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Wireless Networked Distributed Controllers for Real-Time Control of Civil Structures

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***Abstract* — Civil structures are often exposed to strong winds and seismic loads resulting in large structural deflections. These undesirable deflections can be reduced by installing a structural control system within the structure. To reduce the costs associated with structural control systems, the eradication of expensive wiring required to transmit sensor data to a centralized controller is proposed. Taking advantage of decentralized control and wireless sensor network paradigms, a new approach to the design of a structural control system is presented. In this study, the feasibility of employing a wireless sensor network to both collect state-response data from sensors and to determine control forces is explored in detail. Wireless active sensing units designed to collect data from sensors, execute embedded algorithms and command actuators are adopted to serve as sensor/controller nodes within the wireless structural control system. Provided the real-time demands of the control system, wireless networks present some technological challenges (limited bandwidth, delays and loss of data packets) that must be addressed during the design of the control system. A distributed estimator framework is proposed to limit the use of the wireless communication channel leading to large-scale structural control systems with enhanced reliability.**

I. Introduction

SINCE the introduction of feedback control concepts to the structural engineering field thirty years ago [1], the use of active and semi-active control systems in civil structures (e.g. buildings and bridges) has grown in popularity. In recent years, semi-active actuators (e.g. variable dampers) have emerged as the preferred actuation technology for structural control. Unlike ordinary actuators that apply control forces directly to the structure, semi-active actuators are passive energy dissipation devices with the additional capability to change their dissipation properties in real-time. Semi-active actuators are attractive because they are compact, inexpensive and consume little power during operation; a direct result of these attributes is the continuously increasing number of semi-active actuators installed in a single structure, as witnessed by some recent structural control system designs [2]. Semi-active structural control systems defined by a large number of sensors and actuators present two challenges: first, the large-scale system places a heavy computational burden upon the centralized controller [3], and, second, greater lengths of cable are needed for communication between the centralized controller and system sensors and actuators. Since the installation of extensive lengths of coaxial cable in a civil structure is labor-intensive, structural control systems suffer from high installation costs [4].

Emerging advanced technologies can be adopted to address the challenges associated with large-scale structural control systems. In particular, mobile computing (e.g. microcontrollers) and wireless communication technologies can be employed to enhance functionality while driving total system costs down. For example, to measure the state of a dynamically excited civil structure, wireless structural monitoring systems have been proposed as low-cost alternatives to expensive tethered structural monitoring systems [4, 5, 6]. Wireless structural monitoring systems are constructed from wireless sensing units installed throughout the civil structure. Each wireless sensing unit consists of a sensing interface to which sensors can be attached (i.e. accelerometers), a computational core for local data interrogation, and a wireless radio for communication of data. A recent wireless sensing unit prototype, designed by Lynch, *et al.* [7], also includes an actuation interface that can be used to command actuators. The unit is termed a wireless active sensing unit and could be used in a real-time structural control system for collecting state data, calculating control forces and issuing commands to semi-active actuators embedded in the structure; a picture of the prototype wireless active sensing unit is shown in Fig. 1.

While the use of wireless telemetry is compelling from both cost and functional standpoints, the wireless communication channel presents some technical challenges

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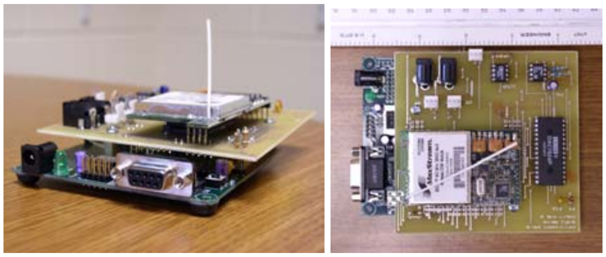

Fig. 1. Wireless active sensing unit prototype proposed for decentralized control of civil structures: (left) perspective view, and (right) top view.

that must be addressed during the design of a closed-loop control system. The physical layer of the wireless channel can experience four naturally occurring phenomena that render it less reliable than cable-based counterparts: noise, path losses, multi-path effects and interference [8]. To overcome some of these challenges, a significant amount of hardware and software engineering has been invested by engineers to produce wireless technology that ensures reliable data delivery in a wireless network. For example, to minimize interference and corresponding bit errors, spread spectrum radio techniques are widely used. Similarly, network abstraction layers (e.g. TCP/IP) can be written in software to minimize the occurrence of data losses in the network. While these innovations greatly improve the reliability of the network, the occurrence of delays and data loss is still possible.

Delays and data loss (due to range or other factors) can greatly diminish the performance of a closed-loop control system. In recent years, a number of researchers have begun to explore the use of wireless communications in real-time closed-loop control systems. For example, Horjel [9] has investigated the suitability of using Bluetooth wireless communications for closed-loop control of an open-loop unstable plant (specifically, an inverted pendulum). Bluetooth communication is employed between a controller and a remote input/output unit that reads the pendulum state and commands a DC-motor actuator. Delays existing between the controller and input/output system are delineated into two types: static and stochastic delays. Static delays are a result of software processing the Bluetooth protocol and transmitting data over an RS-232 interface between a computer and the Bluetooth radio. Stochastic delays are a result of the wireless channel properties. For example, packet collision avoidance and the retransmission of data when data is not received can both contribute to the wireless channel's stochastic delays. Both static and stochastic delays are quantified by Horjel [9] and compensated for in a linear quadratic regulator controller using compensation techniques originally proposed by Nilsson [10].

Ploplys *et al.* [11] have explored the feasibility of closed-loop control over an IEEE 802.11b wireless network. Their study emphasizes the use of the user datagram protocol (UDP) to minimize communication overhead in the wireless network. Unfortunately, UDP does not guarantee data delivery thereby necessitating a unique timing scheme to ensure suitable closed-loop performance in the face of potential data loss between the controller and system sensors and actuators. For example, the sensors and actuators are both operated according to a real-time clock with sampling and actuating occurring on a regulated timing schedule. In contrast, the remote controller is operated in an event-driven manner with the controller calculating and wirelessly transmitting a control force only when sensor data is received. If no sensor data is received (due to the wireless channel), then no control force is calculated. If the channel prevents the actuator from receiving the command signal, the actuator is preprogrammed to not issue any actuation command for that time-step. Using an inverted pendulum, Ploplys *et al.* [11] has shown that feedback control of the inverted pendulum is possible at high-sample rates (200 Hz) and with minimal data loss (less than 5% of the total packets lost).

In this study, the feasibility of using wireless communications to eliminate the need for cables in a real-time structural control system is assessed. The wireless active sensing unit proposed by Lynch, *et al.* [7], is used to collect response data from sensors, calculate control forces, and issue actuation commands to the actuators of the structural control system. Recognizing the inherent limitation of using a wireless network to transmit data within the control system, the approach advocated in this study is to minimize the use of the wireless communication channel wherever possible. To accomplish this goal, a decentralized control approach using a distributed estimator framework is pursued for implementation within a network of wireless active sensing units. The approach is validated in a simulation environment using a numerical model of the semi-actively controlled Kajima-Shizuoka Building.

II. WIRELESSLY IMPLEMENTED DECENTRALIZED CONTROL

As structural control systems grow in size (increasing numbers of sensors and actuators), the centralized control solution becomes increasingly difficult to implement [3]. One alternative to a centralized control approach is to pursue a fully decentralized control solution. In a decentralized control system, multiple controllers are distributed throughout the structure with each controller determining control forces for a local set of actuators using a local set of sensors. The fully decentralized control solution preserves the computational autonomy of the individual controller since no communication is permitted between controllers. The performance of the fully decentralized control solution is generally below that of the traditional centralized approach since distributed controllers are provided limited global state data from which to calculate control forces. Improvements in the global system performance can be gained if distributed controllers are given the opportunity to communicate with one another as would be the case in partially decentralized control solutions.

The control solution proposed in this study is formulated for implementation upon a wireless network of distributed controllers (wireless active sensing units) installed in a civil structure. For each actuator in the structure, a wireless active sensing unit is collocated to calculate control forces based on measurement data obtained from sensors associated with the actuator's degree-of-freedom. The wireless communication channel can be used to transmit structural response data between wireless active sensing units. Traditional centralized control solutions would be difficult to implement upon a wireless controller network because the approach requires each wireless active sensing unit to wirelessly transmit its sensor data to all of the other controllers at each time step. With huge communication demand disproportionate to the available wireless bandwidth, delay in the delivery of time critical data and outright data loss might commonly occur. At the other extreme, a fully decentralized control solution could easily be implemented upon the network of wireless active sensing units but this approach would not take advantage of the wireless communication channel. Hence, a partially decentralized control solution with mild usage of the wireless channel is the most attractive solution.

In partially decentralized control, some communication is permitted between controllers. To implement a partially decentralized control solution upon a wireless network of distributed controllers, a control methodology initially proposed by Yook *et al.* [12] is considered for adoption. In networked control systems (traditionally implemented upon wired networks), network-induced delays can degrade the global system performance of the control solution. In particular, degradation of the control system performance can be significant for distributed networks defined by high nodal densities and excessive bandwidth demand. To minimize delays in the communication network, Yook *et al.* [12] have proposed a novel approach to minimize the use of the network, by introducing state estimation at each distributed controller. Identical estimators are coupled with each controller so that the controllers estimate the plant's full state response, given sensor data associated with the i^{th} controller's degree-of-freedom, y_i. The estimated state is used in the controller's feedback control loop to determine a control force, u_i, for the actuator associated with the i^{th} controller. To ensure that errors in the estimated state do not diminish the performance of the control solution, every controller is programmed to compare the estimated state response of its measured degree-of-freedom, $\hat{y}_i$, with its true sensed measurements, y_i. Only when the difference in the true and estimated response parameter exceeds a given threshold, does the controller broadcast the true measured degree-of-freedom response to the other controllers on the network. When the other controllers receive measured state data, they update their won estimated states with the true measured parameter. This approach gives additional computational responsibility to the controller (i.e. state estimation) in order to minimize the use of the network bandwidth. In their study, Yook *et al.* [12] have proven the stability of the closed loop networked control solution implemented using an estimator framework.

The goal of this study is to improve the reliability of the wireless communication channel that connects the large number of wireless active sensing units (acting as distributed controllers) installed in a structure. Similar to cable-based networks, increases in the use of the available bandwidth in a wireless network will result in greater delays in the delivery of data [13]. Therefore, the state estimation framework introduced by Yook *et al.* [12] would be appropriate for use in the distributed control system constructed from wireless active sensing units. In this study, state estimation will be performed by each wireless active sensing unit to achieve a partially decentralized control solution that minimizes the use of the wireless channel (thereby minimizing packet losses and delays) without sacrificing the performance of the control system.

III. The Kajima-Shizuoka Building

To validate the performance of a partially decentralized control strategy proposed for implementation upon a network of wireless active sensing units, the Kajima-Shizuoka Building located in Shizuoka, Japan will be employed. As shown in Fig. 2, the Kajima-Shizuoka Building is a 5-story steel structure whose floor area is 11.8 m by 24 m and total structural height is 18.6 m [14]. Located in a region of Japan known for routine seismic activity, a semi-active structural control system is installed in the structure to reduce structural deflections during earthquakes. Four semi-active hydraulic dampers (SHD) are installed in each of the structure's two external frames (in total, 8 SHD actuators are installed) to control the structure in its soft flexural direction. An advantage of using the Kajima-Shizuoka Building in this feasibility study is that the structure has been widely used in the past to validate the performance of other control methods [4, 14, 15].

A semi-active hydraulic damper is a passive hydraulic damper modified to contain an orifice valve between two adjacent chambers in the damper; the orifice opening is widened or narrowed to respectively yield a lower or higher damping coefficient. SHD actuators require little power to control the size of the orifice opening resulting in a power-efficient actuator consuming only 70 W of power. The damping coefficient of the damper can be varied from 1,000 to 200,000 kN-s/m. The damper generates an internal control force in the structure when the damper is attached to two portions of the structure that experience relative structural motion. When applied in civil structures,

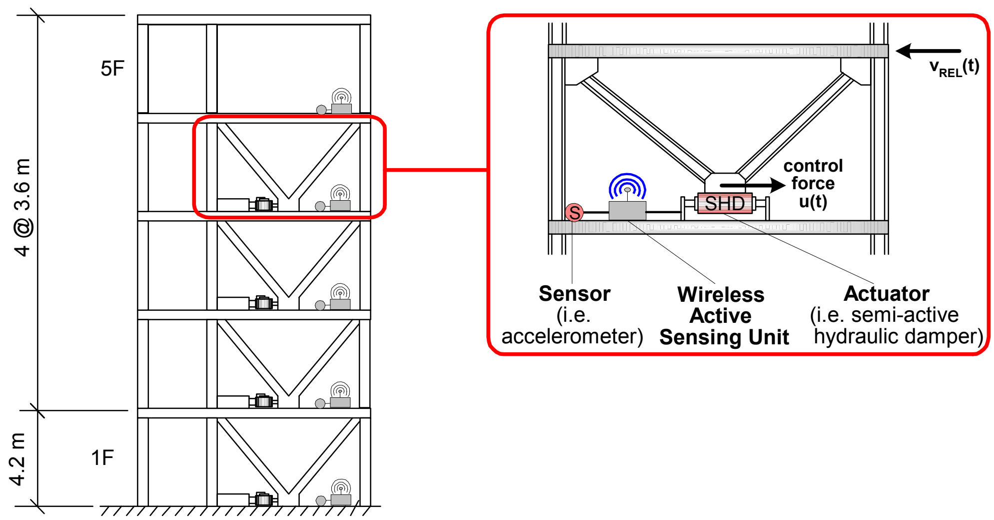

Fig. 2. The Kajima-Shizuoka Building is instrumented with wireless active sensing units acting as partially decentralized controllers commanding semi-active hydraulic dampers (SHD). State estimators are embedded in the computational cores of the wireless active sensing units to minimize the use of the wireless communication channel

SHD actuators are often attached to adjacent floors through a K-brace. The control force applied to the structure by an SHD actuator is equal to the relative inter-story velocity of the two floors to which the SHD device is attached times the SHD damping coefficient. To attain a desired control force, each controller must divide the control force by the inter-story velocity to determine what damping coefficient the SHD should be set to. The maximum permissible control force an SHD device can apply to a structure is documented as 1,000 kN [14].

A simulation environment is used to model the Kajima-Shizuoka Building so that the performance of a wirelessly networked partially decentralized control solution can be assessed. A linear time-invariant lumped-mass model of the Kajima-Shizuoka Building is formulated in MATLAB. The El Centro earthquake (North-South, 1940) ground motion record is applied to the base of the structure with the structural response determined using the central difference numerical integration technique. Numerical integration of the Kajima-Shizuoka structural model is done at a data rate of 100 Hz ensuring stability of the central difference approach. To account for possible delay in the transmission of commands to the actuators, a one time-step delay (0.01 sec) is intentionally introduced in the analysis. The dynamics of the actuator are included in the numerical model of the structural system with the SHD actuator - K-brace mechanism modeled as a Maxwell damping element [16].

In the model of the Kajima-Shizuoka Building, a wireless active sensing unit is installed in the structure upon each floor. As illustrated in Fig. 2, each wireless active sensing unit records the acceleration response of its respective floor and calculates desired control forces to be applied by the two SHD actuators located on each of the first four floors. When appropriate, the wireless active sensing unit can wirelessly transmit sensor data to the other wireless active sensing units installed in the structure. The wireless active sensing unit employs the low-cost MaxStream XCite wireless radio for communication. The radio communicates on the unregulated 900 MHz ISM radio band with ranges approximately 300 m in open space and 90 m on the interior of civil structures. The MaxStream radios are chosen for integration with the wireless active sensing unit design because of their low-power consumption characteristics (the radio only consumes 55 mA of electrical current when wirelessly transmitting and 35 mA when receiving). The MaxStream radios can communicate at an over-the-air data rate of 38.4 Kbps. The radios employ frequency hopping spread spectrum encoding so that their communication channel is reliable. The wireless active sensing units have been thoroughly tested in the laboratory to empirically measure the performance characteristics of the wireless communication channel.

IV. Performance of Decentralized Control System

A. *Centralized LQR Control Solution*

A centralized linear quadratic regulation (LQR) control solution is first determined for the Kajima-Shizuoka structure. In this study, the LQR control solution will be utilized in the implementation of a partially decentralized control system using an estimator based framework. Second, the performance of the LQR solution provides a baseline to which partially decentralized control solutions can be compared.

The Kajima-Shizuoka Building is modeled in state space form:

$$\begin{aligned}\{\dot{X}\} &= [A]\{X\} + [B]\{U\} + [G]\{w\} \\ \{Y\} &= [C]\{X\} + [H]\{w\} + \{v\}\end{aligned} \tag{1}$$

where $\{X\}$ is the state vector consisting of the displacement and velocity of each floor, $\{w\}$ a vector of the process noise and $\{v\}$ a vector of the measurement noise. An optimal controller gain is determined by minimization of the LQR cost function:

$$J = \int_0^\infty \{Y\}^T\{Y\} + \{U\}^T[R]\{U\} \tag{2}$$

In this study, the measured response of the system, $\{Y\}$, is a vector consisting of the displacement of the structure's floors. The matrix used to weigh the actuation signal relative to the response of the structure is set to $[R] = 1\text{x}10^{-13}[I]$. The centralized LQR solution is implemented in the structural system assuming that each controller is provided the global gain matrix, $[K]$ and is provided the complete state of the system, $\{X\}$ from which the control force can be calculated, $\{U\} = [K]\{X\}$. For each controller to have an accurate measurement of the state response, {X}, perfect lossless communication is assumed to exist between the wireless active sensing units. Each wireless active sensing unit wirelessly transmits the displacement and velocity of its associated floor to the other units. While the assumption of perfect communication is not realistic, the analysis of the centralized controller with perfect communication would represent the best possible control performance to which other more realistic control implementation can asymptotically converge towards.

The centralized control solution is simulated for the Kajima-Shizuoka Building using the El Centro ground motion record. The maximum absolute displacement for each floor of the controlled structure is plotted in Fig. 3. As can be seen, the maximum absolute displacement of the structure when controlled by a centralized controller is well below that of the uncontrolled structure. The centralized LQR solution implemented upon an ideal wireless communication channel (no delay or data loss) will serve as one baseline to which a partially decentralized control solution can be compared.

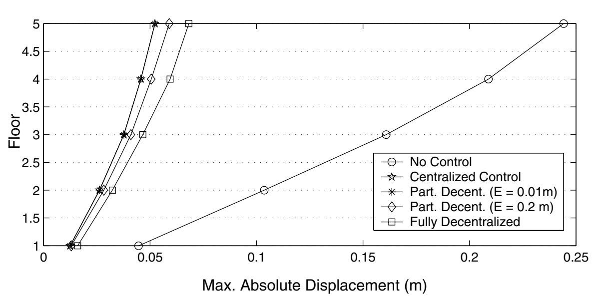

Fig. 3. Maximum absolute displacement of each story of the Kajima-Shizuoka Building exposed to the El Centro earthquake (1940 NS)

B. Fully Decentralized LQR Control Solution

In a fully decentralized control solution, the wireless active sensing units do not take advantage of the available wireless communication channel since they determine their control forces based on a single sensor measurement, y_i. To determine an appropriate control force, u_i, each wireless active sensing unit is programmed with a Kalman estimator to estimate the full state response, $\{X\}$ given the measured displacement, x_i, of its degree-of-freedom. For the design of a Kalman estimator for each controller, the covariance matrices of the process noise, $[Q] = E(\{w\}\{w\}^T)$, and measurement noise, $[R] = E(\{v\}\{v\}^T)$, are established as:

$$[Q] = \left[\begin{array}{c|ccccc} \ddots & & & \ddots & & \\ \quad 0 & & & 0 & & \\ \quad\quad \ddots & & & & \ddots & \\ \hline & 2.16 & 0 & 0 & 0 & 0 \\ \ddots & 0 & 2.28 & 0 & 0 & 0 \\ \quad 0 & 0 & 0 & 2.33 & 0 & 0 \\ \quad\quad \ddots & 0 & 0 & 0 & 2.38 & 0 \\ & 0 & 0 & 0 & 0 & 0 \end{array}\right]_{10x10} \tag{3}$$

$$[R] = 1$$

The controlled response of the Kajima-Shizuoka Building using a fully decentralized control solution is plotted in Fig. 3. As can be seen by the maximum absolute displacement of each floor of the structure, the controlled response is far lower than that of the uncontrolled structure. However, because of the fully decentralized architecture, the control performance is not as good as that of the centralized LQR solution.

C. Partially Decentralized LQR Control Solution

In the final analysis, a partially decentralized architecture is implemented within the Kajima-Shizuoka Building. In this approach, each wireless active sensing unit calculates an estimate of the system state response, $\{\hat{X}\}$, using the displacement of its respective floor, x_i. At each time step, the estimated displacement of the floor, $\hat{x}_i$, calculated by the wireless active sensing unit is compared to the true floor response, x_i. If the difference between the estimated and true floor response, $d_i = \hat{x}_i - x_i$, is small, then the controller does not communicate its displacement and velocity response. However, if the difference is larger than a pre-established error threshold, E, then the unit is programmed to wirelessly broadcast the true displacement and velocity of the floor to allow the other controllers to update their state information. The error threshold selected has direct bearing upon both the congestion experienced in the wireless communication channel and on the quality of the state vector used to calculate the control force. Both congestion and state quality must be balanced to determine a reasonable error threshold that reduces the amount of

TABLE I
PROBABILITY OF THE LOSS OF TRANSMITTED STATE UPDATE DATA

	Receiver at Floor 1	Receiver at Floor 2	Receiver at Floor 3	Receiver at Floor 4	Receiver at Floor 5
Transmitter at Floor 1	-	0.17	0.34	0.51	-
Transmitter at Floor 2	0.17	-	0.17	0.34	-
Transmitter at Floor 3	0.34	0.17	-	0.17	-
Transmitter at Floor 4	0.51	0.34	0.17	-	-
Transmitter at Floor 5	0.68	0.51	0.34	0.17	-

delay experienced on the wireless channel to tolerable levels.

In this study, the error threshold is varied so that the corresponding control performance can be assessed as a function of the threshold. Two performance metrics are introduced to aid in understanding how the estimation error threshold impacts the control performance. The first evaluation criterion considers the maximum displacement of the structure based on inter-story drifts, $d_i = x_i - x_{i-1}$[17]:

$$J_1 = \frac{\max_{t,i}(|d_i(t)|/h_i)}{\max(x_{UC5})} \tag{4}$$

The J_1 evaluation criterion is the maximum absolute inter-story drift ratio, $|d_i|/h_i$, of the structure with h_i the height of the i^{th} story. The evaluation criterion is normalized by the peak displacement of the 5th story for the uncontrolled structure, x_{UC5}. The second evaluation criterion, J_2, is the total kinetic and strain energy of the structural response:

$$J_2 = \sum_{t=0}^{\infty} \{X\}^T \begin{bmatrix} K & 0 \\ 0 & M \end{bmatrix} \{X\} \tag{5}$$

The structure's stiffness, [K], and mass, [M], matrices are used to calculate J_2. The error threshold is varied from 10^{-9} m to 1 m with J_1 and J_2 calculated for each threshold.

Before running an analysis of the partially decentralized control solution using a state estimator framework on the Kajima-Shizuoka Building, the loss of data in the wireless network must be appropriately modeled. Similar to the work done by Ploplys *et al.* [11], if data is delayed in the wireless network and arrives after the control force is to be applied at a given time step, the late arriving state update is ignored. Provided the reduction of the signal-to-noise ratio (SNR) as a transmitter and receiver are spaced further apart, the probability of data loss in the Kajima-Shizuoka Building is modeled as dependent upon the location of the wireless active sensing units. Table 1 presents conservative estimates for the probability of data loss (or delay) in the wireless network. During simulation of the structure, a random number generator is used to determine if for a given time step and transmitter-receive pair, if the data is lost or not based on the probabilities presented in Table 1.

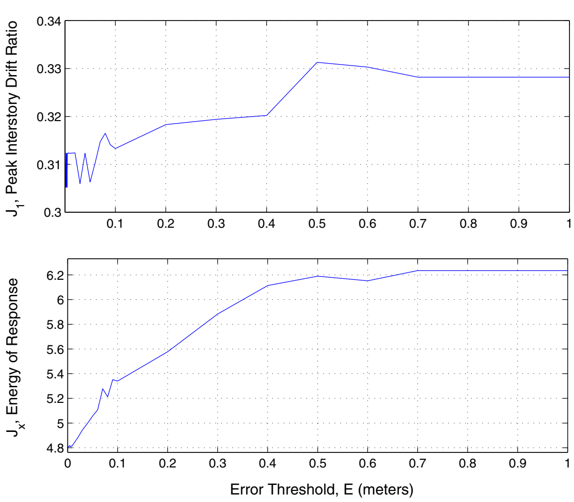

Fig. 4. Evaluation criterion, J_1 and J_2, of the Kajima-Shizuoka Building when exposed to the El Centro earthquake (1940 NS) as a function of the error estimation threshold.

As shown in Fig. 4, the evaluation criterion , J_1 and J_2, reduce as the error threshold is decreased from 1 to 10^{-9} m. As the error threshold decreases, the wireless communication channel is increasingly used. In the limit of reducing the error threshold to zero, the system converges towards the behavior of the initial centralized implementation. As the error threshold increases, the wireless channel is used less but the performance of the control system reduces. As shown in Fig. 4, the reduction in control performance is manifested by an increase in the evaluation criterion. Shown in Fig. 3 for an error threshold of 0.2 m, the maximum absolute displacement of the Kajima-Shizuoka is still superior to that of the fully decentralized control architecture (with no communication between controllers permitted).

V. CONCLUSION

In this study, the control of civil structures is proposed using a wireless network of wireless active sensing units. A partially decentralized control solution is utilized using state estimation to minimize the use of the wireless communication channel. Using a numerical model of the Kajima-Shizuoka Building, the wirelessly networked distributed controller architecture is shown to be capable of effectively controlling the structure during seismic disturbances. The unreliability of the wireless communication channel is modeled with estimates for the probability of updated state data being loss or delayed at a given time-step. The performance of the partially decentralized control solution is assessed as a function of the error threshold imposed on the difference in the estimated and true state response at each of the structure's degrees-of-freedom. As the threshold is reduced, the wireless communication channel is increasingly utilized and the control performance improves. In contrast, as the error threshold is increased, use of the wireless channel is reduced and the control performance decreases.

The work presented in this paper illustrates the potential of a wireless network of distributed controllers for the control of large-scale civil structures. The main contribution of the work is a numerical validation of a distributed control scheme tailored for implementation upon a wireless sensor network installed within a civil structure. Further work is needed to refine the assumptions made on the performance of the wireless network. In particular, the assumption of a one time-step delay in one wireless sensor sending data to another is potentially optimistic. As a result, future simulation is necessary to confirm the robustness of the advocated distributed control solution in the face of longer delays. Towards this end, work is already underway to empirically determine the probability of data loss and delay in data delivery in a wireless sensor network installed within an actual multi-story civil structure.

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