Wireless Structural Sensing and Feedback Control with Embedded Computing

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Outline

- Research Background
- Hardware and Software Design of the **Wireless Structural Sensing** System
- Validation Tests: Geumdang Bridge, Korea

  Laboratory Steel Frame at NCREE, Taiwan

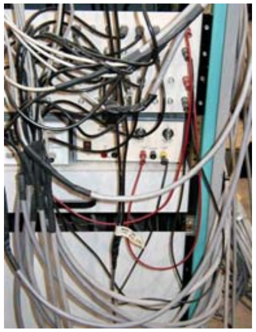
  Gi-lu Bridge, Taiwan
- Hardware and Software Design of the **Wireless Feedback Structural Control** System
- Half-scale Laboratory Steel Frame with MR Damper at NCREE, Taiwan

From Wire-based Sensing to Wireless Sensing

DISADVANTAGES OF WIRED CHANNELS

- E. G. Straser, and A. S. Kiremidjian (1998): Installation of wired system can take about **75% of testing time** for large structures
- M. Celebi (2002): Each sensor channel $5,000, **half of the cost** on installation (cabling, labor, etc.)
- I. Solomon, J. Cunnane, P. Stevenson (2000): over 1000 sensors on Tsing Ma Bridge, Kap Shui Mun Bridge, and Ting Kau Bridge. **36 km of copper cable and 14 km of fiber optic cable. 1 year installation.**

Traditional DAQ: **Wire-based**



Future **Wireless** DAQ System

Wireless SHM prototype system Jointly developed by researchers in Stanford Univ. and the Univ. of Michigan

Challenges in Wireless Structural Sensing

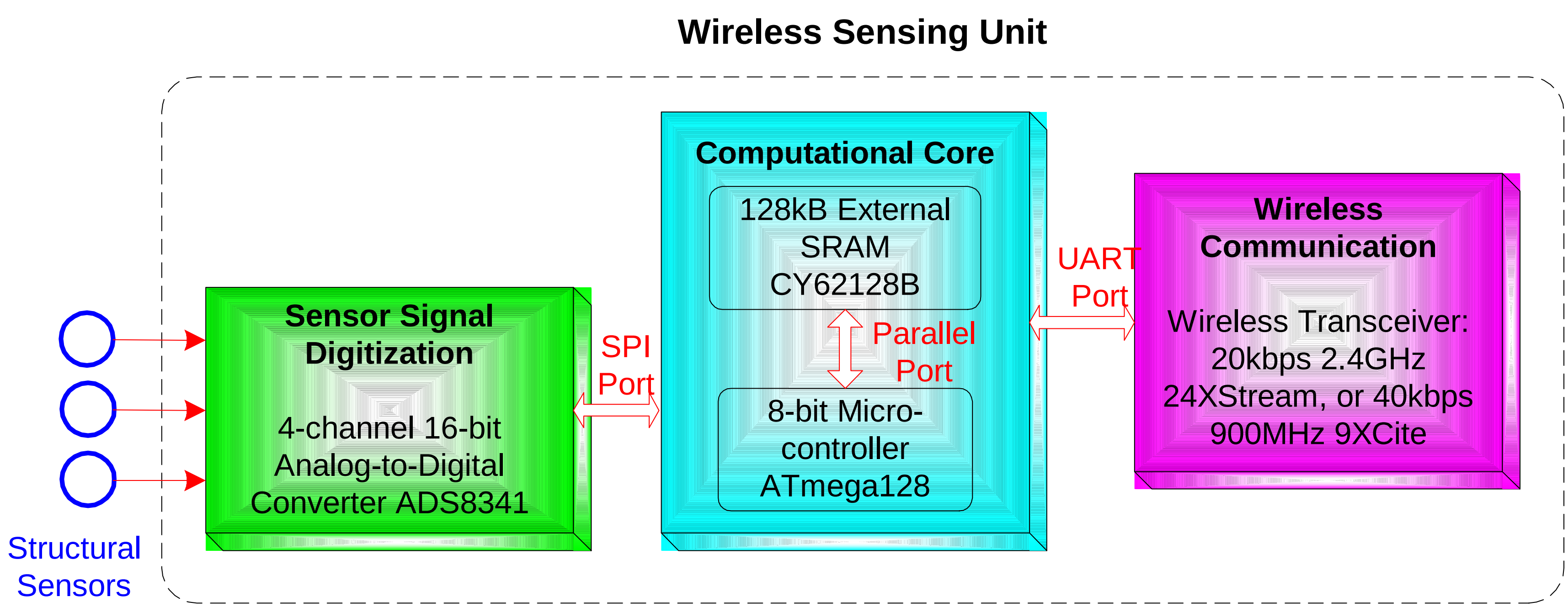
CHALLENGES

- Limited **power** consumption
- Restricted wireless communication **range**, **bandwidth, reliability**
- Difficulty for data **synchronization** and **real-time** data delivery

SYSTEM DESIGN PRINCIPLES

- Judicious **hardware** component selection
- Simple, efficient, and robust **software** design

Functional Diagram of Wireless Sensing Unit



Final Package of the Latest Prototype Unit

Antenna Length:
5.79” (14.7cm)

Container Dimension
4.02” x 2.56” x 1.57”
(10.2 x 6.5 x 4.0 cm)

- **Total power consumption with MaxStream 9XCite modem**
  - 75 – 80 mA when active; 0.1 mA standby. (5 VDC)
- **Wireless communication MaxStream transceiver**
  - **9XCite:** 90 m indoor, 300 m outdoor, 38.4 kbps
  - **24XStream:** 150 m indoor, 5 km outdoor, 19.2 kbps
- **Total unit cost using off-the-shelf components**
  - $130 for small quantity assembly (2004)

Wireless Sensing Network

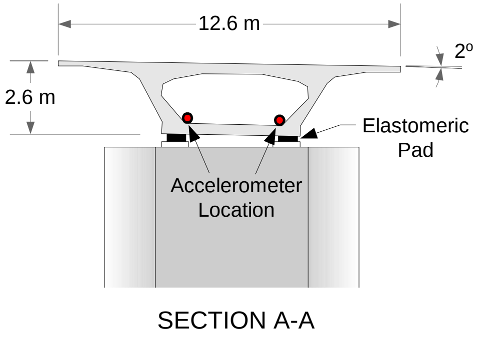
Server-side computer software

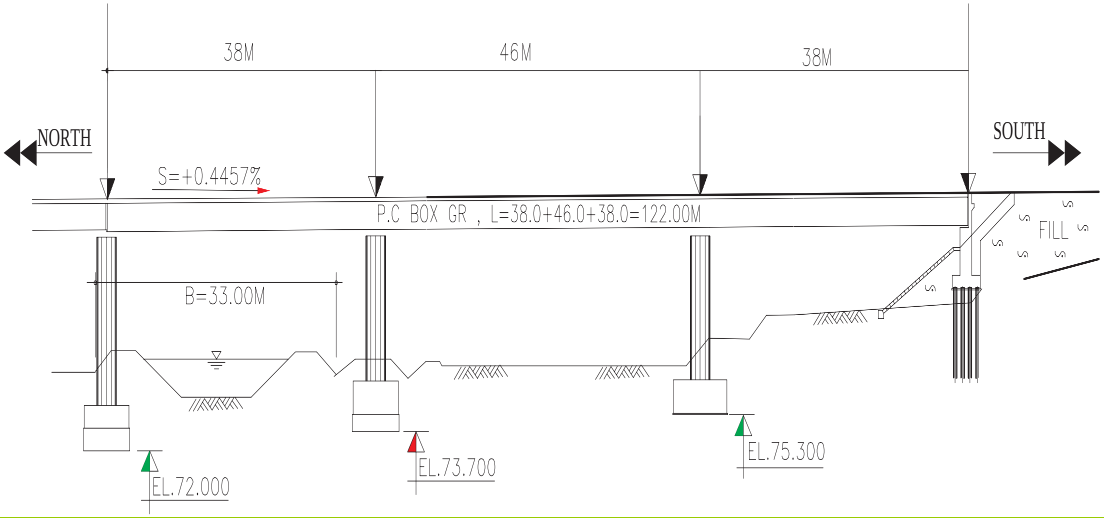
Firmware for wireless sensing units

- Simple star topology network
- Near-synchronized and reliable data collection from all wireless sensing units
- Communication protocol design using state-machine concept

Geumdang Bridge Test, Korea

Collaboration with Prof. Chung Bang Yun, Prof. Jin Hak Yi, and Mr. Chang Geun Lee,
Korea Advanced Institute of Science and Technology (KAIST)

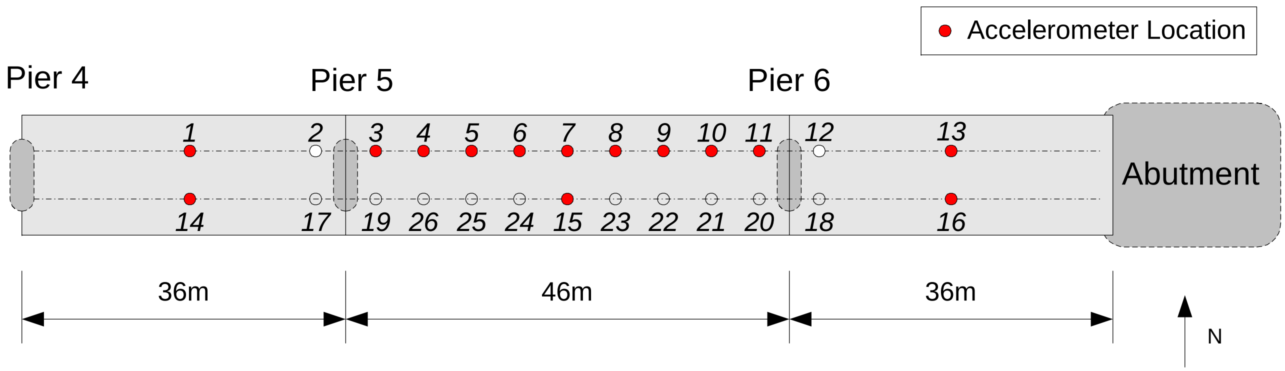


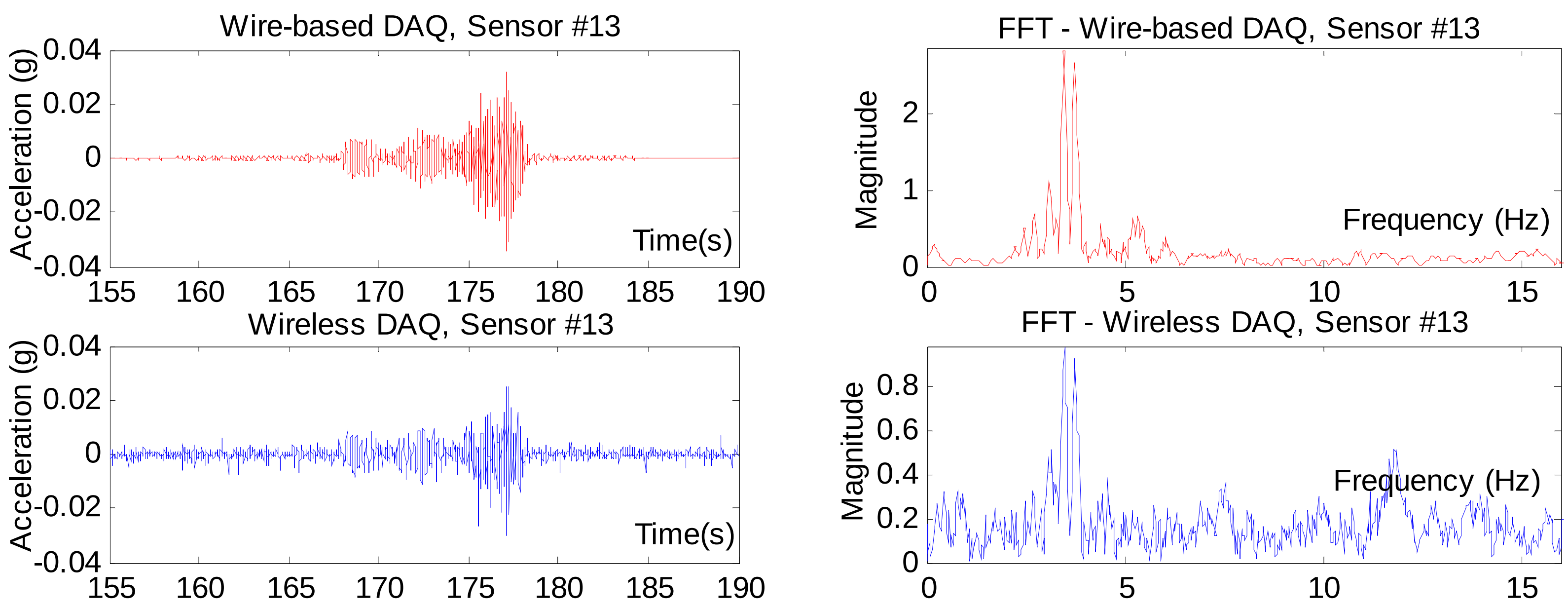


Wire-based System vs. Wireless System

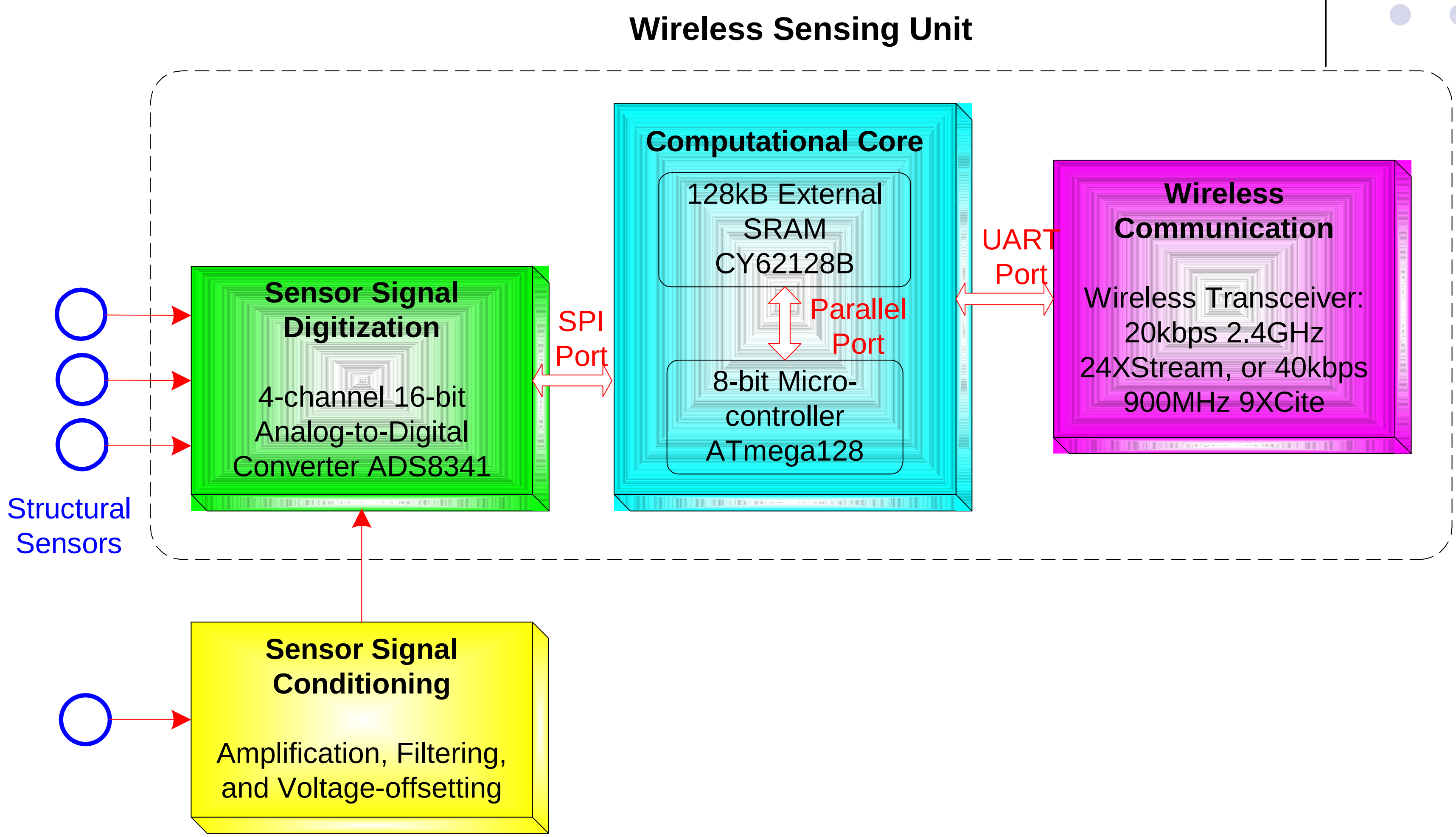
Sensor Property	PCB393 Piezoelectric (Cabled System)	PCB3801 MEMS Capacitive (Wireless System)
Maximum Range	±0.5g	±3g
Sensitivity	10 V/g	0.7 V/g
RMS Resolution (Noise Floor)	50 μg	500 μg
Minimal Excitation Voltage	18 VDC	5 VDC
Sampling Frequency	200Hz	200Hz / 70Hz

Comparison Between Two Systems

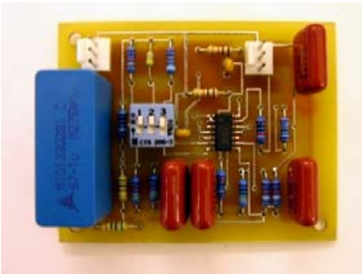




Functional Diagram with Sensor Signal Conditioning Module

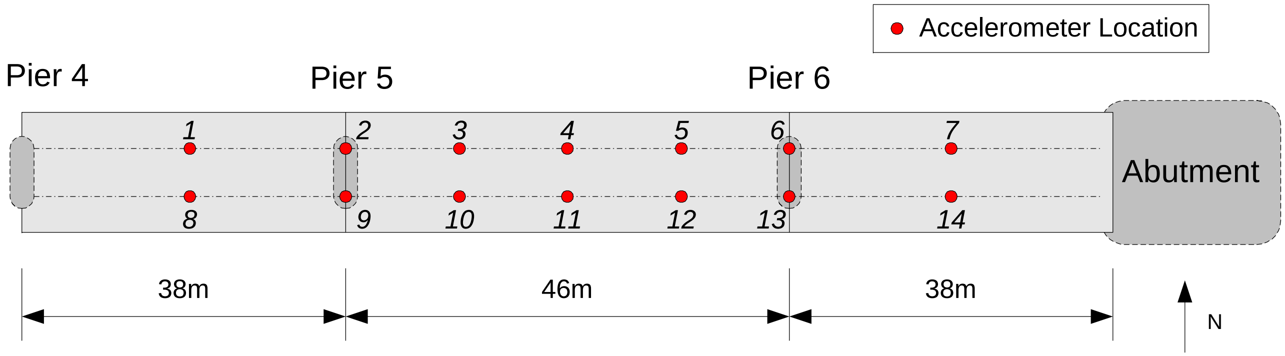


Latest Bridge Tests with Sensor Signal Conditioning



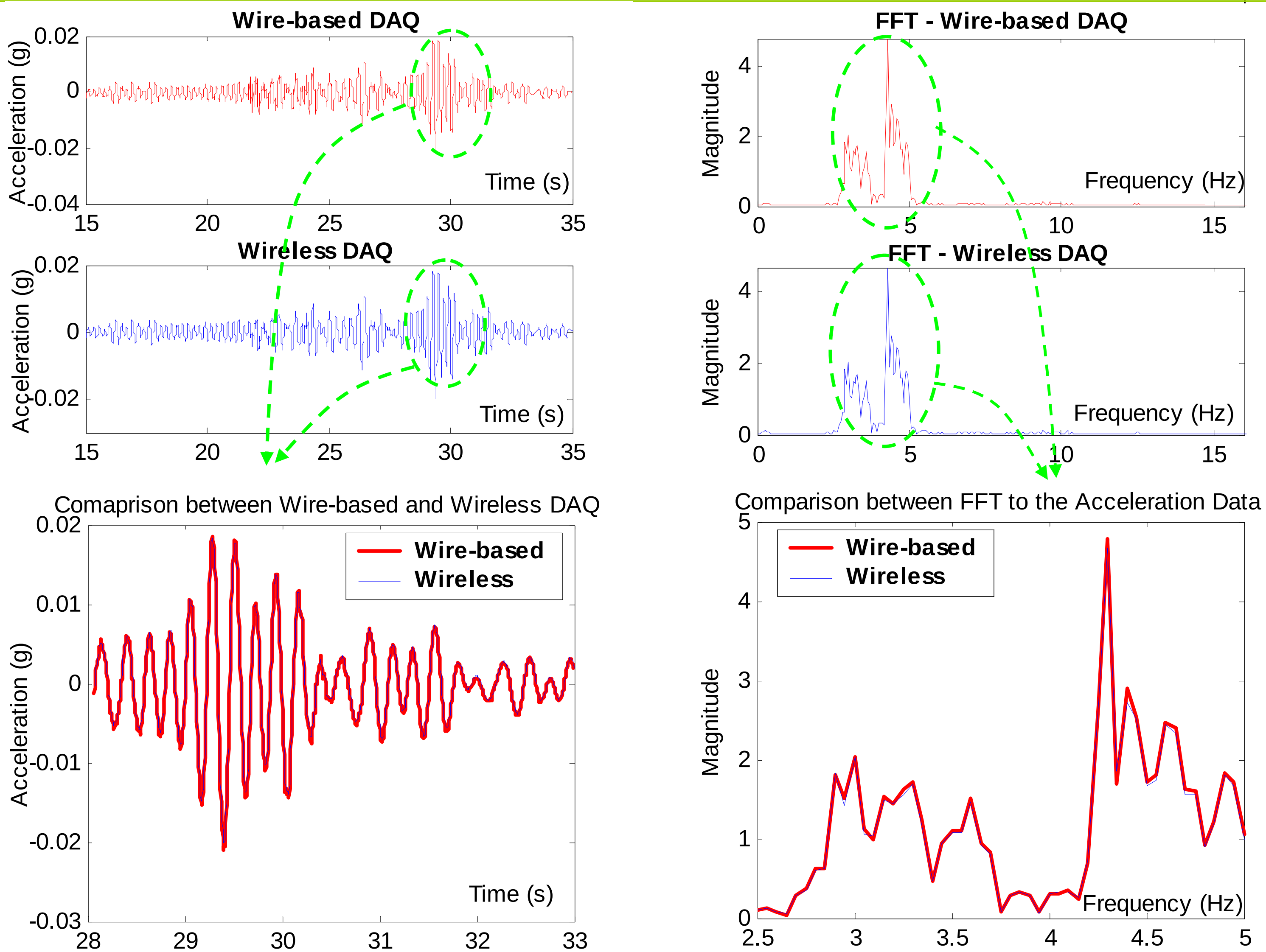
Printed circuit board of the signal conditioning module (5.0 × 6.5 cm)

- **Mean shifting**: any analog signal to 2.5V mean
- **Amplification**: 5, 10 or 20
- **Anti-alias filtering**: band pass 0.02Hz – 25Hz



Sensor Allocation for Tests at Geumdang Bridge, Jul 2005

Comparison for Wireless DAQ with Signal Conditioning

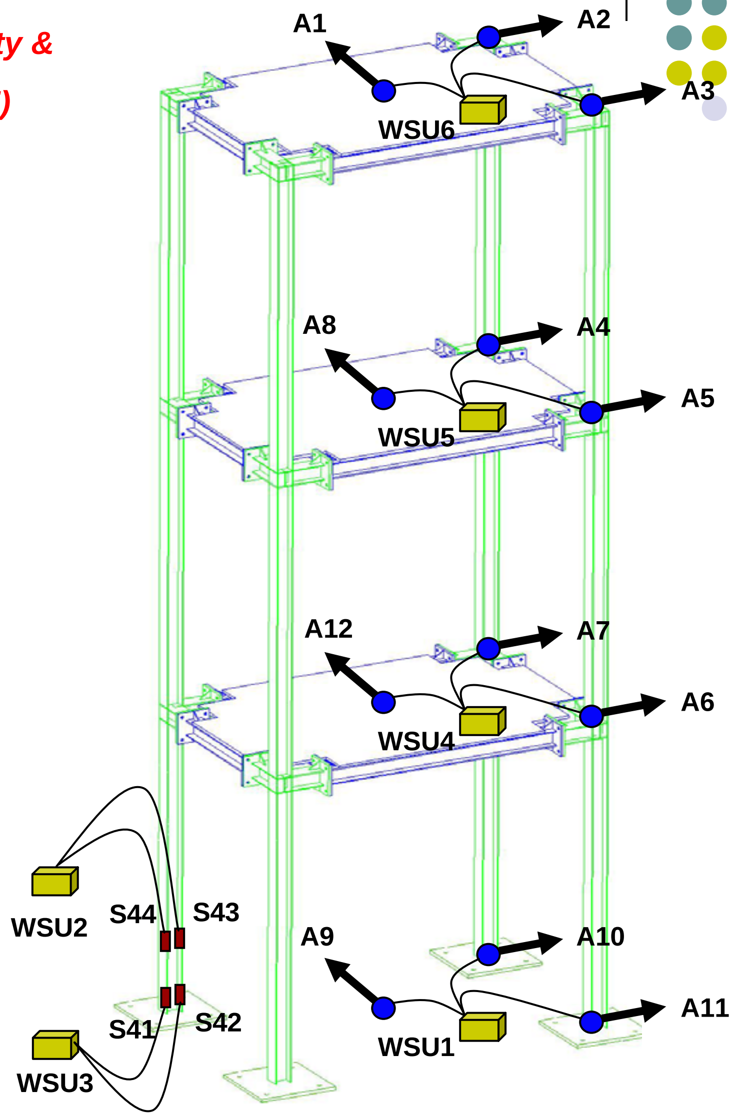


Prof. J.P. Lynch, University of Michigan. Presentation at 10:50 am, Tue. Session 3, Room: Sunset.

Laboratory 3-Story Structure on a 6-DOF Shaking Table

***Collaboration with Prof. C. H. Loh**, National Taiwan University &*

National Center for Research on Earthquake Engineering (NCREE)

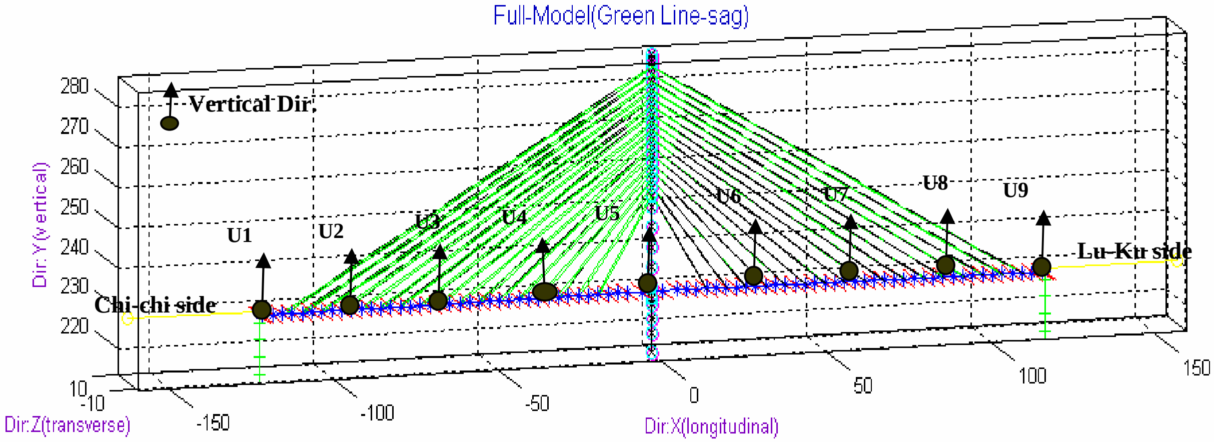


Field Validation Tests at Gi-lu Bridge, Chi-chi, Taiwan

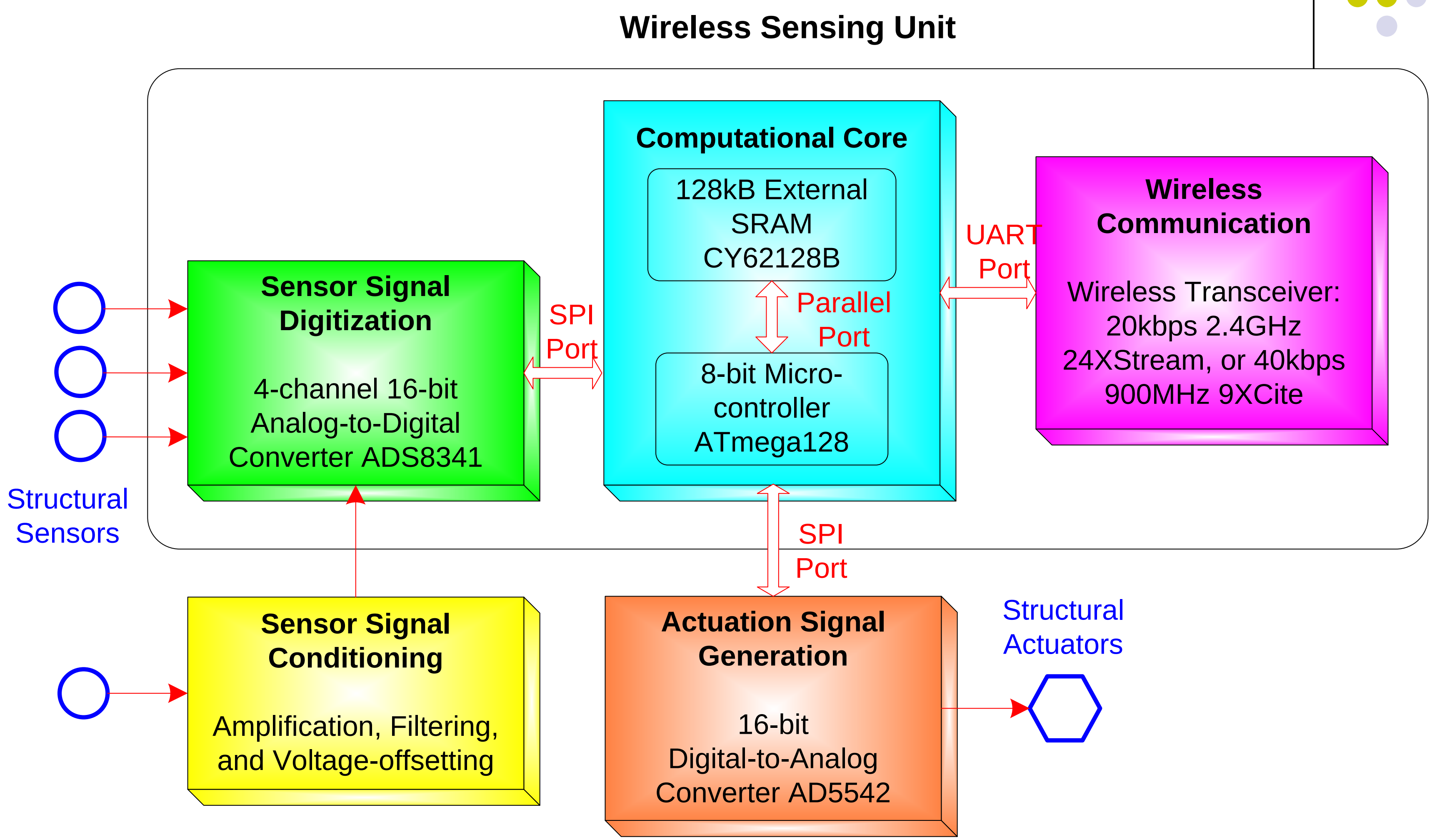
***Prof. C.-H. Loh**, National Taiwan University. Presentation at 9:20 am, Tue. Session 10, Room: Towne*

Gi-lu Cable-Stayed Bridge, Chi-chi, Taiwan

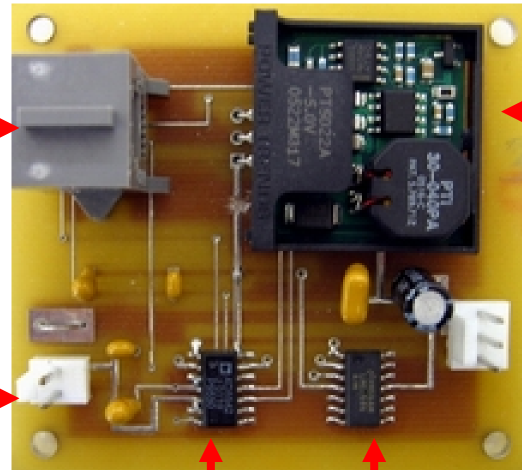
Span: 120m (L) + 120m (R)



Functional Diagram with Actuation Signal Generation Module



Control Signal Generation Module



Digital Connections to ATmega128 Micro-controller

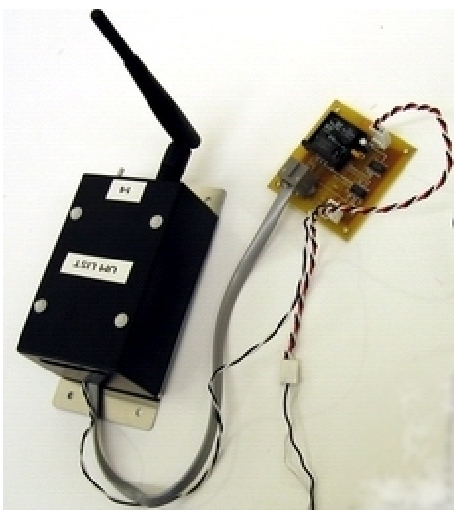
Analog Connections to ATmega128 Micro-controller

Integrated Switching Regulator PT5022

Command Signal Output

Digital-to-Analog Converter AD5542

Operational Amplifier LMC6484



Supply voltage: 5 VDC

Output signal: -5 ~ 5 VDC

Output settling time: 1 μs

Size: 5.5 x 6.0 cm

Wireless Feedback Structural Control Tests

***Collaboration with Prof. C. H. Loh**, National Taiwan University &*

National Center for Research on Earthquake Engineering (NCREE)

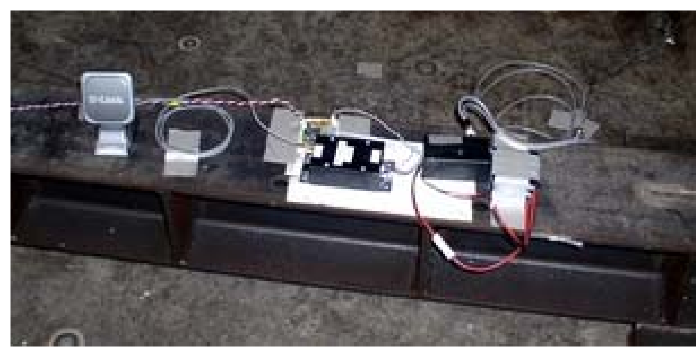
Floor: 3m x 2m

Floor weight: 6,000 kg

Inter-Story height: 3m

Shaking table: 5m x 5m

20 kN Magneto-Rheological (MR) Damper

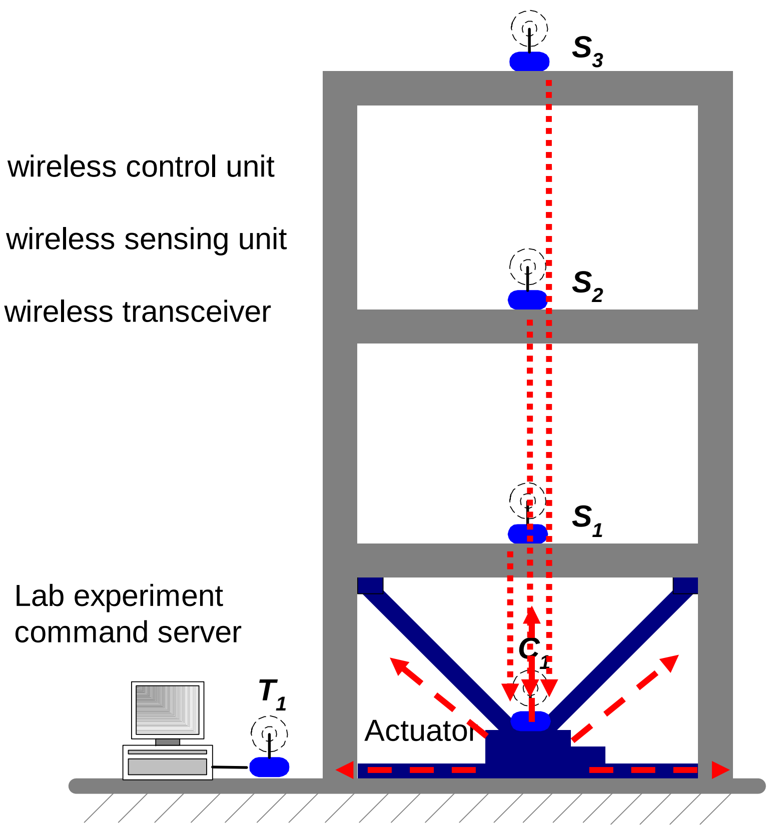


Wireless Sensing and Control System Overview

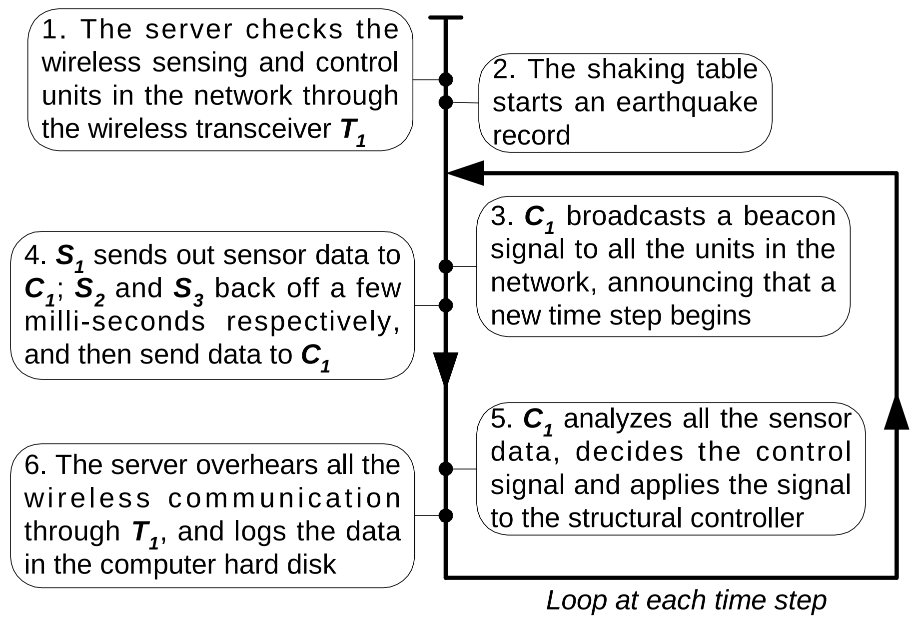
C_i: wireless control unit

S_i: wireless sensing unit

T_i: wireless transceiver



Major Program Flow for a WiSSCon Laboratory Test



Time step length:

20 ms with 9XCite transceiver

80 ms with 24XStream transceiver

Embedded Computing (1)

Discretized Linear Quadratic Regulator (LQR) Control Algorithm:

$$z_d(k+1) = A_d z_d(k) + B_d u_d(k) \qquad z_d(k) = \begin{Bmatrix} x_d(k) \\ \dot{x}_d(k) \end{Bmatrix}$$

Minimize index:

$$J(\{u_d\}) = z_d(k_f)^T Q z_d(k_f) + \sum_{k=0}^{k_f - 1} \left(z_d(k)^T Q z_d(k) + u_d(k)^T R u_d(k) \right),$$

where $Q \geq 0$ and $R > 0$

Optimal control force:

$$u_d(k) = G z_d(k)$$

Real-time sensor data → **LQR Computing** → Desired control force

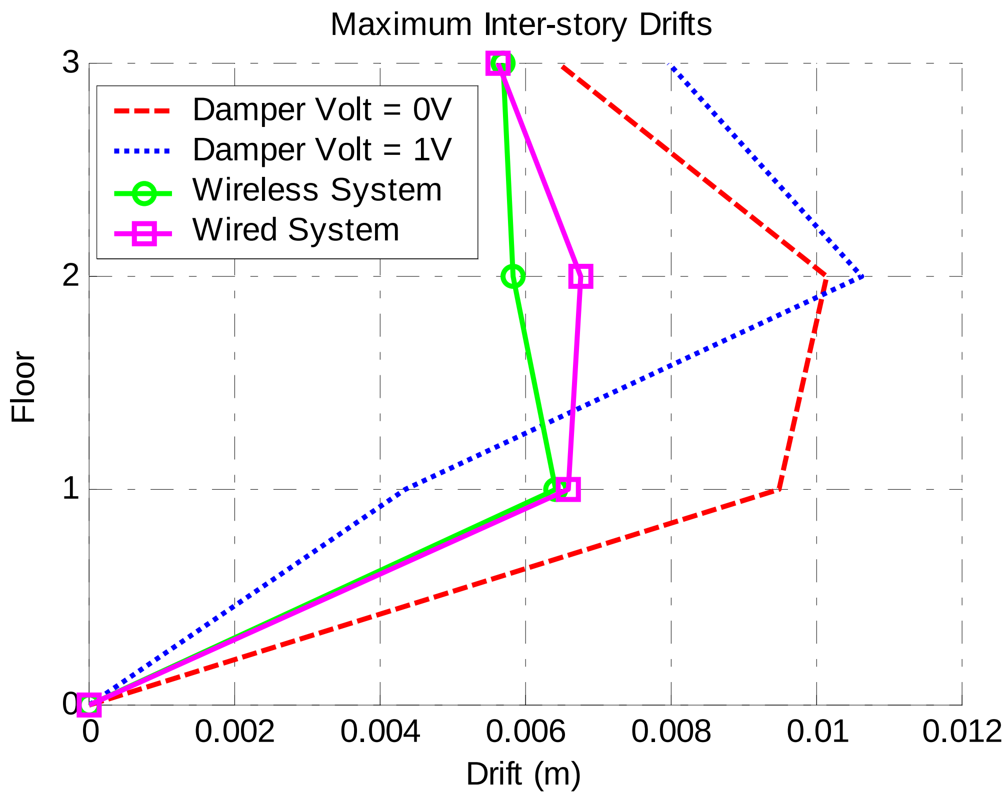
Embedded Computing (2)

Modified Bouc-Wen MR damper model developed by researchers at NCREE:

$$
\begin{cases}
\begin{cases}
F(t) = F_d(t) + z(t) \\
z(k) = z(k-1) + \sum_{i=1}^{5} \theta_i(k-1)\phi_i(k-1)dt \\
\Phi(k) = [\dot{x}(k), |\dot{x}(k)||z(k)|^0 z(k), \dot{x}(k)|z(k)|^1, |\dot{x}(k)||z(k)|^1 z(k), \dot{x}(k)|z(k)|^2]^T
\end{cases} \\
\begin{cases}
F_d(t) = (0.0083V(t) + 0.005)\dot{x}(k) \\
\theta_1 = \text{-}13.2924\text{V}^3 + 22.9678\text{V}^2 + 1.0297\ \text{V} - 1.0762 \\
\theta_2 = \text{-}161.6060\text{V}^2 - 88.7154\text{V} - 389.2721 \\
\theta_3 = \text{-}5.0428\text{V}^2 - 169.2379\text{V} - 160.4490 \\
\theta_4 = \text{-}0.6433\text{V}^2 - 8.0282\text{V} - 0.7757 \\
\theta_5 = 0.3452\text{V}^2 - 6.775\text{V} - 0.316
\end{cases}
\end{cases}
$$

Desired control force → **MR Damper Model Computing** → Appropriate actuation voltage to the MR damper

Preliminary Structural Control Tests

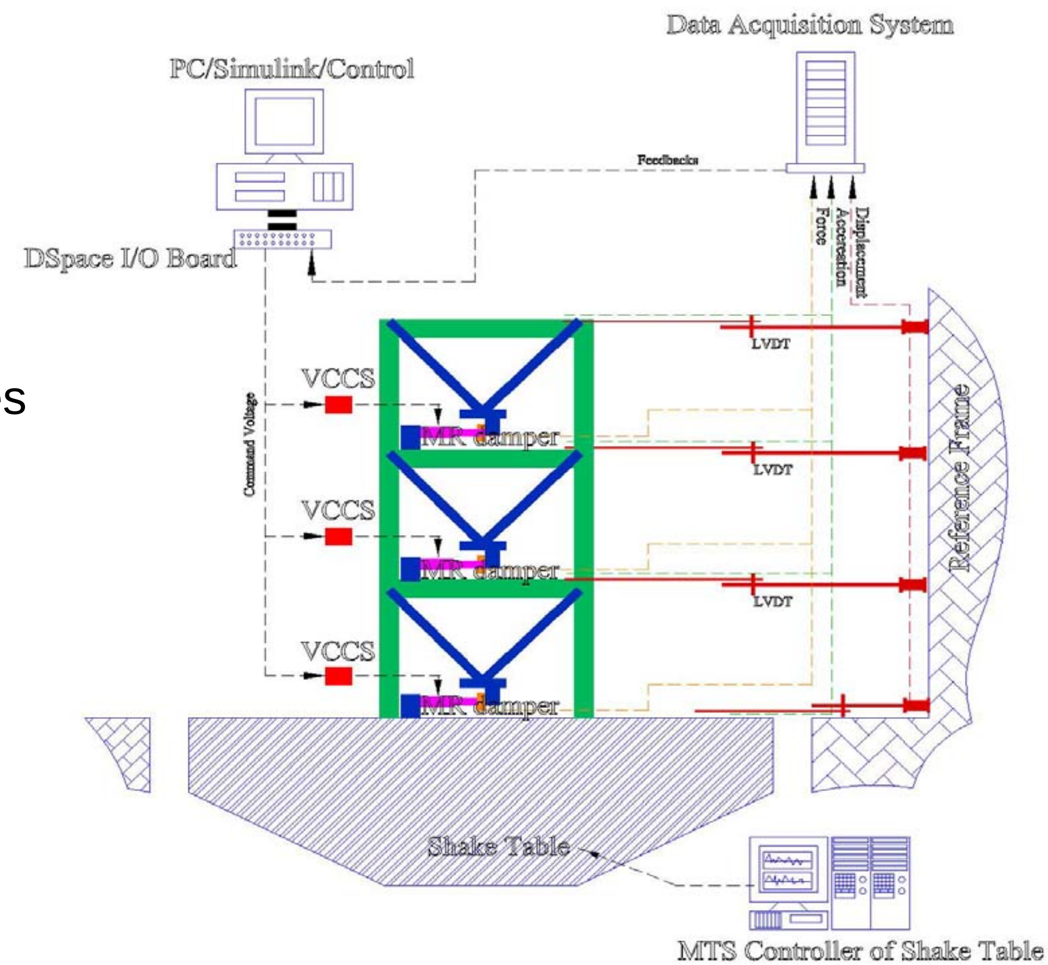


Future Research in Wireless Sensing and Control

***Collaboration with Prof. C. H. Loh**, National Taiwan University &*

National Center for Research on Earthquake Engineering

- Explore more wireless communication technologies
- Multiple MR dampers
- Decentralized Control



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The End

Thank You