# Wireless Sensing and Control

Yang Wang[a], Kenneth J. Loh[b], Jerome P. Lynch[b] and Kincho H. Law*[a]
[a]Dept. of Civil and Env. Engineering, Stanford University, Stanford, CA USA 94305-4020
[b]Dept. of Civil and Env. Engineering., University of Michigan, Ann Arbor, MI USA 48109-2125

**ABSTRACT**

Wireless technologies can play a significant role in the monitoring and control of civil structures. Structural sensing and control technologies can benefit in terms of installation cost and time from wireless communication and embedded computing. This paper discusses the development of a low-cost wireless sensing system judiciously designed for civil structures. By incorporating an actuation signal generation interface, the wireless sensing system has the capabilities to perform structural actuation and support structural control applications. Validation tests have been conducted both in the field and in the laboratory to demonstrate the functionalities and performance of the wireless sensing and wireless control units. While wireless sensor networks are ideally suited for monitoring and control of global structural system, there is a need for sensors installed at the component-level to monitor structures for localized damage phenomena such as cracking and corrosion. Towards this end, this paper describes a passive RFID sensors for strain and pH monitoring applications using a layer-by-layer (LbL) self-assembled carbon nanotube-polyelectrolyte composite thin-film. Wireless sensor network and wireless short-range point-to-point devices are two emerging wireless technologies that can find many practical applications in structural engineering.

**Keywords:** Nanocomposites, RFID, Wireless Sensing, Structural Monitoring, Structural Control

## 1. INTRODUCTION

Over the past few decades, sensing and control have been active areas of research in the structural engineering field leading to their incorporation in the design and operation of our civil structures. Sensing devices have been employed to collect important information to infer the health and safety conditions of structures [3]. In addition to sensing technologies, structural control devices have also been utilized to mitigate the excessive response of civil structures [16]. Current sensing and control systems rely on the use of coaxial wires as a means of transmitting data. Tethered systems are inherently expensive due to their initial installation and long-term maintenance costs. Furthermore, once installed, the wired sensor and control network could be difficult to reconfigure. As wireless technologies advance, there are ample opportunities for developing low-cost wireless sensors for structural monitoring and control applications.

In recent years, multiple wireless communication technologies have emerged. Current research efforts for civil structures' application focus on wireless sensor network technology and short range point-to-point communication devices. Wireless sensor networks consist of spatially distributed autonomous sensing devices that collect physical or environmental data and cooperatively monitor the condition of a facility. Such low-cost wireless sensors have been demonstrated to achieve performance levels just as good, if not better, than cabled systems [13]. This paper describes the development of low-cost "smart" sensors that combine wireless communication, embedded hardware, and software technologies to provide the capabilities that can acquire and process the structural response data while performing computationally intensive algorithms (such as fast Fourier transform, autoregressive models, etc.) suitable for structural monitoring applications [21]. Besides serving as a passive device collecting response data, an actuation interface can be incorporated with the wireless sensor unit for active-sensing (e.g. ultrasonic inspection) as well as for real-time control applications [11,18]. This paper presents experimental results and discusses some of the critical issues on the utilization of wireless sensors for real-time feedback structural control. While wireless sensing network technologies are viable substitutes for traditional wire-based systems and allow for more cost-effective and denser sensor instrumentation, they are most suited for global-based (e.g. modal synthesis) monitoring applications. Current developments typically cannot detect minor, incremental damage (e.g. small cracks) and the onset of corrosion. As damage begins as a localized phenomena, the ability to detect the initiation of such localized deterioration is important for long term structural health

*law@stanford.edu; phone 1 650 725-3154; fax 1 650 723-7514; http://eil.stanford.edu

monitoring (SHM). As a result, local damage requires low-cost densely-distributed *in-situ* sensors. This paper introduces a passive wireless RFID (Radio Frequency IDentification) sensor fabricated using nanocomposites for strain and corrosion measurements [7,9]. Passive RFID sensors utilize short-range wireless inductive coupling to establish point-to-point communication between sensors and a reader. This approach does not require an internal power supply; they are particularly attractive for dense instrumentation for local monitoring/damage applications. Finally, this paper discusses ongoing research on the applications of wireless technologies for structural sensing and control.

## 2. WIRELESS SMART SENSORS

Low cost alternatives to the traditional wire-based monitoring system are now possible as a result of the rapid advancement of embedded system technologies including sensors, microprocessors, and wireless networks. A wireless sensor in the network typically consists of a sensing interface to which analog sensors can be attached, an embedded microcontroller for data processing, a wireless radio transceiver for communication, and an energy source, usually a battery. Wireless sensors eliminate the need for wires and significantly reduce installation costs compared to wire-based counterparts. Furthermore, the wireless infrastructure provides incredible flexibility in the formation of network topologies. The embedded microcontroller, besides managing the operations of various hardware units, provides the computational resources for processing measured data and potentially acts as a smart sensor making "intelligent" prognostic decisions [3,17].

Fig. 1 shows a prototype hardware design of a wireless sensor which consists of three functional modules: sensor signal digitizer, computational core, and wireless communication module. The sensor signal digitization module converts analog sensor signals into digital formats which are then transferred to the computational core through a high-speed Serial Peripheral Interface (SPI) port. The computational core then buffers the sensor data in its local memory or processes the data with embedded routines. Through a Universal Asynchronous Receiver and Transmitter (UART) interface, the computational core communicates with a wireless transceiver, which enables the wireless sensing unit to exchange data with the network server. The wireless sensing unit is designed to be operable in different countries with two different wireless transceivers, namely MaxStream's 900MHz 9XCite and 2.4GHz 24Xstream, both supporting peer-to-peer and broadcasting communication modes. All of the hardware components, including batteries, are packaged within a weatherproof plastic container which has a dimension of 10.2 × 6.5 × 4.0 $cm^3$. Optionally, for field applications where signals subjected to environmental effects and ambient vibrations are relatively noisy, a signal conditioning board is designed to interface with the wireless sensing unit for signal amplification and filtering. The current prototype system includes a wireless network server and multiple wireless sensing units. Each wireless sensing unit can collect data from multiple sensors, including accelerometers, velocity meters, and strain gages, among others.

A series of laboratory and field validation tests have been conducted to verify the performance of the wireless sensor system for structural monitoring [10,12]. Here, we briefly present an overview of the validation tests conducted on the Voigt Street Bridge located at the University of California, San Diego campus in La Jolla, CA [19]. The Voigt Bridge is a concrete box girder highway bridge that carries traffic over US Interstate 5 and has been installed with a sophisticated cable-based structural monitoring system (accelerometers, strain gages, thermocouples, humidity sensors, and video cameras) in the northern-most cells of the bridge [4]. The two-lane bridge is about 89.4m long and consists of four spans (Fig. 2(a) and (b)). Over each bent, a lateral concrete diaphragm with a thickness of about 1.8m stiffens the girder. Longitudinally, the box girder is partitioned into five cells running the length of the bridge (Fig. 2(c)). The Maxstream 9XCite wireless transceiver operating at 900MHz (allowed by US government regulations) is employed in this test.

Two sets of validation tests have been conducted at the Voigt Bridge. First, as shown in Fig. 2(b), thirteen accelerometers interfaced to wireless sensing units are installed within the two middle spans of the bridge to measure

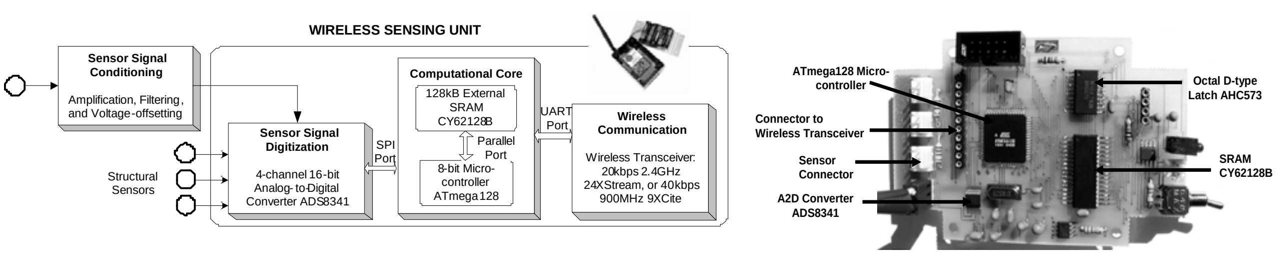
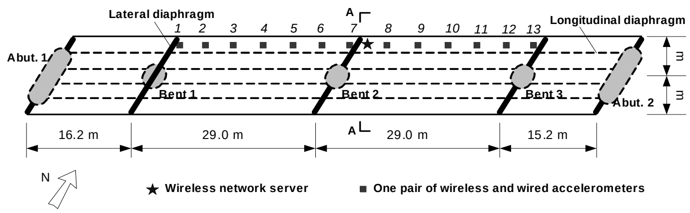
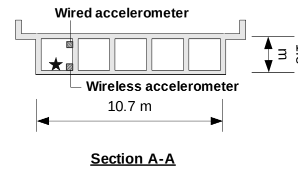



Fig. 1. Functional diagram detailing the hardware design of the wireless sensing unit.

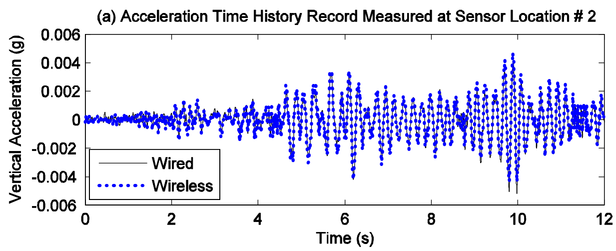
(a) Bridge side view



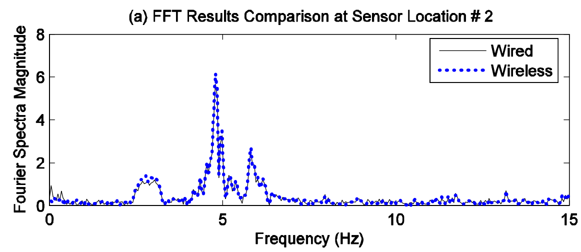

(b) Bridge plan view and sensor locations of wired and wireless systems




(c) Bridge elevation view




(d) Acceleration time histories

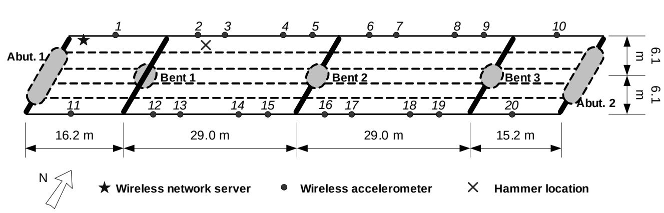



(e) FFT results

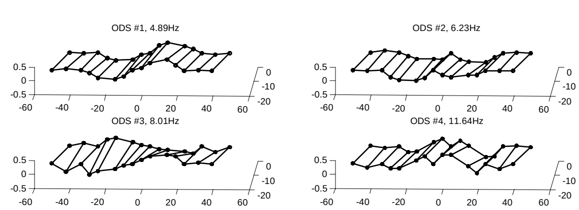
Fig. 2. Validation Test 1 under normal traffic condition on Voigt Bridge.

vertical vibrations. One wireless sensing unit (associated with one signal conditioning module and one accelerometer) is placed immediately below the accelerometer associated with the wired unit (see Fig. 2(c)). While the wired accelerometers are mounted to the cell walls, wireless accelerometers are simply mounted on the floor of the girder cells to expedite the installation process. The installation and calibration of the wireless monitoring system, including the placement of the wireless sensors, take about an hour. During the first set of tests, the bridge is under normal traffic operation. Fig. 2(d) shows the time history data at location #2, collected by the cable-based and wireless monitoring systems when a vehicle passes over the bridge. Fig. 2(e) shows the corresponding Fourier spectrum results derived from the time history data. The FFT results using the data collected by the wired system are computed offline, while the FFT results corresponding to the wireless data are computed online in real-time by each wireless sensing unit. After each wireless sensing unit executes its FFT algorithm, the results are wirelessly transmitted to the network server. Strong agreements between the collected time history data sets and the computed FFT results for the two systems are observed.

One attractive feature of the wireless monitoring system is its easy re-configurability. In the second validation test, the configuration of the original wireless monitoring system is changed to attain a more suitable spatial distribution to determine the operating deflection shapes (ODS) of the bridge deck. Since the bridge loading can not be directly monitored nor assumed broad band, modal estimation will yield ODS in lieu of mode shapes; however, ODS are closely correlated to the modes of the system. Twenty wireless accelerometers and a wireless network server are now mounted to the bridge sidewalks (Fig. 3(a)). The communication distance between the server and the furthest wireless sensing unit is close to the full length of the bridge. The re-installation of wireless sensors and monitoring system takes about an hour. An embedded peak-picking algorithm at each sensor node is employed to identify the bridge's modal frequencies. Upon determining the first four modal frequencies, the imaginary components of the Fourier spectra are transmitted to the wireless server. The ODSs for the first four primary deflection modes can be obtained by plotting the imaginary component of the FFT results for every sensor at each corresponding modal frequency. Fig. 3(b) shows the first four dominant ODSs of the bridge deck using wireless acceleration data during a hammer excitation test. These two sets of validation tests on the Voigt Bridge have demonstrated the functionalities and performance of the wireless sensing units




(a) Wireless accelerometer deployment for operating deflection shape analysis




(b) Operating deflection shapes extracted from wireless sensor data

Fig. 3. Validation Test 2 under hammer excitation on the Voigt Bridge.

for ambient and forced vibration monitoring.

## 3. WIRELESS CONTROL

Structural control can be defined as a mechanical system that is installed in a structure to reduce structural vibrations due to external disturbances, thereby, resulting in enhanced safety and habitability. As illustrated in Fig. 4, a feedback control system consists of three complementary components: sensing system, actuators, and controllers. Sensors are installed to measure the loading or the response of the structure. Sensor measurements are then passed onto a controller to execute control algorithms and to determine control forces. The controller then issues commands to the actuators that in turn apply desired forces (directly or indirectly) to mitigate the undesirable dynamic effects of the structural system. In order to transfer real-time sensor data and control commands in the control system, coaxial wires are normally employed as a communication link. As the number of actuation and sensing nodes of the control system increases, the amount of wires increases in tandem. Wireless communication can serve as an alternative to the high-cost coaxial wires. This proposition is compelling when considering the fact that wireless communication has already proven reliable when used in lieu of coaxial wiring in structural monitoring systems. However, unlike in structural monitoring systems where some minor delay in the delivery of data is acceptable, structural control systems require real-time performance. In other words, sensor data must be sampled, control forces calculated, and commands issued to the actuators, all on a precisely timed schedule.

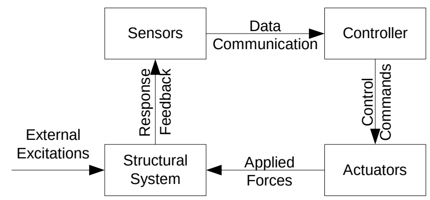
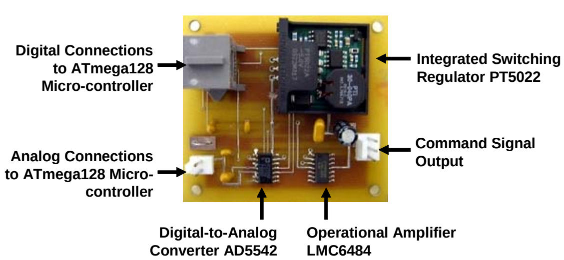


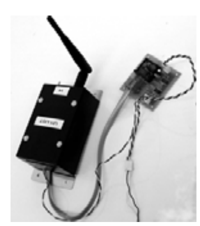

Fig. 4. Schematic of a structural control system [5].

The prototype wireless sensing and control system is built upon the wireless sensing unit discussed earlier. As noted, the wireless sensor is modularly designed so that it can be interfaced with traditional sensors. The modular design also provides the flexibility for interfacing the unit with external actuation devices. Fig. 5(a) shows an off-board control signal generation module which consists of a single-channel 16-bit digital-to-analog converter (Analog Device AD5542) and other support electronics. As shown in Fig. 5(b), the control signal module is attached to the wireless sensing unit via two multi-line wires – one for analog signals and the other for digital signals. The module can output an analog voltage from -5V to 5V at rates as high as 100 kHz.

To assess the potential application of the wireless sensing units and the controller module for structural control, validation tests on a 3-story frame structure instrumented with MR dampers have been conducted at the National Center for Research on Earthquake Engineering (NCREE) in Taipei, Taiwan (see Fig. 6). As shown in Fig. 6(a), the three-story steel frame structure has a 3 x 2m$^2$ floor plan, 3m inter-story height, and a weight adjusted to 6,000 kg per each floor using concrete blocks. Both the beams and the columns of the structure are constructed with H150 × 150 × 7 × 10 steel I-beam elements. The three-story structure is mounted on a 5 × 5m$^2$ 6-DOF shake table. The test structure is heavily instrumented with accelerometers, velocity meters, and linear variable displacement transducers (LVDT), which directly interface with a high-precision wire-based data acquisition (DAQ) system. For the prototype wireless sensing and control system schematically shown in Fig. 6(b), wireless sensors and controllers are mounted on the structure for measuring structural response data and commanding the actuators in real-time. For this experimental study, three 20 kN MR dampers are installed with V-braces on each story of the steel structure (Fig. 6(c)). The damping coefficients of the MR dampers can be changed by issuing a command voltage between 0V to 1.2V. Each wireless sensor is interfaced to a Tokyo Sokushin VSE15-D velocity meter to measure the absolute velocity response for each floor of the structure as



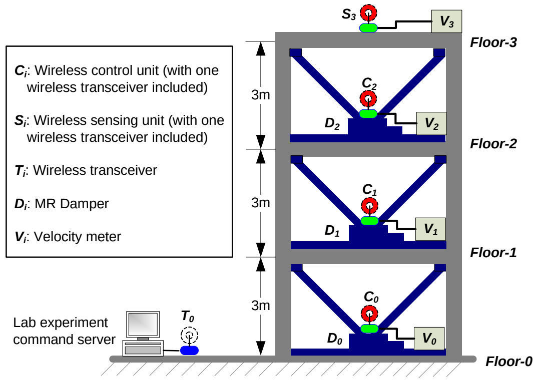

(a) Printed circuit board of the signal generation module



(b) Interfacing the signal generation module with the wireless sensor

Fig. 5. Wireless sensing and actuation prototype unit.


(a) The 3-story test structure



(b) Placement of wireless sensors and actuators


(c) MR damper installed between floors


(d) Wireless control unit

Fig. 6. A laboratory setup for wireless sensing and control tests.

well as the base. The three wireless sensors (C0, C1, and C2) on the first three levels of the structure are also responsible for commanding the MR dampers. For wireless sensing and control, a separate wire is used to output the appropriate voltage from the off-board control generation module to command the MR dampers (see Fig. 6(d)). Due to local requirements, MaxStream's 2.4GHz 24XStream transceivers are employed in this test.

A key feature of the wireless sensor that sets it apart from traditional sensors is the collocation of computational power with the sensor. Prior to the dynamic tests, "gain" matrices, generated using an LQR-based control procedure [20] for different control schemes and time delay parameters are embedded into the microcontroller of the wireless control unit for real-time execution. There are three major components that constitute time delay: sensor data acquisition, control decision calculation, and actuator latency in applying the desired control force. For traditional wire-based control systems, the control decision calculation time is the least among the three, while the actuator latency being the largest. The major difference between a wired control system and a wireless control system is the sensor data acquisition time. For the wired control system, it is estimated that the time delay due to data acquisition is approximately 5ms (200Hz). For the MaxStream 24XStream wireless transceivers, a single transmission time delay is about 20ms. Assuming that each controller uses complete velocity feedback from all four sensor units (in a centralized control strategy), there are four transmissions of data packets from the wireless sensors to the control units for a total time delay of 80ms (12.5Hz). The control algorithms must take into consideration the time delay when computing the control gain matrix as well as estimating the feedback control sampling time. For the results shown in Fig. 7, comparing with the uncontrolled structure, the wireless control system achieves considerable gain in limiting inter-story drifts. The plots also show the strong agreement between the simulated results based on a time-delayed LQR procedure and the experimental results. In short, the experimental study has demonstrated the utilization of the modular wireless sensing unit for actuation and control applications.

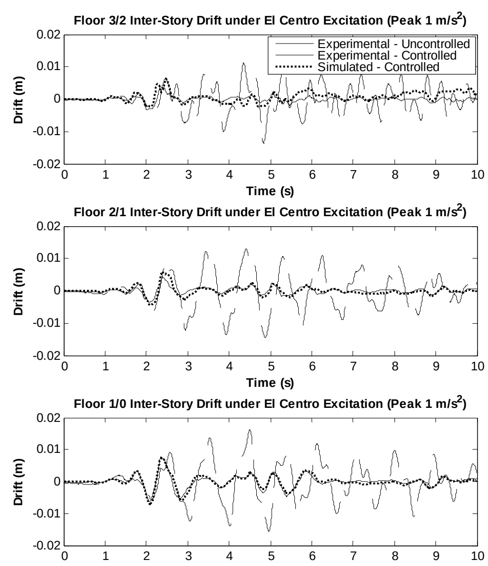


Fig. 7. Wireless control experimental results.

## 4. PASSIVE WIRELESS RFID-BASED STRAIN AND PH SENSORS

Among the wide variety of damage mechanisms, cracking/excessive localized strain and corrosion are among the primary causes of long-term infrastructure deterioration. To accurately quantify the local strain and corrosion processes, low cost sensors that can be embedded within structural components for densely-distributed *in situ* monitoring are needed. Thin film radio frequency identification (RFIDS) sensors are ideal candidates because of their form factor and power requirements [6,14,15]. Since no batteries are required for RFID tags, they can be manufactured into very small

Fig. 8. A Solartron 1260 impedance gain/phase analyzer connected to a coil antenna as the RFID reader.

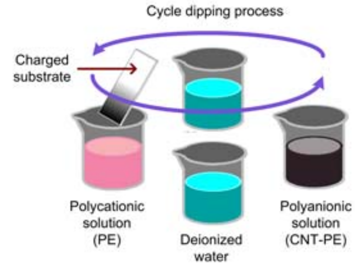



Fig. 9. Schematic illustration of LbL self-assembly process to fabricate multifunctional nanocomposite thin films.

thin films, capable of being embedded in different types of materials and composites. In general, RFID systems comprise of two main components, namely a passive tag (sometimes refered to as a transponder) and portable reader coupled with an AC power source. The simplest RFID tag circuitry consists of a resistor, capacitor, and inductor connected in a series or parallel resonant circuit configuration. Inherent to the series and parallel resonant circuits are two defining properties, namely resonant frequency and bandwidth [2,7,8]. Depending on whether an applied external stimulus will cause the sensor tag's resistance, capacitance, inductance, or any combination of the three to change, a corresponding change in the resonant frequency and/or bandwidth of the tag will occur [7,8]. These sensor responses can be detected by a reader through inductive coupling of the reader and tag; a frequency response analyzer, such as the Solartron 1260 impedance gain/phase analyzer shown in Fig. 8, can be used as the RFID reader. For use in the field, a hand-held dip meter can alternatively be used.

Most current prototype designs of RFID sensors are based on miniaturization of larger mechanical elements and are of unacceptable large form factor for embedment. Here, a novel "bottom-up" thin film RFID sensor fabrication technique derived from the nanotechnology domain is proposed to yield sensors defined by high-sensitivities and small form factors [7]. Using the layer-by-layer (LbL) self-assembly technique [1,7,9], homogeneous multilayer nanocomposite thin films can be tailored with a variety of nanomaterials and polyelectrolyte species (Fig. 9). Briefly, by dipping a charged substrate in alternating oppositely charged polyanionic and polycationic species, multilayer nanocomposites can be fabricated one monolayer at a time. Depending on the specific type of nanomaterial or polyelectrolyte used, one can encode different electromechanical (*e.g.* strain) or electrochemical (*e.g.* corrosion/pH) sensing mechanisms within these thin films [9]. Furthermore, a passive wireless RFID sensor can be realized by patterning these conductive thin film sensors into a coil antenna pattern so that they can be inductively coupled with the reader [7,8].

Validation studies have been conducted by Loh, *et al.* [7-9] for strain and pH monitoring (since pH is one factor integral to identifying corrosion processes) using LbL carbon nanotube-polyelectrolyte composite-based RFID sensors. By embedding single-walled carbon nanotubes (SWNT) within an LbL polymeric matrix, sensing performance can be drastically enhanced. First, in order to realize a resistive pH sensor, SWNTs dispersed in a poly(sodium 4-styrene sulfonate) (PSS) solution and another poly(aniline) emeraldine base (PANI) solution are used as LbL constituents to fabricate SWNT-PSS/PANI thin films. By measuring the resistance of the thin film (using an Agilent 34401A digital multimeter) as different pH buffer solutions are pipetted into a plastic well mounted on the film surface, drastic changes in film resistance are observed. Upon coupling the SWNT-PSS/PANI pH sensor as the resistive element within a parallel resonant circuit sensor tag, passive wireless sensing is realized. Data collected from a portable RFID reader confirms that system bandwidth decreases as the pH of the buffer solutions is increased. On the other hand, an LbL nanocomposite strain sensor can be fabricated with an SWNT-PSS solution and a poly(vinyl alcohol) (PVA) polycationic solution [9]. By depositing electrically conductive SWNT-PSS/PVA thin films on both sides of a poly(ethylene terephthalate) (PET) insulating thin film, a strain-sensitive parallel-plate capacitive sensor is fabricated. It has been demonstrated that as increasing applied strain increases the capacitance of the thin film, the RFID sensor tag's resonant frequency decreases linearly (Fig. 10) [7,8]. In fact, the RFID resonant frequency (*i.e.* controlled by sensor capacitance) can be tailored accurately by the dimensions of the strain sensor (Fig. 11) [7,8]. It should be noted that these SWNT-PSS/PVA capacitive strain sensors have been demonstrated to withstand applied strains up to 10,000 μm/m (well above strains typically encountered in most civil infrastructure applications).

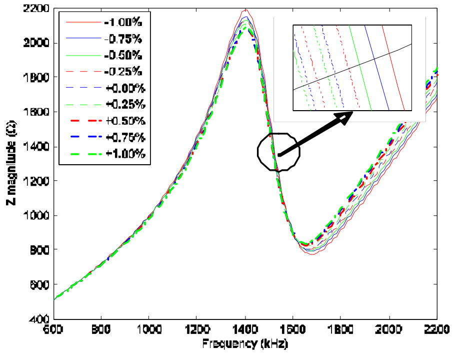



Fig. 10. Experimental RFID reader response of capacitive SWNT-PSS/PVA strain sensor under one-cycle tensile-compressive cyclic loading (inset shows zoomed in plot near resonant frequency).

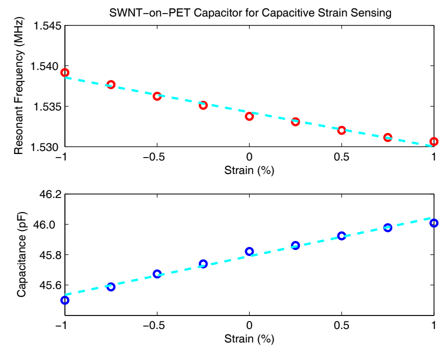



Fig. 11. Resonant frequency shift and corresponding capacitance change of capacitive SWNT-PSS/PVA strain sensor under one-cycle tensile-compressive cyclic loading.

## 5. SUMMARY AND DISCUSSION

Advances in sensors, wireless communication and information technologies promise to have significant impacts in structural monitoring and control systems. This paper describes a prototype wireless sensing unit that can: 1) interface to a heterogeneous array of sensors, 2) process acquired data, and 3) work collaboratively with other units to derive important structural engineering information (*e.g.* health assessment). The prototype wireless sensing unit is capable of monitoring civil structures subjected to ambient and forced vibrations. The cost of wireless monitoring systems, including labor and installation efforts, is significantly lower than that of tethered systems. The performance features of a wireless sensing system differ greatly from their tethered counterparts. For example, wireless systems are highly decentralized, and with embedded microcontrollers coupled with each sensor can perform data processing locally and collaboratively, as opposed to transmitting raw data to a central data server. Furthermore, by including an actuation signal generation module, a prototype wireless system for feedback structural control has been illustrated. In addition to the potential cost reduction by eradicating wires in a control system, the wireless sensing and control system provides a highly flexible and adaptable system configuration because of wireless communication. For real-time feedback control applications, the adverse effects of communication and computation time delay using a wireless system need to be mitigated by using algorithms that can specifically address the time delay issue [20]. Current research also explores decentralized (or partially decentralized) structural control algorithms that provide optimal control decisions using measurement data from its own sensor or from neighboring wireless sensing units [22].

While wireless sensing networks are well suited for global structural monitoring, local damage phenomena require *in-situ* monitoring devices that can be embedded directly within structural components. This paper describes the development of LbL self-assembled carbon nanotube-polyelectrolyte composites for the fabrication of passive RFID sensors for strain and pH monitoring applications. Although the strain and pH sensors utilize traditional copper-wire coil antennas for wireless communications, the concept of using a thin-film nanocomposite for sensing has been illustrated. Current work is aimed towards patterning the coil antenna needed for the RFID sensor directly in the nanocomposite during fabrication. Moreover, future work will directly attached the proposed RFID sensors to concrete reinforcement bars to monitor their strain and corrosion processes *in-situ*.

## ACKNOWLEDGEMENTS

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