New Opportunities for Structural Monitoring: Wireless Active Sensing

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ABSTRACT: Recent years has witnessed a growing interest in wireless structural monitoring as a low-cost alternative to tethered monitoring systems. Past work has considered wireless sensors as passive elements in the monitoring system responsible only for collection of response measurements. This paper explores expansion of a wireless sensing unit design to accommodate active sensors which are sensors capable of simultaneous excitation and sensing. Active sensors could improve the reliability of current damage detection procedures. In this study, the design of a novel self-contained wireless active sensing unit is put forth. After fabrication of a prototype, a series of validation tests are conducted to assess unit performance. Piezoelectric actuators mounted to the surface of an aluminum structural element are commanded by the wireless active sensing unit to excite and record the element. To illustrate the capabilities of the wireless active sensing unit computational core, local identification of the piezoelectric-aluminum element input-output system will be performed by fitting of ARX time-series models.

1 INTRODUCTION

Under extreme loads such as those associated with earthquakes and blasts, structures often under-perform resulting in substantial economic and human losses. Equally serious is the poor structural condition of US infrastructure systems including the national inventory of highway bridges. A large number of highway bridges currently carry traffic loads that far exceed the loads considered in their design, leading to serious wear and tear deterioration (Dubin & Yanev 2001). The pressing nature of these safety issues has motivated many researchers to explore the development of comprehensive structural health monitoring systems for civil structures. Structural health monitoring is a broad field encompassing many synergetic technologies that together can provide automated systems whose purposes are to identify and characterize possible damage within structures. A necessary component of a structural health monitoring system is an underlying data acquisition subsystem that records structural response data during ambient and external loading.

Structural monitoring systems are a familiar tool to the practicing professional engineer. Particularly in California, a large number of buildings, bridges and dams have been instrumented. Response data collected by these installations have been analyzed to better understand the performance of current design practices. Currently, monitoring systems designed explicitly for civil structures make extensive use of coaxial cables to transfer measurements from embedded sensors (often accelerometers and strain gages) to centralized data servers. The centralized architectural configuration is a result of structural monitoring systems having originated from centralized data acquisition systems used within laboratory settings. While structural monitoring systems have proven to be a reliable and accurate technology, their installations are expensive. For example, recent system installations conducted by the United States Geological Survey (USGS) have cost over $5,000 per channel with 12-channel systems costing well over $60,000 (Celebi 2002). A large fraction of the capital and installation cost can be attributed solely to cable installation (Straser & Kiremidjian 1998).

Today, researchers are exploring the adoption of information technologies to reduce monitoring system costs while simultaneously broadening functional capabilities. For example, researchers have explored the adoption of wireless communications in structural monitoring systems to reduce installation and upkeep costs (Straser & Kiremidjian 1998). In eradicating the need to install coaxial cables for data communication, a cost effective wireless structural monitoring system worthy of installation in large-scale civil structures emerges. Lynch, *et al.* (2003a) has extended the initial work done by Straser & Kiremidjian (1998) by including embedded microcontrollers within a wireless sensing unit prototype. The intent of locally coupling embedded computational power with the sensor is for support of a decentralized computational framework. Decentralization of the computational responsibility that has traditionally resided in centralized data servers can lead to an overall energy-efficient monitoring system where portable power supplies (batteries) are optimally utilized. Wireless monitoring systems have been installed on some field structures to assess their performance. The Alamosa Canyon Bridge in southern New Mexico has served as one such structure with a wireless monitoring system installed in parallel to a commercial cable-based monitoring system (Lynch *et al.* 2003b). Testing of the bridge revealed the wireless monitoring system to be as reliable and as accurate as the tethered monitoring system. The commercial sector has also been instrumental in the development of wireless sensing technologies with vendors like Crossbow and Microstrian offering wireless sensing systems capable of installation within civil structures.

Another necessary component of a structural health monitoring system is numerical procedures that can reliably interrogate response measurements in order to hypothesize the existence of possible damage in the structural system. It is only when a structural monitoring system is coupled with reliable damage detection procedures that a comprehensive structural health monitoring system emerges. Many damage detection algorithms have been proposed by researchers in recent years (Doebling, *et al.* 1996). Unfortunately, normal environmental and operational variability render many of the proposed damage detection methods difficult to successfully apply to civil structures. For example, damage detection methods that consider changes in global modal properties are often hindered by modal properties also exhibiting sensitivity to temperature (Sohn, *et al.* 2002). More recently, use of unsupervised pattern classification techniques have been put forth as a possible approach to damage detection. For example, a multi-tiered time-series approach that uses pattern classification techniques to identify structural damage has been proposed by Sohn, *et al.* (2001). The time-series approach to damage detection has been successfully applied to various laboratory and field structures situated in changing operational environments.

Improvements in the accuracy of damage detection algorithms can potentially be gained through active sensing of the structural system. An active sensor is defined by its ability to acquire response measurements based on physical action the sensor initiates (Brooks & Iyengar 1998). Active sensing has been shown to be a valuable tool in some structural health monitoring applications as reported by a number of researchers (Wu & Chang 2001, Dunne, *et al.*2001).

This study will explore extensions of current wireless structural monitoring technologies to include opportunities for integration of active sensors. A wireless sensing unit will be designed with an interface to which actuators can be attached. This wireless active sensing unit provides the structural monitoring system with an opportunity to command actuators for excitation or control of the structure. With capabilities to actuate, sense and compute, the wireless active sensing unit is a self-contained intelligent agent capable of playing a greater role in structural health monitoring applications. While any actuator type can be considered for use with the proposed wireless active sensing unit, piezoelectric actuation will be explored in this study. Piezoelectric pads that are epoxy mounted to the surface of structural elements can provide controllable low-energy surface wave excitations. Changes in the wave signatures could be used for detecting damage in the structural element. A potential advantage associated with local actuated excitations is that they can be repeated, unlike ambient and seismic excitations, thereby enhancing the reliability of the damage detection procedure utilized.

To validate the performance of the proposed wireless active sensing unit design, an aluminum plate with two piezoelectric elements epoxy mounted to its surface will be studied. The wireless unit will command one piezoelectric pad to emit white noise surface waves while the sensing interface will simultaneously record attenuated waves as received at the second pad. To illustrate the use of the computational core's ability to interrogate response data, the wireless sensing unit will locally execute numerical algorithms that calculate the transfer function and autoregressive exogenous input (ARX) time-series model of the structural element.

2 WIRELESS ACTIVE SENSING UNIT

The wireless active sensing unit is intended to 1) collect measurement data from sensors embedded within structural elements that are excited by low-energy actuation elements, 2) store, manage and locally process the measurement data collected, and 3) to communicate data and results to a wireless sensing network comprised of other wireless sensing/actuation agents. To accomplish the specified operational tasks, the design of the wireless active sensing unit is divided into four functional subsystems as shown in Figure 1: the sensor interface, actuation interface, computational core, and wireless communication channel.

The design procedure of each of the four subsystems will emphasize use of off-the-shelf components

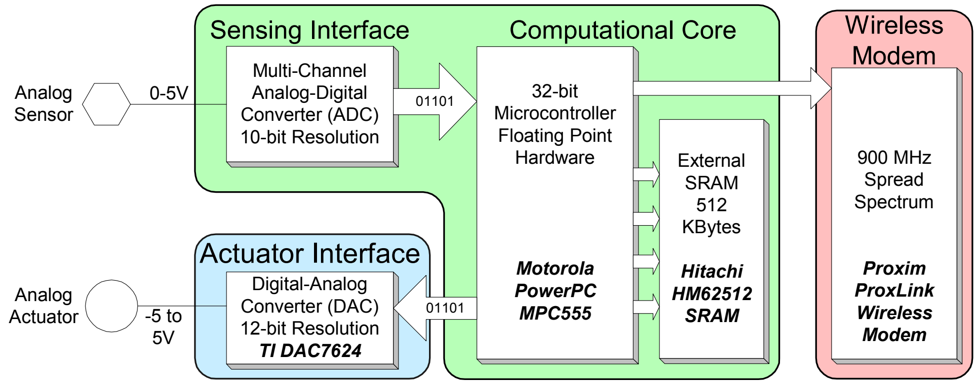

Figure 1. Architectural overview of a wireless active sensing unit design

that satisfy the unique performance requirements of the unit. The sensing and actuation interfaces will be designed as actuator- and sensor-transparent, meaning any analog sensor or actuator, including piezoelectric elements, can be easily integrated with the system. However, the high-frequency operational regimes of piezoelectric elements will require data acquisition and control interfaces with quick real-time responses, well above 1 kHz. The performance goals of the sensing and actuation interfaces represent a significant challenge of the proposed unit design; as such, other design issues such as power consumption characteristics will not be considered in this study.

At the center of the wireless active sensing unit design is the computational core. Similar to previously proposed wireless sensing unit designs, the 32-bit Motorola MPC555 PowerPC microcontroller is selected as the core's primary hardware component. Selection of the MPC555 was motivated by its high-speed clock frequency (40 MHz) and its sophisticated internal arithmetic and logic unit with on-chip floating point calculations. High processor speeds are necessary to operate the high-frequency piezoelectric elements to be connected to the unit sensing and actuation interfaces. Internally integrated with this fast processor is 448 Kbytes of read only memory (ROM) where firmware will be stored for unit operation and embedded data processing. Since only 26 Kbytes of internal random access memory (RAM) is included in the MPC555, 512 Kbytes of external static RAM (SRAM) is added to the unit design for data storage. The read and write operations to the external memory take two clock cycles to complete and are slower than those to internal memory that take one cycle. Therefore, for applications demanding high-sample rates, data collected from the sensing interface will be written first to internal memory. After the data has been collected and real-time constraints no longer in effect, the measurement data will be transferred automatically from internal to external memory.

The on-chip 10-bit analog-to-digital converter (ADC) native to the MPC555 will be used as the sole sensing interface of the wireless active sensing unit. The sensing interface can accommodate 32 simultaneous sensing channels with sample rates as high 100 kHz. Due to the real-time demands of the data acquisition tasks, the MPC555 interrupt services are employed to read data from the interface on a strict timing schedule. Inherent latencies in servicing the interrupt service firmware limit the ADC to a maximum sample rate of 40 kHz.

The actuation interface is designed to output a range of command signals that could be used to control a large number of different structural actuators. At the core of the actuation interface is a digital-to-analog converter (DAC) that converts digital command signals generated by the MPC555 into analog representations acceptable for commanding actuators; the Texas Instruments DAC7624 is selected for this task. The DAC7624 accepts 12-bit digital samples in parallel and outputs a zero-order-hold (ZOH) analog signal from 0 to 2.5 V on four selectable channels. To attain the minimum settling time, only one channel of the quad-DAC is utilized in this study. The settling time associated with each conversion is 10 μsec allowing digital data streams of up to 100 kHz. After the DAC makes a conversion, the output signal of the DAC is feed to an instrumentation amplifier where, the signal is range shifted and amplified. An Analog Devices AD620 amplifier is chosen to shift the DAC output to a zero mean (from 1.25 V) and amplified by 4. This will result in an actuation interface capable of outputting command voltages from -5 to +5 V using a 12-bit digital command signal issued by the MPC555. After the actuation interface is constructed in hardware, embedded firmware is written for the MPC555 to operate the interface with precise timing. Similar to the sensing interface, for each command issued to the interface, the MPC555 requires time to execute embedded firmware resulting in some time delay; as a result, the DAC is effectively limited to a 40 kHz sample rate.

A wireless communication technology that is reliable and can propagate large distances through civil structures is sought. For the wireless active sensing unit design, the Proxim ProxLink wireless modem is chosen. Operating on the 902-928 MHz

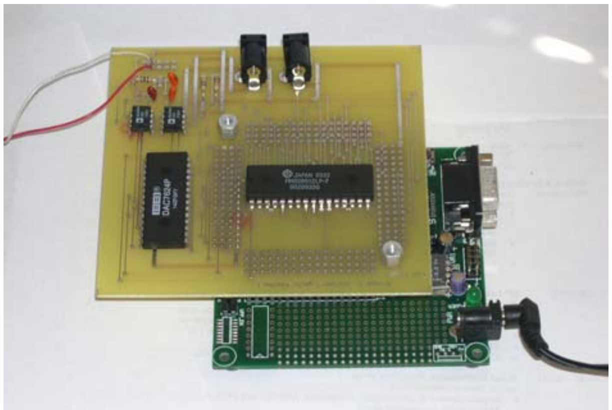

Figure 2. Completed wireless active sensing unit (Top yellow board houses external memory and D/A circuit)

unregulated FCC radio band, this modem can communicate up to 300 m in open space and 150 m within civil structures constructed of heavy material such as concrete. The radio employs frequency hopping spread spectrum techniques and performs error-checking on all received wireless packets to provide a highly reliable wireless transmission channel. One inherent drawback of wireless modems is their power consumption characteristics. When transmitting and receiving, the ProxLink modem draws 150 mA of current at 5 V. Having identified the high power demands of wireless communication gear as the primary cause of battery depletion, Lynch *et al*. (2003) have advocated the use of embedded microcontrollers to screen and consolidate information as a means of minimizing the use of the wireless medium. Their work has shown that local data processing leads to reductions in the energy consumed from portable power sources thereby extending the life expectancy of autonomous wireless sensors.

The completed wireless active sensing unit is compact with dimensions of 7 cm by 7cm in area and 2.5 cm in height. Figure 2 presents a picture of the completed prototype unit. The unit is powered by a portable 9V power source.

3 ALUMINUM PLATE SETUP

The piezoelectricity phenomena is found in materials that have the ability to generate an internal electric potential when mechanically stressed and to undergo strain deformations when an external electric field is applied. Piezoelectric materials are both naturally occurring and laboratory manufactured with lead-zirconate-titanate (PZT) the most common synthetic piezoelectric material. The symmetric strain-electric potential property of piezoelectric materials has lead to their use in a number of smart structure applications. Piezoelectrics have been widely used as strain sensors to measure high-frequency strain loads (Sirohi & Chopra 2000). Similarly, the material has been exploited as an actuator with piezoelectric pads used to apply controllable surface forces to structural members (Sun & Tong 2002). Recently, researchers have explored the simultaneous use of piezoelectric materials as both sensor and actuator in order to measure their electro-mechanical impedance when mounted to structural elements (Park, *et al.* 2000).

To validate the performance of the proposed wireless active sensing unit, piezoelectric pads are selected to actuate a structural element with low-energy surface waves. Piezoelectric actuators are selected because their high-frequency operational spectrum can uniquely illustrate the performance of the unit in high-speed sample rate applications. In this study, lead-zirconate-titanate (PZT) piezoelectric pads purchased from Piezo Systems, Inc. will be employed. A 0.191 mm thick PZT sheet (T105-A4E-602) is cut to obtain small pads approximately 1.43 cm by 1.43 cm in area. The PZT sheet has been nickel plated on both sides making soldering of electrical connections easy.

An aluminum plate is chosen to serve as a sample structural element to which the 1.43 cm square piezoelectric pads will be mounted. The plate is 0.3175 cm thick and has an area approximately 6.8 cm by 28.6 cm in size. As shown in Figure 3, the piezoelectric pads are epoxy mounted to the top surface of the plate 18.9 cm apart from each other. One pad is designated as the transmitting pad which will be attached to the actuation interface of the wireless active sensing unit. The second pad is designated as the receiver and is connected to the unit's sensing interface. The wireless active sensing unit will command the transmitting pad through the actuation interface with a variety of input signals. As the unit commands the transmitting pad, the unit will simultaneously collect response data from the receiving pad and record the response in the MPC555's on-chip RAM memory bank. After data has been collected, embedded engineering analyses can be locally executed using the input-output measurement data.

4 PERFORMANCE VALIDATION

A system identification study of the piezoelectric pad-aluminum plate system will be undertaken to fully illustrate the functionality of the proposed wireless active sensing unit design. In the study, the wireless active sensing unit will be responsible for commanding the transmitting piezoelectric pad, collecting data from the receiving pad, and locally analyzing the data to identify the system transfer function. Assuming the system is linear time invariant (LTI), the discrete transfer function of the system,

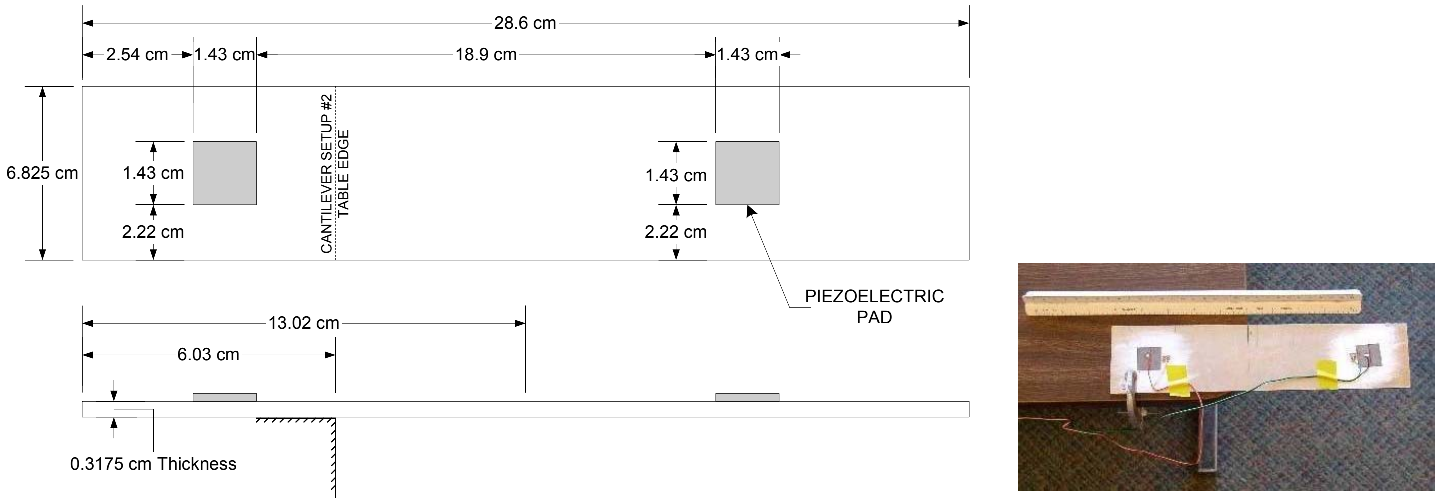

Figure 3. Aluminum plate experimental with piezoelectric pads mounted to the top surface

H(z), will be determined by the wireless sensing unit. A variety of input signals can be used to excite the dynamic system, but stationary stochastic white noise input signals with zero mean are selected. White noise inputs are convenient for system identification studies because they excite the system with equal energy across the full frequency spectrum. As a result, when the colored noise output of the dynamic system is transferred to the frequency domain, it represents the characterizing system transfer function.

To determine a transfer function of the piezoelectric pad-aluminum plate system that captures high frequency dynamics, the actuation and sensing interfaces will both be driven at their maximum sample rates of 40 kHz. At these high-sample rates, only internal memory can be used to store both the input and output time-history records. With only 26 Kbytes of RAM memory available on the MPC555, the amount of data that can be stored during a single validation test is limited. At 40 kHz, it is determined that approximately 8,500 data points can be comfortably stored during testing.

Ten white noise signals with standard deviations varying from 0.3 V to 1.2 V in 0.1 V increments are used for system excitation. With the actuation interface limited to an output signal of $\pm$ 5 V, the white noise signals are cropped to ensure none of their samples exceed the output range. Figure 4 presents the 1.0 V standard deviation white noise input signal and the corresponding system response recorded from the receiving piezoelectric pad. As the Lamb wave propagates across the surface of the aluminum element, the signal attenuates as seen by the reduced standard deviation of 0.4 V corresponding to the output signal. The input-output time-history plots corresponding to the other white noise excitation records are similar to those presented in Figure 4.

After the excitation tests on the aluminum plate have been completed, the computational core of the wireless active sensing unit takes control of the data for post-processing. The computational core is responsible for determining an input-output transfer function, *H(z)*, of the complete system. To identify the system transfer function, an autoregressive with exogenous inputs (ARX) time-series model will be calculated using the input-output time-history records. Defining the input to the system at the discrete time-step *k* by the variable *u(k)*, and the output, *y(k)*, an ARX time-series model can be written:

$$y(k) = \sum_{i=1}^{a} \alpha_i y(k-i) + \sum_{j=0}^{b} \beta_j u(k-j) + r(k) \tag{1}$$

The ARX model weighs past input, *u(k-j)*, and output, *y(k-i)*, measurements with coefficients β_j and α_i respectively, to predict the current output measurement, *y(k)*. The residual error associated with the prediction is denoted as *r(k)*. With Equation (1) holding for all observations of *y(k)* from $k = a$ to N, a matrix representation of the ARX model over all time samples can easily be written:

$$\begin{Bmatrix} y(a+1) \\ y(a+2) \\ \vdots \\ y(N) \end{Bmatrix} = \begin{bmatrix} y(a) & \cdots & y(1) & u(a+1) & \cdots & u(a-b+1) \\ y(a+1) & \cdots & y(2) & u(a+2) & \cdots & u(a-b+2) \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ y(N-1) & \cdots & y(N-a) & u(N) & \cdots & u(N-b) \end{bmatrix} \begin{Bmatrix} \alpha_1 \\ \vdots \\ \alpha_a \\ \beta_0 \\ \vdots \\ \beta_b \end{Bmatrix} \tag{2}$$

$$y = Ac$$

Assuming the matrix of past input-output measurements, *A*, is over-determined and of full rank, least-squares data fitting can be used to determine the coefficients vector, *c*, of the ARX time-series model.

$$c = (A^T A)^{-1} A^T y \tag{3}$$

The wireless active sensing unit assembles the input-output response measurements into the observation matrix, *A*, and executes Equation (3) to determine the ARX coefficients. For example, using the data presented in Figure 4, an ARX model of order $a = 7$ and $b = 2$ is calculated by the computational core:

$$c = \begin{Bmatrix} -0.046 \\ -1.035 \\ \vdots \\ -0.186 \\ 0.0003 \\ 0.0022 \end{Bmatrix} \qquad (4)$$

The coefficients of Equation (4) are then used to determine the transfer function, *H(z)*, of the piezoelectric pad-aluminum plate system:

$$H(z) = \frac{0.0003 + 0.0022z^{-1}}{1 + 0.046z^{-1} + 1.035z^{-2} + \cdots + 0.186z^{-7}} \qquad (5)$$

Figure 4 presents the predicted output response of the ARX model to the white noise input with a standard deviation of 1.0 V. The predicted response is superimposed with the true response to illustrate the magnitude of the model residual error. As shown, the ARX model calculated closely predicts the output response of the piezoelectric pad-aluminum system when excited by a white noise excitation with standard deviation of 1.0 V.

5 CONCLUSIONS

To reduce installation costs and enhance functionality, innovative technologies are currently being adopted in structural monitoring systems. The early work of Straser and Kiremidjian, and more recently, Lynch et al., has illustrated the advantages of using wireless communications and embedded microcontrollers within a structural monitoring system [3, 4, 5]. This study has explored an extension of their work by including an actuation interface in a wireless sensing unit design. Capable of commanding structural actuators, the resulting wireless active sensing unit can enjoy a direct interface to the physical system in which it is installed. The proposed wireless active sensing unit is capable of recording response measurements resulting from the unit's own action. Hence, the sensor is no longer passive and is defined as an active sensor. To illustrate the performance of the prototype wireless active sensing unit, an aluminum plate with two PZT piezoelectric pads epoxy mounted to its surface is employed. With white noise excitations generated on one pad, the unit simultaneously records the response of the second piezoelectric pad. After collection of the system response, the computational core is utilized to calculate an ARX time-series model for the input-output measurement data. As illustrated in this paper, the ARX model determined by the computational core is sufficiently accurate to provide good prediction of the true output response.

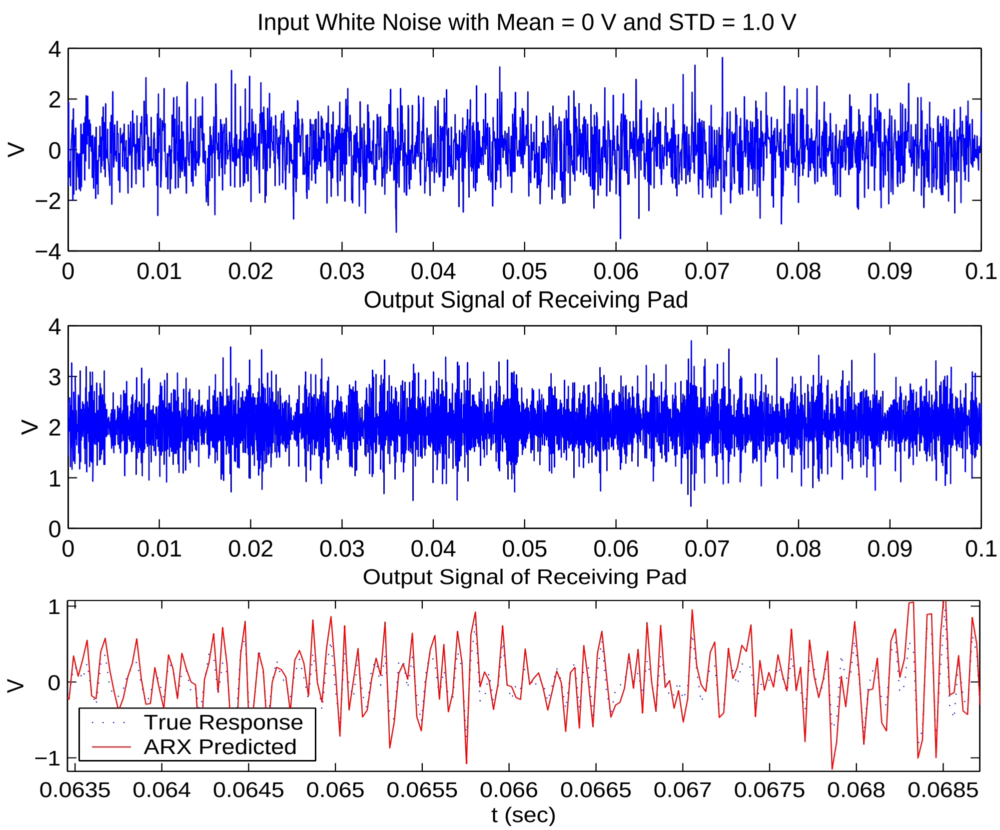

Figure 4 – (Top) Input white noise with a standard deviation of 1.0 V, (middle) system output response, (bottom) predicted ARX output response

Future work will seek to apply the wireless active sensing unit technology to detect damage in structural elements. Various damage detection algorithms will be embedded for local execution using input-output measurement data collected from piezoelectric elements mounted to element surfaces. With some element modal frequencies above 20 kHz sensitive to damage, improvements in the design of the wireless active sensing unit are also sought. For example, to achieve better resolution in the frequency domain, improvements in the actuation and sensing interfaces resulting in higher sample rates is needed.

ACKNOWLEDGEMENTS

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