Wireless Sensing and Structural Control Strategies

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ABSTRACT

Structural sensing, monitoring and control can benefit from wireless communication and embedded computing technologies in terms of installation cost and time. Our prior research has developed low-cost wireless sensing systems for structural monitoring. By incorporating an actuation signal generation module, the functionalities of wireless sensors can be extended to support structural actuation and real-time control applications. This paper discusses the laboratory experiments that are designed to assess the viability of decentralized wireless structural control using a six-story scaled 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 and decentralized feedback control architectures, in combination with different sampling frequencies, are investigated. Decentralized control strategies and information processing issues related to wireless sensing and control are discussed.

INTRODUCTION

Control devices have been employed to mitigate excessive dynamic responses of civil structures subjected to strong dynamic loads (Nishitani and Inoue 2001, Spencer and Nagarajaiah 2003, Chu *et al.* 2005). In observing the recent evolutionary shift from active to semi-active control, control devices have become significantly smaller, cost less, have better energy consumption characteristics and have higher level of reliability (Symans and Constantinou 1999). Inevitably, engineers will have the opportunity to deploy large quantities of devices in a structure, resulting in a control problem entailing hundreds of control devices and sensors. Scalability of current sensing and control technologies are hindered by their dependence on centralized system architectures. Decentralization strategies that can effectively coordinate a dense network of sensing and control devices, will have significant impact to the future development of structural monitoring and control systems.

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Communication technologies, such as wireless and high speed networks, are increasingly being deployed in the civil and structural engineering fields. For example, engineers are now actively exploring the use of low-cost wireless sensors for structural monitoring (Lynch and Loh 2006). As opposed to traditional structural monitoring, where sensors are often used in a passive manner to measure structural responses, researchers have now begun to incorporate actuation interface for self-sensing and prognosis applications (Lynch *et al.* 2004). Alternatively, an actuation interface included in a wireless sensor can be extended for control applications, in addition to performing structural sensing and monitoring functions (Wang et al. 2006). 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 commands to actuators. The demands of a control system to respond in real-time can pose technical challenges for the wireless sensor technology. Specifically, the wireless channel can introduce communication delay between wireless sensors and possible data loss. To assess the feasibility of deploying wireless sensing technology for structural control applications, some of the issues that need to be addressed include decentralized control strategies, communication schemes, and information processing architectures. This paper discusses the laboratory experiments that are designed to evaluate the performance of decentralized structural control architectures and information processing strategies using wireless sensors installed in a base-excited six-story structure.

INFORMATION STRUCTURES AND DECENTRALIZED CONTROL STRATEGIES

The class of (centralized and decentralized) control approach can be defined by the information available to the control units. In the centralized approach, complete knowledge of the system plant (*a priori* information) and a complete set of state data (*a posteriori* information) are assumed during implementation. In decentralized control, local controllers only have access to a portion of the global information. The amount and type of information available to each sub-system defines the information structure of the decentralized control approach. As illustrated in Fig. 1, three types of decentralized information structures can be identified: total, partial and hierarchical (Wang 2007). For a totally decentralized control structure, each controller has access only to the local *a posteriori* information. Knowledge of how the control actions of the local controller affect the overall system response is not available. If information transfer is permitted between certain controllers, thus providing partial knowledge of how a local controller is affecting the global system, the result is a partially decentralized control solution. For hierarchical decentralized control, an additional layer of information flow is included to further support coordinated efforts between the multiple controllers, potentially leading to an improved overall global performance.

Decentralized control of civil structures, such as cable-stayed bridges (Cao *et al.* 2000) and building structures (Kurino *et al.* 2003), have been reported. Typically, 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 without dynamically coordinating with other subsystems (irrespective of their operational status) for achieving a global optimal solution. The system architecture of the totally decentralized control strategy is depicted in Fig. 1(a).

Another approach for decentralized control is to share measured or estimated global or subsystem state information (Yook *et al.* 2002). 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

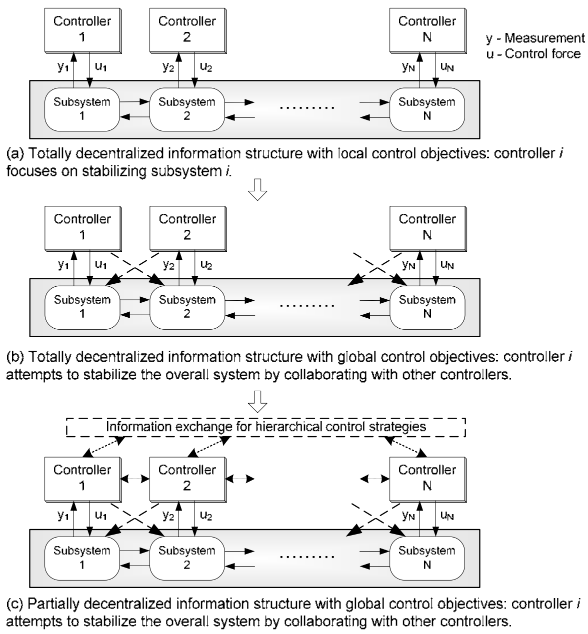


Fig. 1. Decentralized information structures and control objectives.

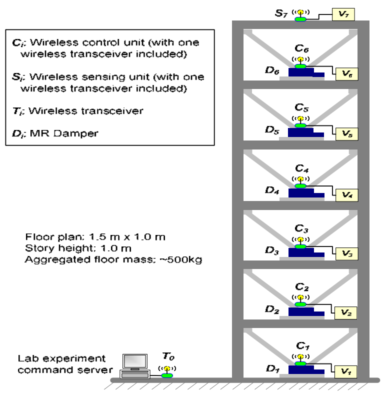
the overall system performance. A decentralized control strategy using distributed Kalman filters can be implemented according to the system architecture shown in Fig. 1(b), assuming that there are no communications between the distributed Kalman estimators. Alternatively, the decentralized scheme can 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 (e.g. wireless 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 other words, decentralized control strategies are necessarily driven by the availability of data, the information structure and communication topologies. Our research intends to investigate and to implement different communication and information processing schemes and to assess the benefits and drawbacks of different decentralized control strategies.

EXPERIMENTAL SETUP FOR DECENTRALIZED WIRELESS FEEDBACK CONTROL

To study the performance of decentralized wireless structural control, experimental tests on a 6-story scaled structure were conducted at the National Center for Research on Earthquake Engineering (NCREE) in Taipei, Taiwan. The six-story steel frame structure, which is mounted on a 5m × 5m six degrees of freedom shake table, is designed and constructed by researchers affiliated with the National Center for Research on Earthquake Engineering (NCREE) (see Fig. 2(a)). The test structure is 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 installed in the NCREE facility.

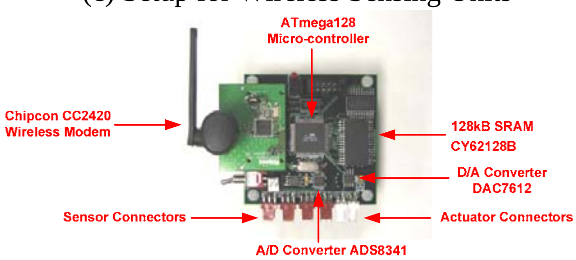
On the test structure, each story is instrumented with a RD-1005-3 magnetorheological (MR) damper manufactured by Lord Corporation (see Fig. 2(b)). The damper is capable of applying a maximum damping force over 2kN. The properties of the MR dampers change with the magnetic field generated through an input electric current. The damper can respond to magnetic field changes within 15ms. A modified Bouc-Wen force-displacement hysteresis model for the MR dampers is developed prior to the tests. The hysteresis model parameters for the MR dampers are used in the calculation of damper input signals. 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.


(a) Test Structure



(c) Setup for Wireless Sensing Units


(b) An MR damper under a V-brace



(d) Narada wireless sensing/actuation unit

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

The experimental setup of the wireless control tests is schematically shown in Fig. 2(c). The experiments employ the Narada wireless sensing/actuation units developed by Swartz and Lynch at the University of Michigan (Swartz and Lynch 2006). 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 for 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. With the Chipcon CC2420 wireless radio, 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. 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.

A total of seven Narada wireless units (with one on each floor) are installed on the test structure. 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). For each 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.

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

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

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. As noted by Chung et al. (1995), the time delay problem can be dealt with by introducing a modified first-order difference equation. 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, $\mathbf{p_d}[k] = \mathbf{G_d}\mathbf{z_d}[k]$ using the measured, or estimated, state information.

Decentralized control architectures based on two distinct communication schemes were performed. The first decentralized control scheme is designed to reflect a communication network architecture where a channel is assigned as a communication subnet (Wang et al. 2008). 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. An iterative procedure presented by Lunze (1992) is employed to compute the gain matrix by traversing along the constrained gradient until an "optimal" solution with respect to the imposed constraint is obtained. Fig. 3 shows three wireless sensing and control strategies that were studied using inter-story velocity feedback. For DC1 (see Fig. 3), 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.

Fig. 3 shows the control test results for a Chi-Chi earthquake excitation with peak acceleration scaled to $1 m/s^2$. Among the three control cases, DC2 (a partially decentralized scheme with overlapping information) achieves better performance than fully decentralized DC1 where the wireless subnets do not share any information. The decentralized strategy DC2 also works better than the centralized strategy DC3 with a slower sampling rate. The results indicate that partially overlapping information and lower communication latency are important characteristics to be considered in decentralized control architectures.

Another decentralized control strategy is implemented to examine the influence that the "quality" of data transmitted via wireless communication may have on structural control (Swartz and Lynch 2008). The idea is to compare the locally measured data at each wireless sensor to its corresponding internal state estimation (for example via Kalman estimators) from data collected among other sensors. Should the difference (error, *e*) exceeds a predefined threshold, the measured data replaces the estimated value within the unit. Also, threshold exceedence triggers that unit to broadcast the measured state response to the other units for updating. Varying the error threshold, in essence, affects the tradeoff between bandwidth and controller performance. The higher the threshold, lower communication bandwidth is needed and the control system is more decentralized; i.e. less information from faraway units is used for state updating. On the contrary, setting the error threshold to zero leads to continuous bandwidth usage, thereby reflecting a centralized control scheme. Since the measured data are communicated through the wireless network, the strategy synchronizes the state estimates among the wireless units to within an allowable error range. Fig. 4 shows the control test results from the El Centro 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, the fully decentralized case, as well as the passive control case (where the output voltage of the wireless sensors actuation interface is set to a constant 0.8V to achieve maximum damping in the MR damper). 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.

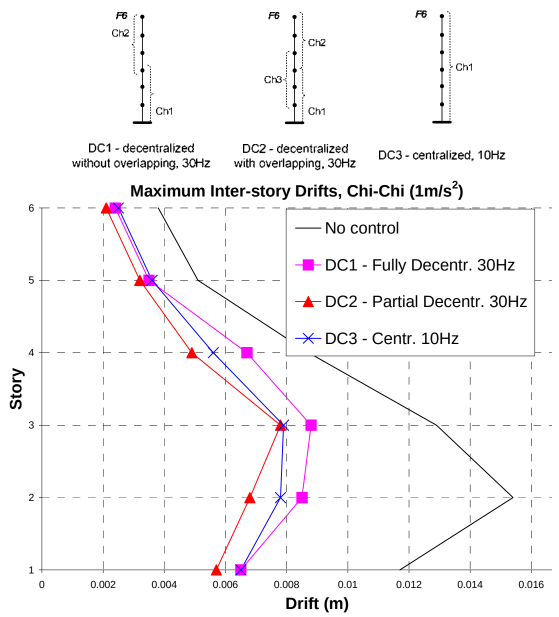


Fig. 3 Decentralized control based on subnet communications

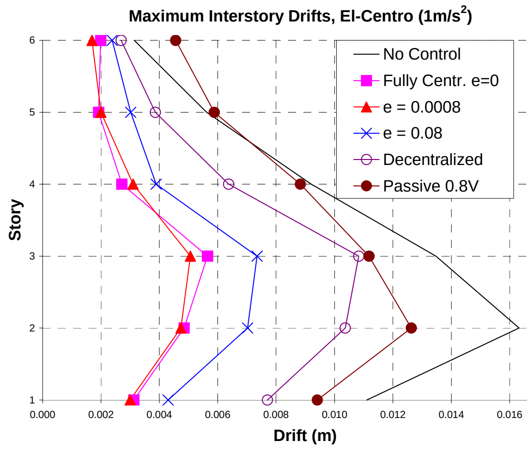


Fig. 4 Decentralized control based on data communication quality

SUMMARY AND CONCLUSION

This paper describes the 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 are investigated. The results indicate 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. Furthermore, this experimental study has explored the effects of wireless communication bandwidth on structural control. Last but not least, these preliminary laboratory experiments illustrate that a broad spectrum of wireless communication schemes could be explored for designing decentralized structural control systems.

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