Decentralized wireless structural sensing and control with multiple system architectures operating at different sampling frequencies

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ABSTRACT

Recent years have seen growing interest in applying wireless sensing and embedded computing technologies for structural health monitoring and control. The incorporation of these new technologies greatly reduces system cost by eliminating expensive lengthy cables, and enables highly flexible system architectures. Previous research has demonstrated the feasibility of decentralized wireless structural control through numerical simulations and preliminary laboratory experiments with a three-story structure. This paper describes latest laboratory experiments that are designed to further evaluate the performance of decentralized wireless structural control using a six-story structure. Commanded by wireless sensors and controllers, semi-active magnetorheological (MR) dampers are installed between neighboring floors for applying real-time feedback control forces. Multiple centralized/decentralized feedback control architectures have been investigated in the experiments, in combination with different sampling frequencies. The experiments offer valuable insight in applying decentralized wireless control to larger-scale civil structures.

Keywords: decentralized structural control, wireless sensing, direct velocity feedback, magnetorheological damper

1. INTRODUCTION

During the last few decades, real-time feedback structural control has attracted a great amount of interest in the structural engineering community [1-4]. It was reported that about 50 buildings and towers had been instrumented with various types of structural control systems from 1989 to 2003 [5]. A feedback structural control system contains a network of sensors, controllers, and actuators. Components in this network collaboratively mitigate structural vibration when strong external excitations (such as earthquakes or typhoons) occur. When the excitation begins, dynamic responses of the structure are measured by sensors in real time. Sensor data are immediately communicated to a controller, which makes appropriate control decisions and dispatches the optimal decisions to the actuators. The actuators then apply corresponding forces to the structure to counter-balance the external excitation, so that excessive structural vibration is effectively mitigated. Typical actuators for feedback structural control include semi-active hydraulic dampers (SHD), magnetorheological (MR) dampers, active mass dampers (AMD), etc. Semi-active control devices are currently preferred by many researchers and engineers, because of their power efficiency, inherent stability, and adaptability in real-time feedback control.

In traditional semi-active structural control systems, coaxial wires are normally used to provide communication links between sensors, controllers, and actuators. As the size of the structure increases, the cost of installing the wires grows rapidly. Furthermore, once a cabled control system is installed, reconfiguring the system would require costly rerouting of the cables. With the increasing availability of wireless communication and embedded computing technologies, there has been extensive work towards the development of wireless sensing technologies for structural monitoring applications [6, 7]. The adoption of wireless sensing technologies can remedy the high installation cost of commercial cable-based systems, which can cost up to a few thousand dollars per sensing/actuation channel [8]. A natural extension of the wireless sensing technology, as it matures, is to explore its applicability for semi-active or active control by eradicating

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lengthy cables associated with traditional control systems. Sensor data can be transmitted wirelessly to wireless control units where embedded control algorithms are executed to determine control actions for the actuators.

Another feature of traditional feedback structural control systems is their centralized communication schemes. In such a system, one central controller collects data from all the sensors in the structure. The controller then makes control decisions, and commands all the structural actuators. In a centralized control system, requirements on communication range and data transmission rate increase rapidly with the structural size and the number of sensors/actuators being deployed. These communication requirements could result in considerable economical and technical difficulties for implementation in large-scale civil structures, such as high-rise buildings with hundreds of stories. Furthermore, the centralized controller represents a point of potential bottleneck failure for the whole system. In order to resolve these inherent problems of a centralized control system, alternative decentralized control strategies have been explored [9-11]. In decentralized control systems, multiple controllers are distributed throughout the system. Requiring data only from neighboring sensors, each controller commands actuators in its vicinity. As a result, shorter communication range and lower data transmission rate are required; meanwhile, the risk of single-point bottleneck failure is eliminated by decentralization. Decentralized control has been applied to systems such as flocks of aerial vehicles, autonomous automobiles on the freeway, the power distribution grid, spacecrafts moving in formation, etc. However, its application in large-scale civil structural control is still in its infancy.

To overcome the above issues with cabled communication and centralized system architecture, this research explores a novel approach for feedback structural control. While traditional systems are typically wired and centralized, this research utilizes a decentralized wireless system. When replacing wired communication channels with wireless ones for feedback structural control, issues such as coordination of sensing and control units, communication range limit, time delay, and potential data loss need to be examined. For example, time delay due to wireless communication causes degradation of the real-time performance of a control system [12]. On the other hand, the disadvantage of decentralized control is that only sub-optimal control performance can be achieved, because each controller only has local and neighboring sensor data to make control decisions. Theoretical and experimental investigations are needed to discover whether the benefits of lower communication latency surpass the disadvantage of limited sensor data.

To achieve adequate control performance in decentralized wireless feedback control, a decentralized structural control algorithm based on the linear quadratic regulator (LQR) optimization criteria has been proposed by the authors [13]. The algorithm is specifically designed to consider feedback time delay effect when computing optimal control forces. Feasibility and performance of the decentralized wireless structural control system have been illustrated through experimental tests using a three-story laboratory structure [14] and numerical simulations using a 20-story benchmark structure [15]. To further investigate the effectiveness of decentralized wireless feedback structural control, experimental tests with a larger-scale six-story structure were recently completed in the National Center for Research on Earthquake Engineering, Taiwan. In the latest tests, the wireless sensing and control network was constructed using the recently developed wireless sensing/actuation device, named "Narada", which incorporates IEEE 802.15.4 wireless communication standard and achieves much shorter communication delay [16]. Reliability of the Narada units in real-time feedback structural control is to be validated by the experiments. This paper first reviews the wireless feedback structural control system, including the Narada wireless sensing/actuation units and the decentralized wireless structural algorithm. The six-story laboratory structure and experimental setup are then presented. Multiple centralized/decentralized control architectures operating at different sampling frequencies are described. Finally, the control performance of different architectures is compared.

2. OVERVIEW TO WIRELESS FEEDBACK STRUCTURAL CONTROL SYSTEM

The design of a wireless feedback structural control system involves integrating components such as hardware, software, and control algorithms. The hardware components consist of individual wireless sensing and control devices. The networked devices collaborate with each other to reduce overall dynamic responses of the structure. The software components are embedded in individual devices and executed by local microprocessors. Decentralized feedback control algorithms are also need to make real-time optimal control decisions based on sensor data. This section first describes the wireless sensing and control devices, and then reviews the decentralized feedback control algorithm used in this research.

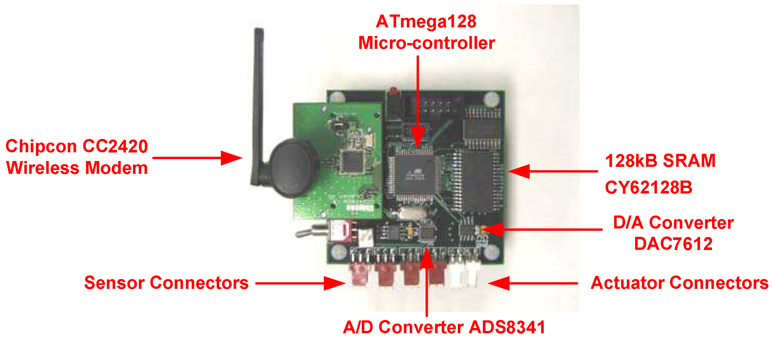


Fig. 1. Narada wireless sensing/actuation unit designed by Swartz and Lynch [16].

2.1 Narada wireless sensing/actuation device

The Narada wireless sensing/actuation prototype was recently designed by Swartz and Lynch [16] (Fig. 1). Each unit consists of four functional modules: sensor signal digitization, computational core, wireless communication, and actuation signal generation. The sensor signal digitization module, which mainly consists of the Texas Instrument 16-bit A/D converter ADS8341, converts analog sensor signals into digital data. Up to four analog sensors can be connected with each Narada unit. Sensor data is transferred to the computational core through a high-speed Serial Peripheral Interface (SPI) port. In addition to a low-power 8-bit Atmel ATmega128 microcontroller, external Static Random Access Memory (SRAM) of 128kB is integrated with the computational core to accommodate local data storage and interrogation. Application programs are embedded and executed by the microcontroller. The wireless unit communicates with other units or a computer server through the wireless modem, Chipcon CC2420. Analog signals as control commands are sent to structural actuators through the Texas Instruments D/A converter DAC7612. Up to two structural actuators can be commanded by one Narada unit.

In the previous wireless feedback control tests completed by the authors [14], WiSSCon (Wireless Structural Sensing and Control) units were used. The WiSSCon and Narada units share certain similarities, in terms of the computing power and high-precision sensor signal digitization. Compared with WiSSCon sensing/actuation units, one major advantage of the Narada units is its low latency in wireless communication. WiSSCon units support two types of wireless transceivers, i.e. the MaxStream 9XCite and 24XStream modules. Wireless transmission of a 10-byte packet takes about 20ms using the 24XStream transceiver, and about 5ms using the 9XCite wireless transceiver. With the Chipcon CC2420 wireless radio in the Narada units, the transmission of a 10-byte packet takes only about 1.5~2ms. This low-latency wireless transmission is particularly beneficial for feedback structural control applications, because low communication latency indicates higher sampling frequency and lower feedback delay.

2.2 Decentralized structural control algorithm considering time-delay effect

A linear quadratic regulator (LQR) output feedback control algorithm that considers time delay effects is summarized below. For a lumped-mass structural model with *n* degrees-of-freedom (DOF) and *m* actuators, the discrete system state-space equations considering *l* steps of feedback time delay can be stated as [17]:

$$\mathbf{z_d}[k+1] = \mathbf{A_d}\mathbf{z_d}[k] + \mathbf{B_d}\mathbf{p_d}[k-l], \text{ where } \mathbf{z_d}[k] = \begin{Bmatrix} \mathbf{x_d}[k] \\ \dot{\mathbf{x}}_\mathbf{d}[k] \end{Bmatrix} \quad (1)$$

In Eq. (1), $\mathbf{z_d}[k]$ and $\mathbf{p_d}[k-l]$ represent, respectively, the $2n \times 1$ discrete-time state-space vector at time step k and the $m \times 1$ control force vector with time delay. The matrices $\mathbf{A_d}$ and $\mathbf{B_d}$ are the $2n \times 2n$ system matrix and the $2n \times m$ actuator location matrix, respectively. The objective to minimize a cost function J:

$$J\Big|_{\mathbf{p_d}} = \sum_{k=l}^{\infty}\left(\mathbf{z_d}^T[k]\mathbf{Q}\mathbf{z_d}[k] + \mathbf{p_d}^T[k-l]\mathbf{R}\mathbf{p_d}[k-l]\right), \text{ where } \mathbf{Q}_{2n\times 2n} \geq 0 \text{ and } \mathbf{R}_{m\times m} > 0 \quad (2)$$

by selecting an optimal control force trajectory $\mathbf{p_d}$. Let the system output be denoted by a $q \times 1$ system vector $\mathbf{y_d}[k]$ measured at time k. The state-space vector $\mathbf{z_d}[k]$ and output vector $\mathbf{y_d}[k]$ can be related by a $q \times 2n$ linear transformation, $\mathbf{D_d}$, that is:

$$\mathbf{y_d}[k] = \mathbf{D_d}\mathbf{z_d}[k] \tag{3}$$

For example, if the inter-story velocities between adjacent floors are available for making control decisions and defined as the output vector, the output matrix $\mathbf{D_d}$ should have following form:

$$\mathbf{D_d} = \left[\begin{array}{c|ccccc} & 1 & 0 & 0 & \cdots & 0 \\ & -1 & 1 & 0 & \cdots & 0 \\ [\mathbf{0}_{n\times n}] & 0 & -1 & 1 & \cdots & 0 \\ & \vdots & \ddots & \ddots & \ddots & \vdots \\ & 0 & \cdots & 0 & -1 & 1 \end{array} \right]_{n\times 2n} \tag{4}$$

The optimal output feedback control force $\mathbf{p_d}$ can be computed using an $m \times q$ gain matrix $\mathbf{G_d}$ as:

$$\mathbf{p_d}[k] = \mathbf{G_d}\mathbf{y_d}[k] \tag{5}$$

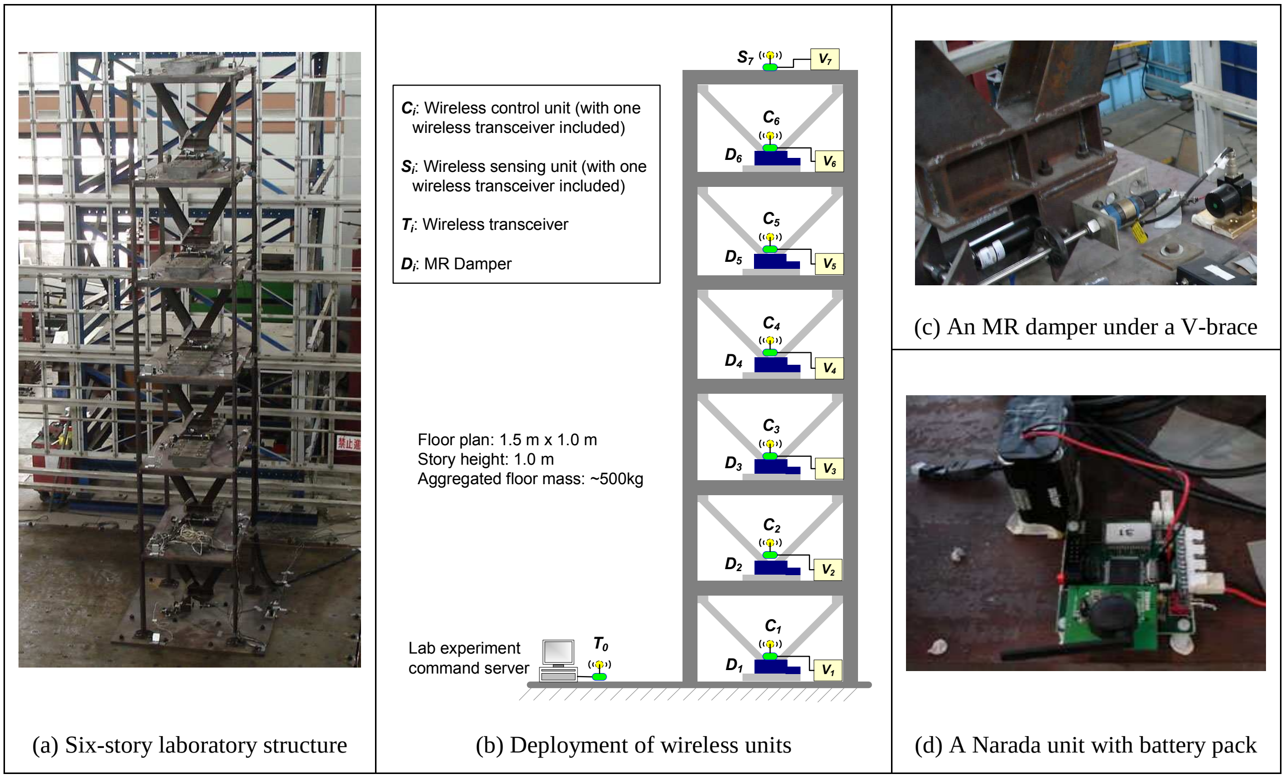
where the gain matrix $\mathbf{G_d}$ is designed so that the cost function J is minimized. Chung *et al*. [18] proposed the formulation to the above output feedback control problem considering time delay (l time steps). As a result, a set of coupled nonlinear matrix equations can be solved for an optimal output feedback gain matrix $\mathbf{G_d}$. In our implementation, an iterative algorithm introduced by Lunze [11] is modified to solve the matrix equations. The algorithm described by Lunze also provides the flexibility to handle additional external constraints. In particular, this algorithm can compute a suboptimal control solution for a decentralized system simply by constraining the structure of $\mathbf{G_d}$ to be consistent with the decentralized architecture. Readers interested in the algorithm are referred to the reference [13].

3. LABORATORY SETUP FOR DECENTRALIZED WIRELESS FEEDBACK CONTROL

To study the performance of decentralized structural control for a larger-scale structure, validation tests are conducted at the National Center for Research on Earthquake Engineering (NCREE) in Taipei, Taiwan. The laboratory setup, including the six-story test structure and the deployment of the wireless feedback control system, is described in this section.

The six-story steel frame structure is designed and constructed by researchers affiliated with NCREE (Fig. 2a). The dimensions of the structure are provided in Fig. 2b. The structure is mounted on a 5m × 5m six-DOF shake table, which can generate ground excitations with frequencies spanning from 0.1Hz to 50Hz. For this study, only longitudinal excitations are used. Along this direction, the shake table can excite the structure with a maximum acceleration of 9.8m/s^2. The excitation has a maximum stroke and force of ±0.25m and 220kN, respectively. The test structure and shake table are heavily instrumented with accelerometers, velocity meters, and linear variable displacement transducers (LVDT) to measure their dynamic response. These sensors are interfaced to a high-precision wire-based data acquisition (DAQ) system permanently installed in the NCREE facility; the DAQ system is set to a sampling rate of 200 Hz. A separate set of wireless sensors are installed as part of the wireless control system.

A RD-1005-3 magnetorheological (MR) damper manufactured by Lord Corporation is installed at each story of the structure. The damper is connected with an upper floor using a V-brace (Fig. 2c). A maximum damping force over 2kN can be provided by each damper. Its damping properties can be changed through an input current source. This input current determines the electric current of the electromagnetic coil in the MR damper, which in turn, generates a variable magnetic field that sets the viscous damping properties of the MR damper. The damper can respond to magnetic field changes within 15ms. Calibration tests are first conducted on the MR dampers before mounting them to the structure, so that a modified Bouc-Wen force-displacement model can be formulated for the damper. The model is similar to a



(a) Six-story laboratory structure (b) Deployment of wireless units (c) An MR damper under a V-brace (d) A Narada unit with battery pack

Fig. 2. Experimental setup for wireless feedback control of a six-story structure.

previous Bouc-Wen damper model developed for a 20kN MR damper [19]. In the real-time feedback control tests, hysteresis model parameters for the MR dampers are an integral element in the calculation of damper input signal. The 0~0.8V analog command signal generated by the wireless unit is fed into a specially designed signal converter module, which converts the voltage signal into a current source for the MR damper.

Basic configuration of the prototype wireless sensing and control system is schematically shown in Fig. 2b. A total of seven Narada wireless units are installed in accordance with the deployment strategy. Each wireless unit is interfaced to a Tokyo Sokushin VSE15-D velocity meter that measures the absolute velocity response of each floor as well as at the base (i.e. shake table velocity). The sensitivity of the velocity meter is 10V/(m/s) with a measurement limit of ±1 m/s. Six wireless units (C1 through C6 in Fig. 2b) are also responsible for commanding the MR dampers. In addition to the wireless sensing and control units, a remote data and command server with a wireless transceiver is included as an optional element responsible for logging the flow of wireless data. During an experimental test, the command server first notifies the wireless sensing and control units to initiate automated operations. Once the start command is received, the wireless units that are responsible for collecting sensor data start acquiring and broadcasting data at a specified time interval. Accordingly, the wireless units responsible for commanding the actuators receive the sensor data, calculate desired control forces in real-time, and apply control commands at the specified time interval.

4. EXPERIMENTAL RESULTS

In this section, the experimental and simulated structural responses are first compared to validate the accuracy of the structural model and the damper model. The different system architectures for the wireless feedback control experiments, including centralized and decentralized, are described. Finally, the experimental results for different system architectures are compared.

4.1 Validation of the structure and damper models

A six degrees-of-freedom (DOF) lumped-mass model, including the structural stiffness, damping, and mass matrices, is constructed for the laboratory structure. Simulated and experimental seismic responses of the structure are compared

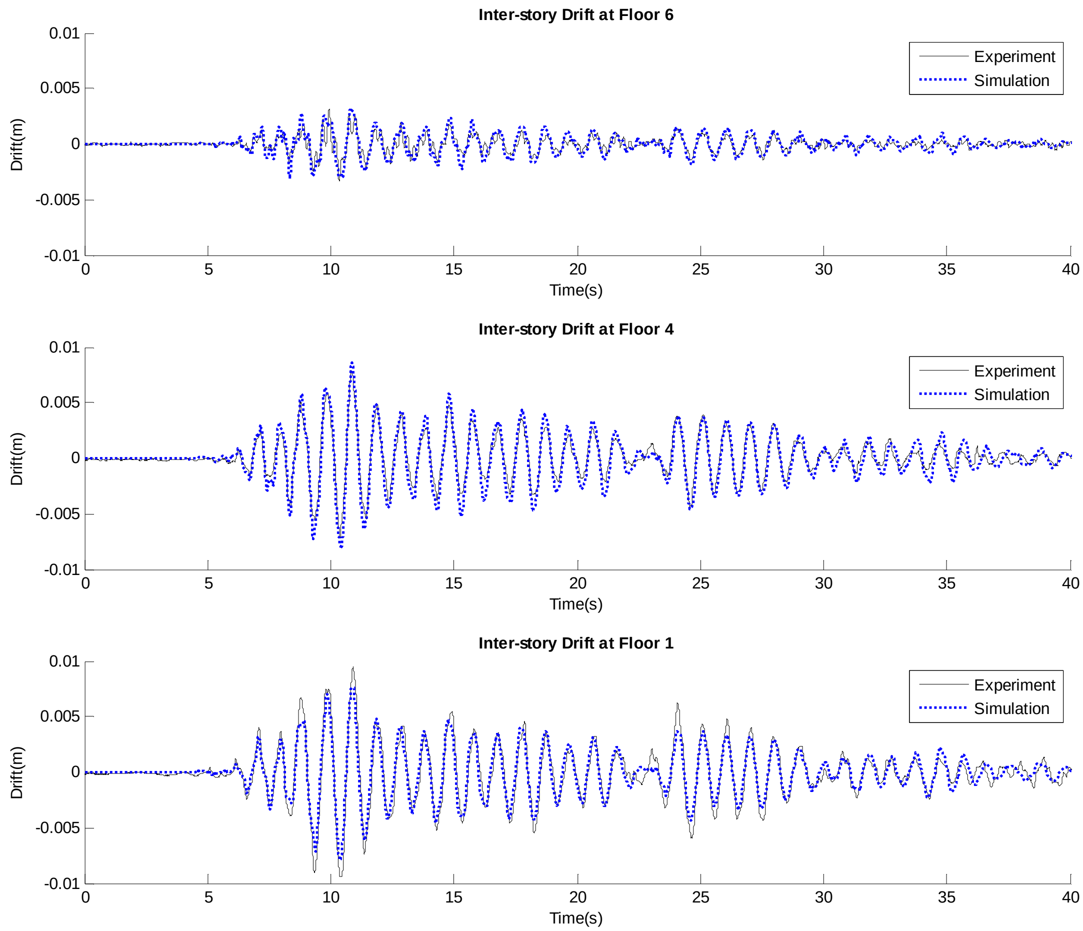


Fig. 3. Experimental and simulated inter-story drifts for a Chi-Chi (TCU-076 Station) earthquake excitation with the peak acceleration scaled to 1m/s^2; command voltages to all six dampers are fixed at 0V.

without the dampers mounted on the structure. Close match between the simulated and experimental responses is observed. In addition, simulated and experimental force-displacement relationships are compared for single MR dampers, so that the damper simulation model is validated. Six dampers are then mounted on the six-story structure. Passive control tests are first conducted, where the command voltages to the dampers are set at a fixed level. Results for the case with the command voltages fixed at 0V are presented in Fig. 3. The solid curves in the figure show the experimental inter-story drifts at the first, fourth, and sixth stories during one test run. The ground excitation is the 1999 Chi-Chi NS record at TCU-076 Station with its peak ground acceleration scaled to 1m/s^2. Also plotted are the simulated inter-story drifts at these three stories with the damper voltages fixed at 0V. The experimental and simulated drifts are close to each other, which indicates that the simulation models for the structure and the damper are reasonably accurate.

4.2 Multiple feedback system architectures for the wireless control experiments

In the feedback control experiments, the velocity meters provide real-time measurement to the absolute velocities on all the floors. Absolute velocities at neighboring floors are then be used to compute inter-story velocities. Therefore, while computing the control gain matrices $\mathbf{G_d}$, the output matrix $\mathbf{D_d}$ has the form shown in Eq. (4). Centralized and decentralized inter-story velocity feedback control schemes are used for the wireless control experiments (Fig. 4). The degrees of centralization (DC) reflect different communication network architectures, with each channel representing one communication subnet. The actuators covered within a subnet are allowed to access the wireless sensor data within that subnet. For example, case DC1 implies each wireless channel covers only three stories and a total of two wireless channels (subnets) are utilized. Constrained by this decentralized information structure, the gain matrix for case DC1 has the following sparsity pattern:

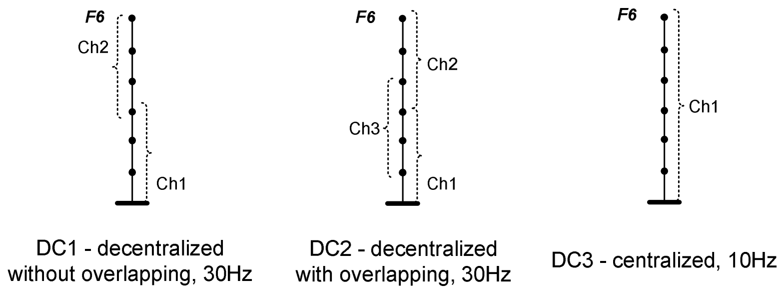


Fig. 4. Information group partitioning for different degrees of centralization (DC).

$$\mathbf{G_d} = \begin{bmatrix} \mathbf{G}^{(I,I)} & \\ & \mathbf{G}^{(II,II)} \end{bmatrix}_{6\times 6}, \text{ when DC} = 1 \tag{6}$$

The matrix $\mathbf{G_d}$ is block-diagonal, with every block $\mathbf{G}^{(i,j)}$ being a 3-by-3 square matrix.

For case DC2, each wireless channel still covers only three stories, but an additional channel, Ch3, is used to cover the second story through the fourth story. As a result, information overlapping is present between wireless subnets Ch1 and Ch3 as well as between Ch2 and Ch3. For example, when the wireless unit controlling the damper at the second story makes control decisions, the unit has sensor data from both subnet Ch1 and Ch3, i.e. the inter-story velocities from the first story through the fourth story. Meanwhile, the wireless control unit at the first story only has data from within subnet Ch1. Constrained by this overlapping information structure, the gain matrix for case DC2 has the following sparsity pattern:

$$\mathbf{G_d} = \begin{bmatrix} * & * & * & & & \\ * & * & * & * & & \\ * & * & * & * & & \\ & * & * & * & * & * \\ & & & * & * & * \\ & & & * & * & * \end{bmatrix}_{6\times 6}, \text{ when DC} = 2 \tag{7}$$

Case DC3 specifies that one wireless channel covers all six stories, which results in a centralized information structure. The decentralized control gain matrices are computed using the previously described control algorithm, and then embedded into the Narada wireless sensing/control units prior to the experiments.

The control sampling frequency for each configuration is determined by the wireless communication latency and the time required for microcontroller computing. The computing procedures include calculating desired control force for a MR damper, updating the damper hysteresis model, and choosing the appropriate command signal to send to the damper. For the Narada units with Chipcon CC2420 radio, each wireless transmission takes about 1.5ms to 2ms. For the seven units to transmit all their associated sensor data sequentially, a maximum of 14ms is needed. Combining the communication and computing delay, for a centralized architecture such as DC3 in Fig. 4, the highest sampling frequency that can be achieved is 30Hz. This means each control sampling period is 33.3ms, and one step of time delay is used in the discrete feedback control formulation, i.e. $l = 1$ in Eq. (1).

As the first group of experiments with the six-story structure, wireless communication using multiple subnets has not been implemented yet. The single channel communication of the CC2420 radio is used to emulate the effects of multiple-channel communication. At every sampling time step, each wireless unit receives data from all other units; when making control decisions, unnecessary sensor data (i.e. data corresponding to zero entries in the gain matrices) are discarded to emulate the effects of decentralized control architectures with partial sensor data. In cases DC1 and DC2, each subnet has the same number of wireless units and requires the same number of wireless transmissions at every sampling time step. Therefore, same sampling frequency of 30Hz is adopted for these two cases. To emulate the effect that the centralized case DC3 should have longer time delay than the two decentralized cases, a sampling frequency of 10Hz is adopted for case DC3.

4.3 Comparison of control performance using different system architectures

Fig. 5 illustrates the structure's peak inter-story drifts for different system architectures, as well as an uncontrolled case where the dampers are disconnected from the structure. Compared with the uncontrolled case, all three wireless control schemes achieve significant reduction with respect to maximum inter-story drifts. Among the three controlled cases, case DC2 (partially decentralized at 30Hz) achieve slightly better performance than other two cases. Comparing with case DC1 (fully decentralized at 30Hz), it is as expected that case DC2 achieves better performance because more sensor

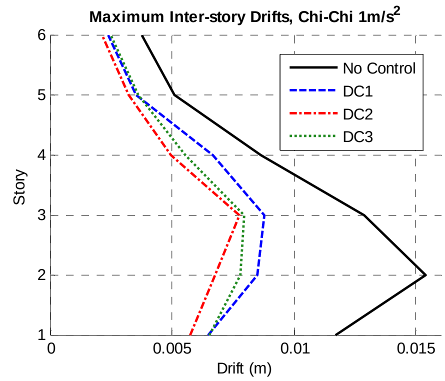


Fig. 5. Experimental peak inter-story drift results of different system architectures for the Chi-Chi excitation scaled to a peak acceleration of 1m/s^2 (different degrees of decentralization as illustrated in Fig. 4).

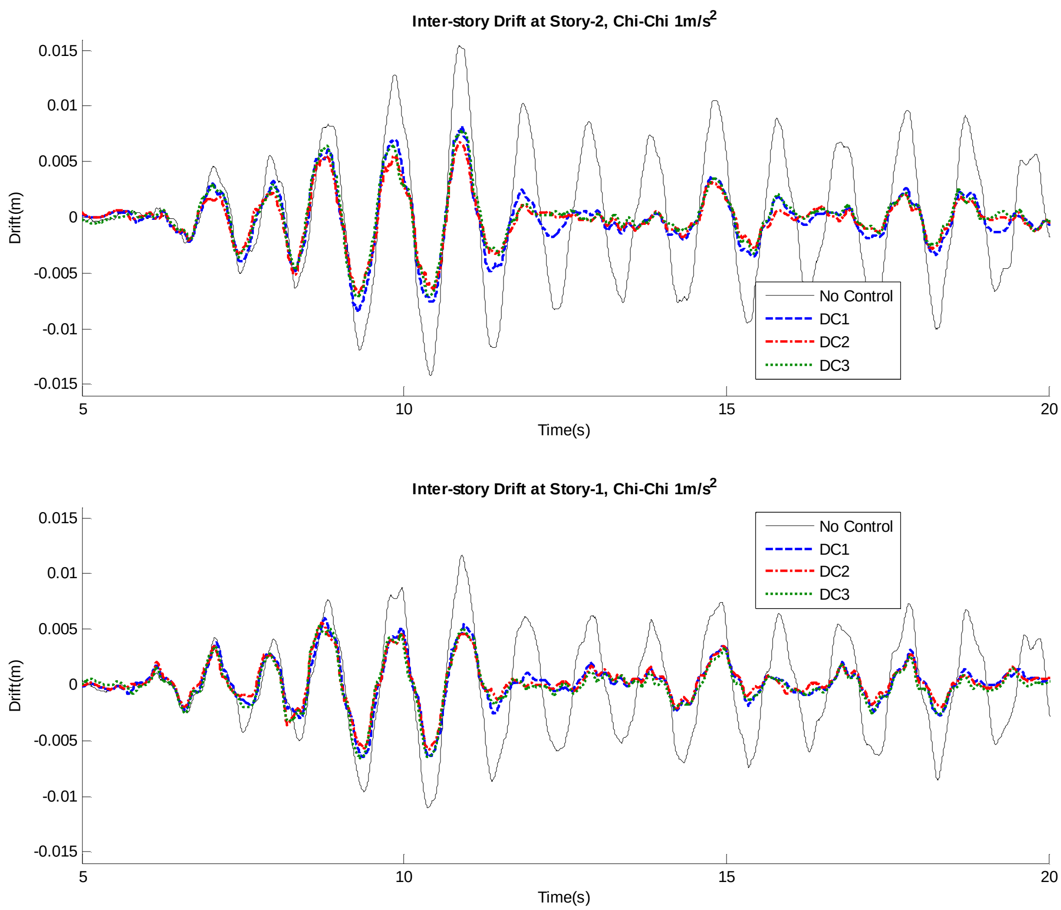


Fig. 6. Experimental inter-story drift histories from different system architectures for the Chi-Chi excitation scaled to a peak acceleration of 1m/s^2 (different degrees of decentralization as illustrated in Fig. 4).

data information is available. The fact that case DC2 is slightly better than case DC3 (centralized at 10Hz) illustrates that in the decentralized wireless control cases, the higher sampling rate (due to lower communication latency) can potentially compensate the loss of data from ignoring the sensor data at faraway stories. Fig. 6 plots part of the time history of the inter-story drifts at the bottom two stories. It shows that peak responses happen between the 9th second and the 11th second. Case DC2 illustrates smallest inter-story drifts at all peaks.

5. SUMMARY AND CONCLUSION

This paper describes latest large-scale laboratory experiments that are designed to evaluate the performance of decentralized wireless structural control on a six-story structure. Commanded by wireless sensors and controllers, semi-active magnetorheological (MR) dampers are installed between neighboring floors to apply real-time feedback control forces. Multiple centralized/decentralized control architectures have been investigated in the experiments, in combination with different sampling frequencies. Results of the first group of experiments described in this paper shows that decentralized control strategies may provide equivalent or even superior control performance, given that their centralized counterparts could suffer longer feedback time delay due to wireless communication latencies.

Future research will continue to investigate both the theory and implementation of wireless decentralized structural control. In addition to LQR, other decentralized control algorithms that may achieve better control performance are worth exploring. Initial progress has been made in developing decentralized $\mathcal{H}_\infty$ control algorithms, where decentralized controllers are designed to minimize the $\mathcal{H}_\infty$ norm of the closed-loop system transfer matrix [20]. With regard to implementation, wireless feedback control systems truly utilizing multiple channel communication will be developed and tested in laboratory experiments. System performance can also be greatly improved by employing more powerful embedded computing devices.

6. ACKNOWLEDGEMENT

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