DECENTRALIZED WIRELESS STRUCTURAL SENSING AND CONTROL USING GENETIC ALGORITHM OPTIMIZATION

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Abstract: This study explores decentralized structural control using wireless sensors and controllers. In a decentralized control scheme, control decisions are based upon data acquired from sensors located in the vicinity of a control device. Specifically, this paper studies a time-delayed decentralized structural control strategy that aims to minimize the $\mathcal{H}_2$ norm of a closed-loop control system. For decentralized control design, one challenge is the non-convexity of the optimization problem caused by a decentralized architecture. A combined homotopic approach with a stochastic genetic search algorithm is explored in this research for designing decentralized structural controllers with minimal closed-loop $\mathcal{H}_2$ norm. Multiple decentralized control architectures are implemented with a network of wireless sensing and control devices. The wireless sensing and control system is installed on a six-story laboratory steel structure controlled by magnetorheological (MR) dampers. The sensor network supports simultaneous communications with multiple wireless subnets. Shake table experiments are conducted to demonstrate the performance of the wireless decentralized $\mathcal{H}_2$ controllers optimized using the homotopic approach with genetic algorithm.

Keywords: Structural control, decentralized control, genetic algorithm, wireless sensing.

1 INTRODUCTION

Utilizing a network of sensors, controllers and control devices, feedback control systems can potentially mitigate excessive dynamic responses of a structure subjected to strong dynamic loads, such as earthquakes or typhoons (Housner, *et al*. 1997). As control devices are becoming smaller, more cost effective and reliable, opportunities are now available to instrument a structure with large number of control devices (Spencer and Nagarajaiah 2003). With densely installed sensing and control devices, scalability of control systems will be hindered by their dependence on centralized control strategies, where a central controller is responsible for acquiring data and making control decisions. To mitigate some of the difficulties with centralized feedback control systems, decentralized control strategies can be explored (Sandell, *et al*. 1978). In a decentralized control system, distributed controllers are designed to make control decisions using only the data from neighboring sensors, and to command control devices in the vicinity area.

Among early research in decentralized structural control, Lynch and Law (2004) proposed market-based structural control strategies that model a structural control system as a competitive market. Following the rules of a free market, distributed sellers and buyers reach the optimal allocation of limited control energy. Wang *et al*. (2007) presented a decentralized static output feedback control strategy that is based upon the linear quadratic regulator (LQR) criteria. Sparsity shape constraints upon the control gain matrices are employed to represent decentralized feedback patterns; iterative gradient searching is adopted for computing sparse gain matrices that optimize the control performance over the entire structure. Lu, *et al.* (2008) studied the performance of fully decentralized sliding mode control algorithms; the algorithms require only the stroke velocity and displacement of a control device to make the control decision. For structural systems that are instrumented with collocated rate sensors and actuators, Hiramoto and Grigoriadis (2008) explored decentralized static feedback controller design in continuous-time domain.

This paper presents a time-delayed decentralized structural control strategy that aims to minimize the $\mathcal{H}_2$ norm of the closed-loop system. Centralized $\mathcal{H}_2$ controller design has been studied by many researchers, through both laboratory experiments and numerical simulations (Johnson, *et al.* 1998; Yang, *et al.* 2003). Their studies have shown the effectiveness of centralized $\mathcal{H}_2$ control for civil structures. In contrast, this research focuses the time-delayed decentralized $\mathcal{H}_2$ controller design. Following the previous development on time-delayed decentralized $\mathcal{H}_\infty$ controller design (Wang 2010), homotopic transformation is adopted to design decentralized $\mathcal{H}_2$ controllers. In addition, genetic algorithm is adopted to further improve the controller optimality.

This paper first presents the formulation for decentralized $\mathcal{H}_2$ controller design. Due to the non-convexity of the decentralized optimal control problem, existing algorithms do not guarantee global optimality. To further improve the optimality of the decentralized controllers computed through the homotopy approach, genetic algorithm, a heuristic and stochastic search method (Goldberg 1989), is investigated. To validate the performance of the decentralized control strategies, shake table experiments are conducted using a 6-story laboratory structure instrumented with a wireless sensing and control system and associated magnetorheological (MR) dampers. Experimental setup and test results are reported.

2 BASIC FORMULATION

For a structural model with n degrees-of-freedom (DOF) and instrumented with n_u control devices, the structural system and a system describing time-delay and sensor noise effect can be cascaded into an open-loop system in discrete-time domain (Wang 2010):

$$\begin{cases} \mathbf{x}[k+1] = \mathbf{A}\mathbf{x}[k] + \mathbf{B}_1\mathbf{w}[k] + \mathbf{B}_2\mathbf{u}[k] \\ \mathbf{z}[k] = \mathbf{C}_1\mathbf{x}[k] + \mathbf{D}_{11}\mathbf{w}[k] + \mathbf{D}_{12}\mathbf{u}[k] \\ \mathbf{y}[k] = \mathbf{C}_2\mathbf{x}[k] + \mathbf{D}_{21}\mathbf{w}[k] + \mathbf{D}_{22}\mathbf{u}[k] \end{cases} \quad (1)$$

The system input $\mathbf{w} = [\mathbf{w}_1^{\mathrm{T}} \ \mathbf{w}_2^{\mathrm{T}}]^{\mathrm{T}} \in \mathbb{R}^{n_w \times 1}$ contains both external excitation $\mathbf{w}_1$ and sensor noise $\mathbf{w}_2$; $\mathbf{u} \in \mathbb{R}^{n_u \times 1}$ denotes the control force vector; the open-loop state vector, $\mathbf{x} \in \mathbb{R}^{n_{OL} \times 1}$, contains $\mathbf{x}_S \in \mathbb{R}^{2n \times 1}$, the state vector of the structural system, and $\mathbf{x}_{TD} \in \mathbb{R}^{n_{TD} \times 1}$, the state vector of the time-delay and sensor noise system. For a lumped mass structural model with n stories, the state vector of the structural dynamics, $\mathbf{x}_S$, consists of the relative displacement q_i and relative velocity $\dot{q}_i$ (with respect to the ground) for each floor i, $i = 1, \ldots n$.

$$\mathbf{x}_S = [q_1 \quad \dot{q}_1 \quad q_2 \quad \dot{q}_2 \ \ldots \ q_n \quad \dot{q}_n]^{\mathrm{T}} \quad (2)$$

The matrices $\mathbf{A} \in \mathbb{R}^{n_{OL} \times n_{OL}}$, $\mathbf{B}_1 \in \mathbb{R}^{n_{OL} \times n_w}$, and $\mathbf{B}_2 \in \mathbb{R}^{n_{OL} \times n_u}$ are, respectively, the discrete-time dynamics, excitation influence, and control influence matrices. The vector $\mathbf{z} \in \mathbb{R}^{n_z \times 1}$ represents the response output (to be controlled through the feedback loop), and $\mathbf{y} \in \mathbb{R}^{n_y \times 1}$ represents the time-delayed and noisy sensor measurement vector. Correspondingly, the matrices $\mathbf{C}_1$, $\mathbf{D}_{11}$, and $\mathbf{D}_{12}$ are termed the output parameter matrices, and the matrices $\mathbf{C}_2$, $\mathbf{D}_{21}$, and $\mathbf{D}_{22}$ are the measurement parameter matrices. Time delay of one sampling period ΔT is assumed for the sensor measurement signal (e.g. due to computational and/or communication latency). The formulation of the time-delay system can easily be extended to model multiple time delay steps, as well as different time delays for different sensors. Furthermore, the formulation can also represent fully decentralized control architecture, as well as information overlapping in a partially decentralized control architecture. Detailed description about the formulation can be found in Wang (2010).

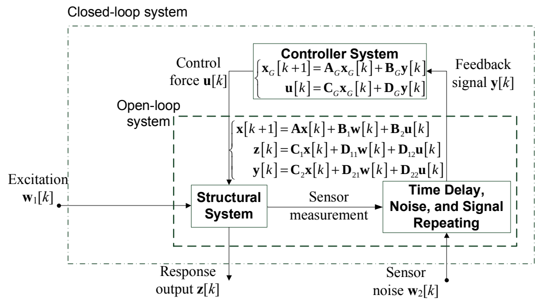


Figure 1. Diagram of the closed-loop control system.

Figure 1 summarizes the components of the control system. As shown in the figure, the open-loop system formulated in Eq. (1) contains the structural system and the system describing time delay, noise, and possible signal repeating. Output of the structural system, i.e. sensor measurement, is an input to the time-delay system. For the overall open-loop system, the inputs include the excitation $\mathbf{w}_1[k]$, the sensor noises $\mathbf{w}_2[k]$, and the control forces $\mathbf{u}[k]$; outputs of the open-loop system include the structural response $\mathbf{z}[k]$ and the feedback signals $\mathbf{y}[k]$. To complete the feedback control loop, the controller system takes the signal $\mathbf{y}[k]$ as input and generates the desired (optimal) control force vector $\mathbf{u}[k]$ according to the following state-space equations:

$$\begin{cases} \mathbf{x}_G[k+1] = \mathbf{A}_G\mathbf{x}_G[k] + \mathbf{B}_G\mathbf{y}[k] \\ \mathbf{u}[k] = \mathbf{C}_G\mathbf{x}_G[k] + \mathbf{D}_G\mathbf{y}[k] \end{cases} \tag{3}$$

where $\mathbf{A}_G$, $\mathbf{B}_G$, $\mathbf{C}_G$ and $\mathbf{D}_G$ are the parametric matrices of the controller to be computed and, for convenience, are often collectively denoted by a controller matrix $\mathbf{G} \in \mathbb{R}^{(n_G+n_u)\times(n_G+n_y)}$ as:

$$\mathbf{G} = \begin{bmatrix} \mathbf{A}_G & \mathbf{B}_G \\ \mathbf{C}_G & \mathbf{D}_G \end{bmatrix} \tag{4}$$

In this study, we assume the controller and the open-loop system have the same number of state variables, i.e. $\mathbf{A}_G \in \mathbb{R}^{n_G \times n_G}$ and $n_G = n_{OL}$.

3 DECENTRALIZED CONTROL DESIGN

For decentralized control design, the feedback signals $\mathbf{y}[k]$ and the control forces $\mathbf{u}[k]$ are divided into N groups. For determining each group of control force, only one group of corresponding feedback signals is needed. To achieve this decentralized feedback pattern, the controller matrices can be specified to be block diagonal:

$$\mathbf{A}_G = diag\left(\mathbf{A}_{G_I}, \mathbf{A}_{G_{II}}, \cdots, \mathbf{A}_{G_N}\right) \tag{5a}$$

$$\mathbf{B}_G = diag\left(\mathbf{B}_{G_I}, \mathbf{B}_{G_{II}}, \cdots, \mathbf{B}_{G_N}\right) \tag{5b}$$

$$\mathbf{C}_G = diag\left(\mathbf{C}_{G_I}, \mathbf{C}_{G_{II}}, \cdots, \mathbf{C}_{G_N}\right) \tag{5c}$$

$$\mathbf{D}_G = diag\left(\mathbf{D}_{G_I}, \mathbf{D}_{G_{II}}, \cdots, \mathbf{D}_{G_N}\right) \tag{5d}$$

The control system in Eq. (3) is thus equivalent to a set of uncoupled decentralized controllers $\mathbf{G}_i$ ($i = I, II, \ldots, N$):

$$\mathbf{G}_i = \begin{bmatrix} \mathbf{A}_{G_i} & \mathbf{B}_{G_i} \\ \mathbf{C}_{G_i} & \mathbf{D}_{G_i} \end{bmatrix} \tag{6}$$

Each controller $\mathbf{G}_i$ requires only one group of feedback signals to determine the desired (optimal) control forces for one group of control devices:

$$\begin{cases} \mathbf{x}_{G_i}[k+1] = \mathbf{A}_{G_i}\mathbf{x}_{G_i}[k] + \mathbf{B}_{G_i}\mathbf{y}_i[k] \\ \mathbf{u}_i[k] = \mathbf{C}_{G_i}\mathbf{x}_{G_i}[k] + \mathbf{D}_{G_i}\mathbf{y}_i[k] \end{cases} \tag{7}$$

The closed-loop system is then formulated by concatenating the open-loop system in Eq. (1) with the controller system in Eq. (3):

$$\begin{cases} \mathbf{x}_{CL}[k+1] = \mathbf{A}_{CL}\mathbf{x}_{CL}[k] + \mathbf{B}_{CL}\mathbf{w}[k] \\ \mathbf{z}[k] = \mathbf{C}_{CL}\mathbf{x}_{CL}[k] + \mathbf{D}_{CL}\mathbf{w}[k] \end{cases} \tag{8}$$

Note that the input to the closed-loop system is $\mathbf{w}[k]$, which contains the external excitation $\mathbf{w}_1[k]$ and sensor noises $\mathbf{w}_2[k]$, while the output is same as the structural output $\mathbf{z}[k]$ defined in Eq. (1). Using Z-transform (Franklin, *et al.* 1998), the dynamics of a discrete-time system can be represented by the transfer function $\mathbf{H}_{\mathbf{zw}}(z) \in \mathbb{C}^{n_z \times n_w}$ from disturbance $\mathbf{w}$ to output $\mathbf{z}$ as:

$$\mathbf{H}_{\mathbf{zw}}(z) = \mathbf{C}_{CL}\left(z\mathbf{I} - \mathbf{A}_{CL}\right)^{-1}\mathbf{B}_{CL} + \mathbf{D}_{CL} \tag{9}$$

The objective of $\mathcal{H}_2$ control design is to minimize the $\mathcal{H}_2$-norm of the closed-loop discrete-time system, which in the frequency domain is defined as:

$$\|\mathbf{H}_{\mathbf{zw}}\|_2 = \sqrt{\frac{\Delta T}{2\pi}\int_{-\omega_N}^{+\omega_N} \text{Trace}\left\{\mathbf{H}_{\mathbf{zw}}^*\left(e^{j\omega\Delta T}\right)\mathbf{H}_{\mathbf{zw}}\left(e^{j\omega\Delta T}\right)\right\} d\omega} \quad (10)$$

where ω represents angular frequency, $\omega_N = \pi/\Delta T$ is the Nyquist frequency, j is the imaginary unit, $\mathbf{H}_{\mathbf{zw}}^*$ is the complex conjugate transpose of $\mathbf{H}_{\mathbf{zw}}$, and $\text{Trace}\{\bullet\}$ denotes the trace of a square matrix.

Using the heuristic homotopy method detailed by Wang, *et al.* (2010), decentralized $\mathcal{H}_2$ controllers can be designed for various feedback architectures. For further improvement, these decentralized controllers are used as the initial population for additional optimization through genetic algorithm. Genetic algorithm (GA) is inspired by natural selection, recombination, and mutation mechanisms in Darwin's theory of evolution (Goldberg 1989). The algorithm starts with adopting a series of possible solutions to a problem as the initial population. Individual members of this initial population are ranked according to how well they satisfy a given objective or fitness function. After all individuals of a previous population of possible solutions are assessed, members of the previous population are selected based on their ranking, and re-synthesized to form the next generation of possible solutions. The re-synthesis process includes interchanging parts of two individuals to create two new possible solutions (also called cross-over) and/or randomly changing parts of one possible solution (called mutation). The process iterates until certain stopping criteria are reached.

For a proper controller implementation, the decentralized controllers should be stable and hence the spectral radius of $\mathbf{A}_G$ should be less than one. In addition, the closed-loop system should be stable, i.e. the spectral radius of $\mathbf{A}_{CL}$ should also be less than one. Considering the multiple objectives, including minimizing the closed-loop $\mathcal{H}_2$ norm, a weighted-sum fitness function is adopted for the genetic algorithm optimization:

$$\underset{\mathbf{G}_i, i=I,II,\ldots,N}{\text{minimize}} \|\mathbf{H}_{\mathbf{zw}}\|_2 + a\cdot\rho\left(\mathbf{A}_G\right) + b\cdot\rho\left(\mathbf{A}_{CL}\right) \quad (11)$$

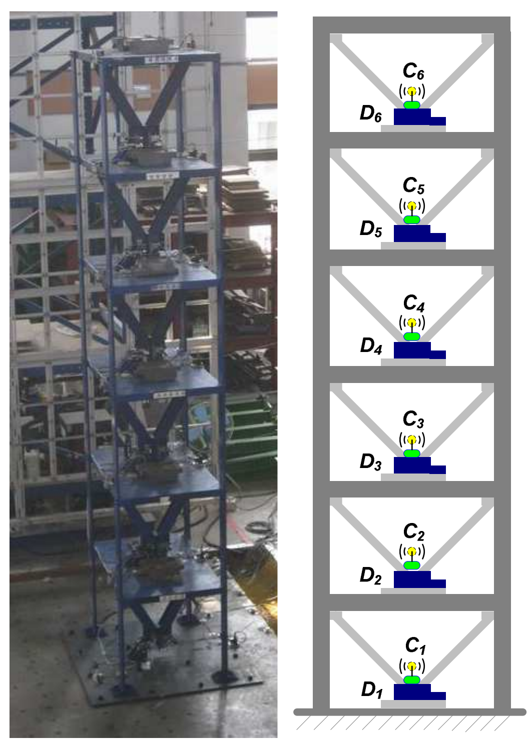
where $\rho(\bullet)$ represents the spectral radius of a matrix, and *a* and *b* are adjustable weights for the two spectral radii.

4 STRUCTURAL CONTROL EXPERIMENTS

This section describes the shake table experiments conducted to evaluate the performance of the decentralized $\mathcal{H}_2$ structural control strategies.

4.1 Experiment setup

Shake table experiments were conducted on a six-story laboratory structure recently designed, built, and improved at the National Center for Research on Earthquake Engineering (NCREE) in Taipei, Taiwan (Loh and Lin 2010). The structure is mounted on a 5m × 5m 6-DOF shake table (see Figure 2a). For wireless sensing and control, the prototype Narada wireless units (Swartz, *et al.* 2005) developed at the University of Michigan is employed. The basic



(a) (b)

Figure 2. Six-story structure for control experiments: (a) picture of the structure on the shake table; (b) schematic of the setup, C_i – wireless sensing/control unit connected with a position sensor measuring inter-story drift; D_i – magnetorheological (MR) damper.

configuration of the wireless sensing and control system for the 6-story structure is schematically shown in Figure 2(b). A total of six Narada wireless units are installed in accordance with the deployment strategy. During the experiments, each Narada wireless unit collects inter-story drift data at its own floor from a magnetostrictive position sensor (MTS Temposonics® C-Series) that is installed between the bottom of a stiff V-brace and the lower floor.

In addition to collecting and transmitting the inter-story drift data, each wireless unit sends command signal to a magnetorheological (MR) damper (RD-1005-3 model manufactured by Lord Corporation) on the same floor. The damper is connected between two floors through the V-brace (Figure 2). Each damper can provide a maximum damping force over 2kN. The damping properties can be changed by the command voltage signal (ranging from 0 to 0.8V) from the wireless unit. Through an input current source, the command signal determines the electric current of the electromagnetic coil in the MR damper, which in turn sets the viscous damping properties.

4.2 Experimental results

Four decentralized/centralized feedback control architectures are adopted in the control experiments (Figure 3). The degrees of centralization (DC) of different architectures reflect the different communication network configurations, with each wireless channel representing one communication subnet. The wireless units assigned to a subnet are allowed to access the wireless sensor data within that subnet. As an example, for case DC3, each wireless channel covers four stories and a total of two wireless channels (subnets) are in operation. Since all wireless units in one subnet share their inter-story drift data, case DC3 represents a decentralized architecture with information overlapping. For case DC1, each wireless unit only utilizes the inter-story drift between two neighboring floors for control decisions; therefore, no wireless transmission is required. For case DC4, one wireless channel (subnet) is shared by all six wireless units, which is equivalent to a centralized feedback pattern. Due to different requirement on communication and computation, each decentralized architecture can have different length of sampling time step ΔT, which is shown in Figure 3.

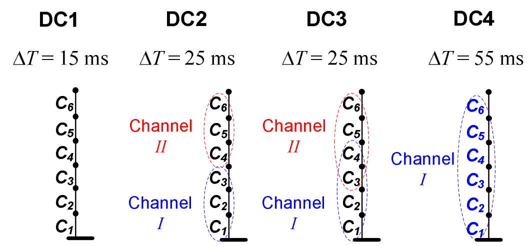


Figure 3. Decentralized feedback control architectures.

The 1940 El Centro NS (Imperial Valley Irrigation District Station) earthquake excitation with the peak ground acceleration (PGA) scaled to 1m/s^2 is employed in this study. Figure 4 shows the peak inter-story drifts for different control architectures during the ground excitation, as well as the peak drifts of the uncontrolled structure (with dampers disconnected) and a passive-on control case (where the damper command voltages are all fixed to the maximum value 0.8V). Among all the passive and feedback control cases, the feedback control case DC3 achieves the most uniform peak inter-story drifts among the six stories. In addition, the three decentralized feedback control cases generally outperform the centralized case DC4 and the passive-on case, in terms of achieving uniformly less peak drifts.

5 CONCLUSIONS

This paper presents some preliminary results exploring homotopic transformation and genetic algorithm for decentralized structural control using wireless sensing feedback. The shake-table experiment results demonstrate that the decentralized $\mathcal{H}_2$ structural control approaches show better control performance than centralized or passive control cases.

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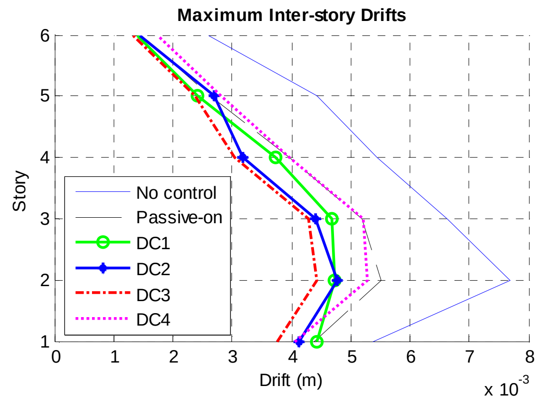

Figure 4. Experimental results on peak inter-story drifts.

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