DISCUSSION ON THE APPLICATION OF WIRELESS ACTIVE SENSING UNIT FOR STRUCTURAL CONTROL

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Abstract

Performance aspects of the wireless active sensing unit, include the reliability of the wireless communication channel for real-time data delivery, and its application to building structural control is explored in this study. The application of the MR-damper to actively control a half-scale 3-story steel building excited by shaking table is studied using the wireless active sensors. With three MR dampers installed in each floors, structural responses during seismic excitation are measured by wireless sensors and communicated to the MR damper's wireless active sensing unit where an H_2 controller has been implemented in the wireless sensing and control unit. The wireless active sensor is responsible for the reception of response data, determination of optimal control forces, and issuing of command signals to the damper. Finally, the control performance is discussed by using both the wired communication system and the wireless active sensing unit.

Introduction

Traditional structural control technology has employed wire-based systems to do the communication for structural control and structural data collection. However, the installation of these wire-based control systems can be expensive in labor, time and price. In order to reduce these monetary and time expenses for the installation of wire-based systems, new technologies in embedded systems and wireless communication have been adopted in academic and industry research for wireless sensing and monitoring. The use of wireless communication for SHM data acquisition was illustrated by Strser and Kiremidjian [1998]. More recently, Lynch et al. extended the work by embedding damage identification algorithms into wireless sensing unit [Lynch et al. 2004] and has already proven reliable when used in lieu of coaxial wiring in structural monitoring systems [Wang et al. 2005; Lynch et al. 2006]. The advantages of using wireless sensing units for structural health monitoring have been verified while in the structural control area, many challenges must still be explored in greater detail. To capitalize on low-cost semi-active actuators installed in high density in a single structure, wireless communication is proposed to minimize the high-cost of coaxial wires. A prototype Wireless Structural Sensing and Control (WiSSCon) system has been proposed [Lynch et al. 2006] for structure response mitigation. The software written to operate the wireless sensors under the real-time requirement of the control problem is presented in this study. The promising performance in applying wireless communication and embedded computing technology into a real-time feedback structural control system was presented. This paper presents the experimental verification of using both fully centralized control and fully decentralized control strategies with the implementation of semi-active control devices and adopting wireless control and sensing system. Two major research directions are emphasized: (1) Develop the theoretical basis of fully centralized and fully decentralized control algorithms and implement to WiSSCon system for structural control, (2) Experimental verification on the wireless communication for structural control is made. Comparison on both the wired control system and the wireless control system is examined.

The Experimental Setup of WiSSCon System

WiSSCon (Wireless Structural Sensing and Control System) is a prototype system designed for real-time wireless structural sensing and feedback control [Wang et al. 2005 and Lynch et al. 2006]. In the WiSSCon system, wireless communication is used for the feedback of structural response data to wireless sensors serving as the control kernel (*i.e.* to calculate control solutions based on received data). It consists of a wireless sensing unit with the embedded control software in the microcontroller and the action board. Fig. 1 shows the basic architecture of the wireless sensing and control unit. The wireless sensing unit is responsible for measuring the dynamic response of the structure and the action board is to convert the digital signal (8 bit) to analog signal (16 bit) for control purpose. For the calculation of control forces at each time-step, the wireless sensing unit was also designated as the control kernel (termed the wireless control unit) utilizes its local embedded computing resources to quickly process sensor data, generate control signals, and apply control commands to structural actuators within the designated time-step duration. On each floor a WiSSCon system is installed and connected to the MR-damper via VCCS (voltage to current converter). The operation of WiSSCon system and the program flow can be explained from server side and the embedded code side which is summarized into five steps: Step 1: Boot up the system from both PC server and embedded system in the WiSSCon system; Step 2: The server checks all the wireless sensing and control units in the network through the wireless transceiver (as shown in Fig. 2a for detail description of step 2) and reset clock/counter the synchronization process is verified; Step 3: From the embedded code, each wireless control unit broadcasts a beacon to all other units in the network sequentially announcing that a new time step begins. The communication latency of each wireless transmission needs to be carefully considered. For the centralized control it is set 20 milliseconds for each sensing unit to receive the signal from other unit in this study (as shown in Fig. 2b). For case of centralized control a total of 60 ms is needed for all units receive all the signals from other units. Then to calculate the control force which 35 milliseconds may need. So a total of 95 milliseconds is required to conduct the centralized active control. This is the reason to set the sampling rate of 10Hz for centralized control; Step 4 and Step 5: Feedback the results to PC server and exit the control program.

The building control system includes: Sensors (velocity meters and accelerometers), MR-dampers, VCCS (voltage converts to current system), and WiSSCon system, as shown in Fig. 3. Because two different

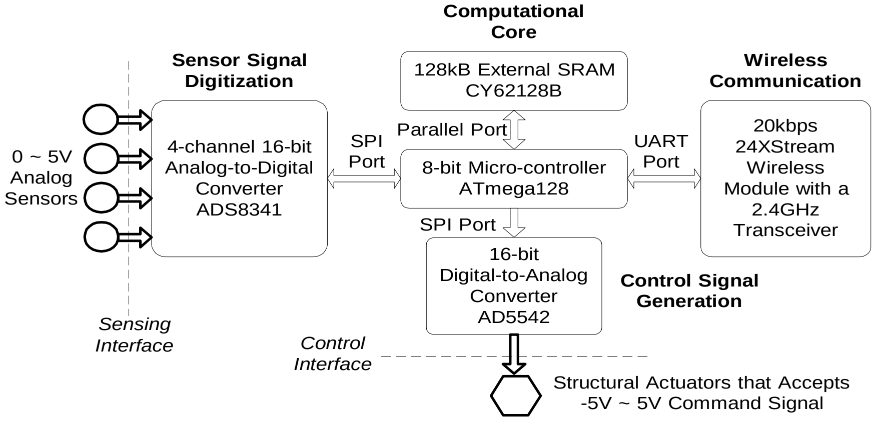

Figure 1: Hard ware architecture of wireless control unit (Lynch et al. 2005).

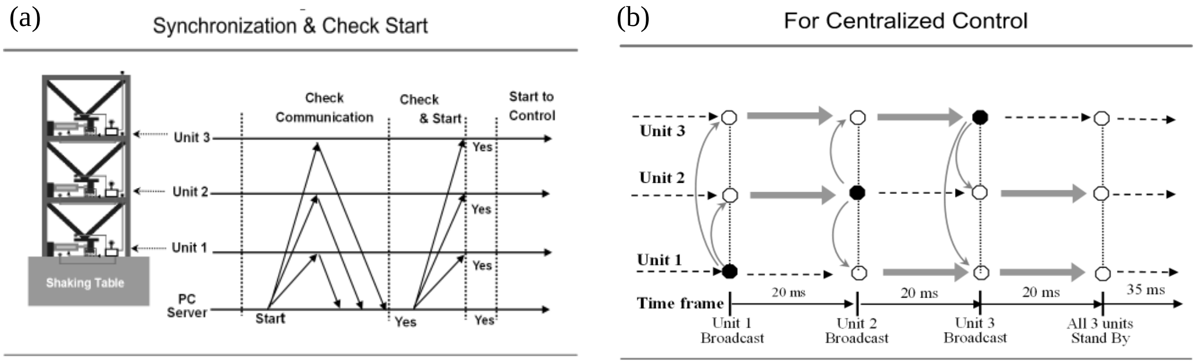

Figure 2: (a) Synchronization of data communication and check start from sever code in Step 2, (b) Data broadcast and time sharing among sensing units for centralized control in Step 3.

control strategies are used in this study, the setup of the control system is also different for using different control strategy. For the de-centralized control three individual sub-systems are considered and each sub-system has its own control device. The velocity meters are installed at both sides of the damper to measure the relative displacement between two adjacent floors (using wired system). This signal will feed into the WiSSCon system to calculate the control force. The floor acceleration data from each particular floor (or sub-system) is collected wirelessly by the WiSSCon system and Kalman estimator will be used to estimate the full state which incorporated with the measured floor relative velocity to calculate the control voltage. Based upon a measure of the shaft velocity of the damper and the estimated control force from WiSSCon system, desired commend voltage for control can be achieved. Through VCCS (Voltage-Current Converter system) the control current will be estimated and feed into the damper for control purpose. As for the centralized control each WiSSCon system will collect all the floor acceleration responses wirelessly instead of just single floor response. Both centralized and de-centralized control algorithms will be introduced in the following section.

Formulation The Control Algorithm

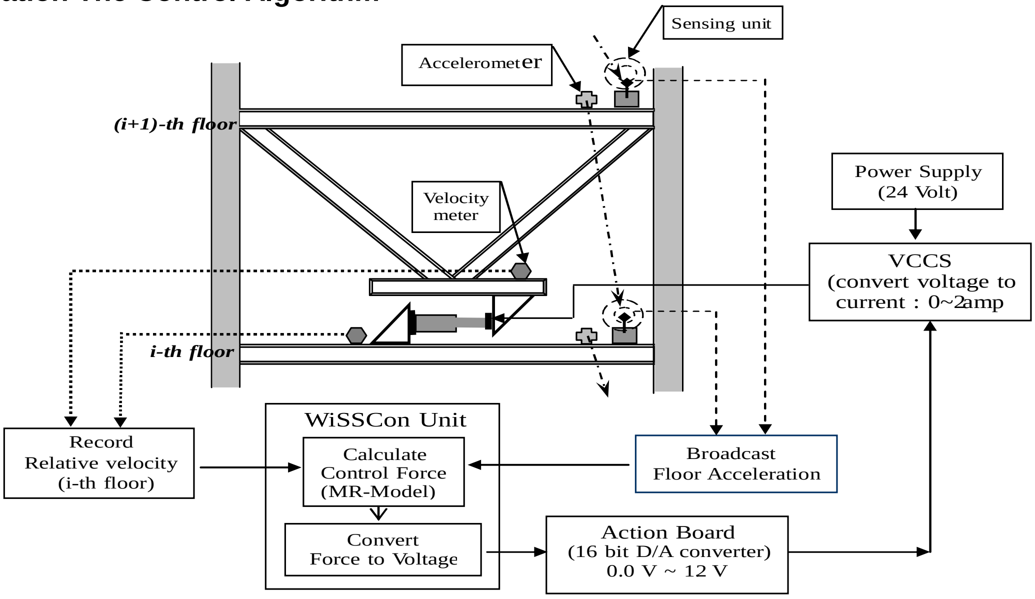

Figure.3: Control setup using wireless sensing and control unit and its connection with the MR-damper.

Two different control algorithms are used for the control experiment: the fully centralized control and fully decentralized control. In developing the fully centralized control algorithm the entire structural system and all measurements are considered to generate the control gain together. Since the full-state measurement is impossible and can not be implemented in the realistic structural control, therefore, the Kalman estimator, which transforms the measured vector into the full-state vector, will be used to estimate the full-state responses of the structural system and to calculate the control gain. Considering the limited sensors in the structure, the Kalman estimator needs to be selected to transform the limited measurements into the full-state measurement estimation. The H_2 control algorithm will be used. First the objective function, including the system matrix and the term of control devices, defined as:

$$J = \sum_{k=0}^{\infty} z^T[k] Q_{6\times6} z[k] + u^T[k] R_{3\times3} u[k] \tag{1}$$

Here, the weighting matrices, Q and R, are related to the full state and the control forces, respectively. After transforming the function by the procedures of variation method, the new form of the function can imply the Ricatti equation and be solved as

$$A_d^T P_{6\times6} A_d - A_d^T P_{6\times6} B_d (2R + B_d^T P_{6\times6} B_d)^{-1} B_d^T P_{6\times6} A_d + 2Q = P_{6\times6} \tag{2}$$

in which the matrix P is the solution of the Ricatti equation, obtained by iterative calculation. Considering the limited sensors in the structure, the Kalman estimator need to be selected to transform the limited measurements into the full-state measurement estimation, as shown below:

$$\hat{z}_d^{red}[k+1] = A_d^{red} \hat{z}_d^{red}[k] + B_d^{red} u[k] + L(y_{d,s}[k] - C_d^{red} \hat{z}_d^{red}[k] - F_d^{red} u[k]) \tag{3}$$

Here, *L* is the solution of the Ricatti equation from the Kalman formulation [Dyke et al. 1996]. The control force can then be replaced by the following form

$$\begin{aligned} u[k+1] &= G z_d^{red}[k+1] = G(A_d^{red} + B_d^{red} G - L C_c^{red} - L F_d^{red} G) z_d^{red}[k] + G L y_d[k] \\ &= G \hat{A}_{cs} \hat{z}[k] + G L_{ms} y[k] \end{aligned} \tag{4}$$

where $\hat{A}_{cs}$ is the modified system matrix in relating to control. Finally, Eq. (7) provides the estimated full-state response ($\hat{z}_d^{red}$) to estimate the control forces in the real response. Because the control force was generated using the full-state response vector, it is called the fully centralized control.

The fully decentralized control emphasizes on the control of local system around the location of control device by using the response measurements from sensors around the local sub-system so as to generate the control force instantly and efficiently. From this point of view, a complete structural system can be separated into many sub-systems and each sub-system contains its own sensor measurements and control devices. n this study, consider three independent sub-systems in the structure, the state-space equation and the measurement equations become:

$$\begin{aligned} z[k+1] &= A_d z[k] + \sum_{i=1}^{3} (B_d)_i u_i[k] + E_d \ddot{x}_g[k] \\ y_1[k] &= (C_{d,1})_{1\times6} z[k] + (D_{d,11})_{1\times1} u_1[k] + \sum_{j=2}^{3} (D_{d,1j})_{1\times1} u_j[k] + (F_{d,1})_{1\times1} \ddot{x}_g[k] \\ y_2[k] &= (C_{d,3})_{1\times6} z[k] + (D_{d,22})_{1\times1} u_1[k] + \sum_{j=1,3} (D_{d,2j})_{1\times1} u_j[k] + (F_{d,2})_{1\times1} \ddot{x}_g[k] \\ y_3[k] &= (C_{d,3})_{1\times6} z[k] + (D_{d,33})_{1\times1} u_1[k] + \sum_{j=1,2} (D_{d,3j})_{1\times1} u_j[k] + (F_{d,3})_{1\times1} \ddot{x}_g[k] \end{aligned} \tag{5}$$

Here, $\hat{R}$ is not a matrix any more and may vary with different control forces because every objective function focuses on one control force of its own sub-system. Since there are three control devices and three acceleration measurements at each floor as feedback, therefore only three subsystems for this decentralized control method are involved and the objective functions are shown below:

$$
\begin{aligned}
J_1 &= \sum_{k=0}^{\infty} z^T[k]Q_{6\times6}z[k] + u_1^T[k]R_{1\times1}u_1[k] \\
J_2 &= \sum_{k=0}^{\infty} z^T[k]Q_{6\times6}z[k] + u_2^T[k]R_{1\times1}u_2[k] \\
J_3 &= \sum_{k=0}^{\infty} z^T[k]Q_{6\times6}z[k] + u_3^T[k]R_{1\times1}u_3[k]
\end{aligned}
\tag{6}
$$

Here, each objective function focuses on each control force so that the number of control gains is also three. The Ricatti equation, which is derived from each objective function, can be presented

$$A_d^T P A_d - A_d^T P(B_{d,i})_{6\times1}(2R_{1\times1} + B_d^T P(B_{d,i})_{6\times1})^{-1}(B_{d,i})_{6\times1}^T P A_d + 2Q = P \tag{7}$$

The control gain can be described as:

$$u_i[k] = -(2R + B_{d,i}^T P B_{d,i})^{-1} B_{d,i}^T P A z[k] = G_{1\times6} z[k] \tag{8}$$

Then the Kalman estimator needs to be modified as:

$$\hat{z}_d^{red}[k+1] = A_d^{red}\hat{z}_d^{red}[k] + (B_d^{red})_i u_i[k] + L_j((y_{d,s})_j[k] - (C_d^{red})_j \hat{z}_d^{red}[k] - (F_d^{red})_{j,i} u_i[k]) \tag{9}$$

It means that based on the measurement from individual sub-system the estimation of full-state is required. where "i" indicates the i-th estimator which is with the same length of the full-state vector. And the control force can be obtained from

$$u_i[k+1] = G_i(z_d^{red})_i[k+1] \tag{10}$$

Analysis of The Experimental Results

From the shaking table test of the 3-story steel frame with the implementation of MR-damper in each floor, the control effectiveness using both wired and wireless control systems are examined. The MR-damper is installed in the middle of the floor system with V-type bracing system. Verification on the communication of control comments is studied first, and then the control effectiveness using different control strategies is discussed. In this control experiment three different communication systems are used: (1) NCREE data acquisition system (Pacific Series 5500 Digital Conditioning System with sampling rate of 200Hz)with Simulink for control, (2) WiSSCon Centralized control system (with sampling rate of 10Hz), (3) WiSSCon De-centralized control system (with sampling rate of 50Hz). Detail description of the three system is described as follows:

(a). NCREE Laboratory Control System: Combine the NCREE digital conditioning system, Simulink and the DSpace I/O board, the traditional laboratory control test using wired system will be used and the results will be used as the benchmark model for comparison. The sampling rate for this control experiment (either centralized or decentralized control) is 200Hz and H2 control algorithm will be used. The result from this control system will be served as a benchmark for comparison with other wireless communication control system. (b). Centralized control with sampling rate of 10 Hz: In the wireless centralized control the sensing unit on each floor will collect all the acceleration data broadcasted from all other sensing units on different floor. If high sampling rate is chosen then data will loss during the communication, so a sampling rate of 10 Hz is used in this case. (3). De-centralized control with sampling rate of 50 Hz: In the decentralized control, each wireless sensing and control unit only receives signal from sensor in each specific subsystem. There is no need to wait the signals transmitted from other sensing units, so higher sampling rate of 50Hz can be used for decentralized control. In order to verify the accuracy of the communication signal during the control process comparison on the recorded signal from different stage will be collected for comparison. Data collected using WiSSCon system and NCREE-wired system will be discussed so as to verify the controlled capability of the wireless control system.

Validation of the WiSSCon system Comparison on the commend voltage need to be verified: one is signal generated from the microcontroller (calculated from embedded program) of the wireless sensing unit in digital format and the other one is generated from the action board in analog form. Comparison on the recorded acceleration data either directly from sensor or broadcasted from other sensing units is also verified. Comparison on the commend voltage collected from action board and from numerical simulation is made for both the centralized and de-centralized control. Comparison between the calculated damper force from the numerical theoretical model (solid line) and the estimated damper force from WiSSCon wireless system (dash line) is also compared, as shown in Figure 4. From all these validation study on WiSSCon system, it is proved that: the commend voltage is correct, there is no loss of data during the communication, and the action board can generate the control voltage correctly.

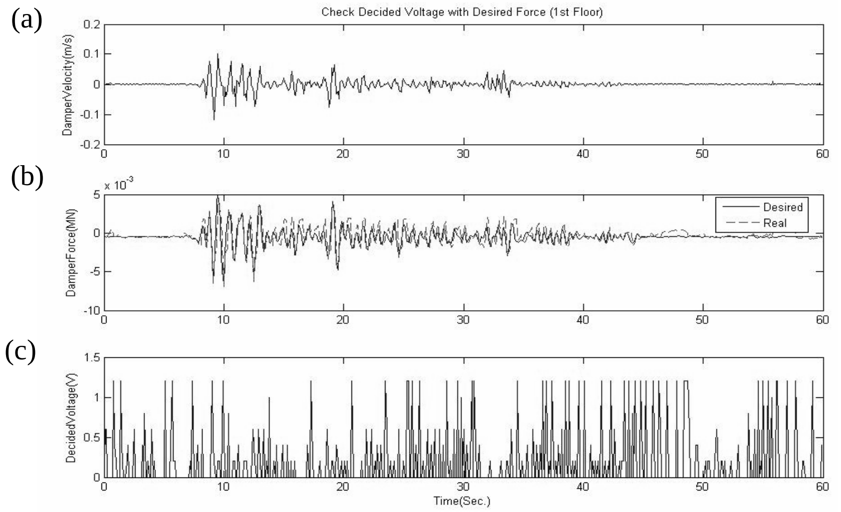

Figure 4: (a) Example shows the measured relative velocity (1st floor) of MR-damper, (b) Comparison between the calculated damper force between the theoretical model (solid line) and the estimated damper force from wireless system (dash line), (c) Decided voltage to be feed into the MR-damper.

Validation of wireless control effectiveness Performance evaluation of MR-damper during the control experiment plays an important rule on control effectiveness. In centralized control the damper's hysteretic behavior is examined by using both wireless system and wired system (NCREE system) under the same sampling rate of 10Hz is compared, as shown in Figure 5a for centralized control and Figure 5b shows the comparison for decentralized control with sampling rate of 50 Hz. To verify the control effectiveness using wireless sensing and control system the control results are compared with the wired control system with sampling rate of 200Hz. Comparison on the floor acceleration and displacement using wired control system (200Hz) and wireless control system for case of centralized control (10Hz) and decentralized control (50Hz) is also conducted. It is proved that the wireless sensing and control system can almost reach the same control effectiveness as the wired system. Comparison on the control effectiveness among different control methods is also made. Figure 6a shows the comparison among un-control case, numerical simulation of fully centralized control and wireless centralized control with 10 Hz, and Figure 6b is the comparison with the decentralized control using wireless with 50 Hz. The results indicated that both centralized and decentralized control using wireless sensing system can reach almost the same control effectiveness as the wire control system.

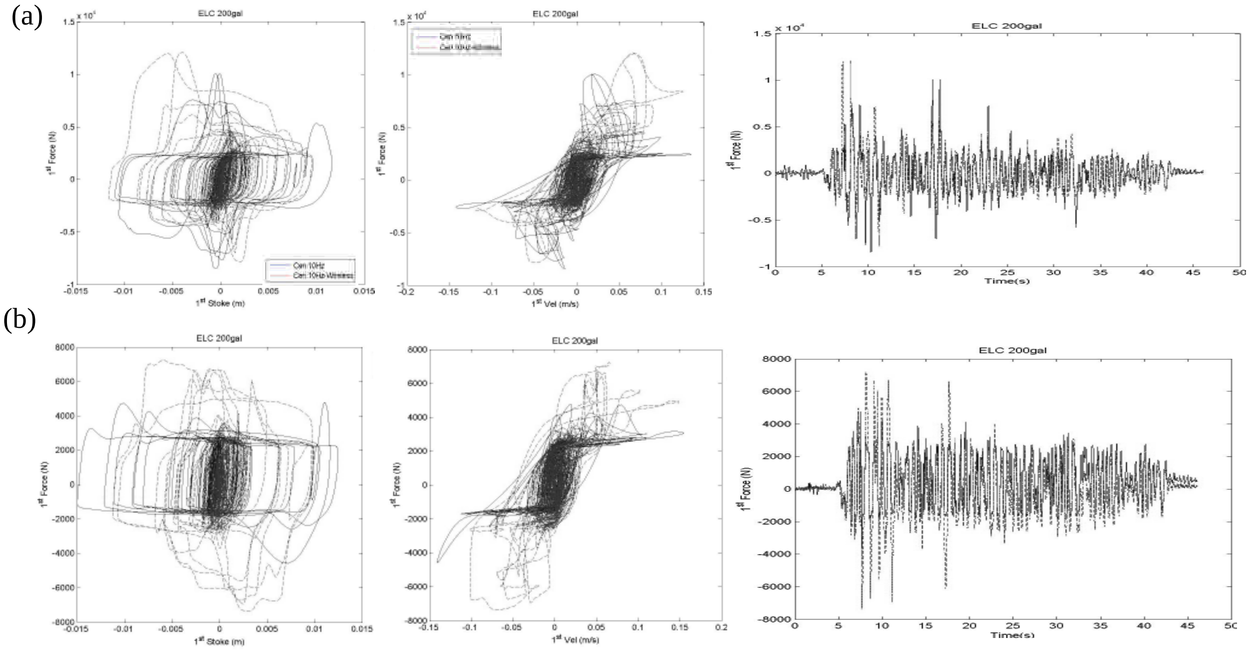

Figure 5: Comparison on force-stroke and force-velocity relationship of MR-damper using both wired and wireless control system; (a) for centralized control with sampling rate of 10Hz, (b) for decentralized control with sampling rate of 50 Hz.

Conclusions

This study examines the potential of wireless communication and embedded computing technologies for real-time structural control application. Based on the implementation of the prototype WiSSCon system in the structure, both the centralized control method and decentralized control method are applied to control a 3-story steel structure with MR-damper in each floor subject to EL-Centro earthquake excitation on shaking table. The following conclusions are drawn:

1. The WiSSCon concept has been demonstrated in this study, the performance of this system is shown to be superior to the case of semi-active control system and nearly comparable to the wired control system. The control effectiveness using either centralized or decentralized control shows reliable performance of the system.
2. The latency limitation associated with wireless communication needs to be carefully examined. Different control algorithm to be embedded in the WiSSCon system may have different latency which has to be figure out in order not to loss the data in communication.
3. In the decentralized control design, only local sensor information has been used to generate the control signal that is send to the dampers of each control subsystem. This de-centralized control algorithm can be carried out successfully for a large-scale structural system. The simulation results demonstrate that decentralized control provides almost the same control effectiveness (indices) as the centralized control.An advantage of the decentralized control is the robustness in the face of failure of control system during strong earthquake. Given one subsystem fails, the other subsystems can be capable of compensating accordingly and ensure suitable global performance of the system.
4. Finally, the wireless sensor networks are a promising technology capable of operation for a real-time communication and control system. The wireless feedback structural control with embedded computing can reduce the cost by eradicating cables in the control system, using low-cost

microcontroller for the control kernel and highly flexible and adaptable system configuration because of wireless communication.

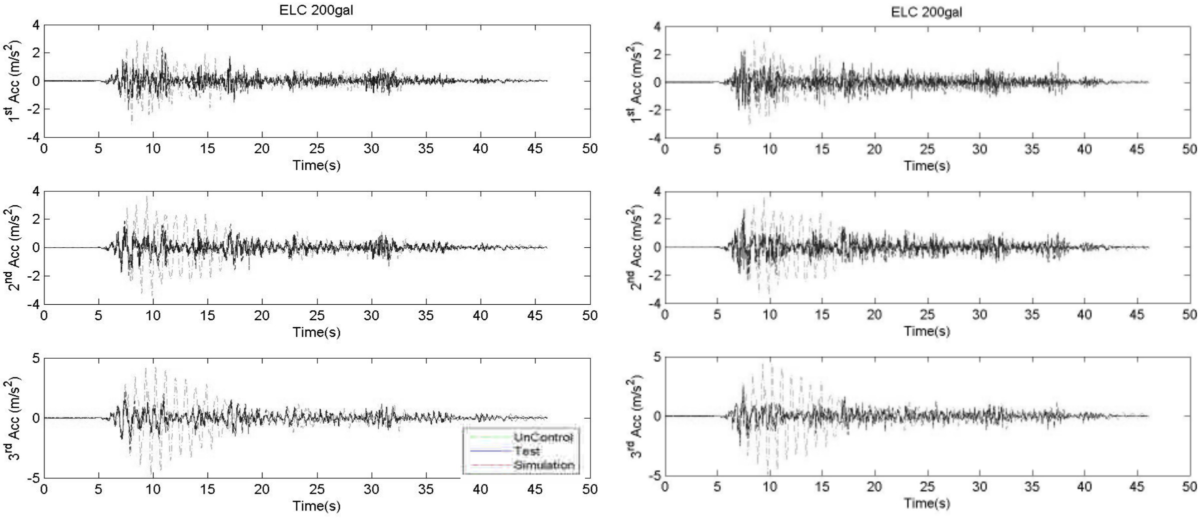

Figure 6: Comparison on the acceleration responses in each floor for un-control case, numerical simulation and experimental results where experimental result is: (a) for centralized control, (b) for decentralized control..

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