Wireless Sensing and Vibration Control of Civil Structures

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Introduction

Significant advances have been made in deploying wireless sensors and sensing network technologies for monitoring the health and safety of civil structures [4]. For monitoring applications, sensors are often used passively to measure structural responses. Equipped with an actuation interface, wireless sensors can be extended to command actuators [7]. This paper discusses a study on the feasibility of deploying wireless sensors for real-time feedback control of structures. Experimental tests on a scaled six-story structure were conducted to assess the performance of different control architectures implemented on a wireless sensor network.

Wireless Control Strategies

There are three basic tasks in a structural control system: collecting response data, calculating desired control forces, and issuing commands to actuators. Traditional cable-based structural control systems are typically fully centralized where 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 making control decisions. Because of technical challenges such as communication range, communication delay and possible data loss, as well as the need to react in real-time, fully centralized control architectures using wireless sensors will likely not be realized for large scale systems. In contrast, decentralization of the system architecture could alleviate these challenges. Based on the availability of plant and state information about a system, Fig. 1 shows three decentralized control strategies: totally decentralized, partial and hierarchical decentralized control schemes [6]. For a totally decentralized system, each controller has access only to the local *a posteriori* information of the subsystem that the controller is responsible for. The physical interactions between the coupled subsystems are treated as

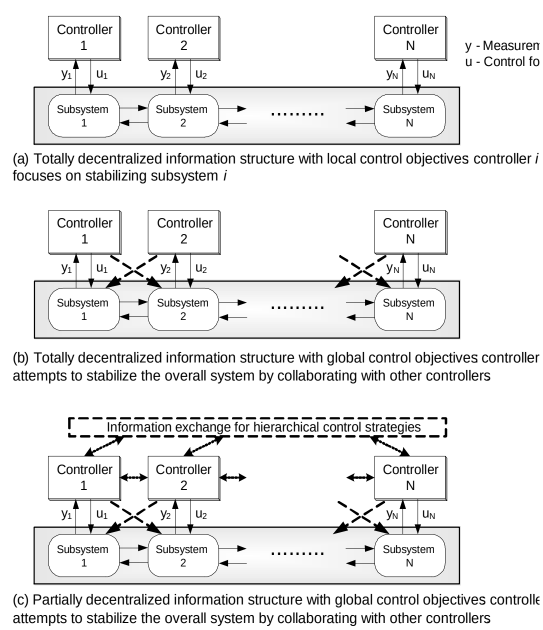

Fig. 1. Decentralized information structures and control objectives.

unknown disturbances. Each controller is designed as a single-input, single-output (SISO) subsystem and focuses on its own performance without any coordination with other subsystems. For partial decentralized control, each controller is also provided with sensor information from other subsystems and makes control decisions based on partial knowledge of the system. For a hierarchical decentralized control strategy, additional global (measured and/or estimated) information is being made available to and shared by the controllers to improve the overall system performance. Information sharing among the subsystems however, could lead to additional demand for communication, resulting in substantial time delays in a shared-use communication channel (*e.g.*, wireless communication channel). For the partially or hierarchically control strategies (or a combination of both), 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.

Experimental Study

To study the performance of decentralized control strategies and the potential deployment of wireless sensor technology for structural control, experimental tests were conducted at the National Center for Research on Earthquake Engineering (NCREE) in Taiwan. Fig. 2 shows a six-story steel frame structure mounted on a 5m × 5m shake table. The test structure and shake table are instrumented with linear variable displacement transducers, velocity meters and accelerometers to measure their dynamic responses. These sensors are interfaced to a high-precision wire-based data acquisition (DAQ) system permanently 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 and is able to respond to magnetic field changes within 15 ms. A modified Bouc-Wen force-displacement model for the damper is constructed via a series of calibration tests prior to the tests [2].

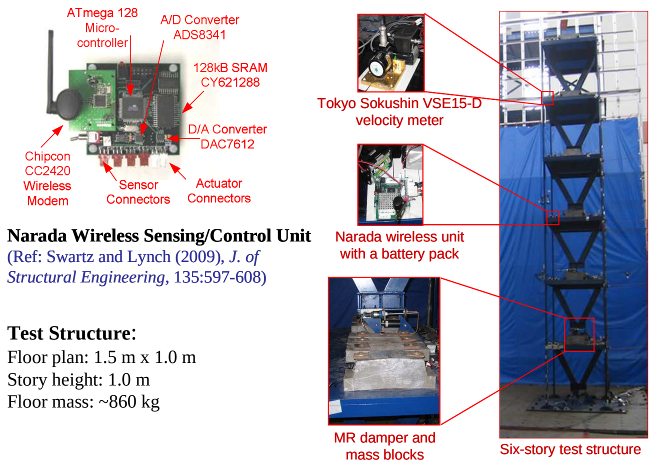

Fig. 2: Experimental Setup

The experiments employ the Narada wireless sensors developed by Swartz and Lynch [5]. 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. Sensor data is then transferred to the computational core, which consists of a low-power 8-bit Atmel ATmega128 microcontroller. An external 128kB Static Random Access Memory is integrated with the computational core for additional data storage and interrogation. The wireless unit communicates with other units or server through the wireless transceiver, Chipcon CC2420, which takes about 1.5~2ms to transmit a 10-byte packet. 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 a single Narada unit.

In the experimental setup, each wireless sensor 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). In addition, a remote data and command server with a wireless transceiver is included to log the flow of wireless data for post-processing purpose. During the test, the command server first notifies the wireless sensors to initiate automated operations. Once the start command is received, the wireless sensors that are responsible for collecting sensor data start acquiring and broadcasting data at a specified time interval. The wireless sensors 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. The analog command signal generated by the wireless sensor is fed into a specially designed signal converter module, which converts the voltage signal into a current source for the MR damper.

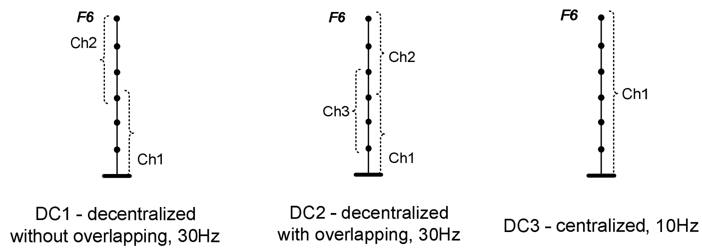

Fig. 3: Experimental Control Strategies

Decentralized Control Strategies and Experimental Results

To evaluate the viability of wireless output feedback control, the commonly employed linear quadratic regulator (LQR) approach, modified to include time delay consideration [1], is adopted. The experimental results presented below 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.

Fig. 3 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 and a lower sampling rate of 10Hz is used to emulate the situation that more wireless units and data communication are involved within

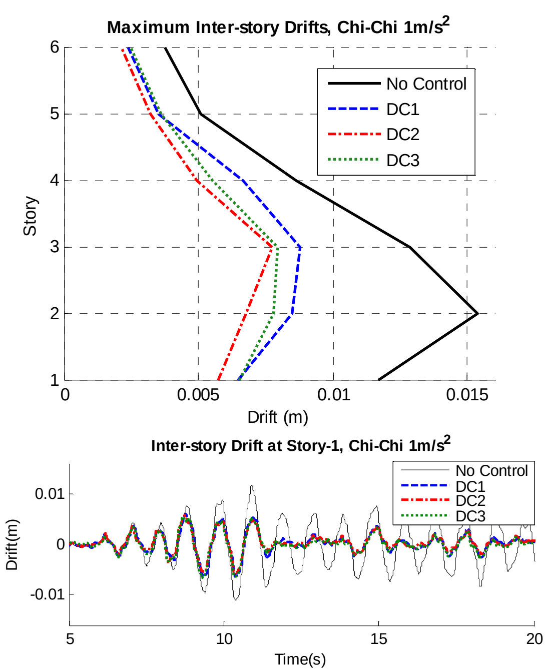

Fig. 4: Experimental Interstory Drift Results

the channel. An iterative procedure is used to traverse along the constrained gradient, which reflects the imposed decentralized architecture, until an "optimal" solution is obtained [3].

Fig. 4 shows the structure's peak inter-story drifts for different control schemes, as well as an uncontrolled case where the dampers are disconnected from the structure. It can be seen that peak responses occur between the 9th second and the 11th second. All three wireless control schemes achieve significant reduction in controlling the inter-story drifts. Case DC2 (sampling at 30Hz) achieves the smallest inter-story drifts at all peaks and performs slightly better than the other two cases. The fact that case DC2 is slightly better than the centralized case DC3 (sampling at 10Hz) illustrates that the higher sampling rate can potentially compensate for the loss of data when ignoring the sensor data at faraway stories.

Summary and Discussion

This paper describes a set of preliminary laboratory experiments to demonstrate the different centralized/decentralized wireless sensing and control architectures. The results have demonstrated the viability and potential of wireless sensing and control devices for large scale decentralized structural control applications. Other robust and dynamic control strategies utilizing wireless sensing network are currently being investigated.

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