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Development of capacitance-based and impedance-based wireless sensors and sensor nodes for structural health monitoring applications

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ABSTRACT

A field demonstration of a new and hybrid wireless sensing network paradigm for structural health monitoring (SHM) is presented. In this paradigm, both power and data interrogation commands are conveyed via a mobile agent that is sent to each sensor node to perform individual interrogations, which can alleviate several limitations of traditional sensing networks. This paper will discuss such prototype systems, which will be used to interrogate capacitive-based and impedance-based sensors for SHM applications. The capacitive-based wireless sensor node is specifically built to collect peak displacement measurements. In addition, a wireless sensor node for collecting electromechanical impedance data has also been developed. Both sensor nodes are specifically designed to accept various power sources and to be wirelessly triggered on an as-needed basis so that they can be used for the hybrid sensing network approach. The capabilities of these miniaturized and portable devices are demonstrated in the laboratory and the field, which was performed at the Alamosa Canyon Bridge in southern New Mexico.

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1. Introduction

The field of structural health monitoring (SHM) is an integrated paradigm of networked sensing and actuation, data interrogation (signal processing and feature extraction), and statistical assessment (classification of damage existence, location, and/or type) that treats structural health assessments in a systematic way [1]. An appropriate sensor network is always required as a first line of attack in observing the structural system behavior in such a way that suitable signal processing and damage-sensitive feature extraction on the measured data can be performed efficiently.

Wireless sensor networks (WSNs) have been extensively investigated in recent years for many SHM applications [2]. However, there are many challenges associated with employing such a WSN in civil and mechanical infrastructure. The WSN must remain in operation over multiple decades with maintenance costs low enough to justify its integration into a given structural maintenance strategy. The technical challenges include ensuring reliable power sources for sensor nodes, reducing installation and maintenance costs, and automating the collection and analysis of data acquired by a WSN. One possible solution to these challenges is the use of sensor nodes that collect measurements from a structure in a completely

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passive manner without any electrical power. When a measurement is needed, energy is wirelessly provided to the sensor node by a ''mobile host'' such as an unmanned aerial vehicle (UAV). The sensor node can be powered by this wirelessly transmitted energy and then it wirelessly transmits its data back to the mobile host. The mobile host can then travel throughout the sensor network collecting data from other sensors of interest. In order to successfully implement this scheme, it is necessary to develop sensors and sensor nodes capable of operating at extremely low-power, being triggered by a wireless means, interrogating the sensors with the required accuracy, and then transmitting the data back to the mobile host.

In this paper, sensors and sensor nodes capable of interacting wirelessly with a mobile host are presented. We developed and demonstrated that our proposed wireless capacitive-based sensor node, referred to as THINNER, can successfully collect peak mechanical displacement measurements for civil infrastructure applications. The novel aspect of this sensor node is that the peak displacement sensors are capacitive-based. Instead of a conventional voltage-to-digital converter, THINNER is equipped with a capacitance-to-digital converter. Furthermore, the peak displacement sensor used is designed in such a way that it can collect and store data in a mechanical fashion independent of an electrical power source. In addition, a similar wireless sensor node, which capitalizes on the well-established impedance-based structural health monitoring technique, is designed and tested by our research team. This hardware is equipped with the capability, which allows the device to be wirelessly triggered to make a necessary measurement. The device is particularly unique because it offers low-cost, low-power, wireless sensing capabilities, and data processing not seen in any other impedance measurement hardware available today.

This paper will summarize prototype systems as they have been applied to the aforementioned mobile-host based SHM sensing network paradigm, where power and data interrogation commands are conveyed via an autonomous aerial vehicle. First, a discussion of the mobile-host based wireless sensing network paradigm is presented. We will then summarize the design, fabrication, and experimental verification of our capacitive-based and impedance-based sensors and sensor nodes in the context of this hybrid sensing network. These experiments were performed on the Alamosa Canyon Bridge, NM in August 2007. The performance and verification of wireless energy transmission is presented in a separate companion paper [3].

2. Mobile-host based sensing network paradigm

Sensor networks, generally speaking, contain four main components: the sensing mechanism, computation, telemetry, and power management [4,5]. The existing sensing network paradigms assume that the power sources are installed at fixed locations on the structural system. However, the deployment of such sensing systems can be costly and the power source may not be always available.

A new and efficient future sensing network is currently being investigated by the authors [4,6] by integrating wireless energy transmission technology and remote interrogation platforms based on unmanned vehicles, such as a robot or an unmanned aerial vehicle (UAV), to assess damage in structural systems. This sensing network is schematically shown in Fig. 1. This approach involves using an unmanned mobile host node to generate an RF signal near receiving antennas connected to the sensor nodes that have been embedded on the structure. The sensors measure the desired response at critical areas on the structure and transmit the signal back to the mobile host again via the wireless communications. This ''wireless'' communications capability draws power from the RF energy transmitted between the host and sensor node and

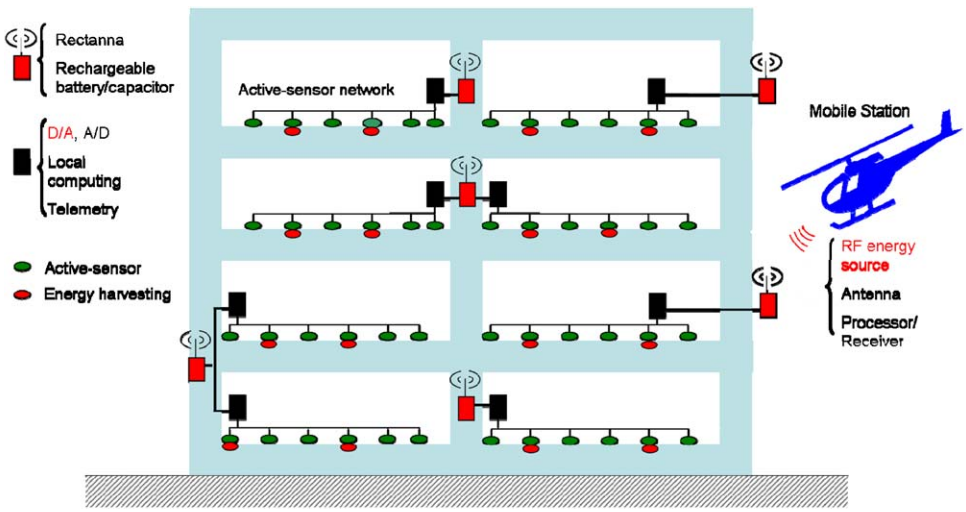

Fig. 1. A schematic of mobile-host based sensing networks.

uses it to power the sensing circuit. This research provides several advantages over traditional sensing networks, as the mobile hosts (such as UAV), that are either remotely-piloted or GPS-programmed, move to the sensor field, identify and locate sensor nodes, power and interrogate each node in turn, and perform necessary local computation to assess the system's structural health. This integrated technology will be directly applicable to rapid structural condition assessment of buildings and bridges after an earthquake as well as assessing the condition of structures where human access is limited because of safety considerations such as monitoring radioactive waste containers. Also, this technology may be adapted and applied to damage detection in a variety of other civilian and defense-related structures such as pipelines, naval vessels, hazardous waste disposal containers, launch platforms, and commercial aircraft.

A few examples of mobile agents being used as structural health monitoring platforms exist. Ma and Chen [7] proposed to use unmanned aerial vehicle to perform power-line inspection to reduce the maintenance cost. Hurston et al. also [8] suggested the use of a robotic agent to inspect structural integrity. In this work, a wireless sensor network using inductively powered sensor nodes was constructed for the purpose of monitoring strain on an I-beam. An I-beam crawling robot was built to crawl along the beam and delivery inductively coupled energy to each sensor node along its path as well as collect data from the sensor nodes. However, inductively coupled sensors are generally near-field devices that operate within a few wavelengths of the transmitter, which imposes difficulties in certain applications.

Other than the SHM area, various researchers have considered augmenting wireless sensor networks with robots and mobile hosts to enhance the performance of wireless networks [9–12]. To the author's best knowledge, however, no field demonstration of a physically unconstrained mobile host that is capable of wireless energy delivery to completely unpowered sensor nodes, as well as collecting data from the sensor nodes has been performed prior to this investigation.

3. Sensor node design

As the proposed approach is a new sensing network paradigm for SHM applications, there is no off-the-shelf hardware available. Therefore, we developed two different types of wireless sensing hardware and associated sensors in this study, which could be used to interrogate capacitive-based and impedance-based sensors for SHM applications. The capacitive-based wireless sensor node is specifically built to collect peak displacement measurements. The other device, referred to as wireless impedance device, is developed to capitalize on the well-established impedance-based structural health monitoring technique. When designing these systems, particular attention was given to (i) low-power operation, (ii) wireless triggering capability, (iii) wireless data transmission, and (iv) interfacing with sensors with the required accuracy for SHM.

3.1. THINNER sensor node

THINNER is made up of an ATmega128L microcontroller, an AD7745 capacitance to digital converter, and an XBee radio. THINNER is unique among wireless sensor nodes in two key ways. First, THINNER was designed to be powered by wirelessly delivered energy supplied from a UAV. In order to operate from such a low energy source, the components were carefully selected in order to ensure that they would perform satisfactorily at low energy levels (<1 J). In addition, the sensor node is equipped with a voltage threshold turn-on switch, which is designed to prevent the THINNER from being turned on until the sufficient energy is accumulated in a rechargeable energy storage medium, in this case, a 0.1 F supercapacitor. Second, THINNER employs a capacitance-to-digital converter instead of the conventional voltage-based analog to digital converter used in most wireless sensor nodes. The capacitance-to-digital converter choice was driven by the need to store peak displacement values in the absence of a power supply. In order to save these data, the sensors that are employed with THINNER are built to store peak data mechanically rather than electronically. Capacitive sensors were best suited for this type of requirement. This device is shown in Fig. 2, having overall board dimensions of 6×4 cm. A block diagram outlining the operation of THINNER can be found in Fig. 3.

The THINNER is designed to measure the peak displacement of a structure. After an extreme event, such as an earthquake, structures can experience large strains (or displacements) at critical locations. This peak displacement provides useful information whether the critical location undergoes the strain beyond certain safety criteria. The THINNER sensor node utilizes a capacitance-to-digital converter instead of a conventional voltage-based analog-to-digital (A/D) converter, which allows the sensor node directly coupled with the capacitive-based sensors. The selected converter was the AD7745 from Analog Devices. The AD7745 can measure capacitance in the range of 0 and 21 pF with ±4 fF accuracy. In addition, the AD7745 has a temperature sensor and a conventional voltage-based A/D converter. This chip uses a voltage range of 2.7–5.25 V and consumes 700 μA of current at 3.3 V. The surface-mount chip measures 5×6.4 mm.

The typical operation of this sensor node can be described as follows. The structure is assumed to be instrumented with the THINNER nodes where information such as peak strain or load is mechanically recorded. These sensor nodes are designed to accept wireless energy transfer from a mobile host, performing a RF-to-DC voltage conversion and subsequent four-fold voltage multiplication. The DC signal is then fed into a 0.1 F supercapacitor for storage purposes. The 0.1 F supercapacitor is isolated from the THINNER sensor node by a voltage threshold turn-on switch. The purpose of this switch is to ensure that the sensor node does not unnecessarily attempt to turn-on and consume energy until the sufficient energy is accumulated in the capacitor in order to ensure correct operation of the sensor node. Once the voltage on the capacitor

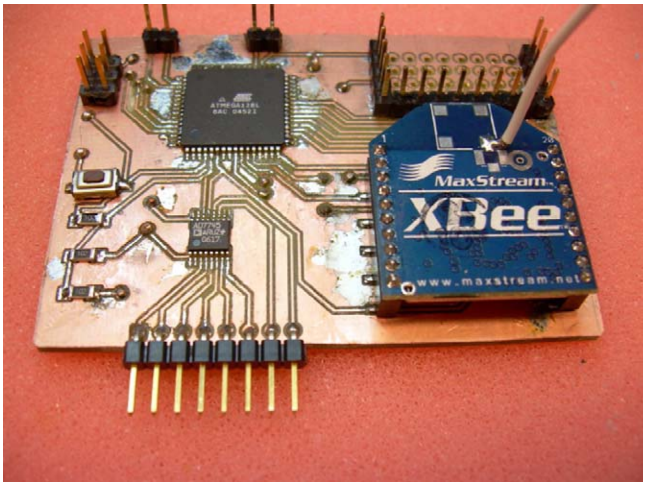

Fig. 2. THINNER wireless sensor node. The size of the node is 6 × 4 cm.

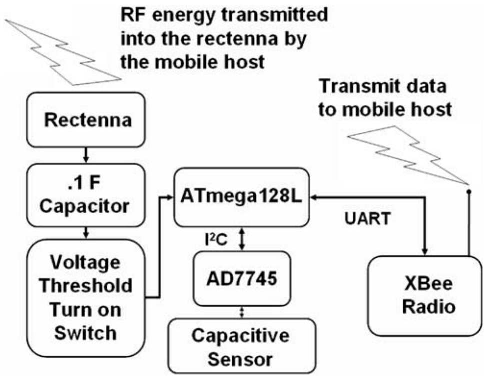

Fig. 3. THINNER block diagram.

has reached 3.5 V, the turn-on switch closes, and the THINNER sensor node turns on. THINNER uses a capacitance-to-digital converter to interrogate the capacitive peak displacement sensor. Once the data from the sensor has been collected, THINNER uses an onboard XBee radio to transmit the data back to the RF/computational payload on the mobile host. The interrogation process for this sensor node is now complete, and the mobile host can store the data and perform any relevant feature extraction and classification procedures. The mobile host can then proceed to other sensor nodes for interrogation in a similar manner. Even if the sensor node is equipped with a power source, such as batteries, the mobile agent can still be used to wirelessly trigger the sensor nodes, collect information and/or provide computational resources, significantly relaxing the power and computation demand at the sensor node level.

In this work a peak displacement sensor capable of storing peak values in the absence of electrical energy was also developed. Commercially available sensors were not able to meet the dynamic range, cost, availability, and/or energy requirements for this investigation. The sensor used in this work is very similar to that developed in [13] and utilizes essentially the same operation principle. The developed peak displacement sensor is shown in Fig. 4. An exploded view of the peak displacement sensor can be found in Fig. 5. The peak displacement sensor is essentially a parallel plate capacitor in a cylindrical configuration. The inner and outer aluminum components are the two plates of the capacitor. The capacitance of the sensor changes when the inner and outer cylinders are moved relative to one another along the axis of the cylinders. The inner Teflon alignment spacer serves the purpose of ensuring that the inner and outer aluminum cylinders remain coaxial. Furthermore, the Teflon alignment spacer also ensures that some level of friction exists to maintain the current axial position of the aluminum cylinders in the face of extraneous disturbances. The presence of friction is what distinguishes this particular sensor as a peak displacement sensor.

In order to identify the sensitivity of the sensor, an experiment was performed. The peak displacement sensor was connected to the THINNER sensor node and three different test runs were performed to measure the sensitivity of the sensor. In each test the sensor node was started at the same point. The 20 measurements were performed with the THINNER sensor node. Then the inner aluminum cylinder was advanced into the outer aluminum cylinder by 0.0254 mm and 20 more measurements were obtained. This process was repeated over the whole range of the THINNER capacitance to

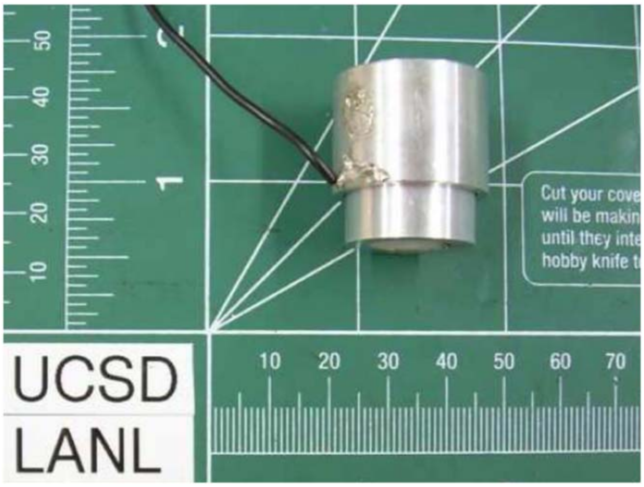

Fig. 4. Peak displacement sensor.

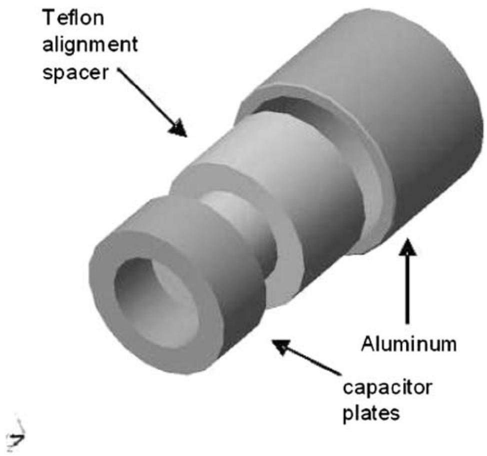

Fig. 5. Exploded view of the peak displacement sensor.

digital converter. The resulting measurements and a linear regression model are plotted in Fig. 6. From the plot, it is obvious that the peak displacement sensor possesses a linear relationship between capacitance and displacement over the range of values tested, as shown in the figure. The equation of the best fit line to the data contains two pieces of information. The slope of the line is the sensitivity in points/mm, and the constant value is proportional to the stray common mode capacitance in the sensor and can be ignored since it does not change. The 24 bit capacitance to digital converter has a dynamic range up to 8 pF, so the sensitivity (or calibration factor) can be calculated using the slope value, which is 3.29 pF/mm and matches very nicely with the predicted sensitivity value of 3.44 pF/mm.

For the THINNER sensor node, power requirements are more important than the typical wireless sensor nodes because the THINNER is intended to operate from wirelessly transmitted power. It was identified that, during the measurement, the power consumption of the THINNER was 36 mW, while 150 mW of power was needed for data transmission. In another test, one 0.1 F capacitor charged to 3.6 V was connected to the THINNER sensor node and THINNER was allowed to make measurements continuously. The result was that THINNER can successfully take 2–3 measurements and wirelessly transmit the data consisting of 3 bytes for each measurement. During field testing, it took 30–300 s to charge a 0.1 F capacitor using various mobile hosts including a remote controlled helicopter and a man-maneuvered truck [3]. With the high reliability and repeatability of the sensor measurement and with the low-power requirement, the current THINNER sensor node is suitable for inclusion in the first version of the mobile host wireless sensor network.

3.2. Impedance-based sensor node

The wireless impedance device (WID2) was developed from the capabilities demonstrated in previous studies of the impedance-based structural health monitoring method. The basic concept of the impedance method is to use high

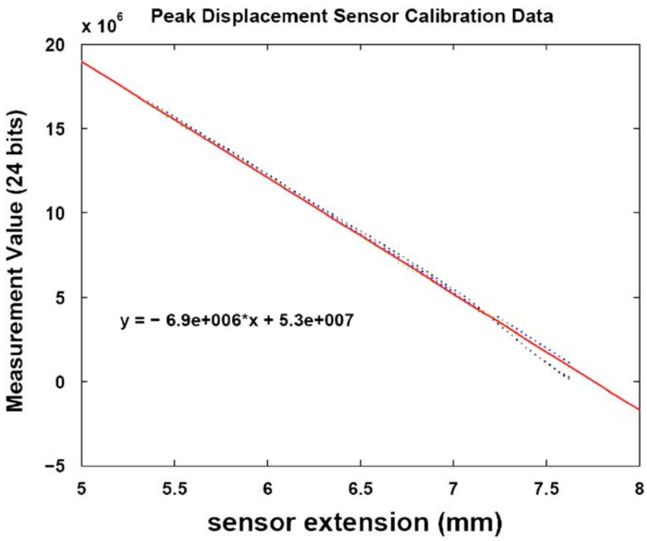

Fig. 6. Peak displacement sensor linearity and repeatability test.

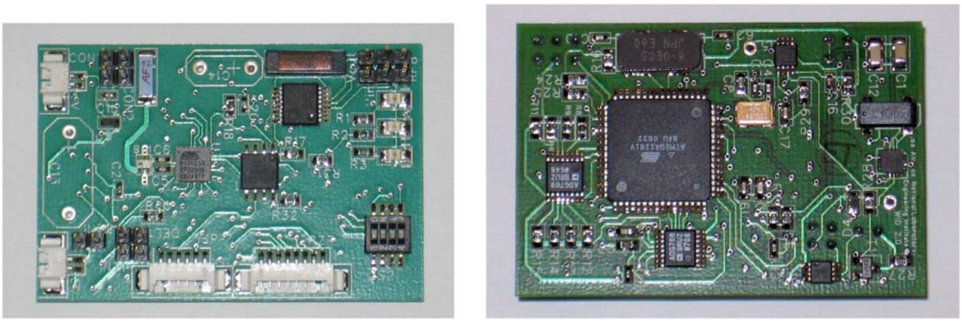

Fig. 7. The front and back side of Wireless Impedance Device (WID 2.0).

frequency vibrations to monitor the local area of a structure for changes in structural impedance that would indicate damage or imminent damage [14–16]. This method uses the electromechanical coupling property of piezoelectric materials, where the electrical impedance of piezoelectric materials is directly coupled with the mechanical impedance of a structure. Therefore, by monitoring the electrical impedance variations, one can identify if structural damage has occurred or is imminent. Recently, a new advance in integrated circuit impedance measurement technology at Analog Devices, Inc, has opened the door for an efficient and low-cost solution for real-world and low-cost impedance measurements for SHM applications. The Analog Devices AD5933 impedance measurement chip is equipped with an analog to digital converter, a digital to analog converter, FFT functionality, and a sampling frequency up to 200 kHz at the size of 6×8 mm. The AD5933 can be used to realize a self-contained, miniaturized impedance measuring solution. The use of this device will broaden its availability to the health monitoring community as well as promote the miniaturization of the equipment needed to implement the impedance method.

The AD5933 is used as a core component of our wireless impedance-based wireless sensor node (WID 2.0). The first generations of the wireless impedance device (WID1, WID1.5) were developed and tested by members of our research team [17,18]. Some limitations were identified in these initial prototypes including the ability to monitor only one single active-sensor, limited triggering capabilities, and the high power demands of the wireless telemetry component. Therefore the WID2 was developed with many unique features to allow for diverse SHM operation. The sensor node also integrates several components, including a microcontroller for local computing, telemetry for wireless data transmission, multiplexers for managing up to seven piezoelectric transducers per node, energy storage mediums, and several triggering options including a wireless triggering circuit into one package to truly realize a comprehensive, self-contained wireless active-sensor node for SHM applications. This newest generation of wireless impedance device is shown in Fig. 7, having overall board dimensions of 5.5×3.7 cm.

The operation of the sensor node is controlled by a microcontroller. This microprocessor is used to program the registers in the multiplexer, AD5933 impedance measurement chip, and the wireless telemetry. Two multiplexers in a single sensor node are used to control and monitor up to seven individual sensors. The microcontroller also performs local processing of the data collected by the impedance chip, and then determines whether or not the structural integrity is compromised. The result of the computation from the microcontroller will be transmitted by the wireless telemetry, AT86RF230 manufactured by Atmel. This telemetry system is an IEEE 802.15.4 compliant radio, which uses a free MAC layer distributed by Atmel. Furthermore, the AT86RF230 has very low energy requirements and low external component counts, making it particularly attractive for a SHM device. Another capability incorporated in the WID2 is a wireless triggering option. This sensor node can be brought out of its sleep states by a low-frequency wake-up chip, which would be useful for on-demand measurements triggered by a mobile station. The power consumption of the WID2 is estimated to be 54 mW for measurement and 59.4 mW for data transmission. Furthermore, the WID2 has the ability to accept power from diverse sources through the built in power port. More detailed information on the sensor node and its capabilities can be found in the Ref. [19].

4. Experimental verification at the Alamosa Canyon Bridge

The first field test of the developed sensor nodes was performed on the Alamosa Canyon Bridge in the southern New Mexico. The bridge is a traditional steel girder bridge with a reinforced concrete deck (25 cm thick), supported by six steel beams. The roadway in each span is approximately 7.3 m wide and 15.2 m long. This bridge has been decommissioned and is utilized by the New Mexico Department of Transportation as a testbed for structural health monitoring systems from university and research organizations.

First, the peak strain sensing capability of the THINNER is tested and compared to that of a traditional foil strain gauge. The peak displacement sensor, the THINNER sensor node, and a foil strain gage were instrumented on the lower flange of the support beam in the middle of the bridge. A 22 t dump truck was driven over the bridge roadway at 35 km/h to provide structural excitation, shown in Fig. 8. A bumper was placed on the roadway in order to provide maximum excitation to the bridge. Next, another set of experiments were performed to test the effectiveness of the WID2 sensor node. Three sensor nodes were mounted along the western longitudinal rail of the bridge as shown in Fig. 9. The nodes were spaced at 10 m intervals. The WID2 sensors were wirelessly triggered by a mobile host for monitoring of several bolted joints in the bridge. All the data were collected through a mobile host.

Only the results of the experiments where the sensor nodes were powered by batteries are shown in this paper in order to illustrate the performance of the sensor nodes in the real-world environment. The results with wireless energy transmission for powering these sensor nodes along with the design of the mobile host and the associated hardware are presented in a separate paper by the authors [3]. In short, it took approximately 30–40 s to charge a 0.1 F supercapacitor to a voltage of 3.6 V in at a distance of 1.2–1.3 m if 1 W of energy is transmitted from a ground-based mobile host. When a UAV is used it took much longer in the range of 95–280 s because of alignment issues in the presence of the wind gusts. Once charged, both THINNER and WID2 were successfully initialized, took measurements, and sent data wirelessly to the mobile host.

4.1. Peak displacement sensing using THINNER

While the truck was driven over the bridge, data were recorded from both the THINNER sensor node and the foil strain gage simultaneously. The resulting data are plotted in Fig. 10. In this plot, the displacements calculated by the peak displacement sensor are converted to strain for comparison with the strain gauge. As can be seen in the figure, the strain gage measurement increases in value as the dump truck drives over the bridge until it reaches a peak value at around 8 s. As the truck drives off the bridge the value on the strain gage decreases. The peak displacement sensor on the other hand

Fig. 8. A dump-truck used to excite the bridge.

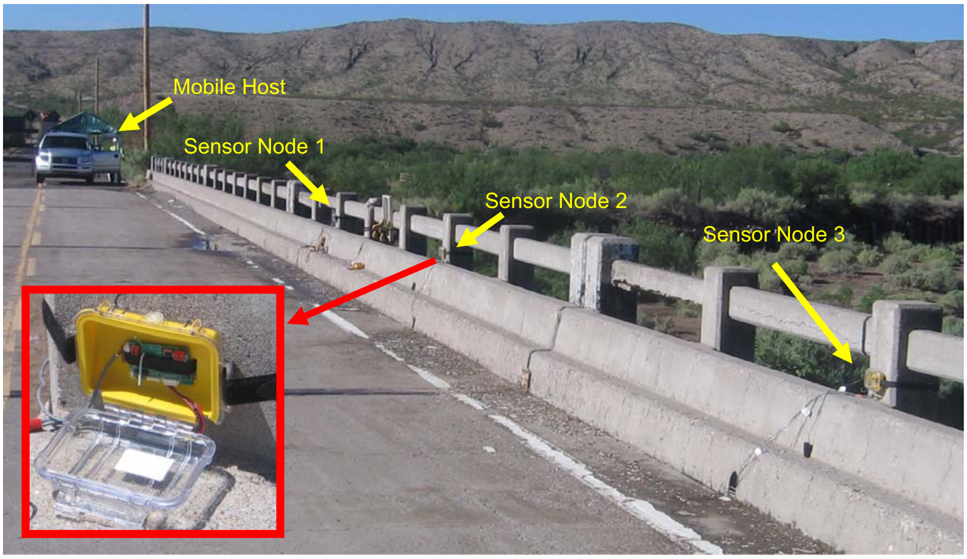

Fig. 9. Layout of the field test using WID2 conducted at the bridge.

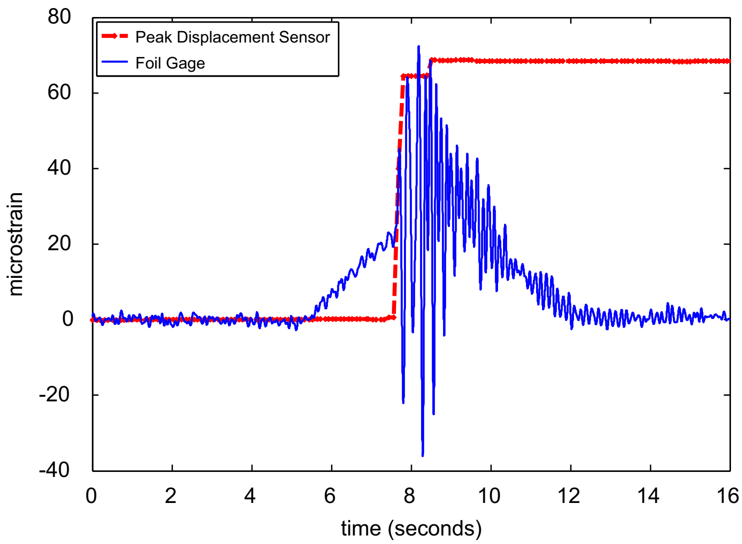

Fig. 10. Peak displacement sensor vs strain gage test on Alamosa Canyon Bridge.

maintains a low value until a threshold value is reached. When a threshold value of displacement is obtained, the peak displacement sensor goes up and follows the strain gage reading until it reaches the peak value. Once the peak value is obtained and the strain begins to drop off, the peak displacement sensor retains its peak state even though the load has been removed from the bridge. The peak displacement sensor essentially has a mechanical memory of its peak state. The peak strain recorded by the strain gauge is slightly higher than the peak strain recorded by the peak strain sensor. This discrepancy is most likely due to compliance and friction in the peak strain sensor.

Overall, the result clearly indicates that the sensor and the THINNER can accurately measure the peak displacement for structural health monitoring applications. It is important to point out that this memory phenomenon is essentially a zero electrical energy data storage scheme. This characteristic is especially useful as the reading from the THINNER is designed to be collected by a mobile host.

4.2. Electromechanical impedance sensing using WID2

Each WID2 sensor node was connected to three instrumented washers that were mounted using steel bolts (19 cm diameter) replacing the original bolts used to secure a steel cross member to the outer girder on the western side of the bridge. A series of three instrumented washers are shown in Fig. 11 with an exploded view of an individual washer clamped between the girder and the steel nut. The torque of the bolted joint was varied from 240 in lb to hand-tightening during the experiment to test the sensor node's ability to identify the state of each instrumented bolt. The WID2 was programmed to monitor the peak magnitude of the washer in the frequency range of 52–59 kHz and was configured to be triggered by a 125 kHz low frequency signal, which will be initiated by the mobile host vehicle.

The operating principle of the PZT instrumented washer is briefly described here. These washers are used in the same manner as their conventional counterparts. If these devices are mounted in a structure, the dynamics of these washers will be changed as the preload is increased. More specifically, the resonant peaks of the washer will shift to slightly higher frequencies, and then, at a certain torque threshold level, the magnitude of the resonant peaks will decrease substantially. These changes can be efficiently monitored by the impedance method and WID2 and used in joint monitoring without storing baselines for each and every bolted joint. More detailed discussion on this principle can be found in the Ref. [20].

Fig. 12 shows a summary of the mobile-host wireless sensing network developed in this test. The mobile-host vehicle approaches close to the sensor node (operated by the driver of the vehicle) within the range of 2 m between the RF triggering antenna installed on the back of the vehicle (shown in the figure) and the sensor node. The triggering command is sent from the base station, which monitors the movement of the vehicle through the wireless video camera using the host computer. The communication box inside the vehicle receives this command and executes it by sending a wake-up 125 kHz RF wake-up signal to the sensor node. The sensor node is brought out of its sleep status by this signal, takes the measurements from the piezoelectric sensors, performs the local computing to find out the magnitude of the resonance of each washer, and broadcasts the data to the mobile-host vehicle. The communication box inside the vehicle receives these data and sends them to the base station so that the decision on health assessment can be made by the user. For the base station, data are wirelessly received by a STK500/501 development board with ATAVRRZ502 Zigbee RF telemetry module that was used as a serial port interface. A MATLAB based graphical user interface was created to facilitate the data processing, as shown in the Fig. 12.

For the first test, all nine bolts were tightened to 240 in lb of torque. The mobile-host vehicle then moves close to each sensor node, wirelessly triggers the nodes, and relays the data back to the base station. The results are shown in Fig. 13. The plot displays the inverse of magnitude. The threshold limit was set at 1000, which corresponds to 5 in lb based on the calibration of WID2 at the laboratory. Each sensor shows three data points which correspond to results from three piezoelectric sensors connected to a node. As can be seen in the figure, each WID shows that the readings from three piezoelectric sensors are well below the threshold limit. For the second test, damage was introduced by loosening one bolt (out of three) to hand-tightened for each sensor node. After triggering each sensor node, the damaged bolts were clearly identified with the increase in the (inverse of) magnitude as shown in Fig. 14.

This study provides an excellent opportunity to demonstrate the feasibility of the mobile-host based wireless sensor network. The measure and transmit operations take a combined time of less than 40 s to complete for all sensor nodes. By using the wireless data transmit and wireless triggering option, the structural health assessment can be made very quickly in an entirely wireless manner. For SHM, the sensor node can be mounted on several locations in order to monitor critical locations in a structure. A mobile host then searches for the sensor nodes on the structure and gathers critical data needed to perform the structural health evaluation. This integrated technology can be adapted and applied to damage detection in a variety of engineering structures.

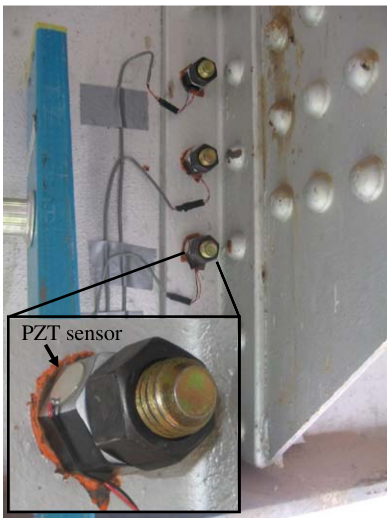

Fig. 11. Instrumented bolts mounted to the outer girder of the Alamosa Canyon Bridge. Preload was monitored using the WID2 sensor node.

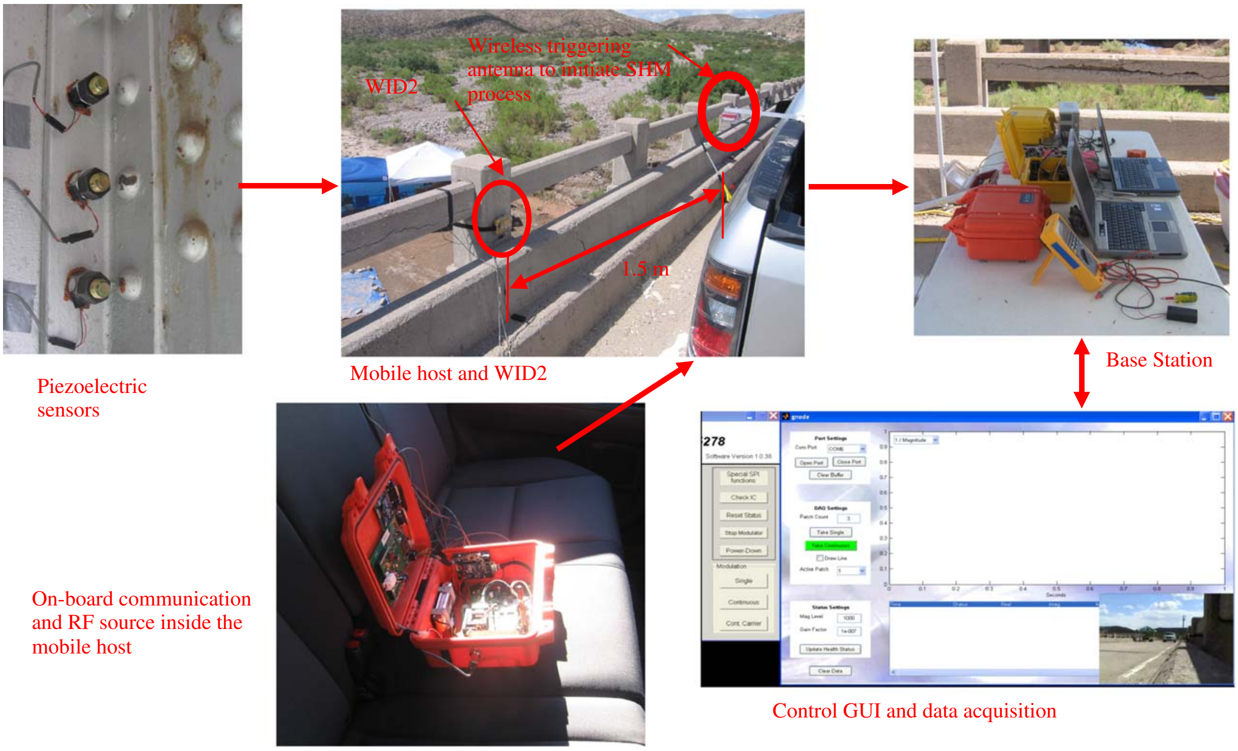

Fig. 12. Summary of the process used for the WID2 interrogation at the bridge.

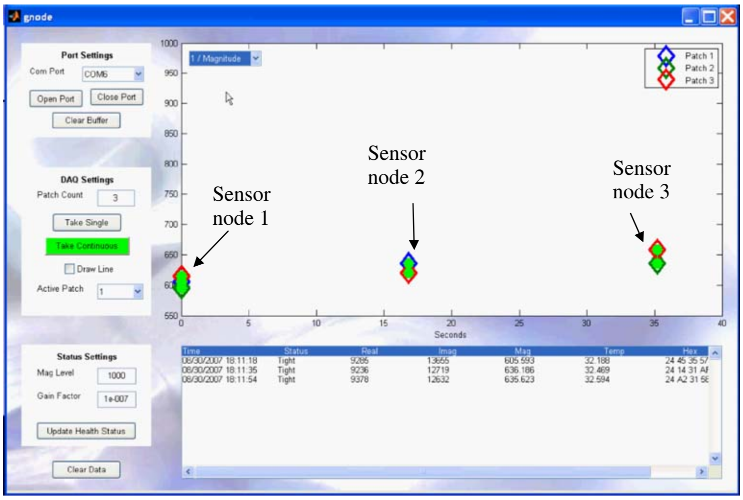

Fig. 13. Data received at the base station, while there is no damage was introduced to the bridge.

5. Conclusion

In this paper, a series of the wireless sensor nodes designed for inclusion in a mobile-host wireless sensor network have been described for intended uses in structural health monitoring applications. The THINNER sensor node was designed to measure the peak displacement in a structure. The peak displacement sensors were also developed and characterized. In addition, the wireless impedance device was also developed, which capitalizes on the well-established impedance-based structural health monitoring technique. Both sensor nodes require very low-power and are capable of being wirelessly

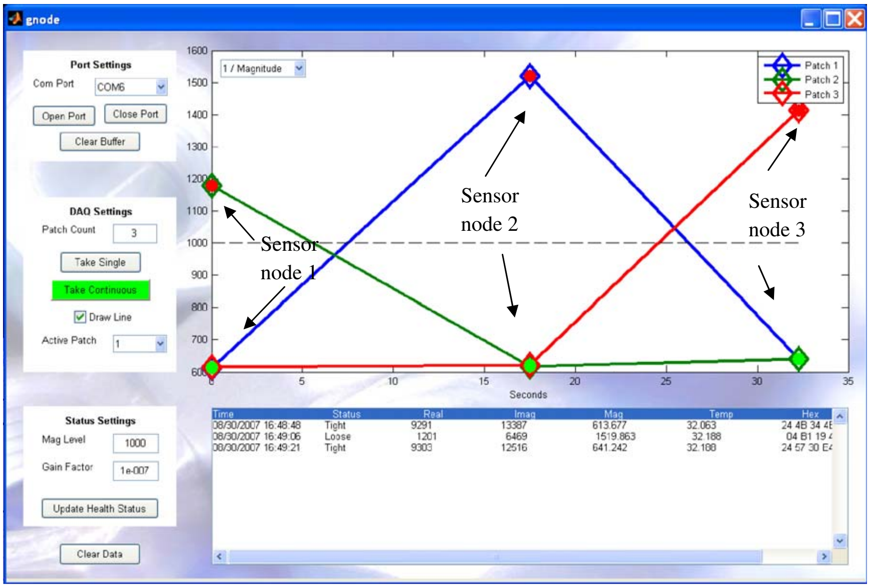

Fig. 14. Data received at the base station with damage bolted connections.

triggered by a mobile agent for use in the proposed mobile-host based wireless sensing network. The performance of these devices is first verified in laboratory. Subsequent field testes demonstrate that these sensor nodes can efficiently monitor several mechanical response parameters suitable for rapid assessment of structural condition.

References

[1] C.R. Farrar, S.W. Doebling, D.A. Nix, Vibration-based structural damage identification, *Philosophical Transactions of the Royal Society: Mathematical, Physical and Engineering Sciences* 359 (2001) 131–149.

[2] J. Lynch, K. Loh, A summary review of wireless sensors and sensor networks for structural health monitoring, *The Shock and Vibration Digest* 38 (2006) 91–128.

[3] D. Mascarenas, E. Flynn, M.D. Todd, T. Overly, K. Farinholt, G. Park, C.R. Farrar, Experimental studies of using wireless energy transmission for powering wireless sensor nodes, *Journal of Sound and Vibration*, submitted.

[4] C.R. Farrar, G. Park, D.W. Allen, M.D. Todd, Sensor network paradigms for structural health monitoring, *Structural Control and Health Monitoring* 13 (2006) 210–255.

[5] C.-Y. Chong, S.P. Kumar, Sensor networks: evolution, opportunities, and challenges, *Proceedings of the IEEE* 91 (2003) 1247–1256.

[6] M.D. Todd, D.L. Mascarenas, E.B. Flynn, T. Rosing, B. Lee, D. Musiani, S. Dasgupta, S. Kpotufe, D. Hsu, R. Gupta, G. Park, T. Overly, M. Nothnagel, C.R. Farrar, A different approach to sensor networking for SHM: remote powering and interrogation with unmanned arial vehicles, *Proceedings of Sixth International Workshop on Structural Health Monitoring*, Stanford, CA, September 11–13, 2007.

[7] L. Ma, Y. Chen, Aerial surveillance system for overhead power line inspection, Center for Self-Organizing and Intelligent Systems (CSOIS), Utah State University, Tech. Rep. USU-CSOIS-TR-04-08, September 2003.

[8] D. Huston, B. Esser, G. Gaida, S. Arms, C. Townsend, Wireless inspection of structures aided by robots, in: A. Emin Aktan (Ed.), *Proceedings of SPIE Health Monitoring and Management of Civil Infrastructure Systems*, *Steven B. Chase*, August 2001.

[9] L. Tong, Q. Zhao, S. Adireddy, Sensor networks with mobile agents, *MILCOM* 1 (2003) 688–693.

[10] Y. Tirta, Z. Li, Y.-H. Lu, S. Bagchi, Efficient collection of sensor data in remote fields using mobile collectors, *Proceedings of 13th International Conference on Computer Communications and Network*, 2004, pp. 515–519.

[11] D. Jea, A. Somasundara, M. Srivastava, *Multiple Controlled Mobile Elements (Data Mules) for Data Collection in Sensor Networks*, Springer, Berlin, Heidelberg, 2005, pp. 244–257.

[12] R. Sugihara, R. Gupta, *Improving the Data Latency in Sensor Networks with Controlled Mobility*, Springer, Berlin, Heidelberg, 2008, pp. 386–399.

[13] A. Mita, S. Takhira, A smart sensor using a mechanical memory for structural health monitoring of a damaged control building, *Smart Materials and Structures* 12 (2003) 204–209.

[14] G. Park, H. Sohn, C.R. Farrar, D.J. Inman, Overview of piezoelectric impedance-based health monitoring and path forward, *The Shock and Vibration Digest* 35 (2003) 451–463.

[15] V. Giurgiutiu, A. Zagrai, J.J. Bao, Damage identification in aging aircraft structures with piezoelectric wafer active sensors, *Journal of Intelligent Material Systems and Structures* 15 (2004) 673–688.

[16] S. Bhalla, C.K. Soh, High frequency piezoelectric signatures for diagnosis of seismic/blast induced structural damages, *NDT&E International* 37 (2004) 23–33.

[17] D.L. Mascarenas, M.D. Todd, G. Park, C.R. Farrar, Development of an impedance-based wireless sensor node for structural health monitoring, *Smart Materials and Structures* 16 (2007) 2137–2145.

[18] T.G. Overly, G. Park, C.R. Farrar, R.J. Allemang, Compact hardware development for structural health monitoring and sensor diagnostics using admittance measurements, *Proceedings of IMAC-XXV*, *A Conference and Exposition on Structural Dynamics*, 2007, Orlando, FL.

[19] T.G. Overly, G. Park, K.M. Farinholt, C.R. Farrar, Development of an extremely compact impedance-based wireless sensing device, *Smart Materials and Structures* 17 (2008) 065011.

[20] D.L. Mascarenas, G. Park, K.M. Farinholt, M.D. Todd, C.R. Farrar, Remote inspection of bolted joints using piezoelectric active-sensors, *The Institution of Mechanical Engineers*, *Part G: Journal of Aerospace* Engineering 233 (2009) 565–575.