as the integration of the systems with the internet. The attachment process for the displacement transducers is basically the same. While differing slightly in size they both consist of a component glued to the wall on either side of the crack. The sensor output wires for the wireless system only need to be connected to the nearest node, while the sensor output wires for the W2 system need to be strung all the way back to the single, centrally-located W2. Both require an internet connection: the wireless base station and the W2 have standard Ethernet ports with statically or dynamically-assigned IP addresses. The main operational difference in sensor installation between these two systems is the process of zeroing the sensor. The W2's high sample rate and real-time display capabilities allow sensor zeroing to be completed in under two minutes per sensor.(the time necessary for the glue to cure), whereas the process requires some 10 or more minutes for each sensor connected to a wireless node because of the 15-second data acquisition interval during the first hour after each node is powered on.

Ease of installation can be assessed by considering wiring, power, sensor power requirements, and location restrictions. Wired systems can require up to 10 person-hours to run the wires to the sensors, often requiring drilling through walls, while the wireless system wiring time is part of the transducer installation. Thus wired systems require some ten hours of additional installation time. Both systems require standard household power. The wired W2 and its associated support electronics supply power to the transducers, while the wireless nodes supply transducer power from their own batteries. The wireless nodes should be placed by windows for solar power or if possible supplemented with a panel in a sunny location. This location requirement complicates the placement of the nodes.

Finally, cost can be determined by considering the wiring, transducers, data loggers, and internet connection. Research grade instrumentation wire and its associated modular connectors cost approximately $5.00per meter. A typical house could require some 90 meters of instrumentation cable costing some $300 to $500 for a wired W2 system, but less than $100 for the wireless nodes. The transducer costs are similar ~ $200 for each of the displacement transducers or a cost of $2000 for each type of system. The main equipment cost difference is the cost of the systems: A 3 node wireless system with base station might cost ~ $3,500, whereas the W2 system might cost as much as $ 10,000.

3) Resolution of SHM measurement

Resolution of the base mote-based system needed to be improved with the signal conditioner module as introduced in the instrumentation section. This enhancement was needed to increase the resolution of the measurement of crack responses. Since a wireless node has only a 10-bit analog-to-digital converter, it can only divide the measurement range into 2^{10} or 1024 subdivisions. Because the excitation voltage is the same as the maximum voltage measureable by the analog-to-digital converter, the mote will always divide the entire 3.8 centimeter range of the potentiometer by 1024, yielding an effective resolution of approximately 0.0025 centimeters

The signal conditioner module improves resolution in two ways: it increases the excitation voltage supplied to the potentiometer and it amplifies the output signal from the string potentiometer as it is fed back into the mote's analog-to-digital converter. Because the range of the analog-to-digital converter is not increased, this effectively decreases the range of the sensor by a factor of 10, but also increases the resolution by a factor of 10. Resolution can be further increased, at the expense of total sensor range, by performing hardware modifications to the signal conditioner module. These modifications were not made for this experiment.

The effect of the improved resolution is shown in the comparison of the long term response the shear crack (from node 2) before and after installation of the signal conditioner in Figure 11. During similar transitions between heating and cooling seasons (September before and May after) the variability produced by the daily swings is more prominent after the addition of the signal conditioner.

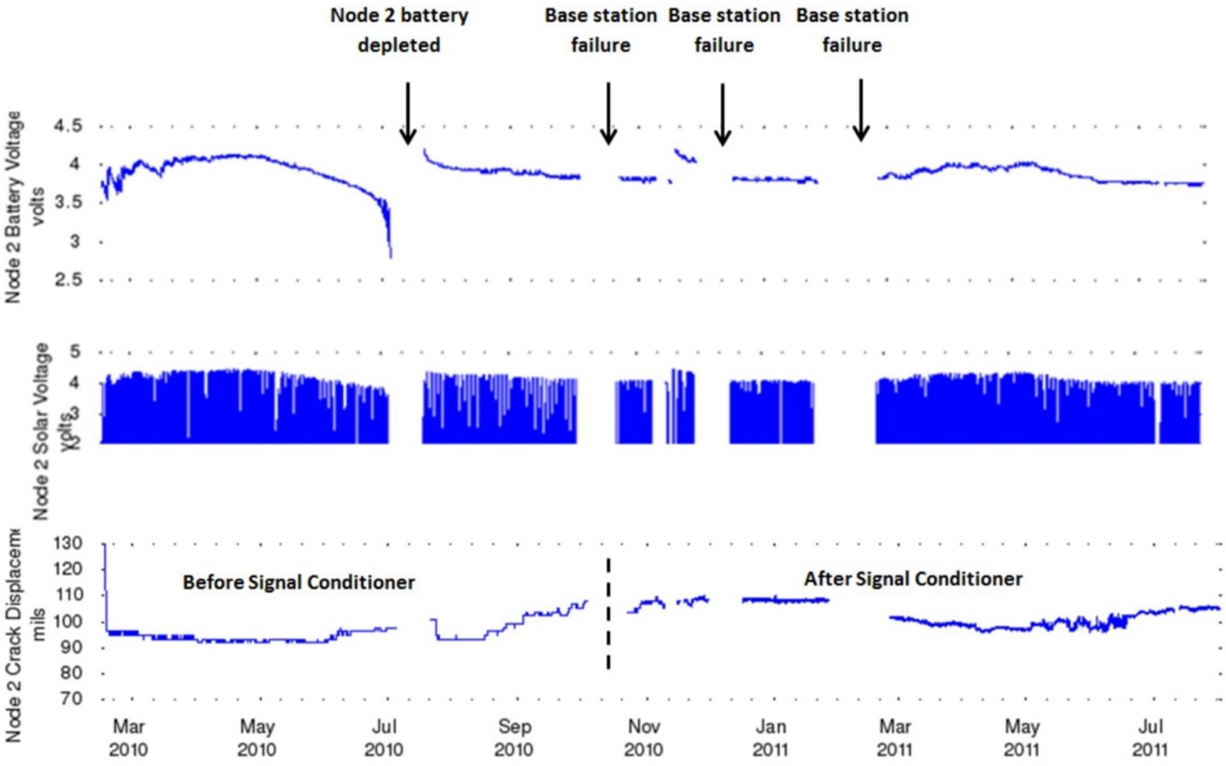

Figure 11: Top: Comparison of wireless system's battery life during one year of operation. Upper graph: Node 2 depletion occurred because of the leaf induced shading of the window in which the node was installed. Middle: Solar voltage shows fluctuations increasing after leaves blossomed. Bottom: Comparison of the crack displacements recorded by the same node before (left) and after (right) addition of the signal conditioning board to amplify the signal.

4) Duration of Operation

Duration of operation is controlled predominantly by the battery life and ease of recharging. Recharging capability is function of exposure to sun light, and exposure is a complex mixture of location and angle between sun and photovoltaic cells. Locations of nodes 2 and 3 present different exposure environments. Node 3 faces east and generally receives less sunlight than node 2. However, both are shadowed by trees, so the density of the leaves as a function of the season also affects the ability of the nodes to recharge. Figure 11 compares solar voltage and battery voltage for the two nodes. First ignore system failures induced by failure of the base station. Node 3's battery died (lack of signal after fall in voltage) twice and node 2 only once. All node failures occurred during the summer when the leafy trees shadowed both windows.

While not shown here, nodes 4 and 5 (the nodes deployed outdoors and away from trees)did not fail during the one and a quarter year of observation.

The base station failures are not related to solar recharging as it operates with 110 v AC power. These failures are a result of long-term instability of the manufacturer-supplied software that runs the base station. This instability has been largely improved by upgrades supplied by the manufacturer.

5) Ease of Operation

The wireless node system includes its own graphical display interface, which can be employed to graph measured response: an example with our test data is shown in Figure 12. As long as the smallest sample interval needed is 15 minutes, this preprogrammed graphical interface can be employed with minimal learning. The crack response as well as the temperature, humidity and battery condition can all be tracked in real time (+/- 15 minutes).

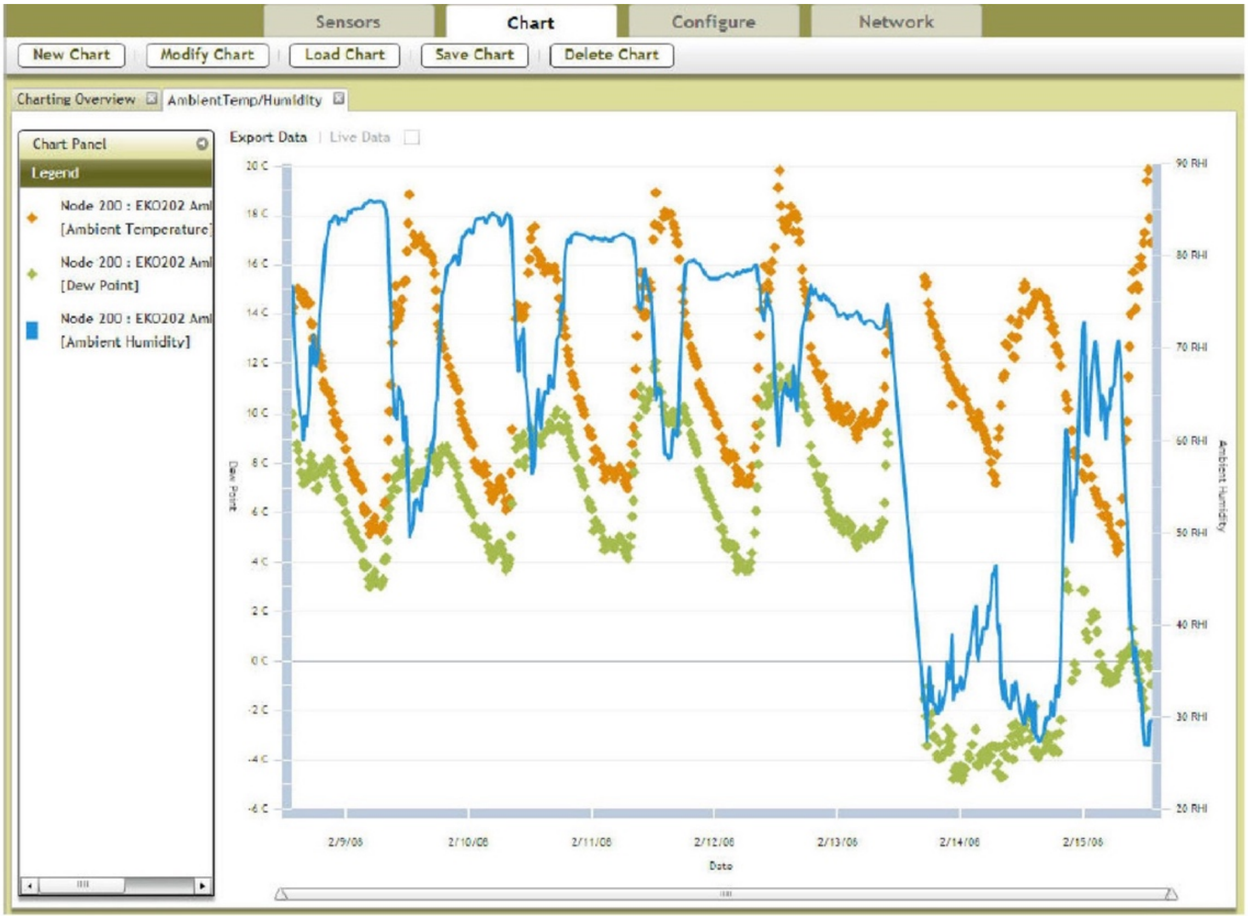

Figure 12: Preprogrammed graphical users interface supplied by the wireless system's manufacturer was employed to produce this graph of system response. Data can be either plotted in their raw point form (triangles) or interpolated line form (solid)

Conclusions

This study was undertaken to qualify the use of a wireless "node" system to track crack responses (changes in crack width) to climatological effects. Systems like this can be employed to monitor performance of any component of a constructed facility that involves cracking or relative displacements. Qualification was assessed by comparison of responses of the same crack as measured by the wireless "node" system compared to two wired systems, W2 and W1. In addition the ease and cost of installation of the wireless system was compared with that for the wired W2. The following conclusions were reached within the scope of the comparisons made. Since the wireless, "node" system is typical of such systems, these conclusions can be extrapolated to the class. If better performing equipment were available, it would have been employed. Of course as development continues with the typical speed of digital electronics, one should expect some of the observations to become dated. The wireless "node" system:

1) measures the long term crack response as well as the wired system(s),

2) has less crack response resolution than does the wired system even if a signal-conditioning unit is installed,

3) cannot capture dynamic responses directly, but can provide indirect detection if large changes in the cyclic response patterns occur at a time of a dynamic event,

4) is easier to install and less complex than wired systems,

5) is less costly (half the cost of a wired system),

6) operates autonomously as does the wired system,

7) graphically displays long term crack responses autonomously over the internet as do wired systems,

8) can operate for intervals of time approaching a year provided that the nodes are placed near windows that are not shaded by deciduous trees.

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