NETWORKED OVERLAPPING CONTROL FOR BUILDING BENCHMARK

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ABSTRACT. The article examines the problem of a wireless overlapped control design for seismically excited buildings. The earthquake-excited 20-story building benchmark study presents a new methodology based on overlapping decompositions, periodic digital network and switched linear systems approach. The solution consists of the construction of a wired overlapped LGQ controller which is followed by a wireless controller design. Simulation results illustrate the effectiveness of the proposed method.

KEYWORDS: Active structural control, networked control systems, overlapping decompositions

1 INTRODUCTION

Benchmark structural models have been proposed as challenging problems to the structural control community to design and compare control schemes for seismically excited structures [1], [2], [3], [4]. The benefits of decentralization in civil structures are used for instance in [5], [6], [7], [8], [9], [10], [11], [12], [13]. This paper deals with a novel method of the wireless overlapping controller design for the benchmark problem. It extends the construction of a wired overlapping controller presented in [14], [15] into a wireless control setting.

2 PROBLEM STATEMENT

The goal is to derive the methodology for the wireless overlapping-based LQG active control to mitigate responses caused by the earthquakes. A 20-story building structure benchmark is used to verify this approach. A complete physical description of the building benchmark problem is available in [1]. It includes in-plane (2D) finite element high-fidelity model presented in MATLAB/SIMULINK simulation framework and performance evaluation criteria. The responses of the structure on the input excitation of the four real world historical earthquake records are evaluated. The real world earthquake records are used to test the performance: (E_1) *El Centro* (1940), (E_2) *Hachinohe* (1968), (E_3) *Northridge* (1994), and (E_4) *Kobe* (1995). The N-S component of each earthquake record is used as the model input. Each proposed control strategy is evaluated for all earthquake records. The models, the number and the location of sensors and actuators should be proposed.

2.1 The Problem

The problem is formulated as follows:

1. Propose the overlapping decomposition of the building structure and the operating number of sensors and actuators including their locations on the floors.

2. Select sensors and actuators, reduce the original structure and design a wired overlapping LQG controller.

3. Perform simulations and evaluate the performance of the closed-loop overall system.

4. Construct the decentralized switched controller and check the performance of closed-loop system composed of the evaluation overall model with this controller.

5. Construct the wireless overlapping controller and check the performance with respect to packet dropouts and sensor/actuator faults.

3 THE APPROACH FOR SOLVING THE PROBLEM

The approach to solve the problem is divided into two parts. The first part deals with the design of a wired controller, while the the second part presents the wireless controller design. The results of the first part are appropriate gain matrices of the overlapped controller and the overlapped observer. These gain matrices serve as the gain matrices of a switched controller which is subsequently used for the construction of the final wireless controller. The wired and the switched controllers operating during each active mode are continuous-time controllers while the final wireless controller is a digital controller. The novelty of the paper are the results presented in the second part, while the results described in the first part are originally developed in [14] and further extended in [15] where the reliability issues are tested with a wired controller. Thus, the methodology corresponding to the first part is only surveyed and the original results of the part are presented in the next section. Note that our procedure needs only a total of 39 actuators while the procedure in the above references uses a total of 40 actuators.

The first part is surveyed as follows:
Given the structure S in Eq. (1), the evaluation model S_E in Eqs. (12)-(15), the evaluation criteria $J_1 - J_{15}$ in Eqs. (25)-(39). Select the model of sensors in Eq. (40) and the model of hydraulic actuators in Eq. (42) by [1]. The criterion J_{16} is defined by the authors as the maximal actuator force.

The controller design is performed using the Inclusion Principle. The details are available for instance in [16]. The basic idea is to expand under certain assumption the original system into with an overlapped part into a larger-dimensional system called expansion without overlapped part, to perform controller design for the expansion and finally to contract such a controller into the contracted controller applied in the original system.

A basic overlapping decomposition into two subsystems is considered as a prototype case. The lower substructure is composed of floors 1-12 and denoted as $S1$, while the upper substructure is composed of floors 8-20 and denoted as $S2$. The overlapping appears in the part of the columns between the 8th and the 12th floors. Sensors and actuators are allowed also in the overlapped part.

The controller design is presented for a given overlapping decomposition by the following scheme

$$S \rightarrow S1, S2 \rightarrow S1_R, S2_R \rightarrow S1_G, S2_G \rightarrow S1_D, S2_D \rightarrow S1_S, S2_S \rightarrow S1_B, S2_B \rightarrow S1_a, S2_a \rightarrow C1, C2 \quad (1)$$

where $S1_R, S2_R$; $S1_G, S2_G$; $S1_D, S2_D$; $S1_S, S2_S$; $S1_B, S2_B$, and $S1_a, S2_a$ denote the substructures $S1, S2$ after applying a Ritz transformation, a Guyan reduction, specification of damping, state space realizations of $S1_D, S2_D$, reduced state space models using a balance truncation, and the inclusion of sensor and actuator models into the resulting substructures, respectively. The proper LQG design performed for the reduced order substructures $S1_a, S2_a$ results in the local controllers $C1, C2$. The controllers $C1, C2$ are designed for the expanded system. They require to be contracted into the closed-loop evaluation system S_E. The procedure follows the design steps proposed in [1] applied on the substructure level.

The performance evaluation is realized by simulations on the overall closed-loop system as follows

$$S_E, C1, C2 \rightarrow S_E \& C_E \rightarrow \text{Simulation/Evaluation} \tag{2}$$

where C_E denotes the contracted controller obtained from the expanded controller composed of the disjoint controllers $C1, C2$.

Summarize only the basic computational details: The mass and stiffness matrices of the system S have the order of 540. A total of 6 sensors are located on floors 2,4,8,14,18 and the roof. A total of 39 actuators are located from the bottom to the roof as 2,1,1,1,1,1,1,1,1,2,3,4,4,4,2,2,1,1,3,3. The resulting controllers $C1$ and $C2$ have the controller gain matrices K1 and K2 of dimensions 12x43 and 13x44 and the observer gain matrices L1 and L2 of dimensions 44x3 and 43x3, respectively. The performance is primarily evaluated for the wired and the wireless feedback closed-loop systems using the values of criteria J_1 (Displacement), J_2 (Drift), J_3 (Acceleration), J_{16} (Maximal actuator force), and dynamic responses:

"Tables present maximal values of the performance criteria over all four earthquakes. Figures display the responses (Bold) to the Northridge earthquake record and the responses (Solid) of centralized sample example by [1] for the pre-earthquake and the post-earthquake models. The open-loop system responses are included (Dotted). The 20th floor displacement and acceleration as well as the 2nd floor drift responses are displayed on all figures", as summarized in [14, 15].

4 THE RESULTS

A novel construction of the wireless overlapping controller including the computational results correspond to the second part of the solution. Suppose availability of the controller C_E selected for the structure S_E from the first part of the solution. Construct a switched system composed of two modes periodically switched with the period of Δ as follows

$$S_E, C1, C2 \rightarrow S_E \& C1_E, S_E \& C2_E \rightarrow S1d, S2d \rightarrow S1w, S2w \rightarrow \text{Simulation/Evaluation} \tag{3}$$

where the closed-loop system $S_E \& C1_E$ active in Mode 1 operates with the controller $C2 = 0$ and vice versa in Mode 2. The switched system operates in continuous-time within each active period. Its digital network counterpart means that the ZOH is applied on the values of variables obtained at the beginning of each active period. $S1d, S2d$ denote the digital counterpart to the systems $S_E \& C1_E, S_E \& C2_E$, respectively. The digital subsystems $S1d, S2d$ are subject to packet dropouts. $S1w, S2w$ denotes the modes with the upper bound on dropouts. Upper bounds on dropouts are determined by the repeated computations for increasing number of particular dropouts till the performance requirements are satisfied.

Nominal cases and faults of sensors/actuators are distinguished for the proposed wireless control.

4.1 Nominal cases

(a)

	Pre	Post
J_1	0.9128	0.9878
J_2	0.8707	0.9975
J_3	0.9513	0.9998
J_4	0.9027	1.0842
J_5	0.8027	0.7841
J_6	0.7772	0.7256
J_7	0.7172	0.7309
J_8	0.7784	0.7304
J_9	0.0159	0.0147
J_{10}	0.0928	0.1006
J_{11}	0.0151	0.0157
J_{12}	0.0428	0.0337
J_{13}	39	39
J_{14}	6	6
J_{15}	62	62
J_{16}	863	796.91

(b)

	Pre	Post
J_1	0.9129	0.9838
J_2	0.8704	0.9975
J_3	0.9510	0.9996
J_4	0.9027	1.0839
J_5	0.8027	0.7841
J_6	0.7772	0.7256
J_7	0.7172	0.7308
J_8	0.7784	0.7305
J_9	0.0159	0.0146
J_{10}	0.0928	0.1004
J_{11}	0.0151	0.0157
J_{12}	0.0428	0.0336
J_{13}	39	39
J_{14}	6	6
J_{15}	62	62
J_{16}	862.86	796.61

(c)

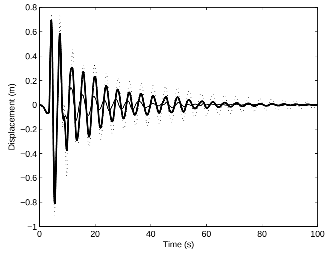
	Pre	Post
J_1	0.9132	0.9838
J_2	0.8705	0.9974
J_3	0.9510	0.9995
J_4	0.9028	1.0839
J_5	0.8028	0.7841
J_6	0.7773	0.7256
J_7	0.7172	0.7308
J_8	0.7785	0.7304
J_9	0.0159	0.0146
J_{10}	0.0928	0.1003
J_{11}	0.0151	0.0157
J_{12}	0.0428	0.0337
J_{13}	39	39
J_{14}	6	6
J_{15}	62	62
J_{16}	863	796.33

Tab. 1: Nominal cases: Maximal values of criteria over both models and all four earthquakes

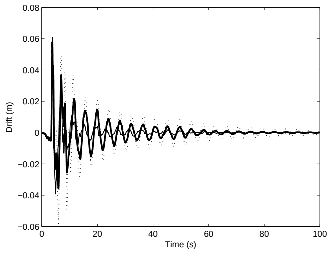
Three nominal cases are considered. Tab. 1(a) and Figs. 1, 2 present the results for the continuous-time LQG design without any faults. Tab. 1(b) and Figs. 3, 4 present the results for the switched system without any dropouts, while Tab. 1(c), Figs. 5, 6 and the details in Fig. 7 show the results with the upper bounds of packet dropouts. Upper bounds for dropouts are possible simultaneous dropouts up to the number 3 for both switched modes. The results are presented for the switched frequency of 100 Hz. The frequency is selected with respect to the stability, the amount of transmitted data and appropriate available wireless protocols such as WirelessHART or MBStar [17], [18].

4.2 Faults

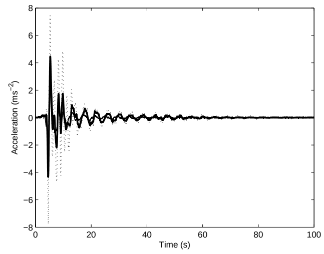
Sensor and actuator faults are considered to illustrate the robustness of the wireless overlapped controller with maximal dropouts. Tab. 2(a) presents the results for a total outage of the first sensor from the bottom, while Tab. 2(b) shows the results for a total outage of two actuators located at the 20th floor. Their responses are similar to those ones shown in Figs. 6,7. Thus, they are omitted.



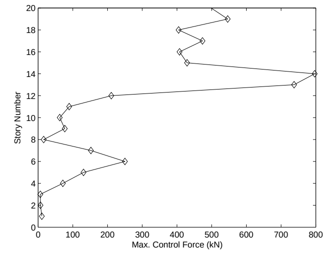
(a) Displacement



(b) Drift

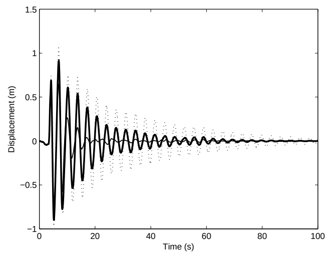


(c) Acceleration

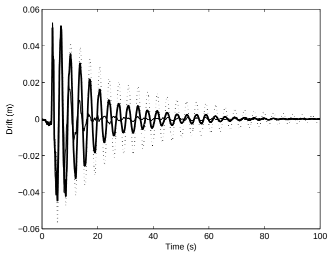


(d) Max. Control Force

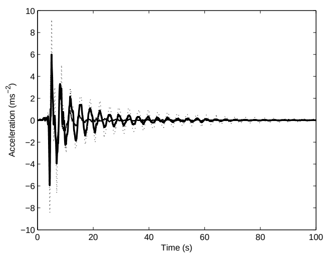
Figure 1: Pre-earthquake: No fault



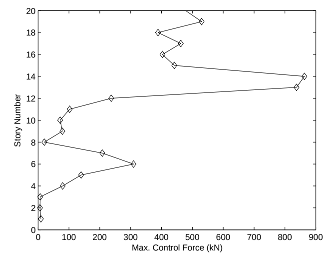
(a) Displacement



(b) Drift

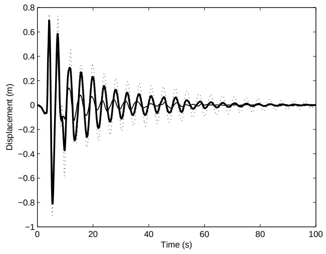


(c) Acceleration

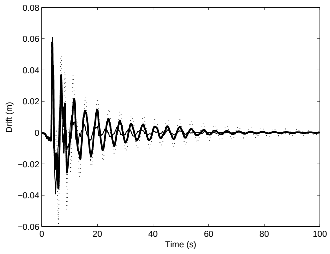


(d) Max. Control Force

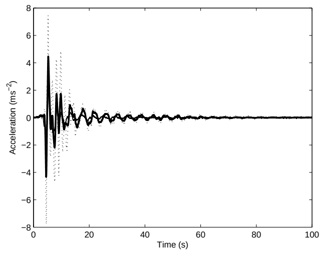
Figure 2: Post-earthquake: No fault



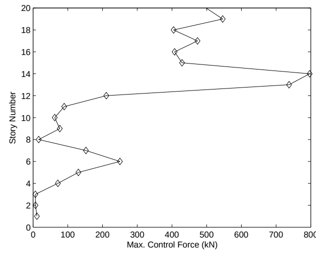
(a) Displacement



(b) Drift

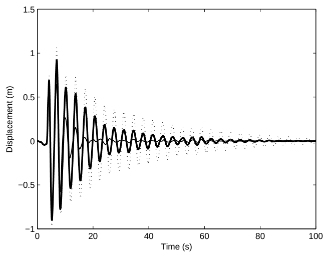


(c) Acceleration

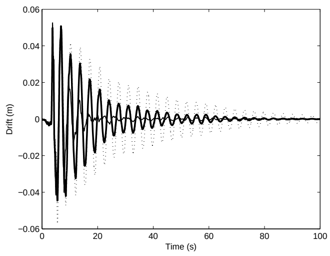


(d) Max. Control Force

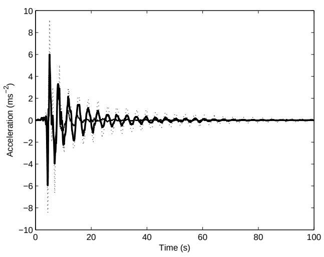
Figure 3: Pre-earthquake: Networked system responses



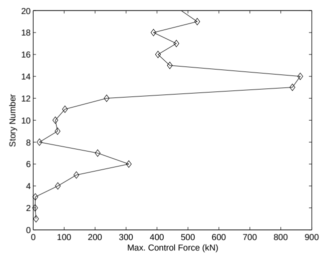
(a) Displacement



(b) Drift

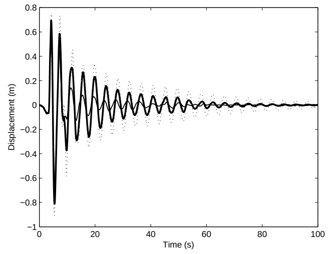


(c) Acceleration

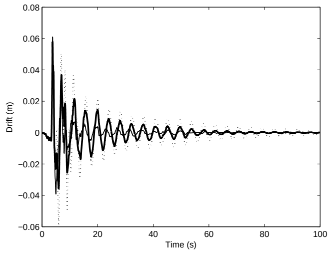


(d) Max. Control Force

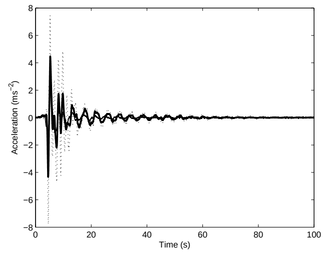
Figure 4: Post-earthquake: Networked system responses



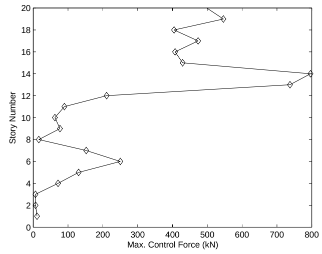
(a) Displacement



(b) Drift

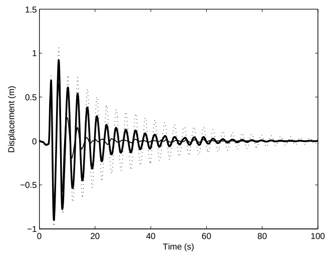


(c) Acceleration

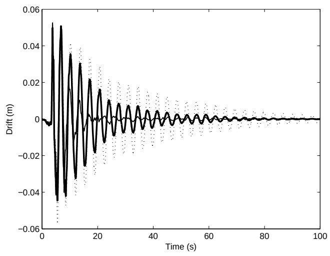


(d) Max. Control Force

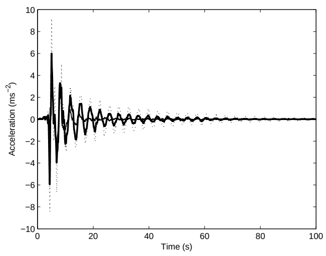
Figure 5: Pre-earthquake: Dropouts



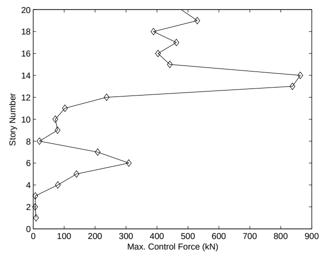
(a) Displacement



(b) Drift

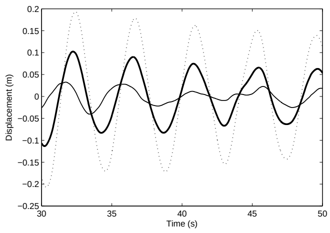


(c) Acceleration

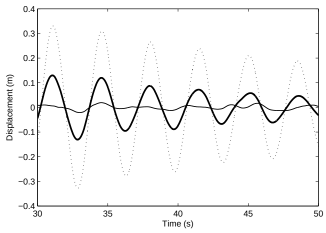


(d) Max. Control Force

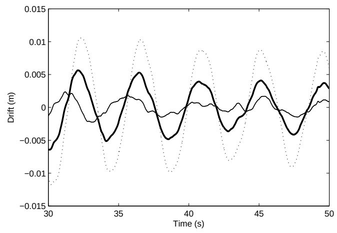
Figure 6: Post-earthquake: Dropouts



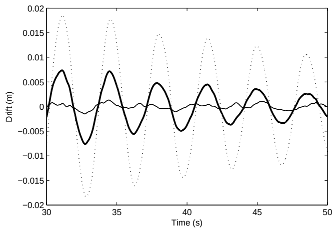
(a) Displacement pre-



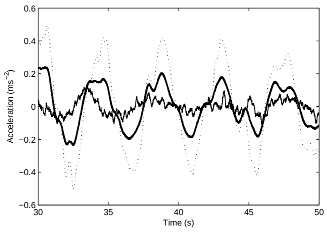
(b) Displacement post-



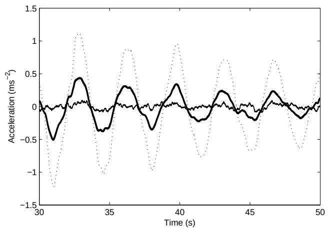
(c) Drift pre-



(d) Drift post-



(e) Acceleration pre-



(f) Acceleration post-

Figure 7: Dropouts: Detail

	Pre	Post
J_1	0.9130	0.9836
J_2	0.8689	0.9987
J_3	0.9558	0.9917
J_4	0.9032	1.0729
J_5	0.8029	0.7843
J_6	0.7774	0.7257
J_7	0.7177	0.7321
J_8	0.7785	0.7304
J_9	0.0159	0.0147
J_{10}	0.0931	0.1005
J_{11}	0.0151	0.0158
J_{12}	0.0420	0.0334
J_{13}	39	39
J_{14}	6	6
J_{15}	62	62
J_{16}	865.22	800.87

(a)

	Pre	Post
J_1	0.9372	0.9845
J_2	0.8904	0.9856
J_3	0.9477	0.9988
J_4	0.9105	1.0617
J_5	0.8414	0.8271
J_6	0.8143	0.7776
J_7	0.7754	0.7650
J_8	0.8152	0.7816
J_9	0.0138	0.0129
J_{10}	0.0994	0.0995
J_{11}	0.0135	0.0143
J_{12}	0.0402	0.0330
J_{13}	39	39
J_{14}	6	6
J_{15}	62	62
J_{16}	748.16	698.93

(b)

Tab. 2: Faults: Maximal values of criteria over both models and all four earthquakes under dropouts

5 CONCLUSIONS

The article addresses a new methodology of wireless overlapping LQG-based design focused on the 20-story in-plane (2-D) building benchmark problem. The benchmark study deals with the high-fidelity building FEM model to mitigate the responses of seismically excited buildings. First, the wired controller is designed. Then, the wireless controller is constructed using the gain matrices obtained in the wired case. The proposed decomposition into two overlapped subsystems serves only as a prototype case to illustrate the potential of this approach. The presented approach offers a variety of possible extensions in decomposition architectures and applied control design strategies.

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