

Wireless Feedback Structural Control with Embedded Computing

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ABSTRACT

In recent years, substantial research has been conducted to advance structural control as a direct means of mitigating the dynamic response of civil structures. In parallel to these efforts, the structural engineering field is currently exploring low-cost wireless sensors for use in structural monitoring systems. To reduce the labor and costs associated with installing extensive lengths of coaxial wires in today's structural control systems, wireless sensors are being considered as building blocks of future systems. In the proposed system, wireless sensors are designed to perform three major tasks in the control system; wireless sensors are responsible for the collection of structural response data, calculation of control forces, and issuing commands to actuators. In this study, a wireless sensor is designed to fulfill these tasks explicitly. However, the demands of the control system, namely the need to respond in real-time, push the limits of current wireless sensor technology. The wireless channel can introduce delay in the communication of data between wireless sensors; in some rare instances, outright data loss can be experienced. Such issues are considered an intricate part of this feasibility study. A prototype Wireless Structural Sensing and Control (WiSSCon) system is presented herein. To validate the performance of this prototype system, shaking table experiments are carried out on a half-scale three story steel structure in which a magnetorheological (MR) damper is installed for real-time control. In comparison to a cable-based control system installed in the same structure, the performance of the WiSSCon system is shown to be effective and reliable.

Keywords: structural control, wireless communication, embedded computing

1. INTRODUCTION

Improving the response of structures due to strong dynamic excitation (*e.g.* earthquakes, typhoons) continues to be a major challenge in current engineering practice. For nearly two decades, structural control technology has matured and is considered an effective means for mitigating extreme structural responses during earthquakes and strong winds [1]. Structural control technology can be categorized into three major types: (a) passive control systems (*e.g.* base isolation), (b) active control (*e.g.* active mass dampers), and (c) semi-active control (*e.g.* semi-active variable dampers) [2]. Semi-active control is currently preferred over active control because it achieves an equivalent level of performance but consumes orders of magnitude less power. Some of the additional advantages associated with semi-active control include adaptability to real-time excitation, inherent Bounded Input / Bounded Output (BIBO) stability, and invulnerability against building power failure. In semi-active control systems, sensors are installed in the structure to record real-time structural response data for the calculation of control decisions. At each step in time, the controller executes an embedded algorithm to determine an optimal set of forces that can be applied to the structure to limit its response. The controller then issues commands to the actuators installed that in turn apply desired forces (directly or, as in the case of a variable damper, indirectly). Examples of semi-active devices include active variable stiffness (AVS), semi-active hydraulic dampers (SHD), electrorheological (ER) dampers, and magnetorheological (MR) dampers.

In order to transfer real-time data in the control system (sensor data to the centralized controller and commands from the controller to actuators), coaxial wires are normally employed as a reliable communication link. However, the installation effort and cost associated with coaxial wire can be as high as \$5,000 per communication channel [3]. As the number of actuation and sensing nodes of the control system increases, the required length of wires installed in the

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structure similarly increases. The added costs associated with wires negate the benefits associated with recent reductions in the size and cost of semi-active actuators. To capitalize on low-cost semi-active actuators installed in high density in a single structure, wireless communication is proposed for the eradication of high-cost coaxial wires [4]. This proposition is more compelling when considering the fact that wireless communication has already proven reliable when used in lieu of coaxial wiring in structural monitoring systems [5-8]. However, unlike in structural monitoring systems where some minor delay in the delivery of data is acceptable, structural control systems require real-time performance. In other words, sensor data must be sampled, control forces calculated and commands issued to the actuators, all on a precisely timed schedule. Simulation studies by Seth *et al.* [4] have shown that any data loss or delay (due to wireless communication) could potentially reduce the performance of a control system.

This research study attempts to assess the viability in using wireless sensors as a fundamental component of a structural control system. In this study, the hardware design of the wireless sensor is based upon an earlier design proposed by Wang *et al.* [6] for structural monitoring applications. This wireless sensor consists of a sensor interface to which analog sensors can be attached, an embedded microcontroller for sensor-based data processing, and a spread spectrum wireless radio for communication. Additional hardware is included in the design so that the wireless sensor can issue voltage commands to actuators within a structural control system. The embedded microcontroller is an important element in the wireless sensor design since it will be responsible for keeping a real-time schedule for control system operations and will also serve as the kernel to determine control forces for the system actuators. With computational power distributed across the wireless sensor network, decentralized control algorithms are a future possibility for wireless structural control systems [9].

In this paper, a Wireless Structural Sensing and Control (WiSSCon) system is introduced for response mitigation in civil structures. An introduction to the overall system design is presented, followed by a detailed description of the system hardware design which is optimized for key performance parameters. The software written to operate the wireless sensors under the real-time requirements of the control problem is also presented. Validation tests are performed using the WiSSCon prototype system installed in a test structure at the National Center for Research on Earthquake Engineering (NCREE) in Taipei, Taiwan. The test structure consists of a half-scale three story steel frame structure instrumented with a 20kN MR damper at its base floor [10]. In addition to the WiSSCon prototype system, a wired control system is employed to control the structure when the same ground excitations are applied to the structure. The wired control system serves as a baseline system to which the performance of the WiSSCon system is compared. The response of the structure controlled by the WiSSCon and wired control systems are presented, showing promising performance in applying wireless communication and embedded computing technologies into a real-time feedback structural control system.

2. WISSCON SYSTEM DESIGN OVERVIEW

WiSSCon is a prototype system designed for real-time wireless structural sensing and feedback control. State-of-the-art wireless communication and embedded computing technologies are employed to eradicate the extensive lengths of coaxial wires traditionally employed in current structural control systems. In the WiSSCon system, wireless communication is used for the feedback of structural response data to wireless sensors serving as the control kernel (*i.e.* to calculate control solutions based on received state data). The wireless sensor which is responsible for measuring the dynamic response of the structure is termed the wireless sensing unit. For the calculation of control forces at each time-step, the wireless sensor designated as the control kernel (termed the wireless control unit) utilizes its local embedded computing resources to quickly process sensor data, generate control signals, and apply control commands to structural actuators within the designated time-step duration.

To illustrate the WiSSCon system architecture, the structure depicted in Figure 1, is instrumented with a WiSSCon system. Besides the wireless sensing and control units that are essential for the operation of the WiSSCon system, a remote data and command server with a wireless transceiver is included as an optional system element responsible for logging the flow of data in the WiSSCon system. The overall program flow for a typical control test is also described in the figure. During the test, the command server first notifies the wireless sensing and control units to initiate automated operation. Once the start command is received by the wireless control unit, it begins to broadcast beacon signals to the wireless sensing units at a specified time interval. Upon receipt of the beacon signal, each wireless sensing unit is provided a brief time window to access the wireless bandwidth for transmitting its sensor data. The wireless control

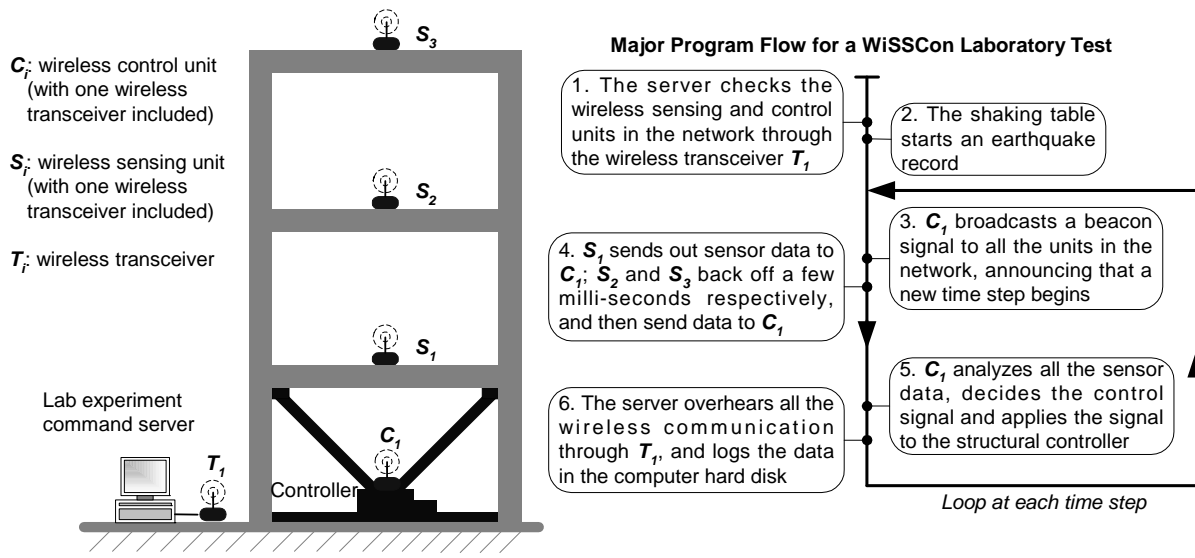


Figure 1. Example illustration of the WiSSCon system instrumented on a 3-story building with one actuator

unit waits to receive sensor data from every wireless sensing unit. After receiving the data, the wireless control unit calculates optimal control forces and issues corresponding command signals to the system actuator. For the laboratory test, the data and command server is used to initiate the start of the control system. However, in real-world applications, activation of the wireless control system could be automatically triggered when an earthquake or strong wind condition occurs.

3. HARDWARE DESIGN FOR WIRELESS SENSING AND CONTROL UNITS

The WiSSCon system described herein is a rapid prototype for exploring the feasibility of real-time feedback control using a wireless sensor network. The hardware design of the wireless sensors of the WiSSCon system are based upon the design of a wireless sensing unit previously proposed for use in wireless structural monitoring systems [11]. Two major hardware features included in the wireless sensors for the WiSSCon system are a wireless transceiver for wireless communication and an actuation interface that allows the wireless sensor to issue command signals to actuators. For the current prototype system, the wireless sensor is designed such that it can be employed as either a wireless sensing or control unit without making any hardware changes. This section will present an overview of the functional modules of the wireless sensor architecture. In addition, the design of a separate control signal module which serves as the interface between a wireless control unit and a structural actuator is introduced.

3.1 Overview of the wireless sensing and control unit

Three basic functional modules are included in the wireless sensing unit design: sensor signal digitizer, computational core, and wireless transceiver. As described earlier, the wireless control unit contains the same three modules as the wireless sensing unit, plus a supplementary control signal module designed to reside off-board of the basic wireless sensor. The architectural design of the wireless control unit is presented in Figure 2. The architectural design of the wireless sensing unit can be obtained by simply omitting the control signal module. The sensor signal digitization module contains the 4-channel 16-bit Texas Instrument ADS8341 analog-to-digital (A/D) converter. This module simultaneously converts the 0V ~ 5V analog output of four sensors into digital formats usable by the wireless sensor's computational core. The digitized sensor data is then transferred to the computational core through a high-speed serial peripheral interface (SPI) port. The computational core consists of a low-power 8-bit Atmel ATmega128 microcontroller and an external 128kB static random access memory (SRAM) chip for the storage of sensor data. To establish wireless communication between wireless sensors to be installed on the test structure at NCREE, Taiwan, the MaxStream 24XStream wireless transceiver operating on the internationally unlicensed 2.4 GHz wireless band is selected. When the wireless sensor is designated as a wireless sensing unit, the wireless transceiver is primarily used to

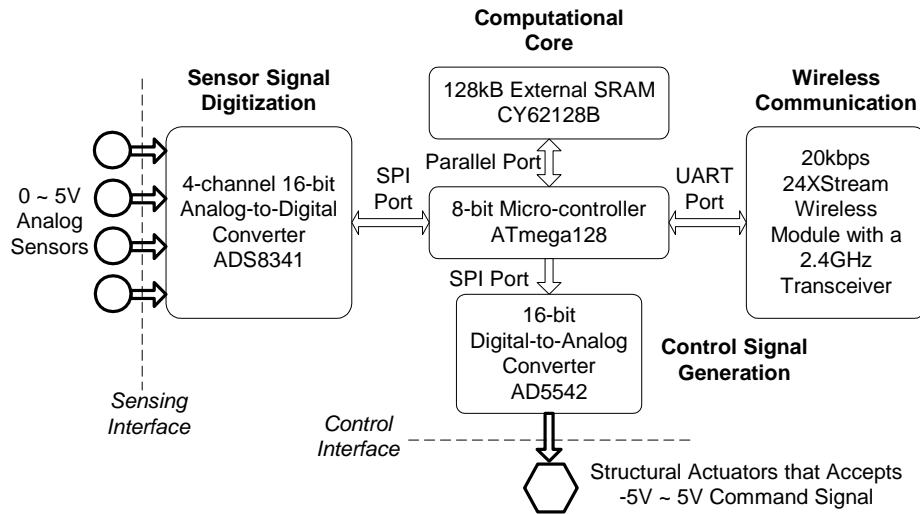


Figure 2. Hardware architecture of the wireless control unit

send sensor data out to the wireless network. In contrast, for the wireless control unit, the wireless transceiver receives sensor data from the network. After receipt of the sensor data, the wireless control unit's ATmega128 computes desired control forces. Once the control force calculation is completed, the wireless control unit issues voltage signal to the system actuators.

3.2 Control signal module

To command control forces, the wireless control unit must be capable of outputting voltages to actuators. A separate hardware module is designed that can be plugged into the wireless sensor module that permits it to generate analog voltage signals. At the core of this control signal module is the single-channel 16-bit, Analog Device AD5542 digital-to-analog (D/A) converter. The AD5542 receives a 16-bit unsigned integer from the ATmega128, and converts the integer value to an analog voltage output spanning from $-5V \sim 5V$. Additional supporting electronics are included in the control signal module to offer stable zero-order hold voltage outputs at high sample rates (1 MHz maximum). The wide voltage output range ($-5 \sim 5V$) of the control signal module, particularly the negative output range, is a key feature of module's design. With the wireless sensor based on $0V \sim 5V$ electronics, the Texas Instruments PT5022 switching regulator is integrated in the module design to convert the output of a 5V regulated power supply into $-5V$. Another auxiliary component required for the AD5542 to generate a bipolar $-5V \sim 5V$ output signal is a rail-to-rail input and output operational amplifier; the National Semiconductor LMC6484 operational amplifier is selected. Typical slew rate of the LMC6484 is about $1.3V/\mu s$, which means that the output voltage can swing about $1.3V$ within $1\mu s$. This output change rate is compatible with the microsecond-level settling time of the D/A converter AD5542.

As shown in Figure 3, a separate double-layer printed circuit board (PCB) is designed to accommodate the D/A converter AD5542 and its auxiliary electrical components. The control signal board is attached via two multi-line wires to the wireless sensor to receive digital commands from the ATmega128. To reduce circuit noise, two separate wires are used: one analog signal cable and one digital signal cable. The analog signal cable transfers an accurate $+5V$ reference voltage from the existing wireless sensing board to the actuation board; the digital signal cable provides all the connections required for the SPI interface between the microcontroller ATmega128 and the AD5542. To command an actuator, a third wire is needed to connect the control signal module with the structural actuator.

3.3 Wireless communication module

A challenge associated with employing wireless sensors for use in a structural control system is the performance of the wireless communication channel. Specifically, the real-time requirements of the control system do not permit sufficient time for the use of send-acknowledge communication protocols that ensure channel reliability. Furthermore, stochastic delays are possible in the channel that cannot be deterministically accounted for *a priori* in the control solution

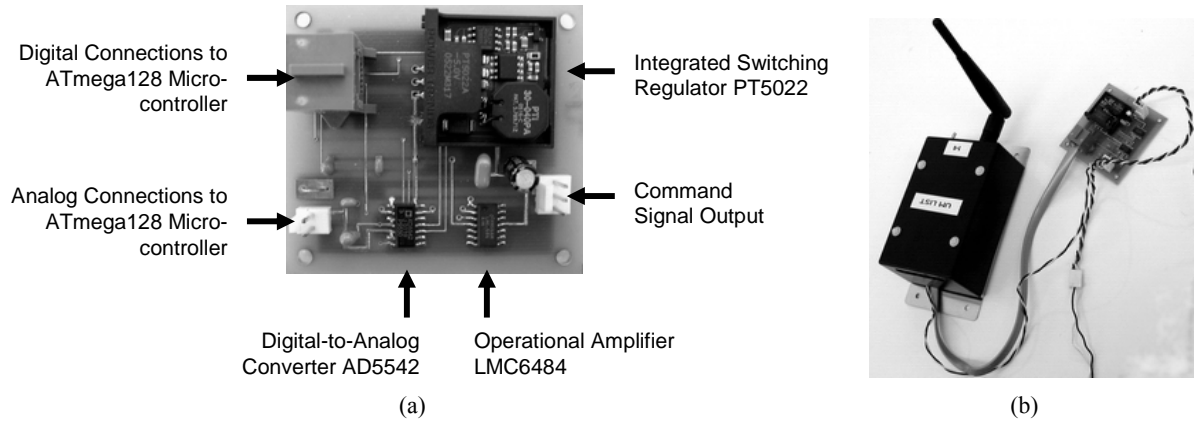


Figure 3. Pictures of the control signal module: (a) PCB board (5.5cm × 6.0 cm); (b) control signal module connected to wireless sensor

formulation [4]. For these reasons, an appropriate radio must be judiciously selected for use in a wireless control system.

The MaxStream 24XStream is selected because it is simple to integrate with the wireless sensor architecture, offers high-speed communication (19.2 kbps), and operates on an internationally unlicensed radio band (2.4 GHz). The key characteristics of the 24XStream wireless transceiver are summarized in Table 1. As specified, the 450m indoor communication range of the 24XStream wireless transceiver is sufficient for application in most small and medium-size civil structures. The 24XStream transceiver consumes a current of 150mA when transmitting and 80mA when receiving data. A much lower current is consumed when the transceiver is set to sleep mode (26 μ A). 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 wireless sensors in the WiSSCon system.

Table 1. Key characteristics of the MaxStream 24XStream wireless transceiver

<i>Communication Range</i>	Up to 600' (180m) indoor, 3 miles (5km) outdoor
<i>Data Transfer Rate</i>	19.2 kbps
<i>Operating Frequency</i>	ISM 2.4000 – 2.4835 GHz
<i>Channel Mode</i>	7 Frequency Hopping Channels
<i>Supply Voltage</i>	5V (\pm 0.25V) regulated
<i>Power Consumption</i>	150mA transmitting, 80mA receiving, 26 μ A standby
<i>Module Size</i>	1.6" × 2.825" × 0.35" (4.06 cm × 7.17 cm × 0.89 cm)
<i>Network Topology</i>	Point-to-point, point-to-multipoint

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. The anticipated latency of the 24XStream radio during transmission of a single data packet is illustrated in Figure 4, The latency is composed of the time to move data from the microcontroller to the radio through the universal asynchronous receiver and transmitter (UART) interface (T_{UART}), and the time required by the radio to transmit (TX) the data packet on the wireless channel (T_{TX}). Assume that the packet to be transmitted contains N bytes, and the UART data rate is R_{UART} bps (bit per second), which is equivalent to $R_{UART}/10000$ bytes per millisecond. The communication latency in a single transmission of this data packet can be estimated as:

$$T_{SingleTransm} = T_{TX} + \frac{20000N}{R_{UART}} \text{ (ms)} \quad (1)$$

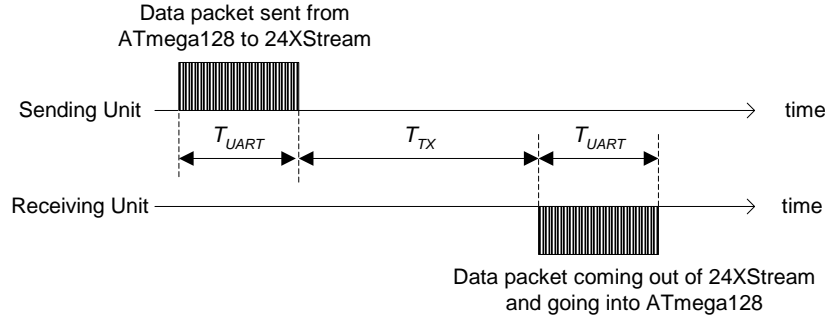


Figure 4. Communication latency of a single wireless transmission

In the WiSSCon prototype system, the transmission latency, T_{TX} , for the 24XStream is estimated to be about 10ms (a mean value obtained from our experimental measurements). If a data packet sent from a sensing unit to a control unit contains 10 bytes, then the total time delay for the transmission is estimated to be:

$$T_{SingleTransm} = 10 + \frac{20000 \times 10}{19200} \approx 20.4 \text{ (ms)} \quad (2)$$

This single-transmission delay represents the communication constraint that needs to be considered when calculating the upper bound for the maximum sampling rate for the control system. For the example system configuration shown in Figure 1, four wireless transmissions are needed for each time step. One beacon packet is broadcasted by the wireless control unit followed by the three wireless sensing units transmitting their response data to the control unit. With the four wireless transmissions occurring sequentially, the total communication latency is approximately 80 ms that sets the maximum sampling rate of the WiSSCon system at 12.5Hz.

4. VALIDATION TESTS

4.1 Laboratory setup

To validate the WiSSCon concept, 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 (Figure 5a) and the experimental setup is depicted in Figure 1. The floor plan of this structure is $3\text{m} \times 2\text{m}$, with each floor weight adjusted to 6,000 kg using concrete blocks. The inter-story height is 3m. Both the beams and the columns of the structure are constructed with $\text{H}150 \times 150 \times 7 \times 10$ steel I-beam elements. The three-story structure is mounted to a $5\text{m} \times 5\text{m}$ 6-DOF shaking table. The shaking table can generate vibrations whose frequencies span from 0.1Hz to 50Hz. For this study, only longitudinal excitation is used in the tests. Along this direction, the shaking table can excite the structure with a maximum acceleration of 9.8m/s^2 . The excitation has a maximum stroke and force of ± 0.25 m and 220,000 N, respectively. The test structure is heavily instrumented with various sensor types. Accelerometers, velocity meters, and linear variable displacement transducers (LVDT) are installed on each floor of the structure to measure its response. Therefore, accurate longitudinal acceleration, velocity, and displacement time histories of each floor are collected for all the dynamic tests. These sensors are interfaced to a high-precision wire-based data acquisition (DAQ) system native to the NCREE facility; the DAQ system is set to a sample rate of 200 Hz. A separate set of sensors are installed as part of the WiSSCon system. Various seismic ground excitations are applied including El Centro (1940), Kobe (1995) and Chi-Chi (1999) records.

For this experimental study, one 20 kN MR damper is installed at the base floor of the three-story steel structure (Figure 5b). The damper has a piston stroke of ± 0.054 m. The damping coefficient of the MR damper can be changed by issuing a command voltage between 0V to 1V. 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 damper before mounting it to the structure so that a modified Bouc-Wen damper model can be formulated for use in simulation study of the structure

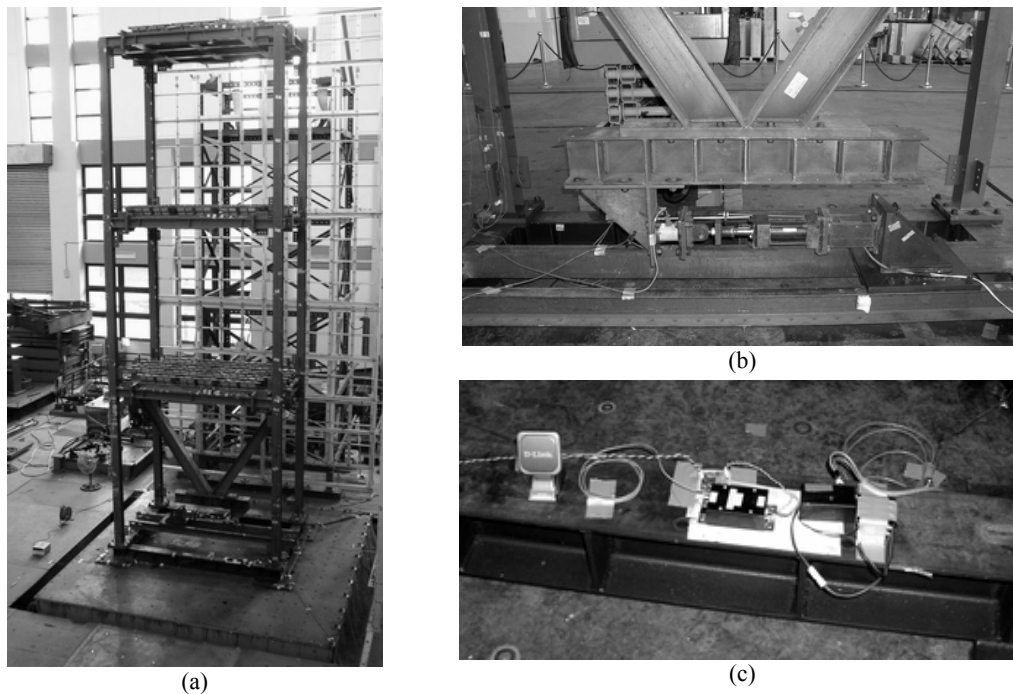


Figure 5. Laboratory setup: (a) the three-story test structure mounted on the shaking table; (b) the MR damper installed between the 1st floor and the base floor of the structure; (c) the wireless control unit commanding the MR damper.

[10]. Hysteresis model parameters for the MR damper are also an integral element in the calculation of control forces by both the wireless and wired control systems. The MR damper's past hysteresis behavior is needed by the control systems to compute appropriate command signals for the MR damper at any given time step.

Passive structural control tests are first conducted by setting the command voltage of the damper to constant values (*e.g.* 0, 0.2, ..., 1V) while exciting the structure with seismic ground motion. After the performance of the MR damper is quantified in its passive state, the MR damper is used as a semi-active actuator in the system. To vary the damping coefficient of the damper for optimal reduction of structural responses, two control systems are installed in the test structure: the wireless WiSSCon system and a traditional wire-based control system. Figure 5(c) shows the wireless control unit installed in the vicinity of the MR damper to which it is connected.

Both feedback control systems utilize typical discrete Linear Quadratic Regulator (LQR) control algorithm to compute control forces applied by the MR damper. In the following sections, the validation tests on two key performance features of the WiSSCon prototype system, namely the overall reliability of accurate state measurement and embedded computation for calculation of control force at the wireless control unit, are presented. Lastly, comparisons between the control results from the three groups of tests (*i.e.* passive, WiSSCon, and wired control) are presented.

4.2 Installation of wireless sensing units for real-time state measurement

One wireless sensing unit is installed upon each floor of the three-story structure (floors 1, 2 and 3). These wireless sensors, as proposed in Figure 1, are installed to record the lateral dynamic response of the structure during application of seismic ground motions at the structure base. Velocity meters are used to record the lateral response of the structure. Tokyo Sokushin VSE15-D velocity meters are selected for installation on each floor of the structure. The sensitivity of this velocity meter is 10V/(m/s) with a measurement limit of ± 1 m/s. The dynamic frequency range of the velocity meter is 0.1Hz ~ 70Hz, which suitably covers the dynamic characteristics of the test structure whose primary modal frequencies fall well below 10 Hz. At each floor, two VSE15-D velocity meters are installed adjacent to one another. At each floor, one velocity meter is attached to the wired DAQ system previously described. The second velocity meter of each floor is attached to a wireless sensor designated as a wireless sensing unit. A customized signal conditioning

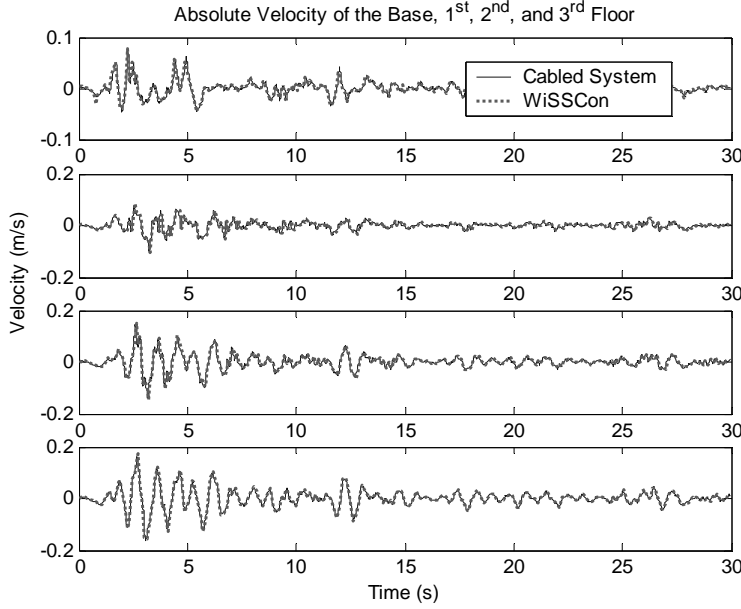


Figure 6. Comparison between real-time velocity data collected by the WiSSCon system and the cabled DAQ system (ground motion is a scaled El Centro earthquake record)

circuit is designed by NCREE researchers to shift and scale the $\pm 10V$ output voltage of the velocity meter to a voltage range acceptable by the wireless sensors ($0V \sim 5V$).

The accuracy of the recorded structural response is critical for making effective control decisions. To assess the quality of the recorded structural response to base excitations, the velocity data collected by the wireless sensing units in the WiSSCon system are compared to the velocity recorded by the wired DAQ system. When an El Centro (1940) ground excitation is applied to the structure, a close match is observed between the velocity time histories recorded by the wireless and wired systems, as presented in Figure 6. It should be noted that the El Centro excitation applied during this test is scaled to a peak acceleration of $1m/s^2$.

4.3 Embedded software to determine optimal control forces

The experimental study is designed to execute velocity feedback control in real-time. The longitudinal velocity data of all three floors, measured by the three wireless sensing units S_1 , S_2 , and S_3 (Figure 1), are wirelessly transmitted to the wireless control unit C_1 at the base floor. Meanwhile, the wireless control unit C_1 collects sensor data from a velocity meter installed at the structure's base. An optimal LQR control solution is determined using the computational core of the wireless control unit, C_1 .

The digital-domain LQR control solution can be briefly summarized as follows. For a lumped-mass structural model with n degrees-of-freedom and m actuators, the system state-space equations in discrete-time can be stated as:

$$z_d(k+1) = A_d z_d(k) + B_d u_d(k) \quad (3)$$

where $z_d(k)$ is the $2n \times 1$ discrete state-space vector written as:

$$z_d(k) = \begin{Bmatrix} x_d(k) \\ \dot{x}_d(k) \end{Bmatrix} \quad (4)$$

$u_d(k)$ is the $m \times 1$ control force vector, A_d is the $2n \times 2n$ system matrix (containing the information about the structural mass, stiffness and damping), and B_d is the $2n \times m$ actuator location matrix. The primary objective of the typical discrete LQR problem is to minimize a cost function J :

$$J(\{u_d\}) = z_d(k_f)^T Q z_d(k_f) + \sum_{k=0}^{k_f-1} (z_d(k)^T Q z_d(k) + u_d(k)^T R u_d(k)), \text{ where } Q \geq 0 \text{ and } R > 0 \quad (5)$$

by selecting an optimal trajectory of the structural response vector, z_d , and simultaneously minimizing the net energy associated with the control trajectory, u_d . The optimal solution for a steady-state discrete LQR algorithm is to equate the control force vector to a linear transformation of the state-space vector at each discrete time step:

$$u_d(k) = G z_d(k) \quad (6)$$

where the optimal gain matrix G can be computed by solving the Riccati equation of the system [13]. Generally, the matrix G depends on system matrices, A_d and B_d , and the weighting matrices Q and R . At each discrete time step k , the Equation (6) is employed to decide the desired control force vector $u_d(k)$.

Prior to the tests, an optimal LQR gain matrix G is determined using user-specified Q and R weighting matrices. The gain matrix is designed to use the velocity measurements at each level of the structure (base and floors 1, 2, and 3) to determine an optimal control force u_d , to be indirectly generated by the MR damper. The wireless control unit (C_7) embedded software is written to determine the MR damper's damping coefficient (set by the damper input voltage) to achieve the desired control force. As part of this calculation, the hysteresis properties of the MR damper must be accounted for. This requires continuous monitoring of the MR damper shaft velocity.

First, the accuracy of the calculations by the embedded LQR control program is assessed. During a closed-loop control test of the three-story structure excited with base motion, the velocity measurement at each level of the structure is recorded by the remote data server with a wireless transceiver. Furthermore, the behavior of the MR damper is simultaneously recorded by the WiSSCon system. After the test, the same input can be fed into a computer Matlab program, so that the computation occurred in the wireless control unit can be re-enacted to check the performance of the embedded software. Using the data from one randomly selected test, Figure 7(a) shows the desired LQR control force computed by the wireless control unit and re-enacted by a Matlab simulation. In a similar fashion, Figure 7(b) shows

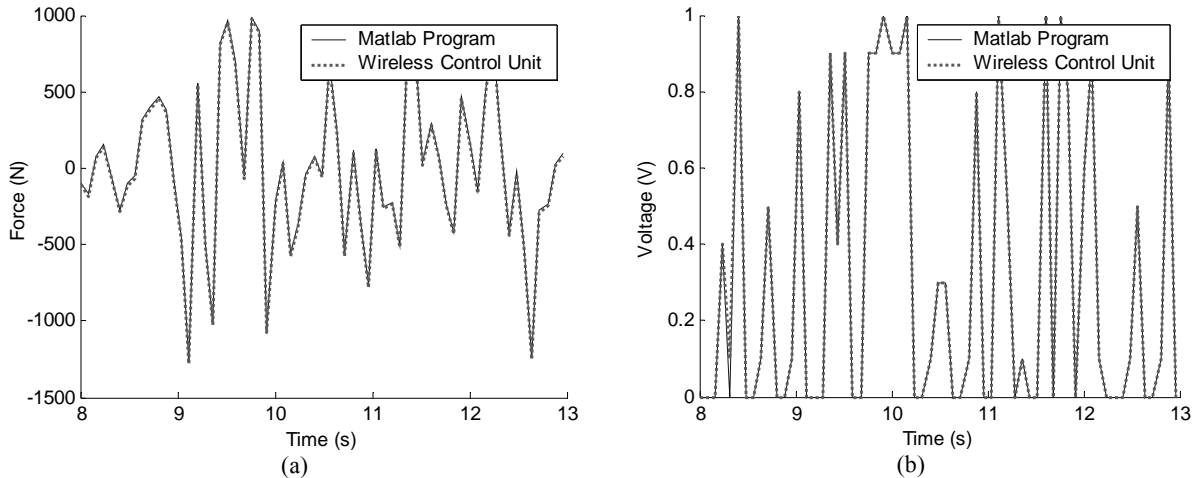


Figure 7. Computation finished by the wireless control unit and re-enacted by the computer Matlab program: (a) desired control force computed from sensor data; (b) decided voltage to be applied to the MR damper

the command voltage applied to the MR damper computed by the wireless control unit and re-enacted in the Matlab simulation. For clarity, the figures are zoomed to show the part containing the major earthquake motions. These two sets of computation results reveal the high precision achieved using the embedded control software.

During the laboratory tests, the computations required for making control decision takes about 10 milliseconds using the ATmega128 microcontroller. Although the performance of the microcontroller is slower than if the computations are carried out on a typical desktop computer, the millisecond-level delay is relatively minor when comparing to the latency inherent to the actuator and the structural response while applying adaptive control forces. Future investigations will consider using other microcontrollers that can provide higher performance throughput but without significant increase in battery power consumption.

4.4 Structural dynamic response of the WiSSCon prototype control system

As previously described, in the LQR problem, different set of weighting matrices, Q and R , can be introduced in the cost function J . For the experimental tests with the WiSSCon system, two sets of weighting matrices (Q_1, R_1), and (Q_2, R_2) are employed:

$$Q_1 = \begin{bmatrix} [I]_{3 \times 3} & \\ & 10[I]_{3 \times 3} \end{bmatrix}, \quad R_1 = 2E-9 \quad (7a)$$

$$Q_2 = \begin{bmatrix} 2 & -1 & & & & \\ -1 & 2 & -1 & & & \\ & -1 & 1 & & & \\ & & & 0.2 & -0.1 & \\ & & & -0.1 & 0.2 & -0.1 \\ & & & & -0.1 & 0.1 \end{bmatrix}, \quad R_2 = 1E-9 \quad (7b)$$

Here $[I]_{3 \times 3}$ refers to a 3-by-3 identity matrix. With the weighting matrices Q_1 and R_1 , the LQR algorithm gives the gain matrix G_1 , which is designed to minimize the cost function J which involves floor displacements and velocities over time, with an emphasis on minimizing the floor velocities. On the other hand, for the weighting matrices Q_2 and R_2 , the LQR algorithm would give the gain matrix G_2 that is designed to minimize the inter-story drifts and inter-story velocities over time, with an emphasis on minimizing the inter-story drifts.

Figure 8 shows the maximum inter-story drifts of each floor obtained from the tests conducted using the El Centro earthquake record with its peak acceleration scaled to 1m/s^2 . In order to take into consideration the effects of different peak ground accelerations (PGA) that are actually achieved in each test, the results shown have been compensated with a scaling factor normalized to the same PGA of 1m/s^2 . As for comparison, two passive control tests where the MR damper voltage is fixed at 0V and 1V, respectively, are also conducted. The results show that the WiSSCon tests give more uniform maximum inter-story drifts for all three floors than the passive control tests. Furthermore, the test that uses the gain matrix G_2 which is designed to minimize inter-story drifts and velocities over time, achieves its objective in obtaining the maximum inter-story drifts which are lower than the other three cases and are fairly uniform over all three floors with little variation.

As for comparison, Figure 8 also includes the test conducted with the wired control system. In that test, the following weighting matrices

$$Q_3 = \begin{bmatrix} [I]_{3 \times 3} & \\ & 100[I]_{3 \times 3} \end{bmatrix}, \quad R_3 = 1E-7 \quad (8)$$

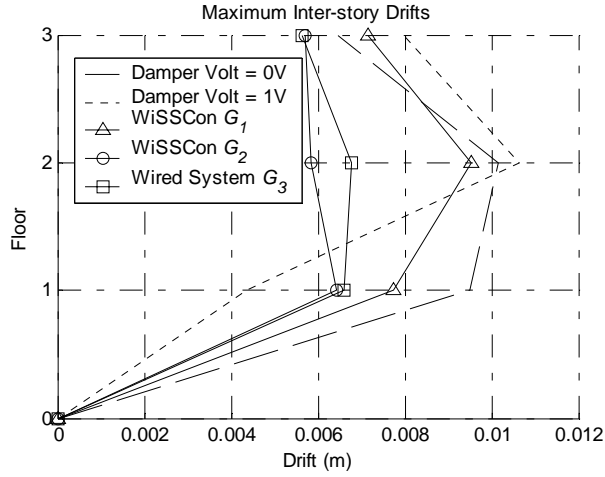


Figure 8. Maximum inter-story drifts for tests with a scaled El Centro record as ground excitation

are employed in the LQR algorithm for calculating the gain matrix G_3 . The wired control system is set at a sampling frequency of 200Hz, which is much higher than the WiSSCon system. As shown in Figure 8, the use of gain matrix G_3 with the wired control system produces better results than when G_1 is employed in the WiSSCon system. This is probably due in part to the different weighting matrices, as well as the much higher sampling rate used by the wired system. Comparing the results shown in Figures 8, it can be seen that when the gain matrix G_2 is employed in the WiSSCon system, the test gives the best control with respect to the maximum inter-story drifts. Most importantly, the experimental results demonstrate the feasibility of a WiSSCon system, even at a lower sampling rate (with 12.5Hz used in this study).

5. SUMMARY AND DISCUSSION

This study explores the potential of wireless communication and embedded computing technologies for real-time structural control applications. A prototype WiSSCon system is designed, implemented and tested. The reliability of using wireless communication and embedded computing is illustrated. Furthermore, the performance of the WiSSCon system is shown to be superior to the passive control test cases and nearly comparable to the wired control system. Other advantages of the WiSSCon system include reduction in system cost by eradicating cables in the control system, and by using low-cost microcontrollers for the control kernel and highly flexible and adaptable system configuration because of wireless communication.

While the WiSSCon concept has been demonstrated in this study, many research issues remain. New wireless communication technology that can provide faster sensor data feedback, while maintaining reliable data quality, should be examined. Different microcontrollers in modern electronics market can be selected to balance the trade-off among computational efficiency, computing cost and battery power consumption. The adverse effects of communication and computation time delay in the WiSSCon system can further be mitigated by using control algorithms that specifically address the time delay issue. To address the range and latency limitations associated with wireless communications in large-scale structures, the wireless sensors can be organized hierarchically based on subnets. For example, subnets would include a number of wireless sensing and control units that communicate with one another. In such an architecture, decentralized structural control algorithms [12] would be required so that wireless control units can make optimal control decisions using sensor data from only their local subnet. The development of decentralized algorithms that can be reliably implemented in the WiSSCon system and applied to real structures is a research subject that is worth investigation.

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7. REFERENCES

1. T. T. Soong and B. F. Spencer Jr., "Supplemental Energy Dissipation: State-of-the-art and State-of-the-practice," *Engineering Structures*, 24(3), 243-259, 2002.
2. S. Y. Chu, T. T. Soong, and A. M. Reinhorn, *Active, Hybrid and Semi-active Structural Control*, John Wiley & Sons Ltd., 2005.
3. M. Celebi, *Seismic Instrumentation of Buildings (with Emphasis on Federal Buildings)*, Report No. 0-7460-68170 United States Geological Survey (USGS), Menlo Park, CA, USA, 2002.
4. S. Seth, J. P. Lynch and D. Tilbury, "Feasibility of Real-Time Distributed Structural Control upon a Wireless Sensor Network," *Proceedings of the 42nd Annual Allerton Conference on Communication, Control and Computing*, Allerton, IL, USA, September 29 - October 1, 2004.
5. E. G. Straser and A. S. Kiremidjian, *A Modular, Wireless Damage Monitoring System for Structures*, Ph.D. thesis in Dept. of Civil and Environmental Eng., Stanford University, Stanford, CA, USA, 1998.
6. Y. Wang, J. P. Lynch and K. H. Law, "Design of a Low-Power Wireless Structural Monitoring System for Collaborative Computational Algorithms", *Proceedings of SPIE 10th Annual International Symposium on Nondestructive Evaluation for Health Monitoring and Diagnostics*, San Diego, CA, USA, March 6-10, 2005.
7. J. P. Lynch, Y. Wang, K.-C. Lu, T.-C. Hou and C.-H. Loh, "Post-seismic Damage Assessment of Steel Structures Instrumented with Self-interrogating Wireless Sensors," *Proceedings of the 8th National Conference on Earthquake Engineering*, San Francisco, CA, USA, April 18 - 22, 2006.
8. J. P. Lynch, K. J. Loh, T.-C. Hou, Y. Wang, J. Yi, C.-B. Yun, K. Lu, and C.-H. Loh, "Validation Case Studies of Wireless Monitoring Systems in Civil Structures," *Proceedings of the 2nd International Conference on Structural Health Monitoring of Intelligent Infrastructure (SHMII-2)*, Shenzhen, China, November 16 - 18, 2005.
9. J. P. Lynch and K. H. Law, "Decentralized Energy Market-Based Structural Control," *Structural Engineering and Mechanics*, Techno Press, 17(3), 557-572, 2004.
10. P.-Y. Lin, P. N. Roschke and C.-H. Loh, "System Identification and Real Application of a Smart Magneto-Rheological Damper," *Proceedings of the 2005 International Symposium on Intelligent Control, 13th Mediterranean Conference on Control and Automation*, Limassol, Cyprus, June 27-29, 2005.
11. Y. Wang, J. P. Lynch, and K. H. Law, "Wireless Structural Sensors Using Reliable Communication Protocols for Data Acquisition and Interrogation," *Proceedings of the 23rd International Modal Analysis Conference (IMAC XXIII)*, Orlando, FL, USA, January 31 - February 3, 2005.
12. J. P. Lynch and K. H. Law, "Decentralized Control Techniques for Large-scale Civil Structural Systems," *Proceedings of the 20th International Modal Analysis Conference (IMAC XX)*, Los Angeles, CA, USA, February 4 - 7, 2002.
13. G. F. Franklin, J. D. Powell and M. Workman, *Digital Control of Dynamic Systems*, Pearson Education, 2003.