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Hardware Design of Hierarchal Active-Sensing Networks for Structural Health Monitoring

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ABSTRACT

This paper presents the use of relay-based hardware in conjunction with piezoelectric active-sensing techniques for structural health monitoring in large-scale structures. In many areas of active sensing technology, hundreds, even thousands of sensors/actuators are needed to truly make health monitoring feasible in a real-world environment. Because interrogating such a large number of sensors is both time and cost prohibitive, it becomes necessary to develop a hardware system that can quickly and efficiently interrogate large numbers of the active sensors. In this work, we have developed a relay-based hardware that can serve as both a multiplexer and general-purpose signal router with special consideration given to piezoelectric active-sensing health monitoring approaches. We have also implemented this device as an expandable design that allows for easy scalability depending upon the size of the structure. Therefore, by using this hardware in conjunction with a centralized monitoring station, any number of sensors can be monitored effectively. Preliminary testing of this hardware on a test structure has experimentally proven the feasibility and advantages. This paper summarizes the hardware design, scalability, and useful advantages given today's structural health monitoring techniques.

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1.0 INTRODUCTION

Structural health monitoring today is a very active field with worldwide interest that seeks to ensure the reliability of the civilian and military infrastructure while protecting the safety of the workers and citizens. Over the years, several different methods for performing structural health monitoring (SHM) have emerged. The piezoelectric active-sensing approach is one of the most popular methods. The molecular structure of piezoelectric materials (PZT) produces a coupling between the electrical and mechanical domains. Therefore, this type of material generates mechanical strain in response to an applied electric field. Conversely, the materials produce electric charges when stressed mechanically. This coupling property allows one to design and deploy an "*active*" and "*local*" sensing system whereby the structure is locally excited by a known input, and the corresponding responses are measured by the same excitation source. Some advantages of these devices are; compactness, light-weight, low-power consumption, ease of integration into critical structural areas, ease of activation through electrical signals, higher operating frequency, and low cost. The employment of a known and repeated input also facilitates subsequent signal processing of the measured output data.

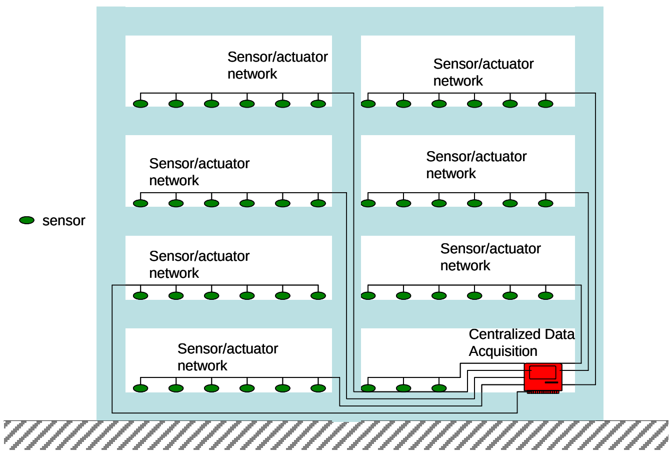


Figure 1: Conventional SHM system with centralized data acquisition

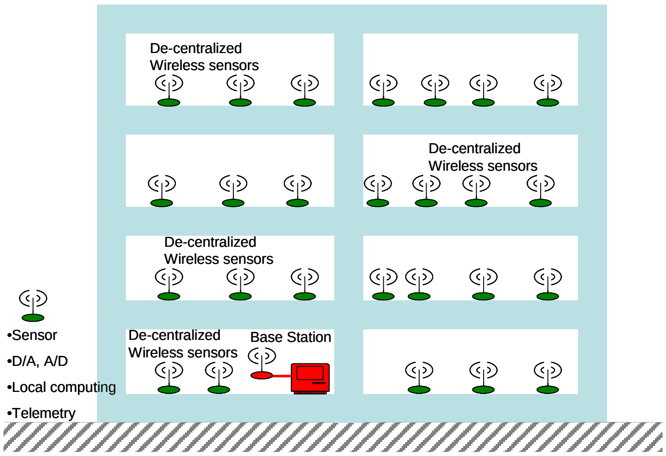


Figure 2: De-centralized wireless SHM system Lynch et al [1] and Spencer et al [5]

While assessing the health of a localized area through the use of a single active-sensor is efficient, once integrated into a large-scale structure, the realistic number of active-sensors easily reaches into the hundreds to even thousands. At this point, data acquisition and management are no longer trivial. Figure 1 describes conventional approaches that consist of running wires between the local sensors and a centralized data acquisition system. The cost associated with management and maintenance of such system can be very high. In addition, the deployment of such system can be challenging with potentially over 75% of the installation time attributed to the installation of system wires and cables for larger scale structures such as those used for long-span bridges [1].

The integration of wireless communication technologies into SHM methods has been widely investigated in order to overcome such limitations. Straser [2] was the first to propose the integration of wireless radios with sensors to reduce the cost of structural monitoring systems. Lynch et al. [3] has extended the functionality of wireless sensors by integrating sophisticated microcontrollers with them to enable sensor-based execution of embedded engineering algorithms. Tanner et al. [4] integrated Microelectromechanical System (MEMS) sensors with wireless communication and embedded systems for structural health monitoring. Because one byte of data transmission consumes the same energy as approximately 11,000 cycles of computation in the employed hardware platform, the use of embedded processors prolongs the battery life of the sensor unit and minimizes the maintenance cost related to battery replacement [4]. Spencer et al. [5] provides the state-of-the-art review of current "smart sensing" technologies that includes the compiled summaries of wireless work in the SHM field using small, integrated sensor, and processor systems. Wireless communication can remedy the cabling problem of the traditional monitoring system and significantly reduce the maintenance cost. The schematic of the de-centralized monitoring system is shown in Figure 2.

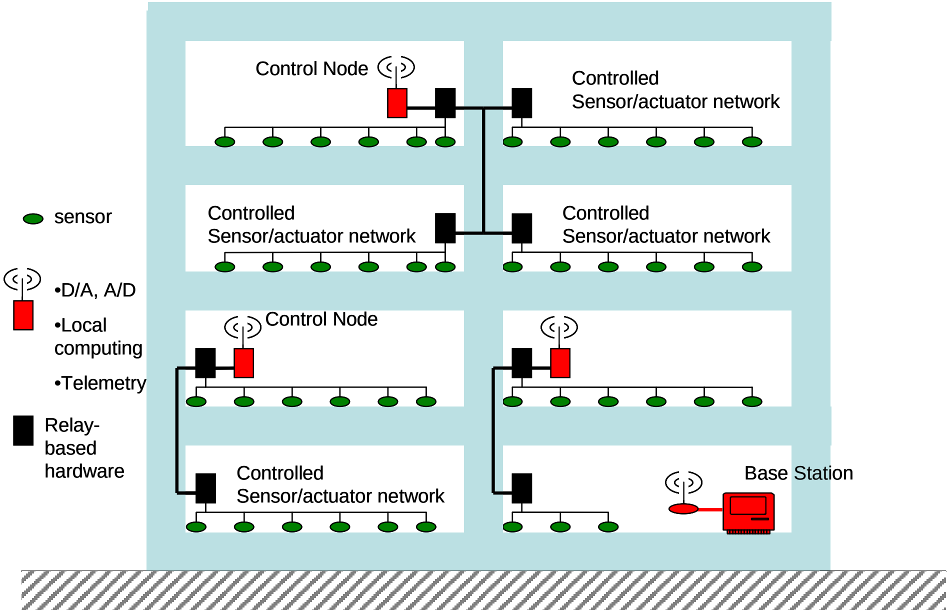


Figure 3: Proposed hierarchal active SHM system

From the active-sensing standpoint, however, several very serious issues arise with the current design and deployment scheme of de-centralized wireless sensors. First, the current wireless sensing design usually adopts ad-hoc networking and hopping that results in a problem referred to as data collision. Data collision is a phenomenon that results from a network device receiving several simultaneous requests to store or retrieve data from other devices on the network. With increasing numbers of active-sensors, a sensor node located close to the base station would experience tremendous data transmission, possibly resulting in a significant bottleneck. Because the workload of each sensor node cannot be evenly distributed, the chances of data collision increase with expansion of the sensing networks. In addition, because active-sensors can serve as actuators as well as sensors, the time synchronization between multiple sensor/actuator units would be an important, yet challenging task. Furthermore, the cost of implementing such a system into a large-scale structure is extremely prohibitive with increasing number of active-sensors. The cost of current de-centralized wireless sensor nodes is at least two orders of magnitude greater than that of an active-sensor, which can usually be obtained for less than $5. Because of the processor scheduling or sharing, the use of multiple channels with one sensor node would reduce the sampling rate, which provides neither a practical nor equitable solution for active-sensing techniques that typically adopt higher frequency ranges. Therefore, in real-life applications, the current design scheme could turn out to be a very expensive operation. In order to effectively and efficiently interrogate a large number of active-sensors, it becomes essential to develop a new design and deployment scheme specifically suited to this task.

To address this problem, we propose a new, hierarchal wireless sensing network as illustrated in Figure 3. This proposed network is somewhat of a hybrid in its combination of the two approaches described above. At the first level, several active-sensors are connected to a relay-based piece of hardware, which can serve as both a multiplexer and general-purpose signal router, shown as a black box. This device will manage the distributed sensing network, control the modes of sensing and actuation, and multiplex the measured signals. The device is also expandable by means of daisy-chaining. At the next level, multiple pieces of this hardware are linked to a de-centralized data control and processing station. This control station is equipped with data acquisition boards, on-board computing processors, and wireless telemetry which is similar to the architecture of current de-centralized wireless sensors. This device will perform duties of a relay-based hardware control, data acquisition, local computing, and transmission of the necessary results of the computation to the central system. At the highest level, multiple data processing stations are linked to a central monitoring station that delivers a damage report back to the user. Hierarchal in nature, this proposed sensing network can efficiently interrogate large numbers of distributed active-sensors while maintaining an excellent sensor-cost ratio because only a small number of data acquisition and telemetry units is necessary.

The focus of this paper is to describe the current design of the relay-based hardware that is used in the first level of the proposed sensing network. The internal relay system of this hardware can be used as a reconfigurable array that allows for one or more sensors to be actuated, while the remaining sensors can be used to monitor the signal propagated through the structure. Commercially available multiplexers can be used for this operation, but they are not specifically designed for active-sensing techniques, i.e., not usually possible to control modes of the self-sensing actuation (pulse-echo) or transfer signal analysis (pitch-catch analysis), which is an important operation in active-sensing monitoring techniques. Such commercially available units are also bulky, expensive, and inflexible for various tasks in SHM. The proposed hardware pays particular attention to the more specific technique of piezoelectric structural health monitoring known as the impedance-based method [6,7], high frequency response functions [8,9], and lamb wave propagation methods [10,11,12]. We have also implemented this device as an expandable design that allows for easy scalability depending upon the size of the structure. The expandability is of the utmost importance in performing the data acquisition of significantly larger numbers of active-sensors as the number of channels on a de-centralized wireless sensor is limited due to the processor sharing and scheduling. Therefore, by using this hardware, large numbers of sensors can be efficiently controlled and managed.

The rest of this paper will involve the hardware design, scalability, experiments conducted on a test structure, and additional issues that can be used as a guideline for future investigations.

2.0 Description of Hardware

Hardware Description

The proposed hardware is a relay-based electronics system, referred to as the BlockBox in this paper, that allows for the efficient interrogation (actuation/sensing) of multiple piezoelectric (or other similar) sensors for use in the field of SHM. At the most basic level, this hardware serves as an active multiplexer that not only condenses previously actuated signals, but also provides the signals for the physical actuation of the sensors themselves. Specifically, the internal relay system of this hardware can be used as a reconfigurable array that allows for one or more input sensors to be activated while the remaining sensors can be used to monitor the dynamic responses of the structure. This technique is used to perform a more systematic approach to structural health monitoring in complex structures.

This hardware system is composed of multiple non-solid state electromechanical relays that control the routing of all external sensors. Twenty-four of these relays define the actual actuation/monitoring matrix while the other sensor serves as a master relay to protect against signal latency and other signal propagation issues. Control of these relays is done using two 64 macrocell Complex Programmable Logic Devices (CPLD) programmed in Very High Speed Integrated Circuit Hardware Description Language (VHDL), with parallel controlling commands received through the Ethernet cables. Each box is assigned its own unique BoxID to avoid box conflict and makes the daisy-chaining possible. All of the primary internal components including the CPLDs and the 25 relays use a 3.3V DC power supply that provides for reduced power requirements. A schematic of the hardware is provided in Figure 4. In the final design, the entire circuit can be implemented on a printed circuit board.

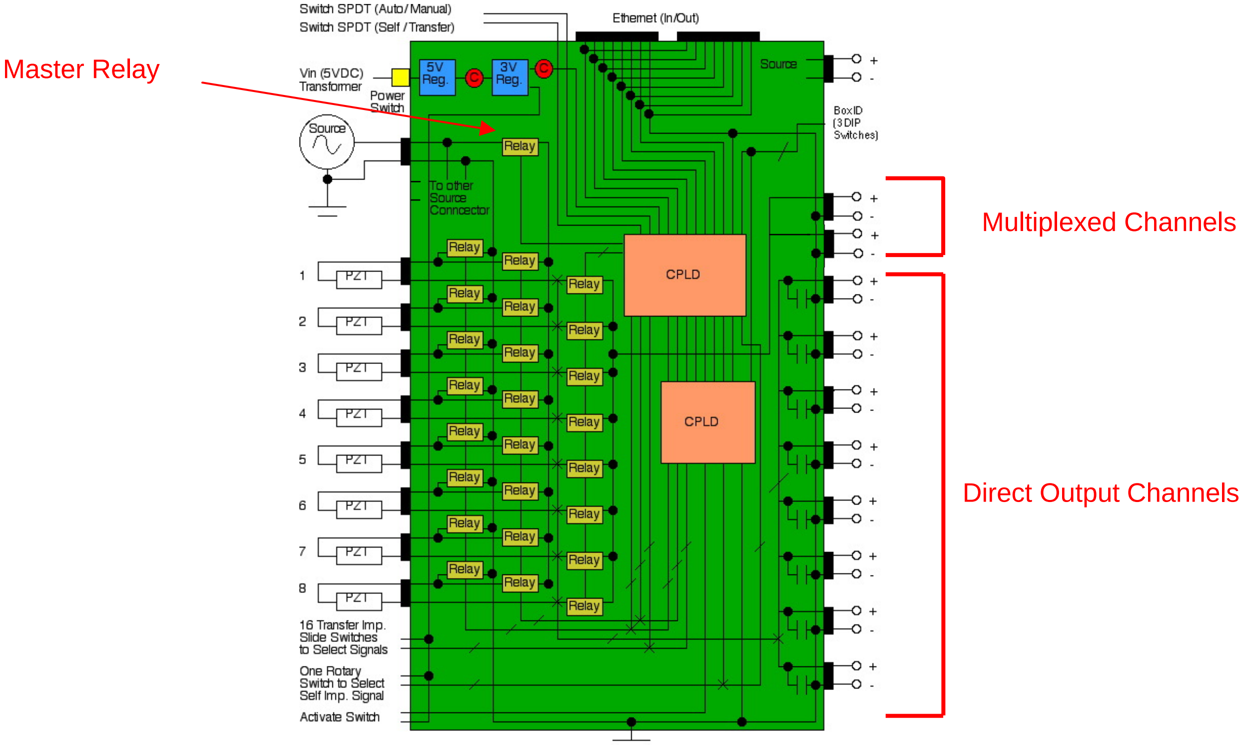


Figure 4: Relay-based hardware With Option Manual Controls Included

In Figure 4, the PZT patches are connected on the left side. There are eight independent channels, each with 3 relays. This number of channels, eight, is a design consideration. Each box could conceivably operate any number of sensors that is a power of two (2,4,8,16,32..). During normal operation, a PZT patch is used as either an actuator or sensor. The relays are used to switch the modes of sensing and actuation of the PZT. A diagram of a single channel is shown in Figure 5. When a PZT is actuated, Relay B closes (i.e. completes the circuit) and Relay A remains open. Conversely, when the PZT is in the sensor mode, Relay A closes and

Relay B remains open. Finally, with regard to Relay C, it is closed whenever that particular channel is the desired channel to be multiplexed. Unless signal mixing is desired, only one relay in Column C (of the eight in a single box) should be closed at any one time. The "channel X output" refers a non-switched connection that provides for constant access to each sensor's output, regardless of which channel is being multiplexed. Therefore, depending on the programming or configuration, the sensing signals are either fed directly into the eight direct output channels or multiplexed to the "multiplexed" output channel in Figure 4. The master relay, the 25th and final relay, exists at the source and serves as a master relay to synchronize all of the channels when the box is activated. This relay connects/disconnects all of the channels' access to the source signal simultaneously. This simultaneity prevents signal latency and also prevents the source from being shorted to ground during switching between their on and off states. A diagram of the master relay setup is shown in Figure 6. It is important to realize that in this hardware, given the different types of signals (i.e. AC and DC), we have chosen to isolate the sensor "grounds" from the DC grounds. This isolation is done to reduce fluctuations in the DC signals that could cause signaling errors.

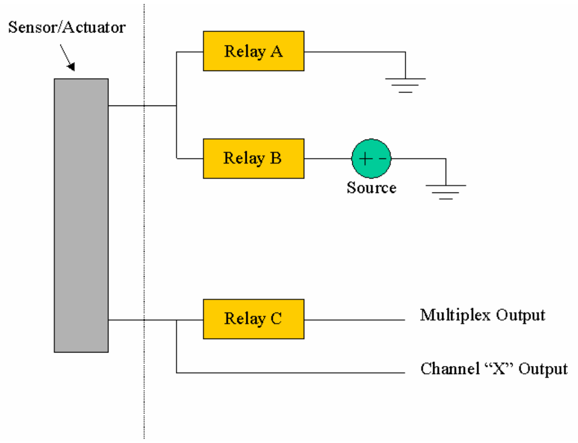


Figure 5: Single Channel Diagram

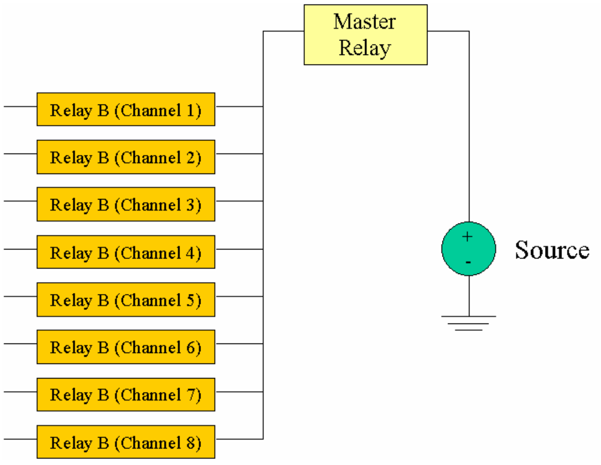


Figure 6: Master Relay Configuration

In order to control the relays, CPLDs manufactured by the Xinlinx Corporation were used. A programmable logic device (PLD) is similar to a microprocessor with the primary exception being that a PLD is based upon logic gates (i.e. AND, OR, XOR, NOR, etc.). The device's internal gates (of which there are 1600) are reconfigurable depending upon the program that is loaded onto it. For this hardware, we have chosen to use two of Xilinx's CoolRunner XPLA3 CPLD's which operate on a 3.3V DC core supply. Two CPLDs are used in each box. One CPLD, the master, controls half of the relay matrix including the master relay. The other CPLD, the slave, controls the other half, but does not have direct control over the master relay. The two CPLD's are interconnected using a single digital signal called "InterCPLD" which is used to indicate to the master CPLD to reset the master relay when called for by the slave CPLD. In addition to the InterCPLD signal, both CPLDs have all of the external control lines in common, i.e. the Ethernet lines. It should be noted that there are two channels available for Ethernet, as well as source and multiplexed connectors. These additional connections are used to chain several of the BlackBoxes together. By connecting one connector to a previous box and another to the following box, the BlackBoxes can be daisy-chained together allowing multiple boxes on a single chain. Virtually any possible number of sensors can then be connected and controlled together by using this design scheme.

The CPLDs are programmed using VHDL, a language specifically suited for CPLDs. In the BlackBox project, there are two major pieces of code, each separated into a system of sub-programs called modules. The two major pieces of code are representative of the two different CPLD's in a single box. Each module is intended to represent different aspects of the relay-matrix control process. Specifically, since the BlackBox is intended to allow for use with self-sensing techniques (i.e. impedance methods, pulse-echo) as well as transfer signal techniques (i.e. pitch-catch), a module is provided for each type of functionality. In effect, by splitting the code into simpler, more task specific pieces of code, the entire design becomes much easier to understand and a great deal more efficient. The BlackBox is controlled by parallel commands, converted from serial by an addional piece of hardware, that are generated by any serial-capable program (i.e. MatLab, C++, LabView, Visual Basic etc). Conceptually, this external control process could be a part of functionality of a de-centralized wireless sensor (the second level of the proposed sensing network) network that will perform duties of data acquisition, signal processing, and wireless transmission.

In summary, the BlackBox allows for the usage of any active sensing technique by employing a matrix system of multiple electromechanical relays, is controllable by means of signals sent via the box's Ethernet port, and is expandable by means of daisy-chaining. The size of the box is about 228 x 139 x 38.1 mm and costs only about $100 as a prototype. While normal commercialized multiplexers are strictly passive in nature, this piece of hardware not only routes the actuation signals to the sensors, but also multiplexes these actuated signals as a part of its functionality. Time synchronization can be readily achieved even between different boxes (i.e. excite one PZT in Box 1 and measure the response from PZTs in Box 2). This reconfigurable hardware design allows for flexible use with any type of active-sensing system with further expansion possibilities using wireless and local computing technology. Figure 7 shows the final design of the Blackbox daisy-chained to another box.

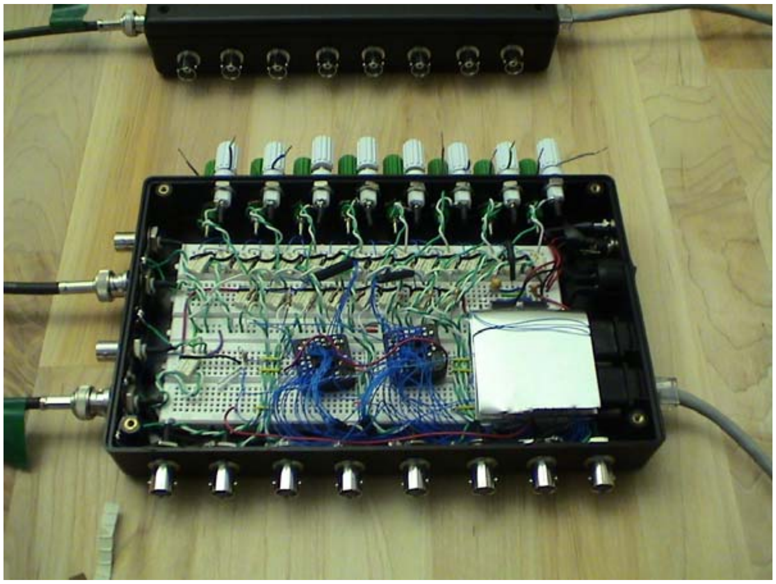
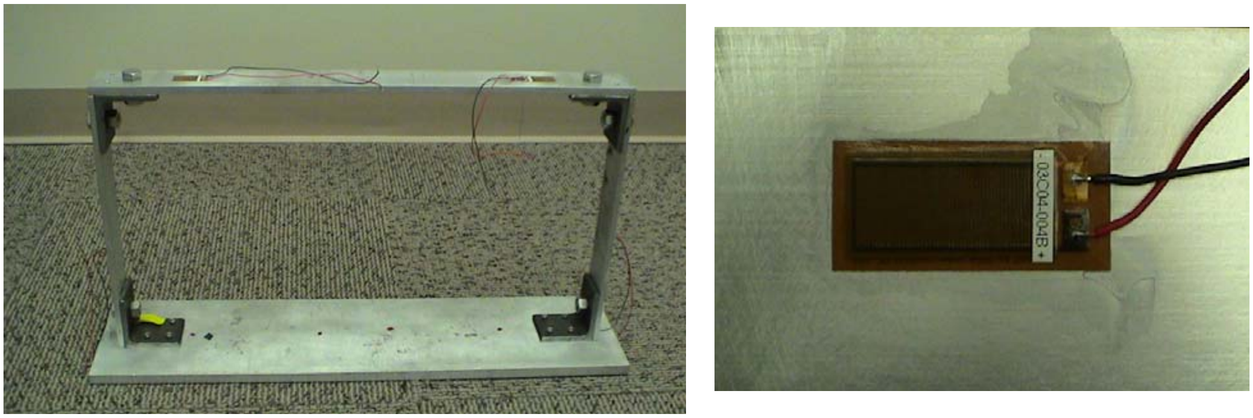


Figure 7: The Blackbox daisy-chained to another box

3.0 EXPERIMENTAL VERIFICATION

Experiments were performed to demonstrate the feasibility of the BlackBox in real-world structures. Two bolted-joint, moment-resisting, frame structures were used as a test bed in this study, shown in Figure 8. The structure consists of aluminum members connected using steel angle brackets and screws, with a simulated rigid base. Two columns (6.35 x 50.8 x 304.8 mm) are connected to the top beam (6.35 x 50.8 x 558.8 mm) using the bolted joints tightened to 17 N-m in the healthy condition. Four Macro-Fiber Composites (25.4 x 25.4 x 0.254 mm) (MFC) were mounted on the structure, as shown in Figure 8. The MFC is a relatively new type of piezoelectric sensor that is more flexible than the conventional PZT.



(a) Portal Frame (b) MFC used for sensing and actuation

Figure 8: The portal frame structure tested

In this study, two BlackBoxes were used with a two-channel commercial data acquisition system. One PC is connected to the data acquisition system and the BlackBox Control Board. The data acquisition system provides actuation signals and measures the responses on a fixed channel, while the BlackBox control board sends commands to the BlackBoxes switching each PZT between the sensing and actuation modes. Depending on applications, control of the PZTs can be performed in real-time with different combinations of sensor-actuator pairs or can be executed as one time configurations before the installation of the sensing network. The schematic of the experiment is shown in Figure 9. Both the numbering scheme for MFCs and the joint used for simulated damage for both structures are shown. It should be noted that the hardware inside the dotted line can be further miniaturized with those typically used in a de-centralized wireless sensor system.

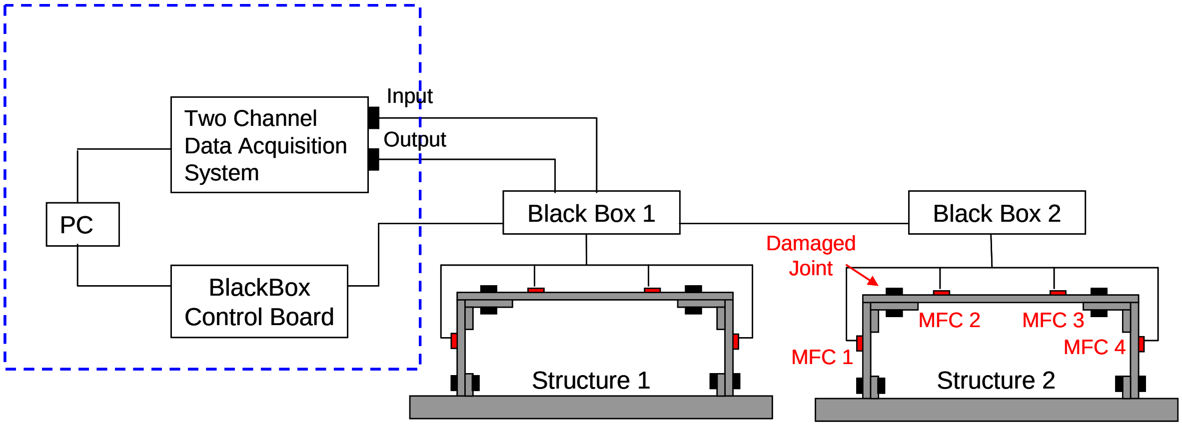
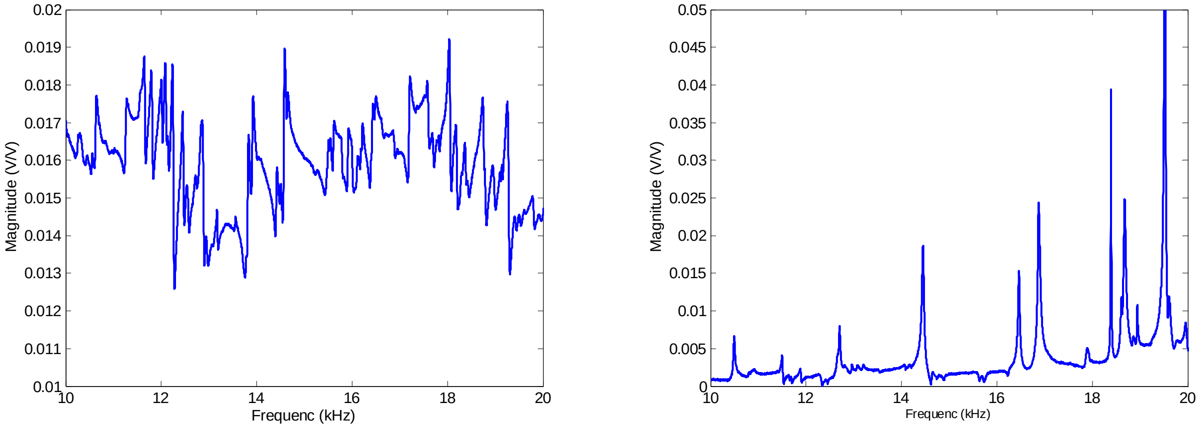


Figure 9: Schematic of the Experimental Setup

In the first experiment, frequency response functions (FRF) were measured from the MFC patches. In each structure, one MFC is designated as an actuator, exerting a random input into the structure. The remaining three MFC patches are used to measure the responses. Time histories were sampled at a rate of 51.2 kHz, producing 32,768 time points. A random signal (2.5 V) was used as the voltage input for the testing. Each time history is split up into 29 separate 4096-point blocks, with 75% overlap. A Fast Fourier Transform is then performed on all data blocks in order to transfer the time history information into the frequency domain for the FRF estimate. This data processing was performed using the PC after the measurements were completed, analogous to the function of data processor systems in de-centralized wireless sensor units.

Frequency baseline responses obtained by MFC 1 (actuator) and MFC 2 (sensor) from Structure 1 and by MFC 2 (actuator) and MFC 3 (sensor) from Structure 2 are shown in Figure 10 in the frequency range of 10-20 kHz. It is a well known fact that the FRF represents a unique dynamic characteristic of a structure. From the standpoint of structural monitoring, the damage will alter the stiffness, mass, or energy dissipation properties of a system, which, in turn, results in the changes in the FRF of the system. The use of FRF to detect and locate damage, especially at higher frequency ranges, is a unique approach primarily because it provides required sensitivities and repeatability, and allows for a judicious selection of frequency ranges for a given structure [13].



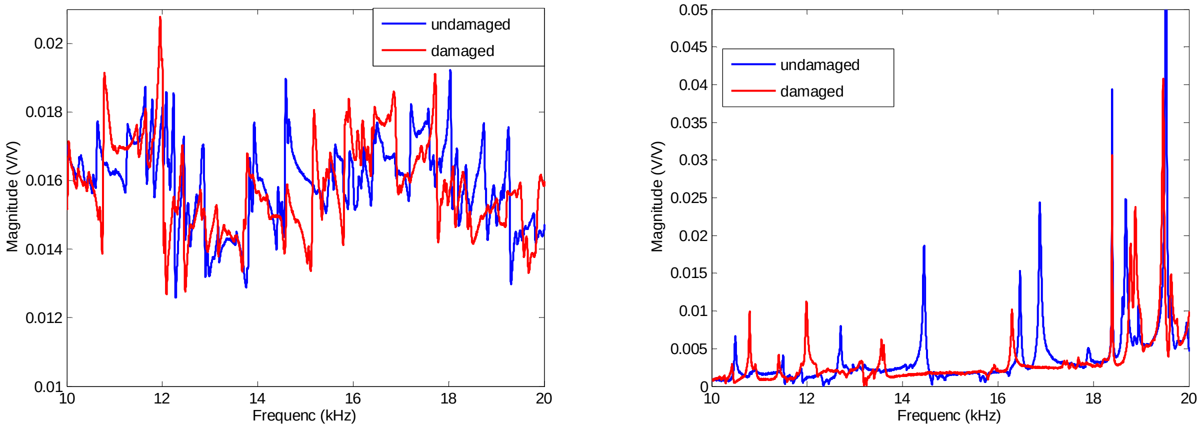
(a) FRF between MFC 1 (actuator) and MFC 2 (sensor) in Structure 1

(b) FRF between MFC 2 (actuator) and MFC 3 (sensor) in Structure 2

Figure 10: Undamaged FRF Measurements

After undamaged FRF measurements were taken, damage was introduced at the specific location (shown in Figure 10) by loosening the bolts to “hand tight” for both structures. After implementing the damage, the time histories were again recorded from each MFC and then processed. It can be seen from the FRF signatures in Figure 11(a) and (b) that the FRF shows a relatively large change in shape, which clearly indicates the presence of damage. This variation occurs because the loosened bolt modifies the apparent stiffness and damping of the joint.

The BlackBox used in this testing provides an efficient way to control sensors and actuators installed in the structures. The BlackBox controls the combinations of all the sensor-actuator pairs remotely and efficiently. The entire data acquisition of each structural condition from all the sensor-actuator pairs took less than one minute using only two signal acquisition channels. In addition, by using daisy-chaining, the requirement on wiring and cabling harness is significantly relaxed compared to traditional approaches. Although this experiment was performed only for the FRF estimates, the Blackbox will be also very efficient for wave propagation methods because it can activate multiple actuators and sensors simultaneously or individually, even those connected in the different boxes.



(a) FRFs between MFC 1 (actuator) and MFC 2 (sensor) in Structure 1

(b) FRFs between MFC 2 (actuator) and MFC 3 (sensor) in Structure 2

Figure 11: Undamaged and Damaged FRF Measurements

Our next experiment is using the impedance-based structural health monitoring technique [6]. The impedance method monitors the variations in mechanical impedance resulting from structural damage, which is coupled with the electrical impedance of a piezoelectric material. Contrary to the methods based on FRF measurements and pitch-catch wave propagation methods, the impedance-based method uses one piezoelectric patch for both actuation and sensing of structural responses because this method utilizes the direct and converse versions of the piezoelectric effect simultaneously. By employing higher frequency ranges, this method is also sensitive to minor defects in a structure. Furthermore, the impedance method is able to perform piezoelectric sensor self-diagnostics in which the operational status of piezoelectric sensors and actuators can be efficiently monitored [14]. In order to facilitate data acquisition for the impedance method and the sensor diagnosis, an impedance measuring circuit is built in the Blackbox at each channel.

The same structural conditions for undamaged and damaged cases were maintained. Figure 12 shows the impedance measurements from MFC 2 mounted on Structure 2 before and after the damage was introduced. As can be seen, the measurements are qualitatively different. The BlackBox was programmed to systematically perform the impedance measurement from all MFC patches mounted on both structures on a one-to-one basis. The BlackBox can be also programmed to scan multiple sensors simultaneously using the multiplexing function, if desired.

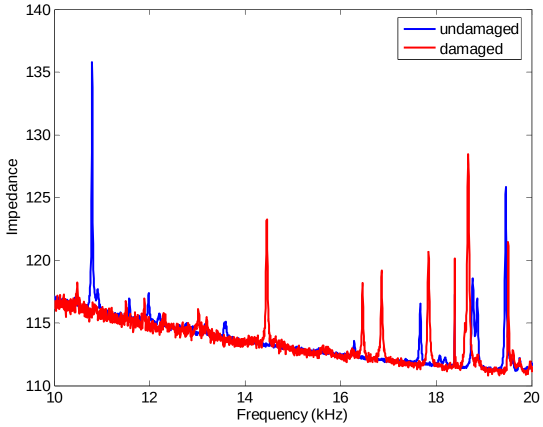


Figure 12: Undamaged and Damaged Impedance Measurements from MFC 2 (Structure 2)

The testing of the BlackBox has experimentally demonstrated the feasibility and advantages. With the remote controllability and expandability, the box can remotely and efficiently control large numbers of active-sensors as the first step of the hierachal sensing network proposed in Figure 3. This approach can perform a more systematic approach to structural health monitoring in complex structures, where a significantly large number of sensor/actuator are required.

4.0 DISCUSSION

The second step of the proposed sensing network, that will perform the duties of the BlackBox control, data acquisition, local computing, and wireless telemetry is also being developed by researchers at Los Alamos National Laboratory and Motorola [15]. To implement such processes, a single board computer is selected to provide true processing power in a compact form. Also included in the integrated system is a Motorola-developed digital signal processing board with analog to digital converters and digital to analog converters providing sensing and actuation capabilities. Finally, a Motorola wireless network board provides the ability for the system to transmit structural information to a central host, across a network, or through local hardware. Each of these hardware parts is built in a modular fashion and loosely coupled through the transmission control protocol or user datagram protocol internet protocols shown in Figure 13. The integration of this system with the BlackBox is currently under investigation.

The development of the hardware for structural health monitoring is only half of the solution. To develop a truly integrated structural health monitoring system, the hardware processes must be transferred to embedded software that automates data acquisition and interrogation for robust and rapid damage identification and returns a key result to end users. For the system shown in Figure 13, DIAMOND II software, developed by Los Alamos National Laboratory [16], is being implemented for easily creating and embedding such processes in remote hardware.

Figure 13: Wireless Data Acquisition Node developed by Motorola and Los Alamos National Laboratory

5.0 CONCLUSION

Current sensing network deployment schemes for structural health monitoring impose several limitations on active-sensing techniques. To address this problem, we propose a hybrid and hierarchal wireless sensing network. As the first step toward this approach, we have developed relay-based hardware that can serve as both a multiplexer and general-purpose signal router with special consideration given to piezoelectric active-sensing health monitoring techniques. We have also implemented this device as an expandable design that allows for easy scalability depending upon the size of the structure. Preliminary testing of this hardware on a test structure has experimentally proven the feasibility and advantages of utilizing such a system.

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