Realistic Case Studies of Wireless Structural Control

Bo Li¹, Zhuoxiong Sun², Kirill Mechitov³, Gregory Hackmann¹, Chenyang Lu¹, Shirley J. Dyke², Gul Agha³, Billie F. Spencer Jr.⁴

¹ Cyber-Physical Systems Laboratory
  Department of Computer Science and Engineering, Washington University in St. Louis
² School of Mechanical Engineering, Purdue University
³ Department of Computer Science, University of Illinois at Urbana-Champaign
⁴ Department of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign
Motivation

- Structural control is crucial in earthquakes/disasters
- Structural control systems with wires are vulnerable and costly
- Wireless Structural Control (WSC) offers flexibility and low cost

Heritage tower crumbles down in earthquake of Finale Emilia, Italy, 2012.  
Hanshin Expressway Bridge after Kobe earthquake, Japan, 1995.
Motivation cont.

- Existing wireless structural control experiments
  - usually rely on small lab structures
  - under ideal networking conditions
    - Line of sight, single hop, no packet loss

- Existing wireless control simulator
  - Truetime: entirely built in Simulink [Cervin 2003]
  - NCSWT: based on ns-2 with simplistic radio model [Eyisi 2012]

- Need high-fidelity cyber-physical simulator
  - Cyber: realistic wireless network characteristics
  - Physical: physical properties of real structures
  - Enable wireless control research and evaluation
Contributions

- Wireless Cyber-Physical Simulator (WCPS)
  - Integrate TOSSIM and Simulink/MATLAB
  - Open source: http://wcps.cse.wustl.edu

- Two case studies on wireless structural control
  - Wireless traces from real-world environments
  - Realistic structural models
  - Excited by real earthquake signals

- Cyber-physical co-design approach
  - Scheduling + Optimal Time Delay Control
  - Improve control performance under wireless delay and loss
WCPS Architecture

Simulink

- Structural controller
- Control information
- Structure model
- Sensor data
- Excitation

Earthquakes

El Centro Earthquake, CA, 1940

User Inputs

Network Manager
- Routing
- Scheduling
- RSSI
- Noise
- Wireless signal
- Wireless noise

Data Block

- Data with SS/UDS decisions
- Packet Collector
- Message pool

Interfacing Block

- Sensor data after delay and loss
- Cross-platform function call

TOSSIM

- Python interface
- Sensor data
- Return values of function call

Wireless Network

- Routing layer
- TDMA MAC layer
- Wireless link model

Sensor data after delay and loss

Return values of function call

TOSSIM

Sensor data

Control information

Structure model
Building Model

Test structure

Active Mass Damping System

1:1

Scaled Simulink Model

Bryan Hall, Washington U.

Mass ratio = 1:206

Acceleration ratio = 7:2

Time ratio = 1:5

Bryan Hall,
Washington U.
Bridge Model

Bill Emerson Memorial Bridge

- Replaced joints of the bridge by actuators
- 24 Hydraulic actuators
- Vibration mode:
  - 0.1618 Hz for 1\textsuperscript{st} mode
  - 0.2666 Hz for 2\textsuperscript{nd} mode
  - 0.3723 Hz for 3\textsuperscript{rd} mode
- Longitudinal direction
Wireless Trace collection: Jindo Deployment

- Largest wireless bridge deployment [Jang 2010]
  - 113 Imote2 units; Peak acceleration sensitivity of 5mg – 30mg
- RSSI/noise traces from 58-node deck-network for this study
Alternative Approaches

Baseline

- Sample Controller (SC) [Spencer 1998]
- Sequential Scheduler (SS)
  - Minimize sensing delay
  - Lose data synchronization

Cyber-Physical Co-Design

- Optimal Time Delay Controller (OTDC) [Chung 1995]
  - Designed for uniform sensing delay
- Uniform Delay Scheduler (UDS)
  - Longer sensing delay
  - Maintain data synchronization
Sample Controller + Sequential Scheduler

- Greedy data delivery
- Reduce sensing delay at the cost of data synchronization

<table>
<thead>
<tr>
<th>Control</th>
<th>Delay</th>
<th>Data eligible for control use</th>
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Base station

Sensor 4
Sensor 3
Sensor 2
Sensor 1

3/23/14
Optimal Time Delay Controller

- Maintain data synchronization at the cost of sensing delay
Reliable Uniform Delay Scheduler

- Trade network delay for reliability
- Maintain data synchronization
Building: Required Control Power

- OTDC (cyber-physical co-design) clearly outperforms SC
- For control power: data synchronization > sensing delay

structural control metrics [Spencer 1998]
Building: Structural Response

- SC vs. OTDC-1 leads to similar acceleration
- OTDC-2 vs. OTDC-3: excessive delay has larger impact than improvement in reliability

3/23/14
Bridge Control: Required Resource

- OTDC-1 needs nearly 50% less control power than SC

Structural control metrics [Dyke 2003]
Conclusion

- **Wireless Cyber-Physical Simulator (WCPS)**
  - Combines realistic wireless and physical simulations
  - Enables CPS research on wireless control systems

- **Realistic case studies**
  - Real-world wireless traces + structural models
  - Wireless structural control involves complex tradeoff
    - Data synchronization, latency, loss
  - WCPS enables WSC study in a realistic, holistic fashion.

- **Cyber-physical co-design: scheduling + control**
  - Improve structural performance under delay and loss


Reliability vs. Delay

By increasing $k$ in OTDC-$k$

- Sensor 1 with 2-hop routing, end-to-end delivery ratio 70% $\Rightarrow$ 90% by one more transmission;
- OTDC-3 has limited improvement of network reliability vs. OTDC-2