

Decentralized Control Strategies with Wireless Sensing and Actuation

Kincho H. Law

Department of Civil & Environmental Engineering
Stanford University
Stanford, CA 94305, U.S.A.

Andrew Swartz and Jerome P. Lynch

Department of Civil & Environmental Engineering
University of Michigan
Ann Arbor, MI 49109, U.S.A.

Yang Wang

School of Civil & Environmental Engineering
Georgia Institute of Technology
Atlanta, GA 30332, U.S.A.

Abstract: Advances in wireless communication and embedded computing technologies can have significant impacts in structural sensing, monitoring and control. Prior research efforts have demonstrated the benefits of low-cost wireless sensing systems for structural monitoring. This paper discusses the possibilities of extending the functionalities of wireless sensors for structural control applications. By incorporating a computational core module and an actuation signal generation module, wireless sensors can be extended to compute and issue appropriate control commands for structural actuation and real-time control applications. This paper discusses laboratory tests to assess the viability of utilizing wireless sensing and actuation for decentralized structural control. A six-story scaled structure installed with semi-active magnetorheological (MR) dampers is employed in the experiment. Wireless sensors and controllers are employed to compute and apply feedback control forces in real time. Different centralized and decentralized feedback control architectures are investigated. Furthermore decentralized control strategies and information processing issues related to wireless sensing and control are discussed.

1. Introduction: Advances in sensor, wireless communication, MEMS and information technologies have had significant impacts in structural monitoring. Many significant innovations have been made in the development of wireless sensors and sensor networks for structural health monitoring applications [7].

Wireless sensing technologies can also be extended to perform self-sensing and actuation [6]. Through the actuation interface, actuators can be attached to wireless sensors to provide excitations or control of a structure [11]. Specifically, wireless sensors can be designed to perform three major tasks in a control system: collection of structural response data, calculation of desired control forces, and issuing of commands to actuators. Integrating wireless sensors with actuation capabilities represents a transformative leap towards an integrated structural monitoring and control system.

As opposed to traditional structural monitoring, where sensors are often used in a passive manner to measure structural responses, the demands of a control system to respond in real-time impose additional technical challenges for the wireless sensor technology, including communication range limitations and delay between wireless sensors as well as possible data loss. This paper discusses a preliminary investigation that is designed to study decentralized control strategies, communication schemes, and information processing architectures as well as to assess the feasibility of deploying wireless sensing technology for structural control applications. The performance of different decentralized structural control architectures and information processing strategies using wireless sensors are demonstrated with laboratory experimental tests on a scaled six-story structure.

2. Information Structures and Decentralized Control Strategies: The information available to the structural controllers in a control system defines the strategy that must be used for decentralized control. For centralized control where decision making is made with the availability of all system information, the controller is assumed to have complete knowledge of the system plant (*a priori* information) and a complete set of state data (*a posteriori* information). For decentralized control, where decisions are made at the local controller or at a subsystem level, local controllers only have access to a portion of the global information. Depending on the amount and type of information available to each controller, different decentralized control schemes result. Fig. 1 shows three types of information structures, namely total, partial and hierarchical, for decentralized control [10].

Fig. 1(a) illustrates a totally decentralized information structure where each controller has access only to the local *a posteriori* information of the subsystem that the controller is responsible for. Knowledge of how the control actions of the local controller may affect the global system response is not available. Most current implementation of decentralized control for civil structures belongs to this information structure [1,3]. The interactions between dynamically coupled subsystems are treated as unknown disturbances and each individual controller is designed as a single-input, single-output (SISO) subsystem. Each individual subsystem focuses on its own control performance

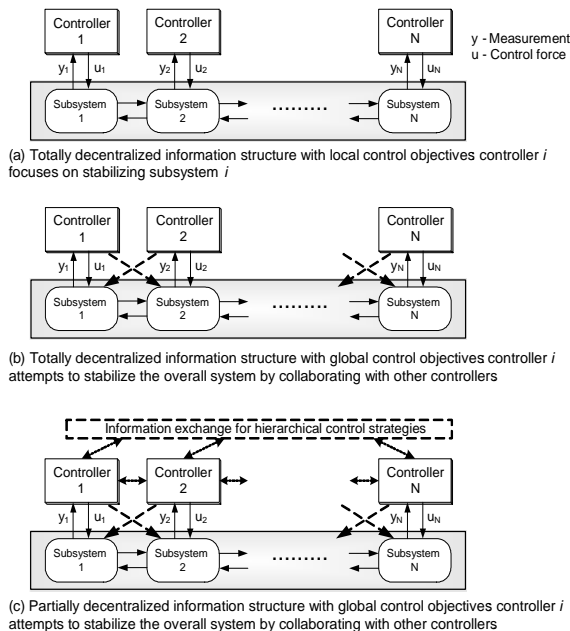


Fig. 1. Decentralized information structures and control objectives.

without dynamic coordination with other subsystems (irrespective of their operational status) for achieving a global optimal solution.

As illustrated in Fig. 1(b), if a controller is provided with information from other subsystems or controllers, the result is a partially decentralized control solution where a local controller has partial knowledge of how its decision may affect the global system. For a hierarchical decentralized control strategy, as shown in Fig. 1(c), additional global (measured and/or estimated) information is being made available to the controllers to improve the overall system performance. Such partially decentralized control schemes can be implemented by sharing measured and/or estimated global or subsystem state information [13]. For example, distributed Kalman filters can be designed for each decentralized subsystem and estimate global structural state using partial sensor data. With the global state information available, the controller is designed to optimize the overall system performance. A decentralized control strategy using distributed Kalman filters can be implemented according to the system architecture shown in Fig. 1(b), assuming that there are no communications between the distributed Kalman estimators. Alternatively, the decentralized scheme can be implemented according to the system architecture shown in Fig. 1(c) where communications between subsystems are allowed. Information sharing among the subsystems however, could lead to additional demand for communication resulting in time delays in a shared-use communication channel. For the architectures shown in Fig. 1(b) and Fig. 1(c) (or a combination of both), different controllers for the subsystems collaborate with each other according to the available (measured or estimated) information and attempt to achieve a control strategy that is globally optimal. In short, decentralized control strategies are defined by the availability of data, the information structure and communication topologies. This preliminary work investigates the different wireless communication and information processing schemes and assesses the benefits and drawbacks of different decentralized control strategies.

3. Laboratory and Experimental Setup: To study the performance of decentralized control strategies and the potential deployment of wireless communication technology for structural control, experimental tests are conducted at the National Center for Research on Earthquake Engineering (NCEE) in Taipei, Taiwan.

3.1 Experimental Test Structure Setup: A six-story steel frame structure, which is mounted on a $5\text{m} \times 5\text{m}$ six degrees of freedom shake table as shown in Fig. 2(a), is designed and constructed by researchers



(a) Six-Story Laboratory Structure



(b) An MR Damper under a V-brace

Fig. 2. Six-Story Test Structure

affiliated with the National Center for Research on Earthquake Engineering (NCEE). The six-DOF shake table 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 $\pm 0.25\text{m}$ and 220kN , respectively. The test structure and shake table are 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 NCEE facility; the DAQ system is set to a sampling rate of 200 Hz.

On the test structure, each story is instrumented with a RD-1005-3 magnetorheological (MR) damper

manufactured by Lord Corporation. As shown in Fig. 2(b), the damper is connected with an upper floor using a V-brace. The damper is capable of applying a maximum damping force over 2kN . 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 [4]. The hysteresis model parameters for the MR dampers are used in the calculation of damper input signals.

3.2 Wireless Sensing/Actuation Device: The experiments employ the Narada wireless sensing/actuation units developed by Swartz and Lynch at the University of Michigan [8]. As shown in Fig. 3, each Narada unit consists of four functional modules: sensor signal digitization, computational core, wireless communication, and actuation signal generation. The sensor signal digitization module, which 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, which consists of a low-power 8-bit Atmel ATmega128 microcontroller, through a high-speed Serial Peripheral Interface (SPI) port. An external 128kB Static Random Access Memory (SRAM) is integrated with the computational core for additional 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 transceiver, Chipcon CC2420, which takes only about $1.5\sim 2\text{ms}$ to transmit a 10-byte packet. Low-latency wireless transmission is needed for feedback structural control applications, because low communication latency indicates higher sampling frequency and lower feedback delay. 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.

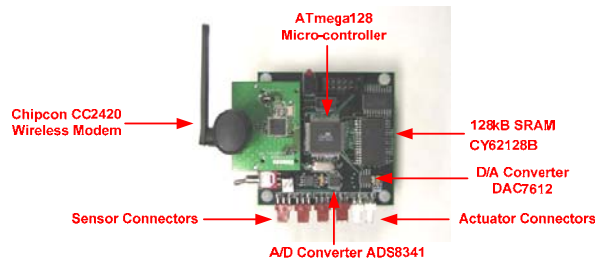


Figure 3: Narada Sensing and Control Unit

3.3 Instrumentation of Wireless Sensing and Control System: The basic configuration of the prototype wireless sensing and control system instrumented on the test structure is schematically shown in Fig. 4(a). A total of seven Narada wireless units are installed. Each wireless unit is operated with a battery pack as shown in Fig. 4(b). The 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. 4(a)) 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. For the wireless control tests, 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 (0 to 1A) for the MR damper.

3.4 Validation of Structural and Damper Models: In order to properly develop control solutions, the experimental and simulated structural responses are first compared to validate the accuracy of the structural model and the damper model. 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 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. 5. The solid curves in the figure show the experimental inter-story drifts at the first, second, fourth, and sixth stories during one test run. The ground excitation is the 1999 Chi-Chi NS record at TCU-076 Station with its

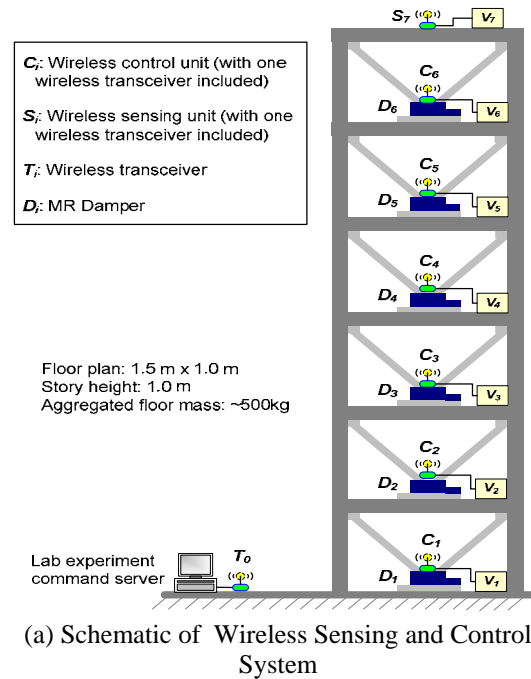


Fig. 4. System Instrumentation of Wireless Sensing and Control

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 indicate that the simulation models for the structure and the damper are reasonably accurate.

4. Decentralized Control Strategies and Experimental Results: The objective of the study is to evaluate the viability of wireless output feedback control. The linear quadratic regulator (LQR) approach, which is commonly employed in practice, is adopted. In essence, LQR control involves selecting a pair of weighting matrices (Q and R) for a scalar cost function that considers the state response of the structure and the energy required by the system actuators. For the time delay control problem with n state variables and m

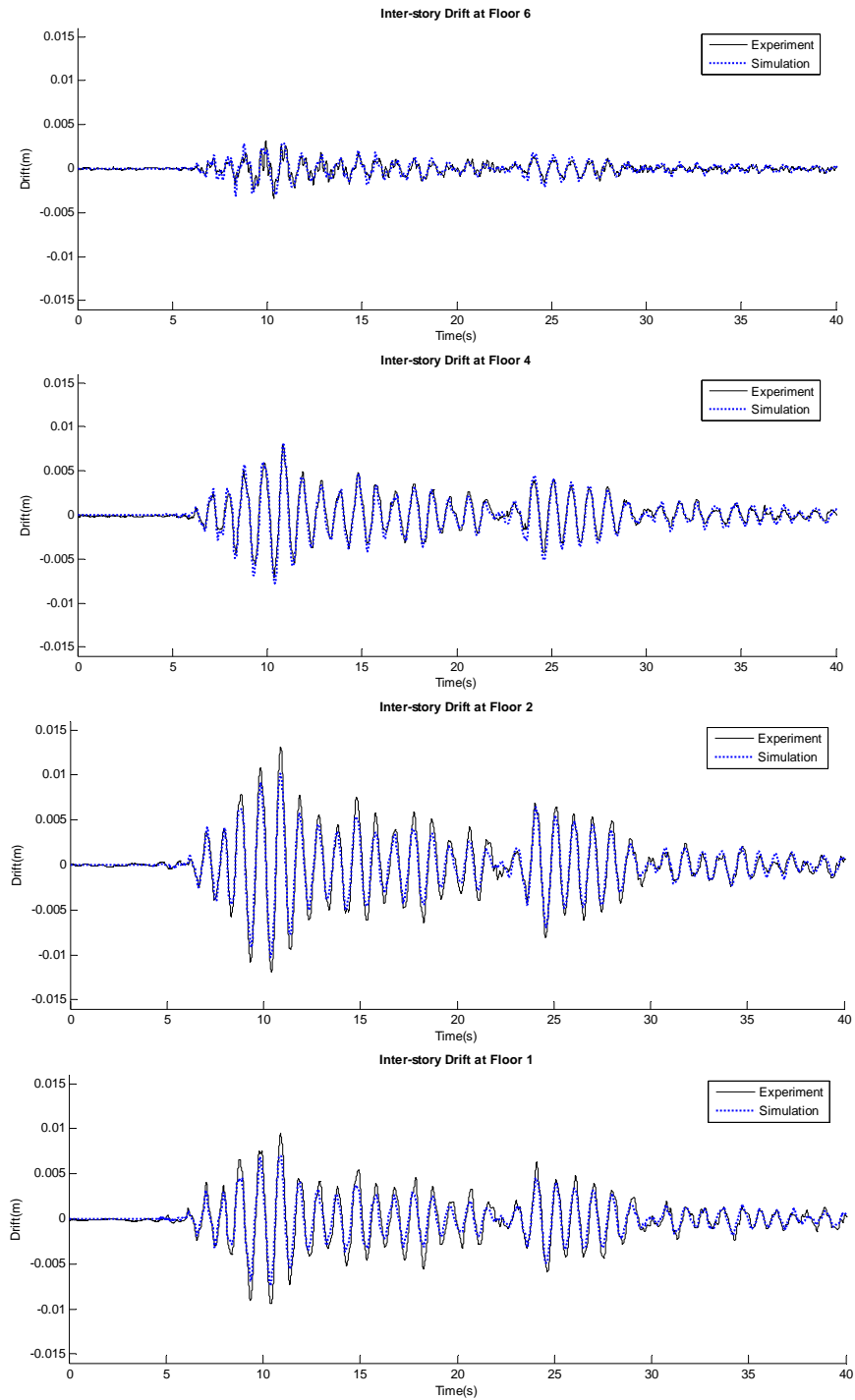


Fig. 5. Experimental and Simulated Inter-Story Drifts for a Chi-Chi (TCU-076 Station) Earthquake Excitation with Voltages for Dampers Set at 0V

actuation locations, the primary objective of LQR is to minimize a global cost function, J :

$$J|_{\mathbf{p}_d} = \sum_{k=l}^{\infty} (\mathbf{z}_d^T[k] \mathbf{Q} \mathbf{z}_d[k] + \mathbf{p}_d^T[k-l] \mathbf{R} \mathbf{p}_d[k-l])$$

where $\mathbf{Q}_{2n \times 2n} \geq 0$ and $\mathbf{R}_{m \times m} > 0$

where $\mathbf{z}_d[k]$ represents the $2n \times 1$ state-space vector, $\mathbf{p}_d[k-l]$ is the $m \times 1$ control force vector considering l ($l \geq 0$) steps of feedback time delay. The time delay problem can be dealt with by solving a modified first-order difference equation [2]. The LQR procedure finds

an “optimal” gain matrix \mathbf{G}_d by minimizing the expected value of the cost function J and computes the control forces, $\mathbf{p}_d[k] = \mathbf{G}_d y_d[k]$ where $y_d[k]$ is the system output vector obtained using the measured, or estimated, state information $\mathbf{z}_d[k]$. Decentralized control architectures based on two distinct communication schemes were performed. In this paper, the experimental results are based on the ground excitation using the 1999 Chi-Chi NS record at TCU-076 Station with its peak ground acceleration scaled to 1m/s^2 .

4.1 Decentralization based on Communication

Subnet: This section describes the centralized and decentralized inter-story velocity feedback control schemes used for the wireless control experiments based on communication network topology [12]. In this feedback control experiment, 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. In this case, $y_d[k]$ is a 6×1 output vector consisting of inter-story velocities. The first decentralized control scheme is designed to reflect a communication network architecture where a channel is assigned as a communication subnet. Fig. 6 shows three wireless

sensing and control strategies that were studied using inter-story velocity feedback. For DC1, each wireless channel covers only three stories and two wireless channels (subnets) are utilized with no overlapping information communicated between the subnets. For DC2, while each wireless channel still covers 3 stories, an additional channel is used for communication among stories 2 to 4; thus providing additional neighboring information that are used in the LQR decentralized control decisions. For both cases, the time delays (including control force calculations and data transmissions from the wireless sensors to control units) are set at 33.3ms (30Hz). DC3 represents a centralized control strategy where one wireless channel covers all six stories; in this case, a lower sampling rate of 10Hz is used to emulate the situation that more wireless units and data communication are involved within the channel. To establish such a decentralized control scheme, a constraint is imposed such that the (sparsity) structure of the gain matrix is made consistent with the decentralized architecture. The structure of gain matrices corresponding to the three control schemes, DC1, DC2 and DC3, are as shown in Fig. 6(a), 6(b) and 6(c), respectively. The gain matrix can be computed using an iterative procedure by traversing along the constrained gradient until an “optimal” solution with respect to the imposed constraint is obtained [5].

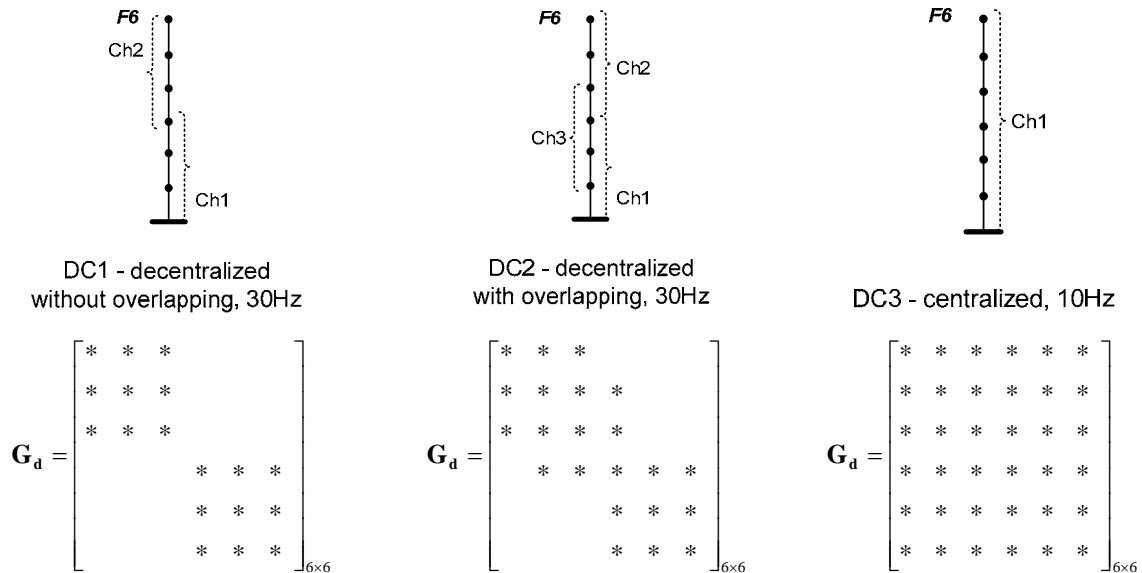
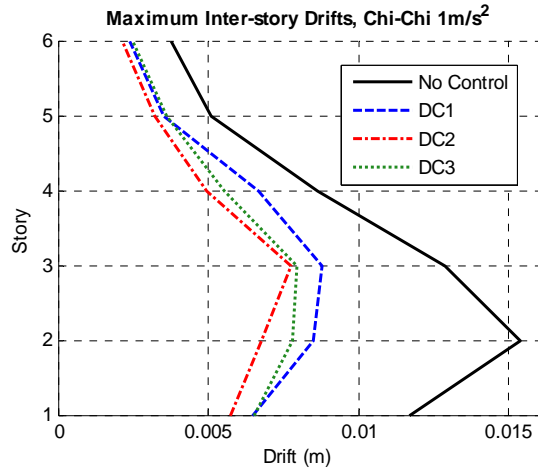
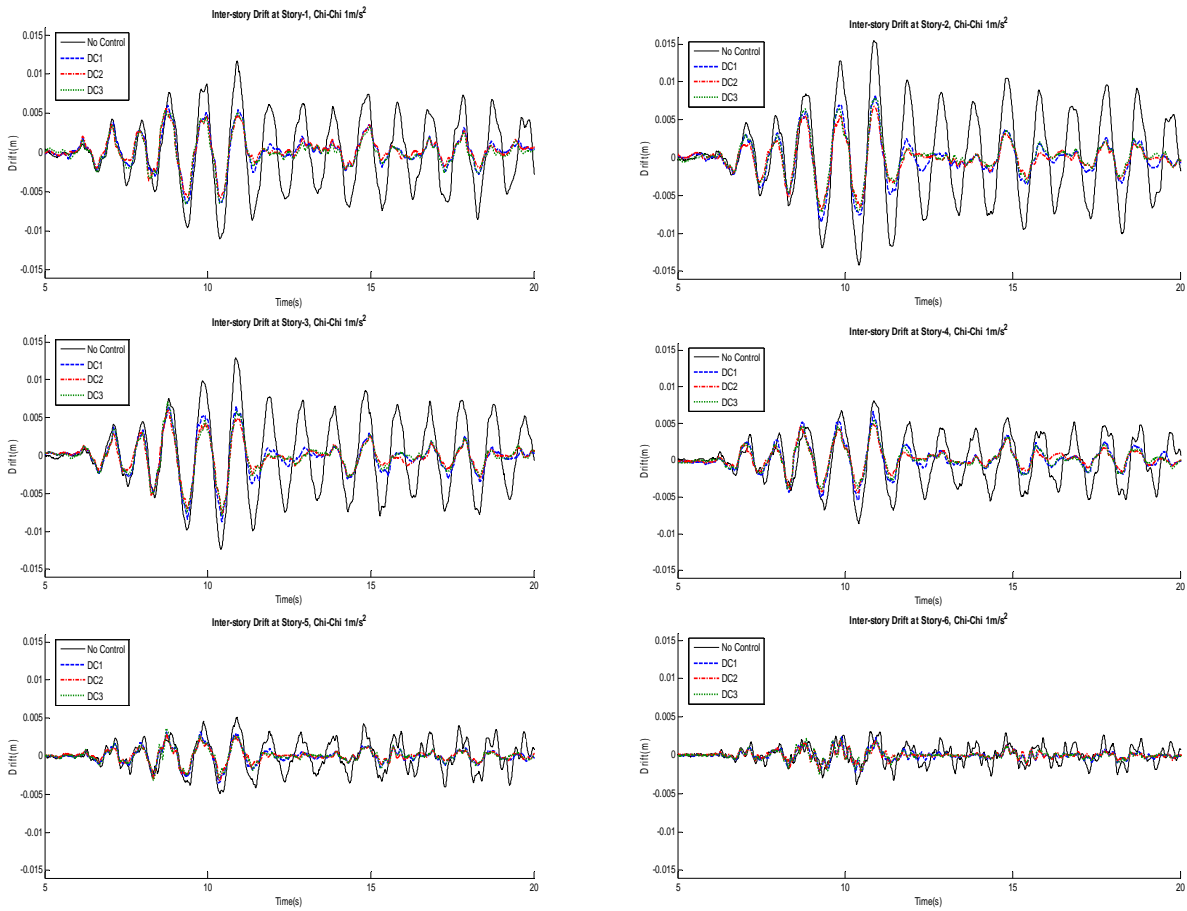


Fig. 6. Information Groups and Corresponding Gain Matrices for Different Degrees of Centralization (DC).



(a) Experimental Peak Inter-Story Drift Results



(b) Experimental Inter-Story Drift Time Histories

Fig. 7. Experimental Inter-Story Drift Results for Different Communication Architectures (as illustrated in Fig. 6) for the Chi-Chi Excitation Scaled to a Peak Acceleration of 1m/s^2

Fig. 7(a) shows 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 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. 7(b) 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.

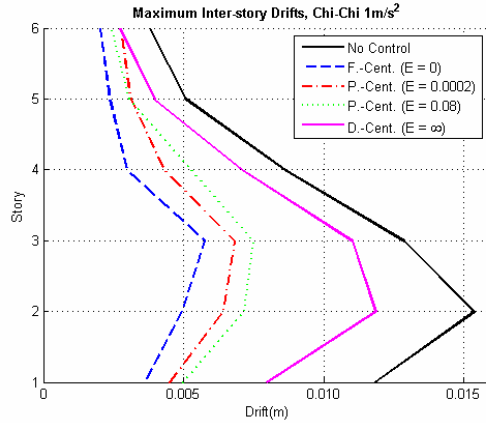
4.2. Decentralized Strategy Based on Transmitted Data Quality: Another decentralized control strategy is implemented to examine the influence that the "quality" of data transmitted via wireless communication may have on structural control [9]. Measurement noise, unknown disturbances, and modeling imperfections introduce error into the estimates of the state values, particularly in decentralized topologies in which the access individual units have to measured data is severely limited. A single unit can however, evaluate the quality of a local state estimate by comparing its error level to a predetermined threshold (ϵ). If the error exceeds this threshold level, then the unit may replace the estimated value with the measured value as well as transmit the measured value to the rest of the network. If all control units within the network are running Kalman estimators based on the same system model, the state estimates will be synchronized, error bounded, and the quality of the control signal generated by the network will be controlled. Varying the error threshold, in essence, affects the tradeoff between bandwidth and controller performance. The higher the threshold, the less data is transmitted and lower communication bandwidth is needed and the control system is more decentralized. In fact, as the error threshold increases, the system performance will approach that of the decentralized case. Conversely, as the error threshold approaches zero, the behavior of the system approaches that of the

centralized case.

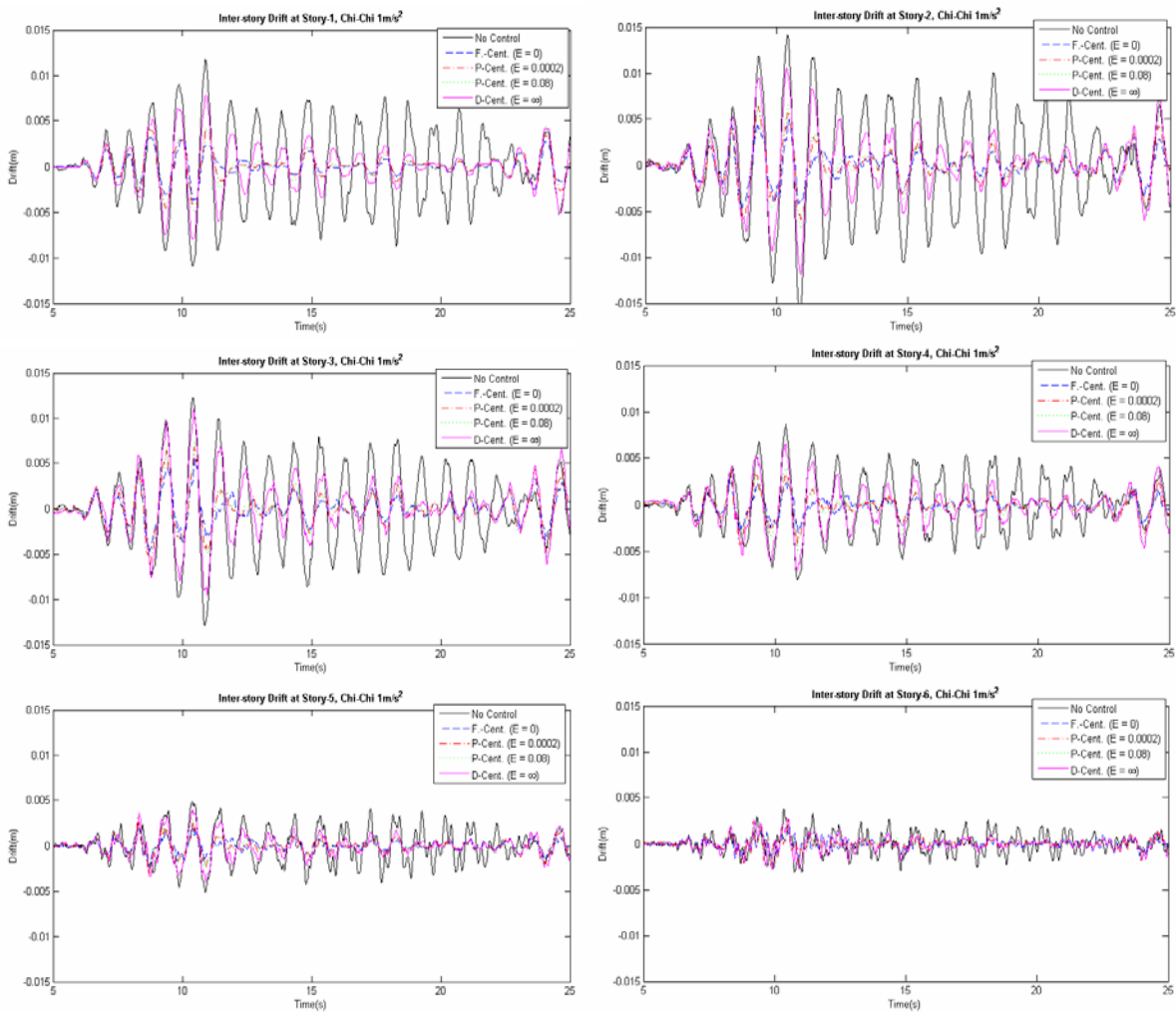
Fig. 8 shows the control test results from the Chi-Chi earthquake excitation with peak acceleration scaled to 1 m/s^2 . The time delay (including state estimation, determination of control forces and data transmission) is set at 33.3 ms (30Hz). It can be seen that the control results with different error thresholds compare favorably with the uncontrolled case and the fully decentralized case. Control performance decreases from centralized control to distributed control as the error threshold varies from low to high. This control strategy in utilizing wireless communication allows a designer to evaluate the tradeoff between acceptable control behavior and minimal bandwidth utilization.

5. Summary and Discussion: As structural control devices are becoming smaller, cheaper and more reliable, engineers will be able to deploy large number of sensors and control devices in a structure. Decentralized control strategies and cost-effective wireless sensing technology will have significant impact to the future development of structural monitoring and control systems. This paper describes a set of preliminary laboratory experiments that are designed to evaluate the performance of decentralized wireless structural control. Multiple centralized/decentralized control architectures based on different communication and information processing schemes have been discussed. The results have demonstrated the viability and potential of wireless sensing and control devices for large scale decentralized structural control applications.

6. Acknowledgements: This research is partially funded by NSF under grant CMMI 0824977 awarded to Prof. Kincho Law at Stanford University, by NSF under grant CMS-0528867 awarded to Prof. Lynch at the University of Michigan, and by the Office of Naval Research (ONR) Young Investigator Program awarded to Prof. Lynch at the University of Michigan. The authors would like to express their gratitude for the invaluable assistance and supports provided by Prof. Chin-Hsiung Loh of National Taiwan University (NTU) and NCREE. The authors would also like to acknowledge the assistance by Kung-Chun Lu of NTU, Andrew Zimmerman of University of Michigan and Amanda Askin of Stanford University. Any opinions and findings are those of the authors and do not necessarily reflect the views of NSF, ONR and their collaborators.



(a) Experimental Peak Inter-Story Drift Results



(b) Experimental Inter-Story Drift Time Histories

Fig. 8. Experimental Inter-Story Drift Results for Different Error Threshold from Wireless Communication Network for the Chi-Chi Excitation Scaled to a Peak Acceleration of 1m/s²

7. References:

- [1] Cao, D.Q., J.M. Ko, Y.Q. Ni, and H.J. Liu (2000). "Decentralized Active Tendon Control and Stability of Cable-stayed Bridges," *Adv. Struct. Dyn.*, 2: 1257-1264.
- [2] Chung, L.L., C.C. Lin, and K.H. Lu (1995), "Time-delay Control of Structures," *Earthquake Eng. Struct. Dyn.*, 24(5): 687-701.
- [3] Kurino, H., J. Tagami, K. Shimizu, and T. Kobori (2003). "Switching Oil Damper with Built-in Controller for Structural Control," *J. Struct. Eng.*, ASCE, 129: 895-904.
- [4] Lin, P.-Y., Roschke, P.N., and Loh, C.-H. (2005), "System Identification and Real Application of the Smart Magnetorheological Damper," *Proc. 2005 Int. Symp. on Intelligent Control*, pp. 989-994, Limassol, Cyprus.
- [5] Lunze, J. (1992). *Feedback Control of Large-scale Systems*, Prentice Hall, Hertfordshire, UK.
- [6] Lynch, J.P., A. Sundararajan, H. Sohn, G. Park, C. Farrar, and K.H. Law (2004). "Embedding Actuation Functionalities in a Wireless Structural Health Monitoring System," *Proc. of the 1st Int. Workshop on Advanced Smart Materials and Smart Structure Technology*, Honolulu, HI.
- [7] Lynch, J.P. and K.J. Loh (2006). "A Summary Review of Wireless Sensors and Sensor Networks for Structural Health Monitoring," *Shock Vib. Dig.*, Sage Publications, 38(2): 91-128.
- [8] Swartz, R.A. and J.P. Lynch (2006). "A Multirate Recursive ARX Algorithm for Energy Efficient Wireless Structural Monitoring," *Proc. 4th World Conf. on Structural Control and Monitoring*, San Diego, CA, USA .
- [9] Swartz, R.A., and J.P. Lynch (2009), "Strategic Network Utilization in a Wireless Structural Control System for Seismically Excited Structures," (in press) *J. Structural Engg.*, ASCE.
- [10] Wang, Y. (2007), *Wireless Sensing and Decentralized Control for Civil Structures: Theory and Implementation*. PhD Thesis, Department of Civil and Environmental Engineering, Stanford University.
- [11] Wang, Y., J. P. Lynch, and K. H. Law (2006), "Wireless Sensing, Actuation and Control -- with Applications to Civil Structures", *Proceedings of the 13th EG-ICE Workshop*, Ascona, Switzerland, pp. 670-689, June 25-30.
- [12] Wang, Y., R.A., Swartz, A. Zimmerman, A.C. Askin, J.P. Lynch, K.H. Law, K.-C. Lu, C.-H., Loh (2008), "Decentralized Wireless Structural Sensing and Control with Multiple System Architectures Operating at Different Sampling Frequencies," *SPIE Annual Int. Symposium on NDE for Health Monitoring and Diagnostics*, San Diego, CA.
- [13] Yook, J.K., D.M. Tilbury, and N.R. Soparkar (2002). "Trading Computation for Bandwidth: Reducing Communication in Distributed Control Systems using State Estimators," *IEEE T Contr Syst T*, IEEE, 10(4): 503-518.