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EXPERIMENTAL VALIDATION OF MARKET-BASED CONTROL USING WIRELESS SENSOR AND ACTUATOR NETWORKS

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Abstract: Structural control is a powerful tool that can effectively limit the undesired responses of civil structures resulting from base motion occurring during a major seismic event. In particular, low cost semi-active control devices (such as varying dampers) are gaining popularity because they accomplish their control objectives by strategically changing the properties of the structure under low power requirements. However, these devices are limited in the amount of force that they can deliver compared to larger (and more costly) active control devices. As a result, high actuator densities are often required to achieve adequate control of a large structure using semi-active control devices. This dense actuator network, coupled with sensors and the structure itself, represents a complex dynamic system that is best controlled through a decentralized approach. In this study, a decentralized market-based control (MBC) solution is adopted for controlling tall buildings that employ a large number of semi-active varying dampers for response mitigation. Specifically, wireless nodes are used to collect response data from sensors (accelerometers) and to command magnetorheological (MR) dampers. The computational capabilities of the wireless nodes are also utilized to formulate the control solution based on the MBC strategy. Wireless nodes collocated with the MR dampers are modeled as marketplace buyers vying for control energy made available by power sources modeled as market sellers. The buyer demand for control action is formulated as a function of the local response of the structure while the seller counter balances the market demand by having the market supply function correlated to the total reserve energy available in the control system. A market price is arbitrated at each point in time by determining the price at which the demand and supply functions equal one another. The theoretical basis of the MBC algorithm is first presented. Next, the method is experimentally validated using a six-story steel structure controlled by MR dampers and excited by a shake table. The results indicate the MBC solution to be effective in minimizing the displacement of the test structure.

1. INTRODUCTION

Limiting the response of civil structures to large external lateral disturbances (*e.g.,* wind loads, earthquakes) helps to ensure overall stability while limiting damage. Aside from the use of lateral-load resisting systems that are designed to resist seismic forces imposed on large buildings, structural control technology offers an additional avenue to designers to limit vibrations. Early structural control systems tended to be characterized by a small number of large and expensive actuators that were either passive (*e.g*., tuned mass dampers, viscoelastic dampers, metallic yield dampers) or active (*e.g*., active mass dampers). In passive control systems undesired response energy is passively drawn out of the system while for active systems, the dynamic behavior of the system is limited through a direct application of energy (Spencer and Nagarajaiah 2003). Passive dampers are effective within the specific bandwidth to which they are tuned but provide less protection outside this bandwidth. In contrast, the electrical energy needed to power active devices is large; this leaves the control system vulnerable because the supply of grid power can be interrupted during a large seismic event. Furthermore, active dampers offer no inherent guarantee of stability for the system.

More recently, semi-active control devices that combine the performance advantages of both passive and active devices have been developed for the control of large civil structures. Semi-active devices consume energy only to modify the configuration of the device; device configurations then minimize the effects of large system disturbances. These devices have a smaller form factor, consume less energy, and are considerably less expensive than active devices (Spencer and Nagarajaiah 2003). Furthermore, unlike passive devices, they can be actively commanded in real time giving them a wide operational bandwidth. Examples of semi-active actuators include variable stiffness devices, variable orifice dampers (*e.g.,* Kajima's HiDAX device), as well as electro- and magneto-rheological (MR) dampers. The drawback of this class of device is that their control potential is limited, thus necessitating dense installations to effectively control large structures such as high-rise buildings.

The large number of actuators and sensors needed for the control system, coupled with the large spatial dimensions of the structure itself, represents as extremely complex environment for the deployment of a cost-effective control system. Specifically, the wiring required to connect these devices to a central computer (*i.e.*, controller) represents a significant installation cost, potentially thousands of dollars on a per channel basis (Celebi 2002). In light of the high installation cost of a wired control system, one solution is to forego connectivity altogether, operating each semi-active actuator as an independent device, such as is implemented in Kajima Corporation's HiDAX system (Kajima Corporation 2006). However, wireless telemetry also presents an attractive alternative. A feedback control system based on the use of wireless communications allows information to be exchanged between sensors and actuators yet avoids the costs commonly associated with the installation of wires. Wireless sensing and actuation devices can be installed at a significantly reduced cost (as low as a few hundred dollars per device) compared with their cabled counterparts. In addition, the computing capabilities integrated with each wireless node (Straser and Kiremidjian 1998; Lynch, *et al.* 2004) may also be harnessed for the real-time computation of the control solution (Wang, *et al.* 2007; Swartz and Lynch 2009).

A network of low-cost wireless sensing and actuation nodes provides an economical computing platform for the implementation of feedback control solutions. Wireless sensing and actuation nodes with embedded computational abilities can be installed to sense the dynamic response of the structure, to compute control forces, and to command semi-active control devices in a manner that achieves the desired control force. Unlike the traditional centralized control system architecture in which one controller calculates the control solution, the wireless system is characterized by the spatial distribution of its computational resources and measurement data. Furthermore, data transmission over the wireless communication channel imposes a cost in terms of power (a critical issue for battery powered wireless nodes) and communication bandwidth (Wang, *et al.* 2007; Swartz and Lynch 2009). These limitations point to the need for decentralized control methods when implementing on the distributed computational system offered by a wireless sensor and actuator network. In this context, decentralized control methods enjoy two distinct advantages over centralized methods. First, employing a decentralized control solution reduces the communication load on the wireless communication channel, thereby improving communication performance (*e.g.*, channel reliability) while simultaneously reducing the amount of energy expended by each node. Second, distributed controllers avoid dependence on a single computational node; therefore, such systems are less susceptible to systemic failure due to the loss of the centralized controller.

In this study, a decentralized control algorithm based on free market economies is adopted for wireless control of a six-story steel frame structure. This study provides the first experimental validation of the market-based structural control methods proposed and simulated by Lynch and Law (2002; 2004). In the implemented control system, wireless nodes are installed at each structural degree of freedom (DOF) to measure its response using accelerometers. In addition, wireless nodes are integrated with the MR dampers installed on each floor. The wireless sensors and actuators are modeled as market buyers vying to acquire control energy. As the structural response of their associated DOF increases, the demand function of the DOF wireless sensor increases in tandem. Energy sources, modeled as market sellers, have their own associated supply function. The supply and demand functions are aggregated (by wireless communication) in a virtual marketplace so that a Pareto optimal price of control energy can be determined. This competitive equilibrium price is then the basis for the amount of control energy each DOF purchases (and applies in the form of a control force). The subject of this study is a six-story steel laboratory shear building controlled using magnetorheological (MR) dampers located between floors. *Narada* wireless sensing and actuation nodes (Swartz, *et al.* 2005) are installed with each actuator and are responsible for measuring the floor response, computing supply and demand functions, allocating control energy, converting control energy into a control force, and commanding the MR damper to apply that force. In this paper, the theoretical foundation of market-based control is presented followed by a description of the *Narada* wireless sensing and actuation nodes. These sections are followed by a description of the experimental setup and test procedure. Finally, results and conclusions are presented as well as recommendations for future work necessary to advance market based control.

2. MARKET-BASED CONTROL

The installation of large numbers of semi-active actuators (such as MR dampers) in a civil structure renders the disturbance rejection control problem as highly complex due to the sheer size of the actuator network. Commanding this actuator network using a distributed network of low cost wireless nodes introduces additional complexities in the form of distributed data, deterministic computing delays, and stochastic communication delays. These complexities make it difficult to administer control actions in a centralized manner. For complex distributed systems, a decentralized, agent-based approach is often more appropriate (Siljak 1991). While many agent-based control methods have been proposed, this study focuses on market-based control (MBC) because of its effectiveness when applied to structural control problems (Lynch and Law 2002).

In market-based control, decentralized controllers are designed to exercise autonomous action as economic agents operating within a marketplace. In free market systems, scarce system resources are allocated from seller agents, (according to their supply) to buyer agents (according to their demand) (Clearwater 1996). The aggregated effect of the buy-sell interaction between market agents results in an equilibrium market price, p, for the scarce resource. Based on the equilibrium price, the amount of resource allocated to each buyer is determined. When buying power (wealth) is distributed equitably and demand is generated rationally, market systems produce an optimal allocation of resources. In MBC, power sources (*e.g.*, batteries) represent the sellers of control energy while control devices (*e.g.*, actuators) represent buyers. Control devices seek to maximize their utility by purchasing power based on the demand imposed on them by vibration of the structure, P_B. Power sources seek to maximize their profit from the power they have to sell, P_S. In a closed system with n sellers and m buyers, the aggregated power supplied from all n sellers will be equal to the aggregated power demanded by all m buyers:

$$\sum_{i=1}^{n} P_{Si} = \sum_{i=1}^{m} P_{Bi} \tag{1}$$

Through aggregation of the supply and demand from all buyers and sellers in the network, the individual buyers' utility functions and sellers' supply functions are maximized within the constraints imposed by the utility and supply functions of all of the other buyers and sellers (respectively) in the system (Lynch and Law 2002). The multiple objectives of these agents are balanced in a Pareto optimal sense through computation of the equilibrium price dictated by the aggregated supply and demand functions. The way in which the supply and demand functions are defined will determine the allocation of control power in the MBC system during extreme loading events.

The objective of the control system is to protect the structure during extreme loading events by minimizing the vibration associated with these unwanted disturbances; thus, the demand for control power is naturally tied to structural response. The demand generated by the i^{th} DOF (and its associated buyer agent), is modeled as a function of displacement, x_i, and velocity, $\dot{x}_i$. A linear demand function is selected for simplicity, with a negative slope to ensure that an increasing price for power will result in a decreasing buyer demand:

$$P_B = -|f(x,\dot{x})|p + |g(x,\dot{x})| \tag{2}$$

where f is the slope of the demand function, g is the intercept, and p is the price for power, P. Both the intercept and magnitude of the slope increase with structural response. Various tuning constants, Q, R, S, and T are introduced into the demand function to provide freedom in establishing the relationship between response and demand (Lynch and Law 2004):

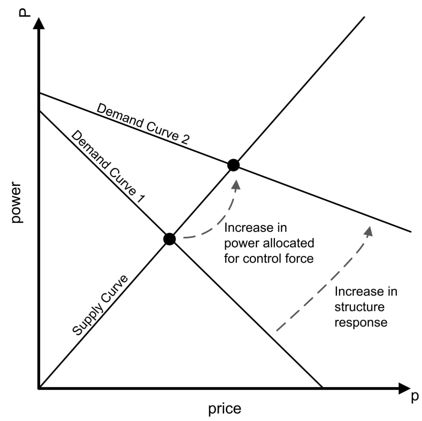

Figure 1 Equilibrium price increase due to increase in demand.

$$f(x,\dot{x}) = \frac{1}{Tx + Q\dot{x}} \tag{3}$$

$$g(x,\dot{x}) = Rx + S\dot{x} \tag{4}$$

As shown in Figure 1, the linear demand function effectively moves on the p-P plot as the response of the structure varies.

A simple linear supply function is selected with a positive slope such that power sources are encouraged to supply additional control power as the price of power increases. Furthermore, in the absence of demand, the supply function should be zero, necessitating the supply function intercept to be at the origin. With adequate tuning ability built into the demand function, a constant supply function with slope of $1/\alpha$ is selected:

$$P_S = \frac{1}{\alpha} p \tag{5}$$

A graphical depiction of the interaction of the supply and demand functions is presented in Figure 1. As demand increases, the price of power increases thereby stimulating additional supply. In a single DOF system, equating the supply (5) and demand (2) functions yields the control force, U:

$$U = K\left(\frac{|Rx + S\dot{x}|}{|Tx + Q\dot{x}| + \alpha} Tx + \frac{|Rx + S\dot{x}|}{|Tx + Q\dot{x}| + \alpha} Q\dot{x}\right) \tag{6}$$

where K is a conversion constant that translates equilibrium price to control force (Lynch and Law 2004). Generalizing this formulation to a multiple degree of freedom (MDOF) system introduces a true energy marketplace. To allow the allocation differential control authority in the design of the MBC system, each controller (market buyer) is allocated a fictitious wealth (*e.g.*, W_i for the i^{th} controller). The wealth factor is included as a multiplier to the i^{th} MDOF demand function (Lynch and Law 2002):

$$P_{Bi} = W_i\left(-\left|\frac{1}{Tx + Q\dot{x}}\right|p + |Rx + S\dot{x}|\right) \qquad (7)$$

To maintain balance in the system, selling agents are not allowed to accumulate wealth gained by selling control power to buyers. Rather, the money spent by each buyer is aggregated and redistributed evenly back to the buyers. Heavy consumers of energy will find their wealth gradually diminished, reflecting depletion of their local power supply. The MDOF equilibrium price is (Lynch and Law 2002):

$$p_{eq} = \frac{\sum_{i=1}^{m} W_i|Rx + S\dot{x}|}{\frac{n}{\alpha} + \sum_{i=1}^{m} \frac{W_i}{|Tx + Q\dot{x}|}} \qquad (8)$$

If a buyer retains sufficient wealth in excess of the equilibrium price of power, the buyer will purchase control power to generate the control force it desires (Lynch and Law 2002):

$$U_i = K\left(\frac{-p_{eq}W_i}{|Tx + Q\dot{x}|} + W_i|Rx + S\dot{x}|sign(Rx + S\dot{x})\right) \qquad (9)$$

The buyer's wealth will be debited by the amount of the control power purchased. The total wealth expended by all buyers is then summed and redistributed equally to all buyers in the network. Finally, the MBC generated control force is translated into a command voltage to be applied to the local semi-active controller.

3. NARADA WIRELESS SENSING AND ACTUATION NODES

Wireless control systems must include the functionality of traditional wired control systems. For example, high-fidelity response data is required for effective feedback control; thus, a wireless sensing node must incorporate sufficient sampling range and resolution to properly characterize the structural response under both relatively large and relatively small excitation levels. Another important functional feature of structural control is the commanding of actuators; hence, a wireless actuation node must be capable of commanding actuators. To exchange information between nodes, a wireless communication interface that introduces minimal communication latency is important to keep the sampling and actuation rate sufficiently high so as to preserve control performance and robustness. Finally, decentralized agent-based structural control (*e.g.*, MBC) over a wireless network requires network nodes capable of embedded, local data processing. These functional requirements strongly influence the design of the wireless nodes used for sensing, actuation and computing. The wireless sensing and actuation device employed in this study has been designed at the University of Michigan for real-time feedback control applications. The *Narada* wireless sensing and actuation node (Figure 2) incorporates a high-resolution, 16-bit sensor interface accommodating up to four sensing channels, an integrated actuation interface, a Zigbee-compatible wireless transceiver capable of communicating data rates up to 250 kbps, and a microcontroller capable of carrying out calculations.

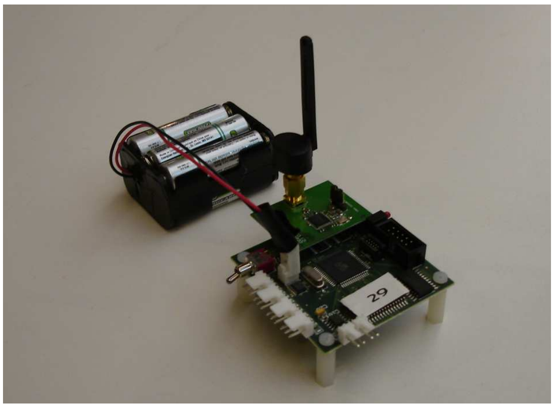

Figure 2 *Narada* wireless sensing and actuation node

The sensing interface of the *Narada* wireless node consists of a Texas Instruments ASD8341, 16-bit, 4-channel, low-power analog-to-digital converter (ADC). Sensor data digitized by the ADC is transmitted to the computational core of the *Narada* node via the serial-peripheral interface (SPI) of the node's microcontroller. The microcontroller is the Atmel Atmega128, a low-power, 8-bit microcontroller with 128 kB of flash memory for program instructions and 4 kB of static random-access memory (SRAM) for data and variable storage. An additional 128 kB of external SRAM is also provided for additional data storage on the sensor node. *Narada*'s link to the world (and other *Narada* nodes) is the Texas Instruments CC2420 IEEE802.15.4-compliant wireless transceiver. The CC2420 has been developed for low-power, ad-hoc wireless network applications, supports 16 independent channels in the 2.4 GHz range, can communicate up to 50 m (line of sight), and consumes approximately 60 mW of power. The *Narada* wireless node also includes an integrated actuation interface consisting of a Texas Instruments DAC7612, 12-bit, 2-channel digital-to-analog converter (DAC). The full capabilities of the wireless node are employed to execute the market-based control tasks outlined herein .

4. EXPERIMENTAL METHODS

The structure that is the subject of this study is a partial-scale, six-story steel structure (Figure 3) employing MR-dampers located between floors to provide control forces that reject seismically induced disturbances. Seismic disturbances are simulated by use of a 5 m x 5 m

Figure 3 Six-story test structure mounted to the 25 m^2 shaking table at the National Center for Research on Earthquake Engineering (NCREE), Taipei, Taiwan

6-degree of freedom (DOF) shaking table. The structure is composed of 2 cm steel plate floors supported at their perimeter by 5 cm x 5 cm x 0.5 cm angles; each floor is vertically spaced by 1.0 m. Floors are supported by 15 cm x 2.5 cm rectangular columns bolted to the corners of the floors and oriented such that lateral loading introduced by the shaking table is applied in their weak direction. Rigid connections are provided for the columns at the base of the structure. Diagonal braces mounted to the bottom of each floor provide the connection points for MR-dampers (Lord Corporation RD-1005-3 MR dampers) that indirectly actuate control forces between floors. By changing the current supplied to the MR-dampers, the level of damping between the floors may be changed in real-time. The interstory force applied by the MR-damper is a function of the input current as well as the differential velocity between those floors.

Narada wireless sensing and actuation nodes are installed on every floor in the structure as well as at the base. Each node is equipped to measure the acceleration response of the floor upon which it is located (using low-cost Crossbow CXL02 capacitive accelerometers). The acceleration measurements are input to a static Kalman state estimator to compute the displacement and velocity of each DOF. The displacement and velocities are input to the MBC demand function embedded in the wireless node measuring acceleration. Local demand functions are calculated at each sensor with the slope and intercept of each DOF's demand function communicated to the network over the wireless channel. Assuming a constant supply function, an equilibrium price for power can be calculated based on the aggregated demand. The equilibrium price is determined based on the aggregated demand and supply functions. The equilibrium price allows each MR damper to determine the power (and amount of control force) to be applied to the structure. However, because the MR-dampers do not generate force directly, computation of a hysteretic bi-linear, bi-viscous model is necessary within the *Narada* node based on the desired control force, damper velocity, and damper state (Lynch, *et al.* 2008). The *Narada* node commands the MR-damper over its actuation interface by issuing an analog command voltage that is converted into a proportional current supply for the damper.

Aggregation of buyer demand and seller supply information implies the existence of a "marketplace" in which market agents interact in a competition. To carry out such a market place, wireless communication would need to take place at each time step so that buyer and seller agents could exchange their information (namely, demand and supply functions). However, heavy use of wireless data transmissions would incur cost in terms of increased latency in the control solution due to deterministic effects (*e.g.*, transmission time and packet overhead) as well as stochastic effects (*e.g.*, lost packets and resend protocols) (Wang, *et al.* 2007). In structural control applications, the latency introduced due to wireless communication has a significant effect on performance (Wang, *et al.* 2007), therefore redundant embedded computation of control parameters can decrease the reliance on the wireless channel, decrease latency, and improve both control performance and reliability of the wireless communications within the network (Swartz and Lynch 2009). In this study's implementation of the market-based control solution, each wireless sensor contains a predetermined supply function that is never transmitted. Rather, the communication channel is reserved only for communication of each buyer agent demand function. In this case, each sensor in the structure takes its displacement and velocity measurement to determine its linear demand function (Equation 7). This information is broadcast by each node with every other node receiving and aggregating all of the demand functions. Once local energy demand is communicated over the network, individual agents will each perform the market aggregation and computation of the equilibrium price in a parallel and redundant fashion, thus trading communication bandwidth for computing. Using the equilibrium price, local control forces can be calculated using the local demand function. In addition, the wireless sensors each determine their wealth, W_i, available for the next time step. This process continues for each time step of the control system.

Design of the MBC controller requires the assignment of values to the tuning parameters in the supply and demand functions in equations (6), (7), and (8), namely, Q, R, S, T, α, and K as well as the initial wealth values, W_i, allocated to each controller. Preliminary studies in the simulation environment found that placing a relatively high weight on the scaling factor applied to the displacement term in the denominator of the demand function (T) yielded the best results in terms of keeping the peak interstory drift experienced by the structure during an earthquake as small as possible. Therefore, the weighting parameters derived

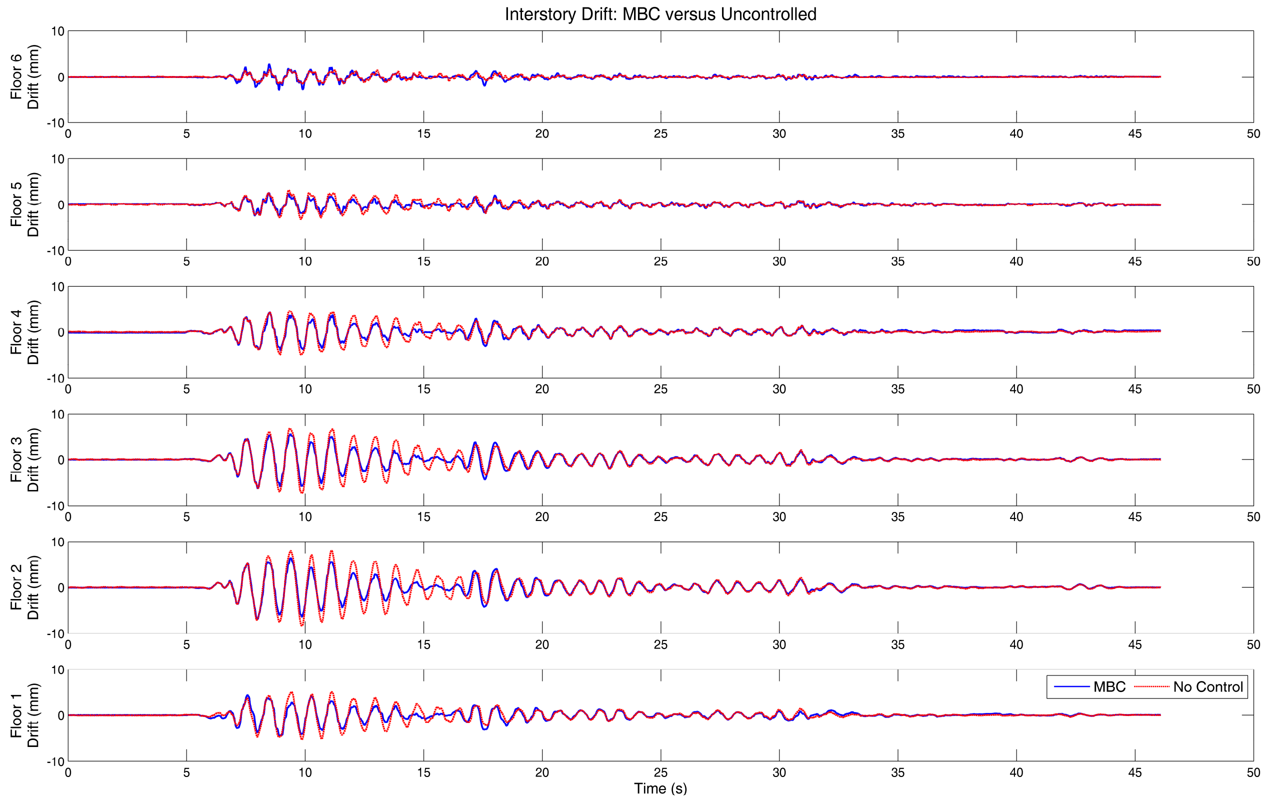

Figure 4 Time-history drift response of the six-story structure to the scaled El Centro ground motion system under MBC (K = 20 and initial wealth W_i = 1000 for all floors)

from the tuning of the method in a simulation environment (MATLAB) and implemented experimentally are:

$$Q = 1,\ R = 1,\ S = 1,\ T = 1000,\ \alpha = 1 \qquad (10)$$

In the MBC formulation, the magnitude of control force can be calibrated in one of two ways. The first method is to adjust the balance between the price of power and the wealth of the controllers (more wealth or lower price results in more aggressive use of control force). The second method is to simply increase the conversion factor, K. In this study, increasing levels of initial controller wealth are allocated to the wireless control agents coupled with varying levels of the conversion factor to explore the effects of these two different computational mechanisms. Tests utilizing uniform (all DOFs) initial wealth values of 400, 700 and 1000 are performed and varying K values of 4, 6, 8, 10, 20, and 30 are applied. The resulting control performance is measured in terms of interstory drift performance during repeated table motions with accelerations corresponding to the El Centro (1940 NS USGS Station 117) ground motion record scaled to a peak acceleration level of 1.0 m/s^2 (100 gals). A parallel tethered data acquisition system is installed in parallel to the wireless system to record displacement, velocity and acceleration of all six DOFs; these tethered measurements will aid in validation of the method. Results are presented in the following section

5. RESULTS

The MBC algorithm is run over the wireless network during eight identical El Centro ground motions simulated using the shaking table. A sample time-history response of the interstory drift recorded at each floor, with K equal to 20 and initial wealth equal to W_i = 1000 is presented in Figure 4. Here, the effectiveness of the MBC algorithm in mitigating the most extreme instances of seismically induced drift is evident. The first six ground motions are carried out with identical MBC parameters with the exception of the K factor which varies from 4 to 30. The peak interstory drift and normed interstory drift measured at each floor is presented for each value of K in Figure 5. It is demonstrated that control performance generally improves as the K value increases, particularly in the normed drift benchmark which is an indirect measurement of the average drift at a floor during the record. This is not true after a certain point however, as the performance suffers when K is increased from 20 to 30 suggesting a point at which the controller becomes too aggressive. Interestingly, extremely low values of K result in very mild improvements in normed drift (as one would expect) but worse performance than the uncontrolled structure as measured by peak drift.

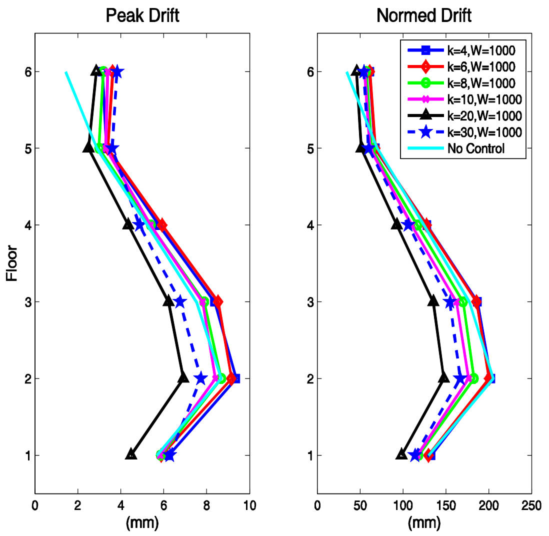

Figure 5 Peak and normed drift by floor due to the El Centro ground motion under MBC as the price to control force conversion factor increases

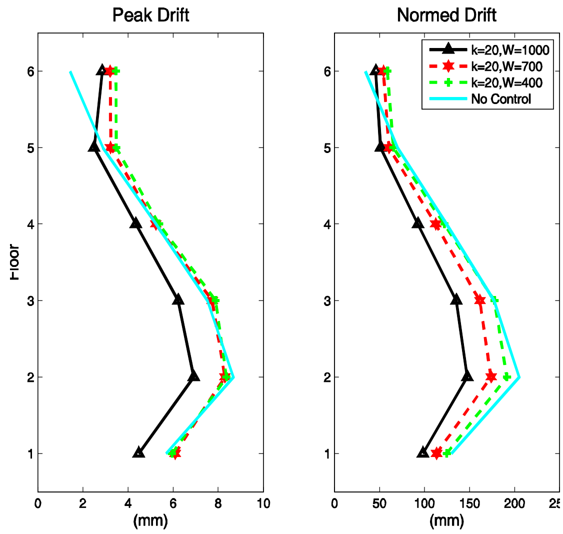

Figure 6 Peak and normed drift by floor due to the El Centro ground motion under MBC as the with diminishing initial wealth allocations

The level of response at which the buyers begin to purchase and exercise control power is affected by the wealth allocated to the agents. Without adequate wealth, the agents do not purchase power even when it would be beneficial to do so. This fact is evident in Figure 6 where peak and normed drift levels are plotted by floor for a constant K (K = 20) and varying values of initial wealth. Here, the lesser values of initial wealth result in very mild control effort (small improvements in interstory drift). With small allocations of wealth, the agents in the system are more successful in reducing the response of the structure as measured in the average sense (normed drift) than in the maximum sense (peak drift) as they are able to purchase power when the price is low. During periods of greater excitation that generate the peak drift values, the price of power increases to the point where it is not affordable to buyers with limited wealth thus demonstrating the need to allocate sufficient wealth to buyers in the system to accomplish the control objective.

6. CONCLUSIONS

This study experimentally assesses the feasibility of the MBC algorithm posed for structural control by Lynch and Law (2002). The algorithm is deployed within a wireless network composed of *Narada* wireless sensing and actuation nodes. *Narada* nodes are responsible for collecting feedback data regarding the response of the structure in the form of acceleration, computing control forces based on the MBC algorithm, and issuing commands to collocated MR-dampers. To find MBC control forces, the nodes must first find displacement and velocity using a Kalman state estimator. This response data is then used to generate demand functions defining the amount of control power desired by the network. A virtual marketplace for power is executed within the wireless network designed to minimize the data transmitted between wireless nodes. Control energy is distributed to controller agents based on the aggregated supply and demand according to their local demand. The power purchased by an agent is subtracted from its individual remaining wealth total. At the end of the control step, wealth collected by the sellers is returned to the buyers, divided equally regardless of how much each buyer purchased.

The MDOF MBC algorithm, as posed, includes several designer defined tuning parameters including demand function response multipliers (Q, R, S, and T), a supply function slope factor (α), a price to control force conversion factor (K) and initial wealth factors for each DOF (W_i). To maximize the effectiveness of the experiments run while the shaking table is available, effective values for the demand function response multipliers and the supply function slope factor are selected based on results found in simulation. For this experimental feasibility study, the effects of the conversion factor and the initial wealth factors on control performance are explored. It is demonstrated that careful tuning of the price-to-control force conversion factor is required to generate control forces large enough to produce meaningful results but not so large as to saturate the controller (similar to a gain factor is more traditional control algorithms). Similarly, adequate wealth allocation is necessary to allow control devices within the MBC network to purchase power when it is necessary. Depending on the price-to-force conversion factor, initial wealth allocation levels will affect the level of control force applied and the effectiveness of the control algorithm.

Future validation work on the MBC algorithm would be beneficial to further explore the effects of the tuning parameters on control performance. In addition, detailed stability analysis of the algorithm should be performed. This study exploits the inherent stability of the semi-active actuators employed to impart the control algorithm, but guaranteed stability for the generic actuator case would be preferable. Furthermore, this feasibility study uses the simplified case in which initial wealth is allocated in a uniform manner to all buyer agents. A rigorous study of the effects of wealth allocation would provide valuable insight into future design of MBC systems.

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