DECENTRALIZED CIVIL STRUCTURAL CONTROL USING A REAL-TIME WIRELESS SENSING AND CONTROL SYSTEM

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Abstract

Over the last few decades, structural control technologies have attracted great interest from the earthquake engineering community as a means of reducing dynamic structural responses. Traditional structural control systems employ large quantities of cables to connect structural sensors, controllers, and actuators into one system. To reduce the high-cost and labor-intensive installations, wireless communication technology can serve as an alternative to provide real-time data links among the nodes in a control system. A prototype wireless structural sensing and control system has been physically implemented and its performance verified in large-scale shake table tests. Our previous study shows that as multiple data links share a common communication channel, communication latency appears to be an important issue with respect to the wireless control system's performance. This paper investigates the feasibility of employing decentralized and partially decentralized control strategies to eradicate communication latency problems associated with wireless sensor networks. Control algorithms are embedded in a wireless sensor prototype designed for use in a structural control system. To validate the integration of decentralized control algorithms with wireless sensors, a 3-story half-scale steel structure is used with a magnetorheological (MR) damper installed on each floor.

Introduction

Structural control is currently considered by many structural engineers as an effective means of mitigating dynamic structural responses (Soong and Spencer, 2002). After decades of development, structural control technologies have matured and can be categorized into three major types: (a) passive control (e.g. base isolation), (b) active control (e.g. active mass dampers), and (c) semi-active control (e.g. semi-active variable dampers). Among these three types of control technologies, semi-active control has the advantage of achieving considerable control performance while consuming relatively low power. In a semi-active control system, sensors are deployed in the structure to collect real-time structural response data during a dynamic excitation. Response data is then fed into control decision modules (controllers) in order to determine and apply control commands to system actuators. Commanded by control signals, the actuators can generate control forces intended to reduce unwanted structural responses. Examples of semi-active actuators include active variable stiffness (AVS) devices, semi-active hydraulic dampers (SHD), electrorheological (ER) dampers, and magnetorheological (MR) dampers. Semi-active control systems are inherently stable because they do not apply mechanical energy directly to the structure. Furthermore, because of their power efficiencies, semi-active actuators can easily be implemented without depending on a structure's native electric system, which can fail during strong earthquakes.

In order to acquire real-time sensor data for control decisions, cables are traditionally used to connect sensors with a controller. For a typical low-rise building, the installation of a commercial wire-based data acquisition (DAQ) system can cost upwards of a few thousand dollars per sensing channel (Celebi, 2002). As the size of the control system grows (increase in the number of sensors or actuators and their distribution in a structure), or the actuator density rises, additional cabling may result in significant increases in installation time and expense. Thus, wireless communication has been widely explored for use in structural monitoring applications (Straser and Kiremidjian, 1998; Lynch and Loh, 2004; Wang et al., 2006a); however, application to real-time feedback control systems has been scarce. In a previous paper (Wang et al., 2006b), the authors proposed a prototype wireless structural sensing and control system. The system consists of multiple stand-alone wireless sensors and controllers that form an integrated wireless network through a common-use wireless communication channel. In the proposed prototype system, sensor data is wirelessly propagated within the wireless control system, and processed by wireless sensors designated as controllers. Appropriate control commands are then applied to semi-active actuators by the wireless controllers.

As the size of the control system grows large, one major difficulty encountered by both wireless and wired structural control systems is the degradation of the system's real-time characteristics. In particular, when a common channel is used for the communication of data between sensors, actuators, and controllers, as is the case in a networked control system, communication latencies can seriously degrade the performance of the system. Communication latencies have been widely explored in the network control field with many solutions proposed (Lian et al., 2002; Ploplys et al., 2004). One such remedy is to consider fully and partially decentralized control system architectures. In a decentralized control system, the sensing and control network is divided into multiple subsystems. Controllers are assigned to each subsystem and require only subsystem sensor data for control decisions. Shorter communication ranges and reduced use of the communication channel required by decentralized control architectures benefit both wireless and wire-based network control systems.

Compared with centralized control, decentralized control architectures only offer sub-optimal control performance because each subsystem has incomplete sensor data available to make control decisions. In contrast, centralized control provides an optimal control solution. However, the overhead needed to communicate data in a centralized system results in a reduction in the system's sampling rate. So while decentralized control solutions might be sub-optimal, their reduced communication latencies allow them to operate at higher sampling rates thereby enhancing their control effectiveness. This study attempts to investigate the tradeoff between the completeness of sensor data offered by centralization and the low communication latencies offered by decentralization. Centralized and decentralized output feedback control algorithms are first introduced. In order to compare the performance of different decentralized and centralized control schemes, an extensive set of large-scale shake table tests are conducted, using a baseline wired control system and the prototype wireless structural sensing and control system. The test structure is a 3-story steel building in which an MR damper is installed on each floor. The wireless control system is shown to be as reliable and as effective as the wired baseline system.

Centralized and Decentralized Linear Output Feedback Control Design

An optimal feedback control design normally requires adequate real-time structural response data to compute optimal control forces. For example, if a multi-story building is modeled by a lumped-mass structural system with actuators deployed among adjacent floors, real-time floor displacements and velocities that constitute the state-space vector are needed for a typical linear quadratic regulator (LQR) controller (Franklin et al., 2003). However, due to instrumentation complexity and cost, not all structural response data may be available in practice. To address this difficulty, output feedback control methods can be used to provide a sub-optimal control strategy under the constraint that only part of the state-space variables are measured in real-time. This section first presents the basic formulation of an optimal centralized output feedback control solution, and then proposes a modified algorithm that allows the output feedback gain matrix to be constrained. The output feedback gain matrix is then formulated for various decentralized control architectures using the constrained gain matrix algorithm detailed herein.

Formulation for Centralized Linear Output Feedback Control

The output feedback digital-domain LQR control solution can be briefly summarized as follows. For a lumped-mass structural model with n degrees-of-freedom (DOF) and m actuators, the system state-space equations considering l time steps of delay can be stated as:

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

where $\mathbf{z_d}[k]$ represents the $2n \times 1$ discrete-time state-space vector, $\mathbf{p_d}[k-l]$ is the delayed $m \times 1$ control force vector, $\mathbf{A_d}$ is the $2n \times 2n$ system matrix (containing the information about structural mass, stiffness and damping), and $\mathbf{B_d}$ is the $2n \times m$ actuator location matrix. The primary objective of the time-delay LQR problem is to minimize a cost function J by selecting an optimal control force trajectory $\mathbf{p_d}$:

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

In an output feedback control design, when control decisions are computed, only data in the system output vector $\mathbf{y_d}[k]$ are available. The output vector is defined by a $q \times 2n$ linear transformation, $\mathbf{D_d}$, to the state-space vector $\mathbf{z_d}[k]$:

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

For example, if the relative velocities on all floors are measurable and no relative displacement is measurable, $\mathbf{D_d}$ can be defined as:

$$\mathbf{D_{d\_cen}} = \begin{bmatrix} \mathbf{0}_{n\times n} & \mathbf{I}_{n\times n} \end{bmatrix} \tag{4}$$

The $m \times q$ optimal gain matrix $\mathbf{G_d}$ is required to provide a linear output feedback control law:

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

Chung et al. (1995) proposed a solution to the above output feedback control problem considering the time delay (l time steps). An augmented system in the first-order difference equations is introduced:

$$\bar{\mathbf{z}}_\mathbf{d}[k+1] = \bar{\mathbf{A}}_\mathbf{d}\bar{\mathbf{z}}_\mathbf{d}[k] + \bar{\mathbf{B}}_\mathbf{d}\bar{\mathbf{p}}_\mathbf{d}[k] \tag{6}$$

This system is equivalent to the original system (Eq. 1) by proper definitions of the augmented matrices and vectors (denoted with over bars). As a result, the following nonlinearly coupled matrix equations are solved for an optimal output feedback gain matrix $\mathbf{G_d}$, the Lagrangian matrix, $\mathbf{L}$, and the Hamiltonian matrix, $\mathbf{H}$:

$$\left(\bar{\mathbf{A}}_\mathbf{d} + \bar{\mathbf{B}}_\mathbf{d}\mathbf{G_d}\bar{\mathbf{D}}_\mathbf{d}\right)^T \mathbf{H}\left(\bar{\mathbf{A}}_\mathbf{d} + \bar{\mathbf{B}}_\mathbf{d}\mathbf{G_d}\bar{\mathbf{D}}_\mathbf{d}\right) - \mathbf{H} + \left(\bar{\mathbf{Q}} + \bar{\mathbf{D}}_\mathbf{d}^T\mathbf{G_d}^T\mathbf{R}\mathbf{G_d}\bar{\mathbf{D}}_\mathbf{d}\right) = \mathbf{0} \tag{7a}$$

$$\left(\bar{\mathbf{A}}_\mathbf{d} + \bar{\mathbf{B}}_\mathbf{d}\mathbf{G_d}\bar{\mathbf{D}}_\mathbf{d}\right)\mathbf{L}\left(\bar{\mathbf{A}}_\mathbf{d} + \bar{\mathbf{B}}_\mathbf{d}\mathbf{G_d}\bar{\mathbf{D}}_\mathbf{d}\right)^T - \mathbf{L} + \bar{\mathbf{Z}}_{\mathbf{d}l} = \mathbf{0} \tag{7b}$$

$$2\bar{\mathbf{B}}_\mathbf{d}^T\mathbf{H}\left(\bar{\mathbf{A}}_\mathbf{d} + \bar{\mathbf{B}}_\mathbf{d}\mathbf{G_d}\bar{\mathbf{D}}_\mathbf{d}\right)\mathbf{L}\bar{\mathbf{D}}_\mathbf{d}^T + 2\mathbf{R}\mathbf{G_d}\bar{\mathbf{D}}_\mathbf{d}\mathbf{L}\bar{\mathbf{D}}_\mathbf{d}^T = \mathbf{0} \tag{7c}$$

Derivation details are referred to Chung et al. (1995).

Heuristic Solution for Centralized and Decentralized Output Feedback Gain Matrices

An iterative algorithm to solve the continuous-time feedback control problem has been presented by Lunze (1990). The algorithm (Fig. 1) starts from an initial guess for the gain matrix $\mathbf{G_d}$. Within each

```
G_d1 = [0]_{m×q} ;
s = 1;
for i = 1,2,…
    Solve equation (7a) for H_i ;
    Solve equation (7b) for L_i ;
    Find gradient using equation (7c): Δ_i = −(2B̄_d^T H(Ā_d + B̄_d G_d D̄_d) L D̄_d^T + 2 R G_d D̄_d L D̄_d^T) ;
    iterate {
        G_d(i+1) = G_di + s·Δ_i ;
        Solve equation (7a) again for H_(i+1)' using G_d(i+1) ;
        if trace(H_(i+1)' Z̄_dl) < trace(H_i Z̄_dl) and max(|eigen(Ā_d + B̄_d G_d(i+1) D̄_d)|) < 1
            exit the iterate loop;
        else
            s = s / 2;
            If (s < machine precision), then exit the iterate loop;
        end
    };
    s = s × 2;
    If ‖G_d(i+1) − G_di‖ < acceptable error, then exit the for loop;
end
```

Figure. 1. Heuristic algorithm solving the coupled nonlinear matrix equations (Eq. 7) for centralized optimal time-delay output feedback control (Lunze, 1990).

iteration step i, the Hamiltonian matrix $\mathbf{H}_i$ and the Lagrangian matrix $\mathbf{L}_i$ are solved respectively using the current guess $\mathbf{G}_{\mathbf{d}i}$. Based on computed $\mathbf{H}_i$ and $\mathbf{L}_i$, a searching gradient $\boldsymbol{\Delta}_i$ is calculated, and the new gain matrix $\mathbf{G}_{\mathbf{d}i+1}$ is computed by traversing along a gradient from $\mathbf{G}_{\mathbf{d}i}$. An adaptive multiplier, s, is used to dynamically control the search step size. At each iteration step, two conditions are used to decide whether $\mathbf{G}_{\mathbf{d}i+1}$ is an acceptable guess. The first condition is $trace(\mathbf{H}_{i+1}'\bar{\mathbf{Z}}_{\mathbf{d}l}) < trace(\mathbf{H}_i\bar{\mathbf{Z}}_{\mathbf{d}l})$, which guarantees that $\mathbf{G}_{\mathbf{d}i+1}$ is a better solution than $\mathbf{G}_{\mathbf{d}i}$. The second condition is that the maximum magnitude of all the eigenvalues of the matrix $\bar{\mathbf{A}}_\mathbf{d} + \bar{\mathbf{B}}_\mathbf{d}\mathbf{G}_{\mathbf{d}i+1}\bar{\mathbf{D}}_\mathbf{d}$ is less than 1, which ensures the stability of the augmented system.

The iterative algorithm put forth by Lunze (1990) has an attractive feature, i.e. the algorithm can also formulate an optimal control solution for a decentralized system simply by constraining the structure of $\mathbf{G}_\mathbf{d}$ to be consistent with the decentralized architecture. The following equation illustrates two decentralized output feedback gain matrices for a simple 3-story lumped-mass structure.

$$\mathbf{G}_{\mathbf{d\_dec1}} = \begin{bmatrix} * & 0 & 0 \\ 0 & * & 0 \\ 0 & 0 & * \end{bmatrix}, \mathbf{G}_{\mathbf{d\_dec2}} = \begin{bmatrix} * & * & 0 \\ 0 & * & * \\ 0 & * & * \end{bmatrix} \tag{8}$$

The pattern in $\mathbf{G}_{\mathbf{d\_dec1}}$ specifies that when computing control decisions, the actuator on each floor only needs the entry in the output vector $\mathbf{y}_\mathbf{d}$ that corresponds to that floor. The pattern in $\mathbf{G}_{\mathbf{d\_dec2}}$ specifies the control decisions also require information from a neighboring floor. In order to find a decentralized gain matrix that satisfies certain shape constraint, the algorithm described in Fig. 1 is modified by zeroing out the corresponding entries in the gradient matrix $\boldsymbol{\Delta}_i$. The next estimate $\mathbf{G}_{\mathbf{d}i+1}$ is computed by traversing along the constrained gradient. Using the above decentralized gain matrices and the following output matrix $\mathbf{D}_\mathbf{d}$, inter-story velocities between adjacent floors can be used for decentralized control decisions:

$$\mathbf{D}_{\mathbf{d\_dec}} = \begin{bmatrix} 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & -1 & 1 & 0 \\ 0 & 0 & 0 & 0 & -1 & 1 \end{bmatrix} \tag{9}$$

Validation Tests using a Real-time Wireless Sensing and Control System

In order to examine the tradeoff between the amount of sensor data available to a controller and the communication latency using various decentralized control schemes, validation tests are conducted at the National Center for Research on Earthquake Engineering (NCREE) in Taipei, Taiwan. Both a baseline wired control system and a prototype wireless structural sensing and control system are used to implement the real-time feedback control of a 3-story steel frame instrumented with three MR dampers.

Design of the Wireless Structural Sensing and Control System

The feasibility of the proposed wireless structural sensing and control system has been previously validated in a simpler set of control tests (Wang et al., 2006b). Wireless sensing and control units are the building blocks of the real-time wireless feedback control system. The major responsibilities assumed by the wireless sensing and control units include: (a) collect real-time structural sensor data; (b) wirelessly transmit or receive the sensor data within a wireless communication network; (c) process data and compute control decisions; and (d) apply control signals to semi-active actuators. The hardware design of the wireless sensing and control unit (Fig. 2) is based upon a wireless sensing unit previously proposed for use in wireless structural monitoring systems (Wang et al, 2006a). The three original functional modules included in the wireless sensing unit design are the sensor signal digitizer, the computational core, and the wireless transceiver. To extend the functionality of the wireless sensor for actuation, an off-board control signal generation module is designed and fabricated. The control signal generation module consists of a single-channel 16-bit digital-to-analog converter and support electronics. The module can output an analog voltage from -5V to 5V at rates as high as 100kHz.

A challenge associated with employing wireless sensors for use in a structural control system is the performance of the wireless communication channel. Because of local frequency band requirements in Taiwan, the MaxStream 24XStream wireless transceiver (MaxStream, 2005) operating at 2.4GHz spectrum is employed for the wireless sensing unit. The 450m indoor communication range of the 24XStream wireless transceiver is sufficient for installation in most small and medium-sized civil structures. The peer-to-peer communication capability of the wireless transceiver makes it possible for the wireless sensing and control units to communicate with each other, thus supporting flexible information flow among multiple wireless units. As previously discussed, one critical issue in applying wireless communication technology into real-time feedback structural control is the communication latency while transmitting sensor data from the wireless sensing units to the wireless control units. Previous analysis and experimental validation show that each peer-to-peer wireless transmission takes

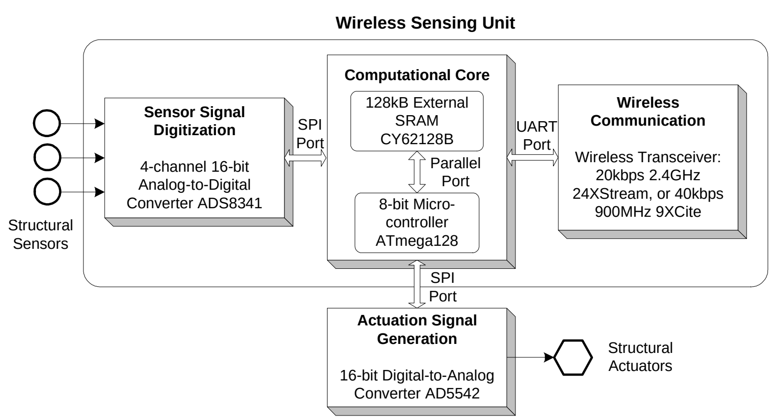

Figure. 2. Functional diagram detailing the hardware design of the wireless sensing unit interfaced to the actuation signal generation module.

roughly 20ms using the 24XStream transceivers.

Validation Test Setup and Results

Experimental tests were conducted at the National Center for Research on Earthquake Engineer (NCREE) in Taipei, Taiwan. A three-story steel frame structure is designed and constructed by researchers affiliated with NCREE (Fig. 3). The floor plan of this structure is 3m × 2m, with each floor weight adjusted to 6,000 kg using concrete blocks; inter-story heights are 3m. The three-story structure is mounted to a 5m × 5m 6-DOF shake table. For this study, only longitudinal excitation is used in the tests. The test structure is heavily instrumented with various types of sensors. For example, accelerometers, velocity meters, and linear variable displacement transducers (LVDT) are installed on each floor of the structure. These sensors are interfaced to a high-precision wire-based data acquisition (DAQ) system native to the NCREE facility; this wired DAQ system is set to a sampling rate of 200 Hz.

For this experimental study, three 20 kN MR dampers are installed in a V-brace upon each story of the steel structure (Fig. 3). The damping coefficients of the MR dampers can be changed by issuing a command voltage between 0V to 1.2V. This command voltage determines the electric current of the electromagnetic coil in the MR damper, which in turn, generates a magnetic field that sets the viscous damping properties of the MR damper. Calibration tests are first conducted on the MR dampers before mounting them to the structure so that modified Bouc-Wen damper models can be formulated (Lin, 2005). In the real-time feedback control tests, hysteresis model parameters for the MR dampers are an integral element in the calculation of damper actuation voltages.

Two control systems are installed in the test structure: the wireless control system and a traditional wire-based control system. For the wireless system, a total of four wireless sensors are installed (Fig. 3). Each wireless sensor is interfaced to a velocity meter to measure the absolute velocity response for each floor of the structure as well as the base. The three wireless sensors on the first three levels of the structure (C_0, C_1, and C_2) are also responsible for commanding the MR dampers. As described by Lynch et al. (2006), Bouc-Wen hysteresis models and LQR gain matrices are embedded in these wireless control units to

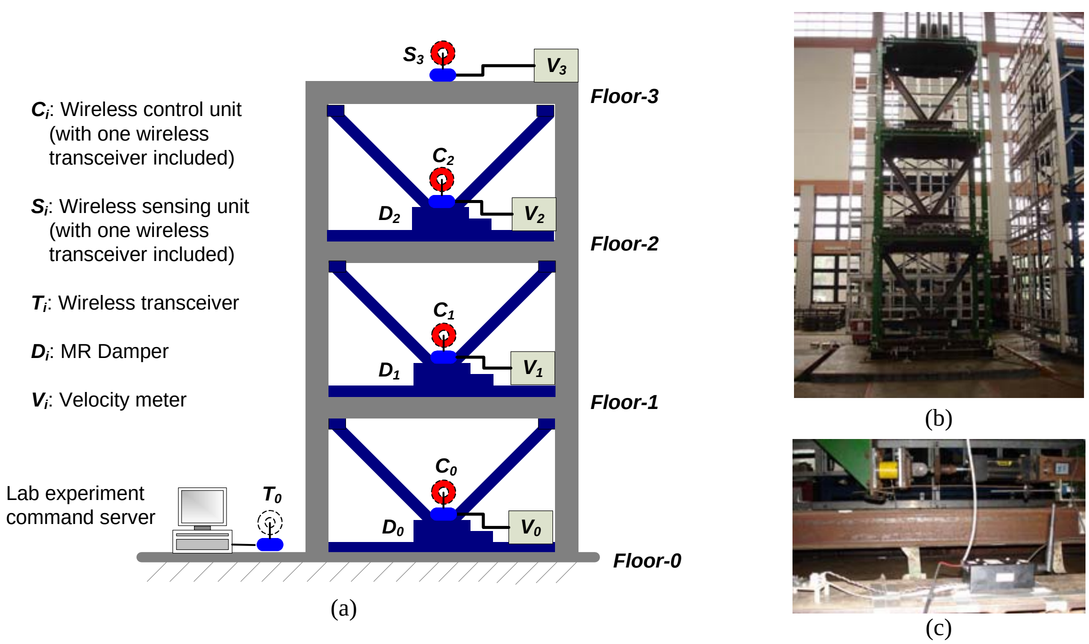

Figure. 3. Laboratory setup: (a) sensor, MR damper, and wireless unit deployment; (b) the three-story test structure; (c) a wireless control unit commanding an MR damper.

determine MR damper command signals using real-time structural response data.

Centralized and decentralized velocity feedback control algorithms presented before are used for both the wired and the wireless control systems. Tokyo Sokushin VSE15-D velocity meters are selected for measuring velocities on each floor of the structure. The sensitivity of this velocity meter is 10V/(m/s) with a measurement limit of ±1 m/s. An LQR weighting matrix **Q** designed to minimize inter-story drifts over time, and a diagonal weighting matrix **R** are used for all the wireless and wired control tests that are presented herein. As shown in Table 1, different decentralization patterns and sampling steps are tested using the two control systems. For the test structure, the wire-based system can achieve a short sampling step of 5ms. Mostly decided by the communication latency of the 24XStream wireless transceivers, the wireless system can achieve a sampling step of 80ms for the centralized control scheme. This is due to each wireless sensor waiting in turn to communicate its data to the network (20ms for each transmission). An advantage of the decentralized architecture is that fewer communication steps are needed, thereby reducing the time for communication.

The El Centro NS (1940) earthquake record is scaled to a peak acceleration of 1m/s^2 for the experimental results shown in Fig. 4. Fig. 4 illustrates the peak inter-story drifts and floor accelerations for the original uncontrolled structure and the structure controlled by four different wireless and wired control schemes. Compared with the uncontrolled structure, all wireless and wired control schemes illustrate obvious reduction in peak drifts and accelerations. Among the four control cases, the wired scheme shows superior performance by achieving the least peak drifts and second least overall peak accelerations. This is as expected, because the wired system has advantages in terms of both low communication latency and sensor data completeness. The wireless system, although running at longer sampling steps, achieves

	Wireless System			Wired System
Decentralization	#1 Decentralized	#2 Partially Decentr.	#3 Centralized	Centralized
Gain Constraint	$\mathbf{G}_{\mathbf{d\_dec1}}$ in Eq. (8)	$\mathbf{G}_{\mathbf{d\_dec2}}$ in Eq. (8)	N/A	N/A
Output Matrix	$\mathbf{D}_{\mathbf{d\_dec}}$ in Eq. (9)	$\mathbf{D}_{\mathbf{d\_dec}}$ in Eq. (9)	$\mathbf{D}_{\mathbf{d\_cen}}$ in Eq. (4)	$\mathbf{D}_{\mathbf{d\_cen}}$ in Eq. (4)
Sampling Step/Rate	20 ms / 50 Hz	60 ms / 16.67 Hz	80 ms / 12.5 Hz	5 ms / 200 Hz

Table 1. Different decentralization patterns and sampling steps for the wireless and wire-based control systems used in the validation experiments.

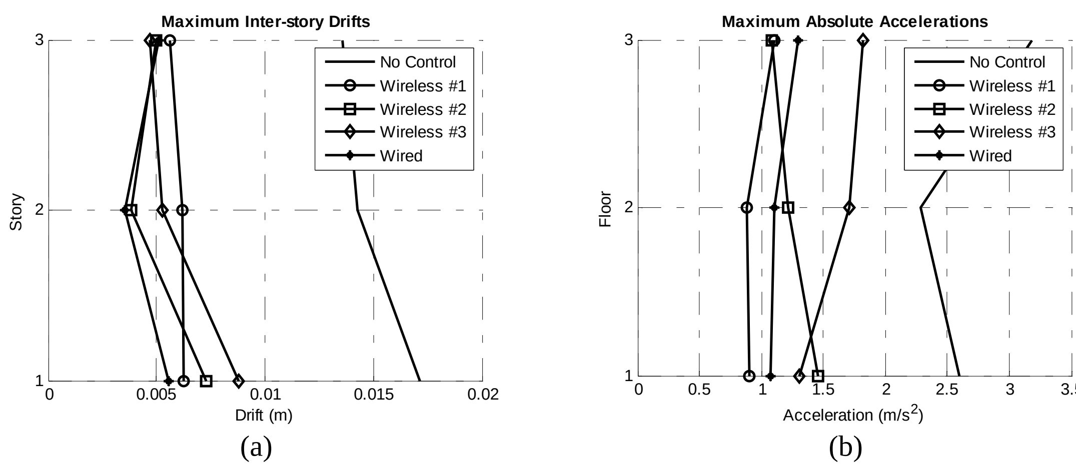

Figure. 4. Experimental results of different control schemes using the El Centro excitation scaled to a peak acceleration of 1m/s^2: (a) peak inter-story drifts; (b) peak accelerations.

control performance comparable to the wired system. The wireless case #1, a fully decentralized control scheme, results in uniformed peak inter-story drifts and the least peak floor accelerations. This shows that in the decentralized wireless control cases, the disadvantage of incomplete sensor data is compensated by the benefit derived from lower communication latency (and hence higher sampling rate).

Conclusions

This paper investigates the feasibility and effectiveness of decentralized control strategies in civil structures. We first present a heuristic computational algorithm for an optimal output feedback structural control design using both centralized and decentralized communication patterns. Experimental tests are conducted to examine the tradeoff between sensor data completeness offered by centralization and low communication latencies offered by decentralization. The results show that decentralized wireless control strategies may provide equivalent or even superior control performance, given that their centralized counterparts suffer longer sampling steps due to communication latencies. The experiments also successfully validate the reliability of the prototype wireless structural sensing and control system.

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