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Wireless Structural Control Benchmark Problem

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ABSTRACT
In this work, a benchmark problem is proposed that allows the research community, through simulation, to examine the use of wireless accelerometers to provide feedback to the active control system. This benchmark problem considers an original 3 story building model equipped with an active mass driver (AMD) with the modification that it is instrumented using a wireless sensor network. The dynamics of the structure and control device and control-structure interaction (CSI) and realistic wireless sensor network are considered in this benchmark problem.

KEYWORDS: *Benchmark Problem, Wireless Structural Control, Wireless Sensor Networks, Dynamic Hazard Mitigation, Cyber-physical System.*

1. INTRODUCTION

Structural control systems are a class of cyber-physical systems that use real-time data from embedded sensors to make decisions and modify the behavior of a physical structural system. These systems have been demonstrated to be effective in improving the performance of structural systems exposed to extreme dynamic natural hazards. A broad set of control devices and systems have been investigated over the last few decades, each with its own pros and cons [1]. To enable the research community to compare various control algorithms using common performance measures and specified structures with realistic constraints, benchmark problems have been initiated by the American Society of Civil Engineering Committee and the International Association of Structural Control and Monitoring. A series of benchmark problems, initiated in 1998, are developed including the linear active mass driver control problem [2], the linear active tendon control problem [3], the linear full scale building control problem [4], the cable-stayed bridge control problem [5], the nonlinear full scale building control problem [6], the base isolation control problem [7] and the highway bridge control problem [8].

In recent years, wireless control systems are being considered as an alternative approach for structural vibration control. Several successful implementations of wireless control systems for building systems are reported [9-11]. However, a benchmark problem that captures both the dynamics of the structure and the realistic features of a wireless network is not available. In this work, a wireless control benchmark problem is proposed. The problem considers a representative benchmark AMD building model that is instrumented using a wireless sensor network (WSN). A time division multiple access (TDMA) protocol is employed in the WSN. The features of the WSN are simulated using TOSSIM, a state-of-the-art open-source simulator for WSNs. Wireless signal and noise traces collected from a real-world multi-story building are used as inputs to TOSSIM to realistically simulate the WSN such as the stochastic properties of transmission failures over different wireless links. To enable researchers in both civil engineering and computer science to use this benchmark problem to investigate a range of scenarios, users have the flexibility to change the features of the network (e.g. transmission schedule, route, signal and noise traces) as well as the characteristics of the wireless controllers (e.g. control algorithm, feedback measurements, sensor prioritization).

2. WIRELESS BENCHMARK PROBLEM

This wireless control benchmark problem integrates a representative benchmark AMD building model developed by [2] and a simulated wireless network developed with TOSSIM. The overview of the wireless building control model is shown in Fig. 2.1. Sensor measurements obtained from the structural model are fed through the simulated wireless network. Thus, delayed measurements that incorporate realistic data loss are used for closed-loop feedback control. The computed control command from the controller block is applied to the AMD to control the structural vibrations under seismic excitations.

The architecture of the benchmark model is presented in Fig. 2.2. The wireless benchmark model is running as a Matlab Simulink program. Transmitting data through the wireless network is accomplished by using an embedded Matlab function interfacing block to call python interface. Then a python program will supply the communication with TOSSIM. Pre-compiled binary files of TOSSIM are provided in this benchmark model. With these binary files, users save the effort to install TinyOS and TOSSIM to run the benchmark model. To change the schedule and route of the network as well as the wireless signal and noise traces and topology, users only need to change the corresponding input text files which are designed to be user friendly. More detail on how to modify the schedule, route, RSSI and noise traces is available in the benchmark user manual on the NEEShub (https://nees.org/groups/wireless_control_benchmark).

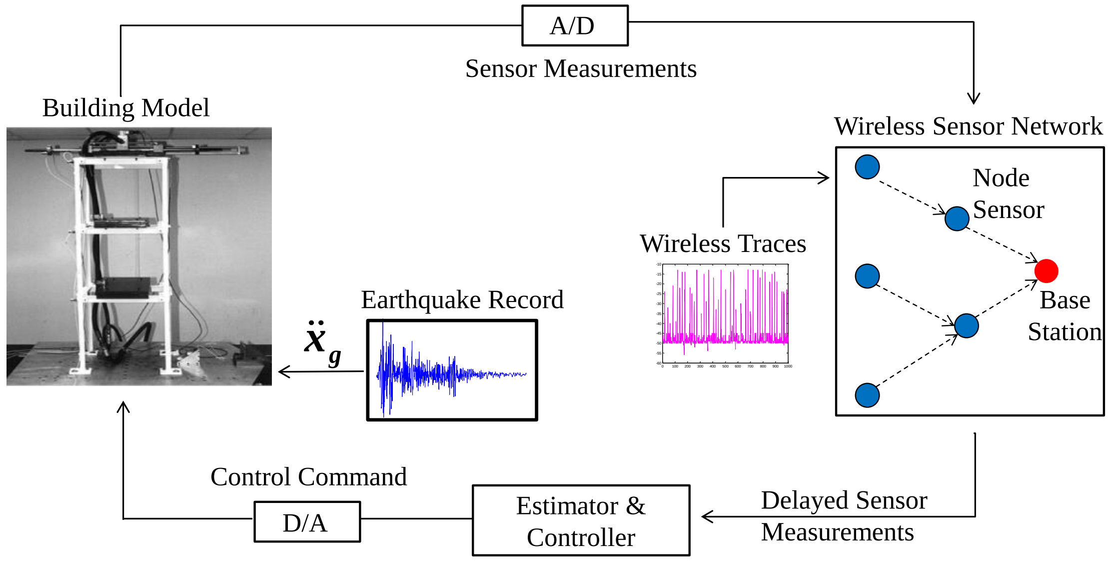

Figure 2.1 Overview of the wireless control benchmark model

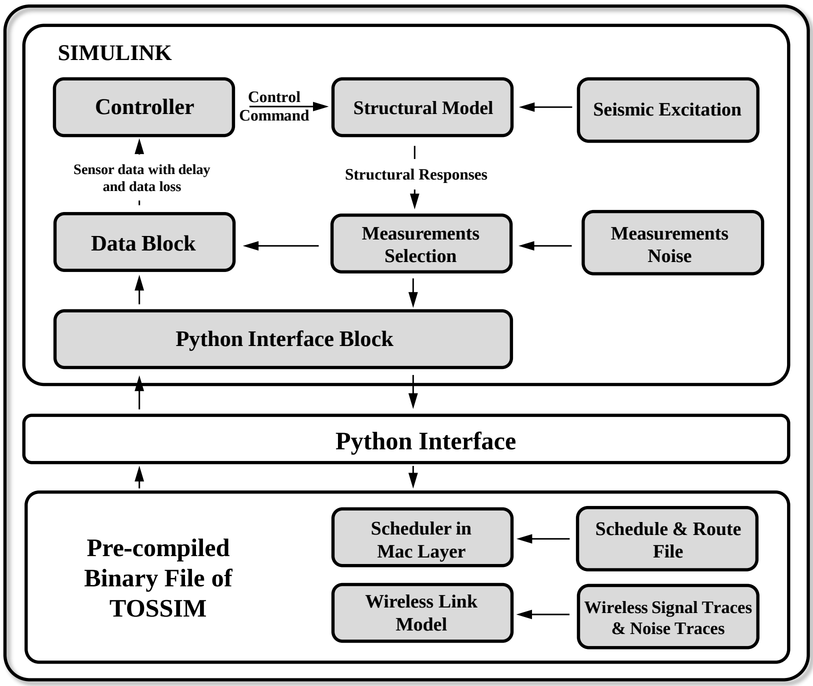

Figure 2.2 Architecture of benchmark model

2.1. Structural Model

The benchmark AMD structure is scaled model of a three-story building with an AMD installed on the top floor. The structure represents a prototype building with scaling parameters defined in the benchmark AMD model [2]: force = 1:60, mass = 1:206, time =1:5, displacement = 4:29 and acceleration = 7:2. The first three modes of the structure are at 5.81 Hz, 17.68 Hz and 28.53 Hz, with associated damping ratios 0.33%, 0.23% and 0.30%. The AMD consists of a single hydraulic actuator with steel masses attached to the ends of the piston rod. The structural dynamics, actuator dynamics along with CSI are included in the experimentally identified evaluation model of the structure. The evaluation model provided with this benchmark problem statement has good representation of the structure up to 100 Hz [2]. Four absolute acceleration measurements [$\ddot{x}_{a1}$, $\ddot{x}_{a2}$, $\ddot{x}_{a3}$, $\ddot{x}_{am}$] from the 1st floor, 2nd floor, 3rd floor of the 3-story structure and the AMD may be selected in any combination for feedback in the controller. The original building benchmark problem that considered this structure has been investigated by numerous researchers around the world.

2.2. Wireless Network Model

To realistically simulate the wireless network, experimentally collected noise traces and received signal strength indication (RSSI) traces are utilized as inputs to TOSSIM, which predicts the transmission success or failure based on a probabilistic signal to noise ratio model [12]. The traces are collected using Telosb devices [13] each equipped with a TI CC2420 radio (compatible with the IEEE 802.15.4 standard) deployed in a five-story building at Washington University in St. Louis. The building is a typical 1970's reinforced concrete construction with 3m floor height. A Telosb device is placed 10cm above the floor slab on each floor between the 2nd floor and the 5th floor. A single base station is placed on the 5th floor because the control device (AMD) is located on the top of the original benchmark AMD structure. The physical setup of the AMD anticipates the base station to be located on the top floor collocated with the control device. The network employs a TDMA protocol that divides time into time slots synchronized among all sensors and each time slot can accommodate the transmission of a data package. WSN standards based on IEEE 802.15.4 radios commonly employ 10msec time slot [14]. Each slot can accommodate the transmission of a data package and the local processing time. As the building model used for this benchmark is a scaled model and both time and length are scaled in the simulation using standard similitude laws, the 10msec time slot is scaled to 2msec to incorporate the 1:5 time scale into the same system simulation.

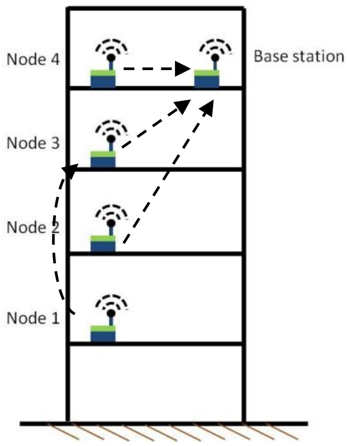

Figure 2.3 Wireless sensor deployment

3. BENCHMARK PROBLEM DEFINITION

The task of the researchers/designers in the benchmark control problems is to define an appropriate control strategy for this problem. An overview of the task is shown in Fig. 3.1. It is left to the researchers/designers to define the number of sensors (with the maximum number four) and their locations, the wireless network (data transmission schedule, route, etc.) and the control algorithm. The same set of evaluation criteria is adopted to evaluate the various applied control strategies.

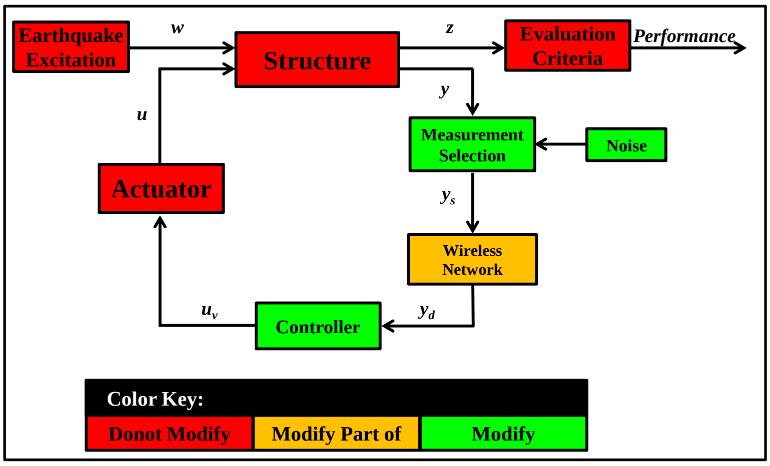

Figure 3.1 Overview of the researcher/designer tasks

3.1. Control Design

The control design problem is to determine a discrete-time, feedback controller of the form

$$\boldsymbol{x}_{k+1-l}^{c} = f_1\left(\boldsymbol{x}_{k-l}^{c}, \boldsymbol{y}_{k-l}, \boldsymbol{u}_{k-l}, k\right) \tag{3.1}$$

$$\boldsymbol{u}_{k-l} = f_2\left(\boldsymbol{x}_{k-l}^{c}, \boldsymbol{y}_{k-l}, k\right) \tag{3.2}$$

where $\boldsymbol{x}_{k-l}^{c}$, $\boldsymbol{y}_{k-l}$, $\boldsymbol{u}_{k-l}$ are the l step delayed state vector for the controller, the l step delayed output vector, and the control command, respectively, at time $t = kT$.

A reduced order model is developed for the control design by forming a balanced realization of the system and condensing out the states with relatively small controllability and observability grammians. The reduced order system is shown as follows

$$\dot{\boldsymbol{x}}_r = \boldsymbol{A}_r \boldsymbol{x}_r + \boldsymbol{B}_r \boldsymbol{u} + \boldsymbol{E}_r \ddot{x}_g \tag{3.3}$$

$$\boldsymbol{y}_r = \boldsymbol{C}_{yr} \boldsymbol{x} + \boldsymbol{D}_{yr} \boldsymbol{u} + \boldsymbol{F}_{yr} \ddot{x}_g + \boldsymbol{v}_r \tag{3.4}$$

where $\boldsymbol{x}_r$ is the reduced order states. Here, dim($\boldsymbol{x}_r$) = 10. $\boldsymbol{A}_r$, $\boldsymbol{B}_r$, $\boldsymbol{E}_r$, $\boldsymbol{C}_{yr}$, $\boldsymbol{D}_{yr}$, and $\boldsymbol{F}_{yr}$ are the reduced order state-space matrices. $\boldsymbol{v}_r$ is the measurement noise. $\boldsymbol{y}_r$ is the output vector of the reduced order model.

3.2. Sample Control Design

To illustrate the control design, two sample controllers are provided (the detail is in [15]). The sample controllers combine data aggregation strategies (for communication and control) with an optimal time delay (OTD) control algorithm [16], which considers a linear time-invariant system with a constant delayed control input. The sample control design is included to serve as a guide to the participants in this study and is not intended to be a competitive.

4. CONCLUSIONS

A wireless control benchmark problem is developed that combines a representative AMD benchmark model and realistic WSN. The high-fidelity benchmark model can be used as a numerical testbed to investigate wireless control issues such as network induced delay, data loss and sensor failure. The wireless control benchmark problem is released on the Neeshub (nees.org) with source codes, instructions and documentation files at https://nees.org/groups/wireless_control_benchmark. A journal version of the benchmark problem definition paper is also available online [15].

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