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Implementation of a Decentralized Control Algorithm Embedded within a Wireless Active Sensor

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ABSTRACT

Structural control systems have shown the potential to effectively reduce the response of civil structures to a variety of loads including strong winds and earthquakes. However, current structural control systems necessitate the installation of a wired monitoring system to provide communication between a centralized controller and system sensors and actuators. As semi-active control systems continue to incorporate greater numbers of sensors and actuators, centralized architectures are increasingly difficult to implement. Furthermore, the cost and effort associated with installing wires in large civil structures are significant. In response to these limitations, a decentralized wireless structural monitoring system is proposed for use in a structural control system. To render wireless sensors suitable for such deployments, an actuation interface is integrated in the design of a wireless active sensing unit prototype. In this study, the major focus is the implementation of a decentralized control algorithm within the computational core of the wireless active sensing unit prototype. The ability of the wireless active sensing unit to perform real-time feedback control is assessed.

INTRODUCTION

A smart structure is loosely defined as a structure with the capability to measure its own response to loading coupled with the ability to physically control this response. Civil structures have been an early adopter of smart structure technologies. For example, structural monitoring systems have been used to monitor the behavior of buildings, bridges and dams exposed to seismic events since the 1960s (Bolt 2001). In 1989, construction of the Kyobashi Seiwa Building in Tokyo, Japan, was completed making it the first structure in the world to employ an active mass damper for structural control (Kobori *et al.* 1991). While both sensing and control technologies have been successfully implemented in civil structures, wide-spread adoption of these novel technologies have been hampered by a number of factors. For structural monitoring systems, the need to install cables between sensors

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and a centralized data repository has resulted in high installation and upkeep costs. Similarly, structural control has enjoyed limited adoption due to high capital costs and excessive system power demands.

Today, new smart structure technologies that address the limitations of current techniques and equipment are emerging. In the area of structural control, semi-active actuators have recently offered engineers low-power actuation devices that can be used to control structures exposed to wind or seismic loading. A large number of semi-active actuators have been proposed by the field, including variable hydraulic dampers, magnetorheological dampers and variable stiffness devices (Connor 2002). In recent years, the popularity of variable hydraulic dampers have grown with many structures in Japan employing large numbers of devices; for example, the 54-story Mori Tower in Tokyo employs over 350 variable hydraulic dampers (Spencer and Nagarajaiah 2003).

In the structural monitoring domain, new technologies are also emerging. In particular, wireless sensors have been explored for adoption in a variety of structural monitoring applications (Lynch and Loh 2006). Wireless sensors are an exciting technology due in part to two important features. First, the use of wireless communication eliminates the need for installing extensive lengths of cables in large civil structures. Eradication of cables can substantially reduce the costs often associated with traditional tethered systems. The second desirable feature of wireless sensors is the integration of mobile computing power with the sensing transducer. This integrated computing power can be used to locally process structural measurement data for damage detection or system identification (Lynch *et al.* 2003).

The current state-of-practice in the design of structural control systems is largely based upon centralized architectures. First, a monitoring system is installed in the structure to measure the structure’s dynamic response and to provide this information to a centralized controller. Upon receipt of the structural response data, the controller makes an estimate of the full state response of the structure which it then uses to determine optimal control forces. Finally, the controller commands actuators to apply the calculated control forces. To date, structural control systems have made extensive use of wires to facilitate communication between the centralized controller and system actuators and sensors. With the growing size of control systems, there is a need for extensive cabling for communication between the centralized controller and sensors and actuators, thus requiring higher installation and labor costs. The need for greater lengths of cabling increases both the labor and cost of installing the entire control system. Another limitation associated with current control system designs is their use of centralized architectures. As the number of sensors and actuators increase, implementation of centralized system architectures become increasingly challenging (Lunze 1992). To keep pace with the reducing cost of smart structure technologies and the trend towards larger control systems, new approaches to the design of structural control systems are needed.

In this study, wireless sensors are considered for use within the framework of a structural control system. First, the design of a wireless “active” sensor that can be used for sensing, computing and actuation, is proposed. With sufficient computational power coupled with the wireless active sensor, the sensor can serve as a controller for the determination of control forces based on sensor measurements. In particular, a decentralized control solution proposed by Yook *et al.* (2002) is implemented within the core of the wireless active sensor prototype for automated execution. This control solution has been previously explored for control systems implemented within semi-actively controlled civil structures (Seth *et al.* 2005). The performance of the wireless active sensor, with the decentralized control algorithm embedded, is assessed in the laboratory.

IMPACT OF WIRELESS COMMUNICATIONS UPON REAL-TIME CONTROL

Before wireless sensors can be adopted in a feedback control system, the performance of the wireless communication channel must first be considered. Unlike a tethered communication system, wireless communications present unique challenges that can greatly impact the performance of the closed-loop control system. For example, naturally occurring phenomena such as noise, interference, multi-path effects and attenuation can all diminish the quality of service provided by a wireless communication system (Rappaport 2001). Modern wireless communication systems can successfully manage many of these issues at the physical link layer and in software through the use of network protocols. At the physical radio level, spread spectrum encoding is often used to spread data across many frequencies in a broad spectrum; such techniques can avoid narrow-band interference. Network protocols (*e.g.* TCP/IP) employing acknowledgement-retry techniques can also minimize the impact of interference and corresponding bit errors. Even with all of these techniques adopted, delay or outright data loss can still occur in a wireless communication system.

For a real-time control system, delay in the delivery of sensor data or actuator commands can reduce the control system effectiveness and could even lead to the loss of closed-loop stability. With delay and data loss always possible in a wireless communication system, researchers have begun to consider how to implement stable control solutions using wireless networks. For example, Horjel (2001) has considered implementation of a stable closed-loop control solution for the inverted pendulum problem using a Bluetooth wireless network. Two types of delays are identified in the Bluetooth communication channel: static and stochastic delays. Static delays, such as software processing, are deterministic and can therefore be accounted for in the design of the controller. In contrast, stochastic delays are the result of retransmissions of packets that are randomly lost or contaminated within the wireless channel. The static and stochastic delays of a Bluetooth network are quantified and compensated for in the control solution. Others have explored the use of IEEE 802.11 wireless networks for closed-loop control of an inverted pendulum. For example, recognizing communication overhead as a major contributor to delay in 802.11b wireless networks, Ploplys *et al.* (2004) proposes the adoption of the less complex communication protocol, UDP (user datagram protocol). Since UDP can not guarantee the successful transmission of data transmitted, their control solution must be tolerant of losses occurring during the transmission of sensor data or actuation commands.

DECENTRALIZED CONTROL ARCHITECTURES FOR WIRELESS SENSOR NETWORKS

Using wireless sensors as the primary data acquisition infrastructure of a structural control system, implementation of centralized architectures could be attempted. In such a system, wireless sensors would be responsible for the collection of response data from sensors, determination of control forces, issuing commands to actuators, and wirelessly broadcasting sensor data to other wireless sensors in the network. If at each time-step, every wireless sensor was to broadcast its local state data to the entire network, the complete state of the structure would be known to every wireless sensor. With every wireless sensor possessing identical state data, a centralized control solution, such as linear quadratic regulation, can be implemented. Unfortunately, this attempt at implementing a centralized control solution would not be successful in systems defined by high nodal densities. With huge communication demand disproportionate to the available wireless bandwidth, delay in the delivery of time critical data, and outright data loss, would commonly occur. The delay and loss of data in the communication system would impact the optimality, and potentially the stability, of the control solution. As a result, a centralized control system seems undesirable when wireless sensors are used in the control system. Alternatively, decentralized architectures provide an opportunity for implementing closed-loop control within a wireless sensor network.

Fully Decentralized Control

One potential technique that avoids the challenges associated with the delay or loss of data is to eliminate the wireless channel. In this approach, wireless sensors would act as self-sufficient local controllers that command interfaced actuators based on data collected from interfaced sensors. Because the wireless sensors would not be able to share pertinent state data, the performance of this fully decentralized control solution would be below that of a traditional centralized approach; therefore, fully decentralized control architectures will not be considered further in this study.

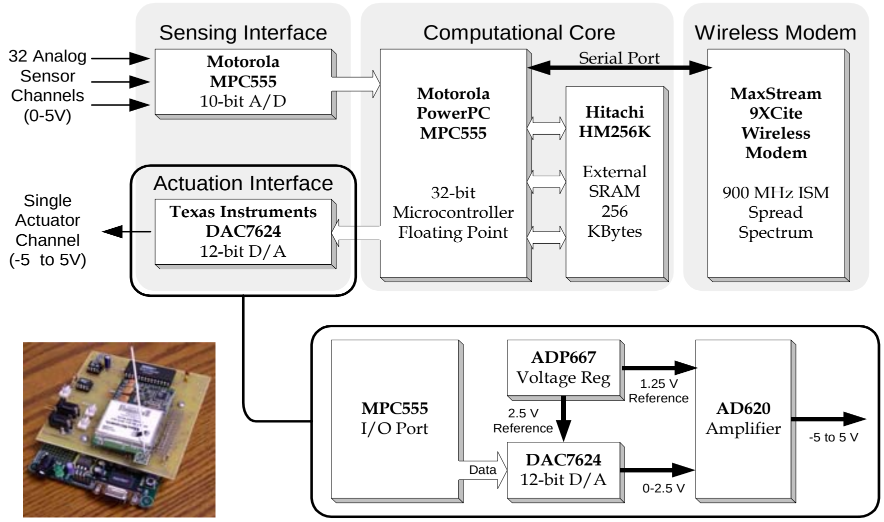
Partially Decentralized Control

A partially decentralized control solution is proposed to provide better closed-loop control performance than the centralized and fully decentralized solutions. To implement a partially decentralized control solution upon a wireless network of distributed controllers, a control methodology initially proposed by Yook *et al.* (2002) is considered for adoption. The approach seeks to minimize delays in the communication system by minimizing the use of the wireless channel. As demand for use of the wireless channel lowers, the probability of data delay or loss also gets reduced. To minimize wireless channel usage, state estimation is adopted at each wireless sensor. Using identical estimators at each wireless sensor, estimates of the structure's full state response can be made using sensor data associated with the i^{th} wireless sensor's degree-of-freedom, y_i. This dependence upon state estimation can help avoid the constant use of the wireless channel. However, factors including the presence of noise in the sensor output, can lead to errors in the state estimation. To ensure that errors in the estimated state do not diminish the performance of the control solution, every wireless sensor is programmed to compare the estimated state response of its measured degree-of-freedom, $\hat{y}_i$, with its true measured response, y_i. Only when the difference in the true and estimated response parameter exceeds a given threshold, does the wireless sensor broadcast the true measured response to the other wireless sensors in the structure. When the other controllers receive the measured state data, they update their own estimated states with the true measured parameter. This approach gives additional computational responsibility to the wireless sensor (*i.e.* state estimation) in order to minimize the use of the network bandwidth.

Before the partially decentralized control approach is implemented in an actual wireless sensor network, the feasibility of the approach is first analyzed. Using a simulation environment (MATLAB), the semi-active Kajima-Shizuoka Building is modeled (Seth *et al.* 2005). Assuming wireless sensors installed at each floor to measure acceleration responses during earthquakes, each wireless sensor is designated the responsibility of determining the appropriate damping coefficient for the variable damper associated with its degree-of-freedom. Embedded within each wireless sensor is a Kalman steady-state estimator for state estimation, and a global gain matrix corresponding to a centralized linear quadratic regulation (LQR) control solution. Thresholds are set for the minimum error in the state estimation that triggers the wireless sensor to broadcast its state data to the other wireless sensors. To gain a fair assessment of this partially decentralized approach, conservative probabilities of data loss in the wireless channel are modeled. A random number generator is employed at each wireless sensor to determine if a given time step's data is transmitted successfully or lost based upon the assumed data loss probabilities. Seth *et al.* (2005) reports that the partially decentralized control approach is capable of attaining excellent control performance even in the face of conservative probabilities of lost state data. While the performance of the partially decentralized solution is below that of a traditional centralized control system, its does surpass the fully decentralized architecture.

DESIGN OF A WIRELESS SENSOR FOR COMMANDING ACTUATORS

A wireless sensor that collects measurements from a broad class of sensors, determines control forces using its computational resources, and commands structural actuators is needed for implementation within the proposed wireless control system. A wireless "active" sensor prototype proposed by Lynch (2005) will be adopted for this purpose. As shown in Figure 1, the wireless active sensing unit design is divided into four functional components. The first three components, the sensing interface, computational core and wireless channel, are common to almost all academic and commercial wireless sensors platforms (Lynch and Loh 2006). Analog sensors can be connected to the sensing interface where sensor outputs are converted to a digital format using analog-to-digital converters (ADC). Once sensor data is digitized, it is then passed to the computational core where it is stored, processed and readied for transmission. The wireless communication channel is then used



Completed Prototype

Detailed Overview of the Actuation Interface

Fig. 1. Architectural design of a wireless active sensing unit prototype (Lynch 2005)

to establish wireless connectivity between other wireless sensors or with data repositories. What sets this wireless active sensor prototype apart is the fourth component, the actuation interface. Similar to the sensing interface, the purpose of the actuation interface is to allow the wireless sensor to command a broad class of actuators. In previous studies, the wireless active sensing unit was used to command piezoelectric active sensors for structural health monitoring applications (Lynch 2005). In this study, use of the actuation interface is proposed for commanding semi-active variable dampers in a structural control system. The key design features of the wireless active sensing unit prototype will be highlighted below.

Computational Core

A powerful 32-bit microcontroller, the Motorola MPC555 PowerPC, is selected to serve as the computational core of the wireless active sensing unit design. This microcontroller is selected because of its capability to rapidly execute embedded algorithms such as those required in a closed-loop control system. The microcontroller operates at a high clock frequency of 40 MHz. A convenient feature of the MPC555 is its on-chip floating point arithmetic and logic unit (ALU); this feature accelerates calculations involving floating-point numbers. The microcontroller also contains sufficient on-chip memory for both the storage of measurement data and embedded algorithms (448 Kbytes of read-only memory (ROM) and 26 Kbytes of random access memory (RAM)). An additional 256 Kbytes of off-chip RAM is provided for even greater data storage capacity.

Sensing Interface

For the sensing interface, the internal 10-bit ADC provided by the MPC555 is utilized. While higher conversion resolutions are desired, this low-resolution ADC is sufficient for illustration of the wireless active sensing unit functionality. The input to the ADC is multiplexed allowing for 32 sensing channels to be utilized at any one time. The maximum sample rate of the ADC is 100 kHz.

Wireless Communications

To allow for seamless connectivity with other wireless sensors and remote data servers within the wireless network, a long-range wireless modem is integrated with the wireless active sensing unit design. For the wireless active sensing unit prototype, the Maxstream 9XCite wireless modem, operating on the unlicensed 900 MHz radio spectrum, is selected. The radio has an over-the-air data rate of 38.4 Kbps and can communicate for up to 300 m line-of-sight. An unusual feature of this long-range modem is its low power consumption. When transmitting data, the modem consumes 250 mW, while during receiving data, the modem consumes 150 mW. This low power consumption will preserve the life of a portable battery power source in the field.

Actuation Interface

The actuation interface is designed to output analog voltage signals to a broad class of actuators. To allow the computational core's microcontroller to generate an analog output signal, a digital-to-analog converter (DAC) is needed to convert digital signals into analog outputs. For this purpose, the 12-bit Texas Instruments DAC7624 DAC is selected. The DAC7624 is capable of high-speed operation with a maximum sample rate of 100 kHz. The voltage output signals can also range from 0 to 2.5 V. Since some actuators require negative command voltages, the actuation interface is designed with additional circuit elements that allow the 12-bit actuation interface to output signals from -5 to 5 V.

As shown in Figure 1, the final wireless active sensing unit prototype is a compact device with dimensions of 11 cm by 10 cm in area and 4.5 cm in height. The total cost of constructing the prototype, including the cost of the wireless modem, is less than $200. The unit is powered by 5 AA lithium batteries providing 7.5 V of voltage power.

VALIDATION OF REAL-TIME CONTROL USING WIRELESS SENSORS

With the role of the wireless active sensing unit well defined in a partially decentralized control system, a series of laboratory tests are carried out to assess its performance as a controller. The purpose of the laboratory tests is to illustrate the ability of the wireless active sensing unit to record structural response data from interfaced sensors, estimate the full system state using an embedded steady-state Kalman estimator, determine an optimal control force, and issue a corresponding command signal to an interfaced actuator. Another important experiment goal is to assess the execution time of the entire embedded algorithm; ideally, the execution time is a small fraction of the system time-step.

Without access to an actual semi-actively controlled structure, structural response data generated by the Kajima-Shizuoka Building simulation study (Seth *et al.* 2005) must be used in lieu of implementation in a true civil structure or partial-scale laboratory test structure. The velocity time-history response of the 4th floor of the Kajima-Shizuoka Building under the El Centro (1940) north-south earthquake record is loaded into the memory bank of a Hewlett-Packard 15 MHz Function/Arbitrary Waveform Generator HP33120A. The waveform generator is intended to emulate the behavior of a velocity sensor as if it was installed upon the closed-loop controlled structure. The wireless active sensing unit is programmed to measure the velocity response of the 4th story at 100 Hz. At each time-step, the velocity response measured by the wireless active sensing unit is used to estimate the structure's full-state and to determine an optimal control force. The voltage command signal that would be generated by the wireless active sensor is then output to an Agilent 60 MHz Mixed-Signal Oscilloscope 54621D. The recorded command signal output by the wireless active sensing unit is stored by the oscilloscope to allow for a direct comparison to the signal generated in the Kajima-Shizuoka simulation study. Implementing a partially decentralized control solution, the displacement error threshold that triggers the 4th story wireless active sensing unit to wirelessly broadcast its state data to the other units in the network, is set to 1.5 cm. The broadcast state update is recorded by a laptop as if it was another wireless active sensing unit in the network. The complete experimental setup is summarized in Figure 2.

Embedded software is written to allow the wireless active sensing unit to fulfill its role as a distributed controller. The software is written in three parts. First, an integrator is coded to determine the displacement of the 4th story, y_4, using the measured velocity response, $\dot{y}_4$. Second, a steady-state Kalman estimator is encoded to predict the system state response using the current time-step's velocity and displacement measurement, as well as the previous time-step's estimated state, $\bar{x}$,

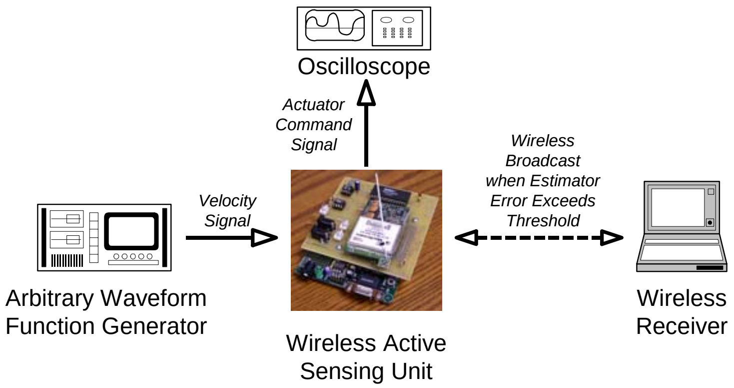


Fig. 2. Overview of the laboratory experiment to validate the performance of a partially decentralized controller embedded within a wireless active sensing unit

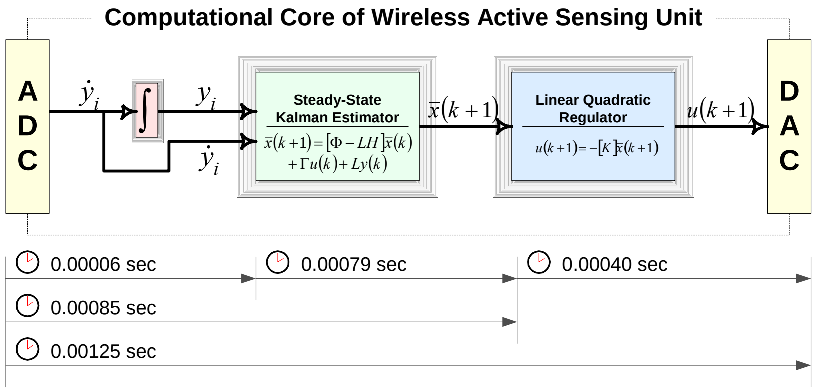


Fig.3. Measured execution time of the wireless sensor's embedded control force algorithm (Note: algorithm execution time based upon a 5 degree-of-freedom structure)

and applied control force, u. With an accurate estimate for the structure state, the gain matrix, K, corresponding to a linear quadratic regulation (LQR) control solution is used to determine the applied control force, u_4. The embedded software is written to ensure that the real-time requirements of the control system are met. For this purpose, the interrupt services provided by the wireless active sensing unit microcontroller are utilized. When an internal microcontroller timer triggers an interrupt (every 0.01 sec, 100 Hz), the embedded software is initiated with the internal ADC taking a measurement of the 4th story velocity response (which is being output in real-time by the HP33120A arbitrary waveform generator). An important issue to be addressed is the time needed by the wireless active sensing unit to complete the entire algorithm execution; it is highly desirable for the microcontroller to minimize the time needed. After the code has been implemented in the MPC555, the execution time is precisely measured using an internal timer. The measured times of execution for the three stages of embedded software are presented in Figure 3. In total, the wireless active sensing unit requires 0.00125 sec to carry out the necessary calculations. This execution time represents only 12.5% of the time-step (where the total time-step is 0.01 sec).

Figure 4 provides a screen shot from the oscilloscope used to measure both the 4th story velocity input to the wireless active sensing unit and the corresponding outputted control force command signal. The control force command signal is recorded by the oscilloscope so that a comparison can be made to the command signal determined by the simulation model. As can be seen in Figure 5, the command signal calculated by the wireless active sensing unit is nearly identical to that determined in the Kajima-Shizuoka simulation study. This one-to-one comparison attests to the accuracy of the embedded calculations carried out by the MPC555 microcontroller.

When the estimated state parameter that corresponds to the 4th story displacement is greater than the established 1.5 cm threshold, the wireless active sensing unit wirelessly broadcasts the true response measurement to the wireless network. A laptop computer is used to monitor the wireless communication channel for when updated state data is communicated. As shown in Figure 6, the estimated 4th story displacement does exceed 1.5 cm during the applied earthquake resulting in updated state data being successfully received by the wireless receiver that is attached to the laptop computer.

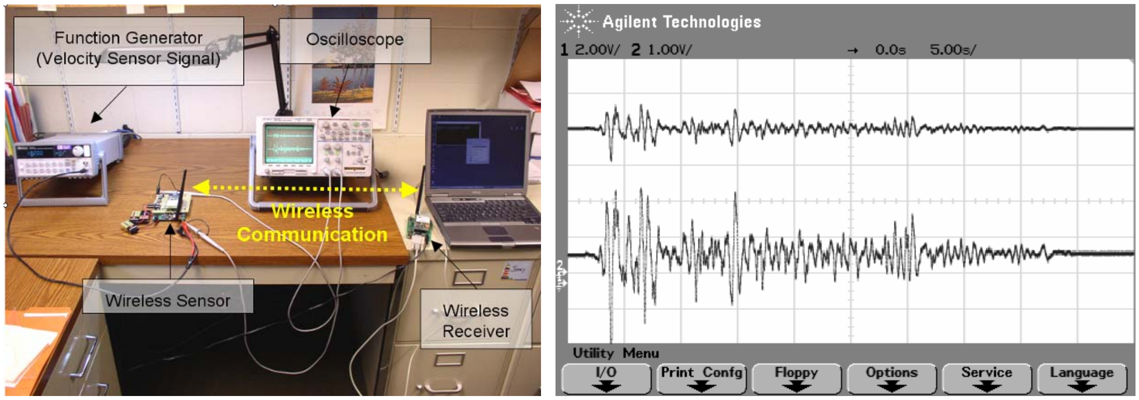


Fig. 4. (a) Overview of the experimental set-up, and (b) screen shot of the oscilloscope with the top signal the velocity input and the bottom signal the control force command output

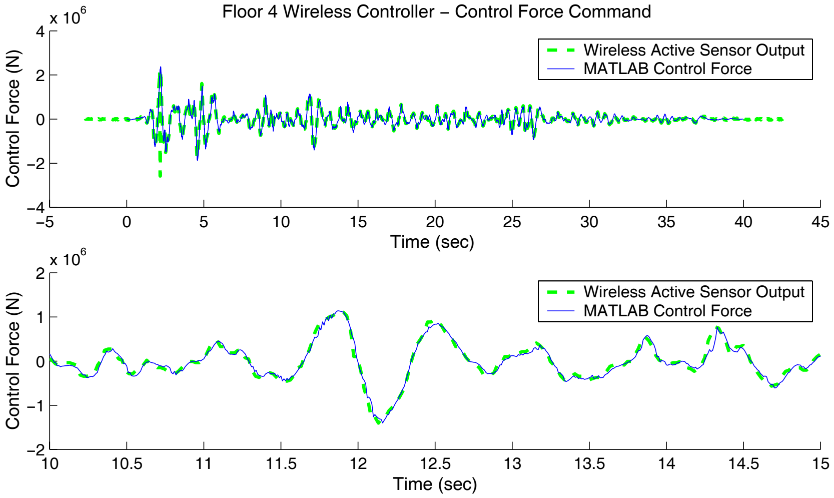


Fig. 5. Real-time control command signal emitted by wireless active sensor using velocity sensors

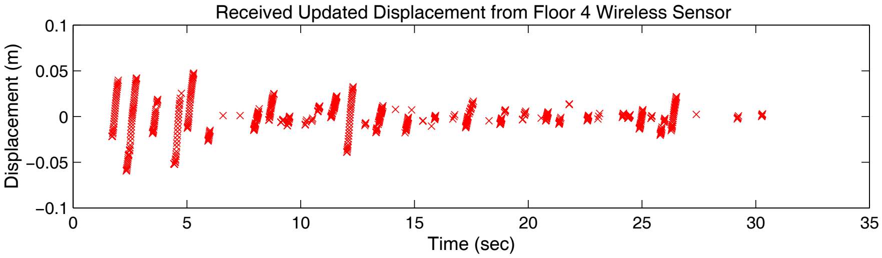


Fig. 6. Received state data wirelessly broadcast by the wireless active sensor unit

CONCLUSIONS

This study represents the first step towards the implementation of a partially decentralized control solution upon a wireless sensor network. With a wireless communication channel lacking the reliability of wired counterparts, a partially decentralized control solution is attractive because it preserves the use of the wireless channel for times when most needed, such as when estimation errors are large. In the proposed control framework, the wireless sensors all implement the same state estimator to determine the full system state. This is in effect trading off local computation for improved wireless channel reliability. Using a wireless sensor with an actuation interface installed, the proposed control strategy is successfully implemented in the laboratory using structural response data obtained from a simulation model. Future work is focused upon the validation of the wirelessly implemented control solution in a dynamic laboratory model. The reliability of the wireless modem integrated with the wireless active sensor prototype, including the rate of data loss and delay, is currently being measured in an actual multi-story building.

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