Innovative Characteristics and Opportunities of NHERI@UCSD

Gilberto Mosqueda, Professor

University of California, San Diego

December 12, 2016

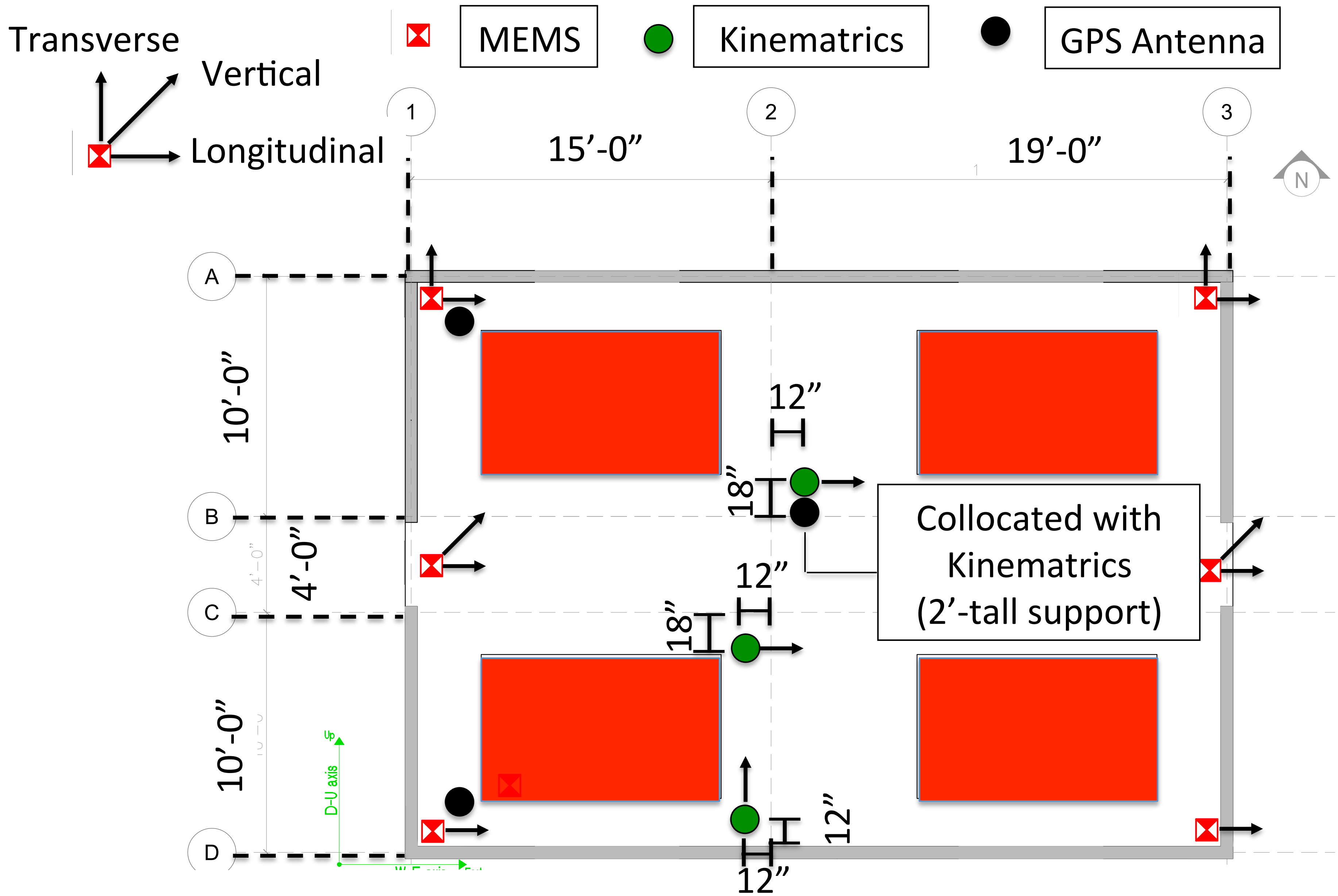
Overview

- Instrumentation
  - GPS sensors
  - Drones
  - Testbed Structure
- Hybrid Simulation Hardware available at NHERI-UCSD
  - Control system, ScramNet, and Matlab xPC Environment
  - External actuators
- Implementation of Hybrid Simulation
  - Example by Andreas Schellenberg

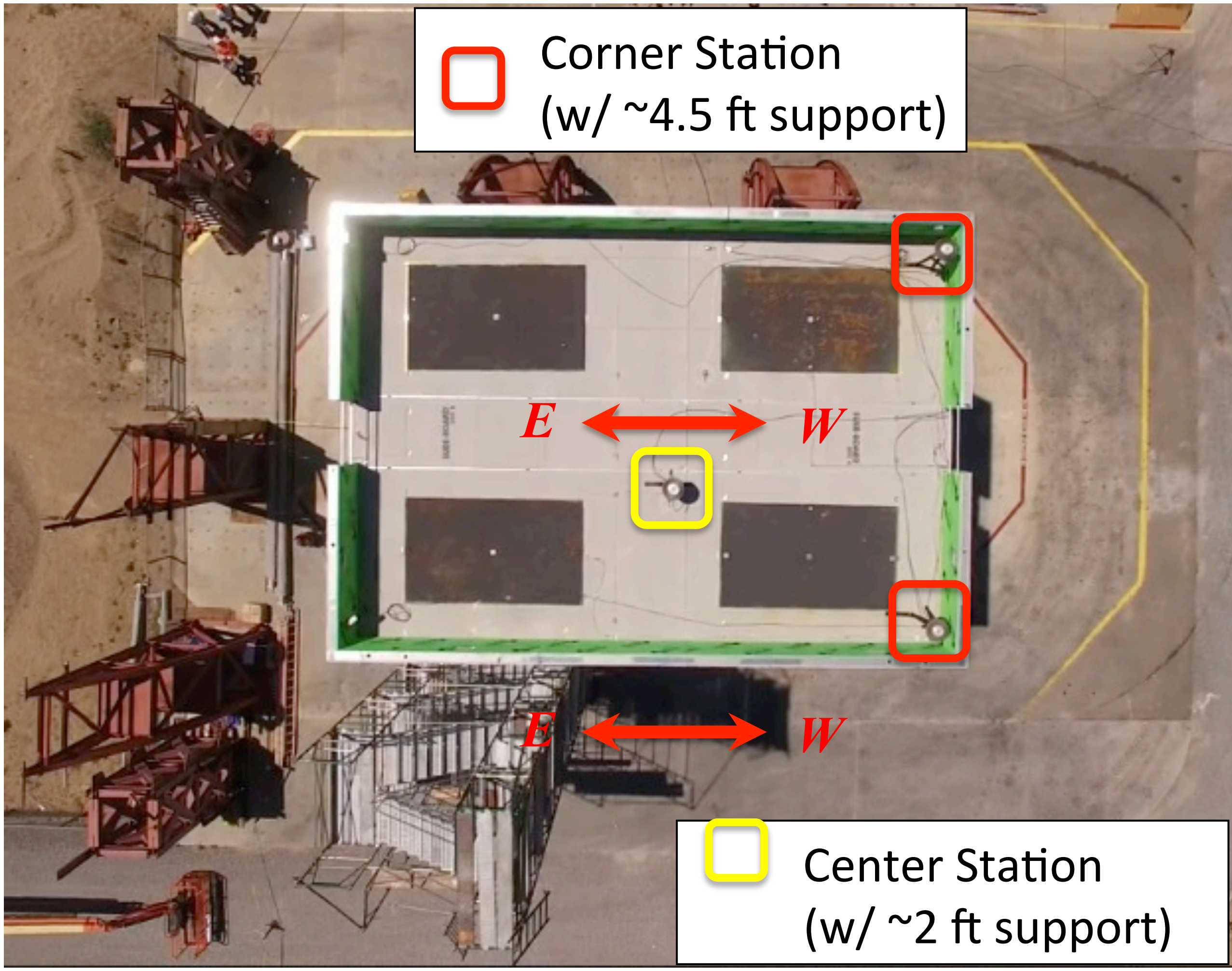
Use of GPS Displacement Sensors

- Example application includes a total of 6 GPS stations (provided by Prof. Tara Hutchinson and Xiang Wang)
  - 3 on the roof (see plan layout)
  - 2 at building mid floors (cantilevered at 3rd and 5th floors)
  - 1 reference ground station (~150 ft west of building)
- GPS stations co-located with high-rate MEMS & Kinematric accelerometers
- Accurate displacement measurements
  - captures large residual displacements
- Data shown from
  - EQ9:RRS-150: near-fault MCE motion, Sa=2.5 g at T1
  - Building sustained extremely large residual displacement demand (> 1 % residual roof drift & ~6% residual story drift at level 2)

GPS and Accelerometer Layout (Roof)



GPS and Accelerometer Layout (Roof)

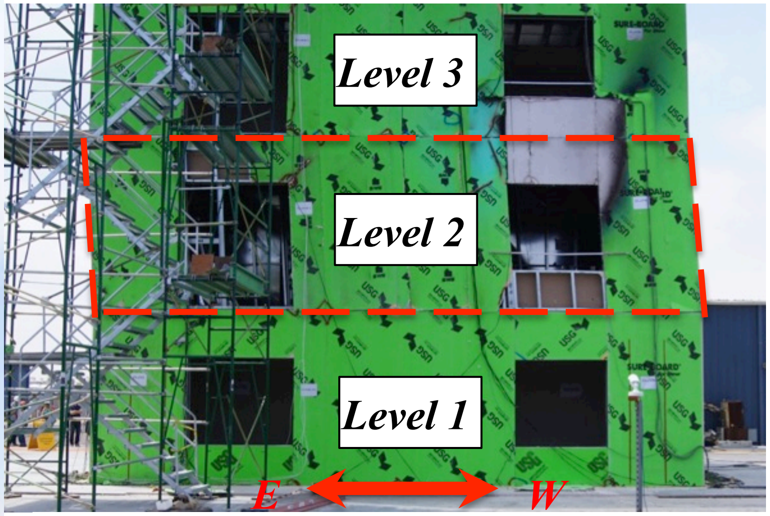


GPS stations on the roof
(UAV image)

Test Building before and after EQ9

Before EQ9

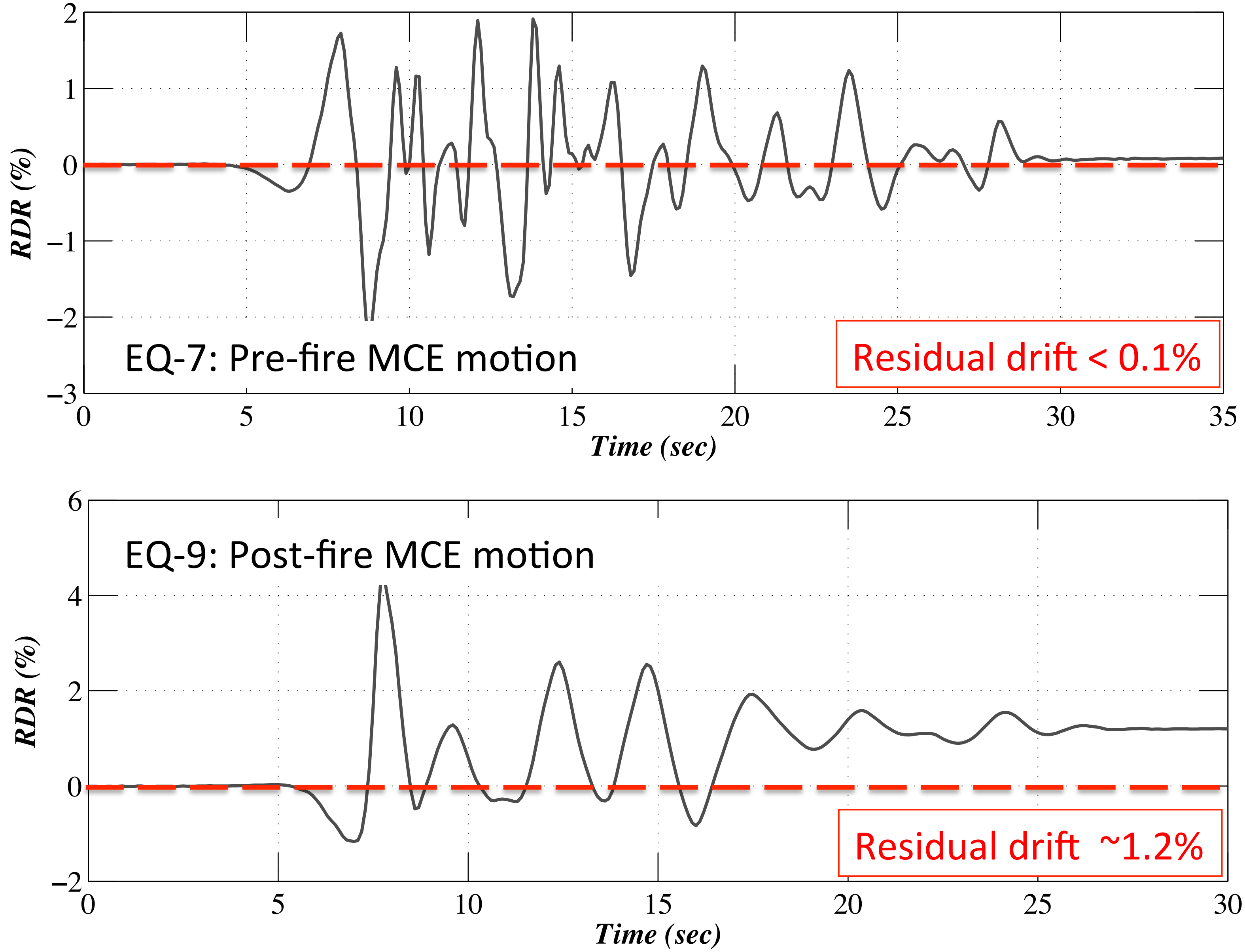
After EQ9



North face of the building after EQ9 (lower three levels)

- ~6% residual story drift ratio at level 2
- > 1% residual roof drift ratio (> 20 cm)

GPS Roof Measurement in EQ7 & EQ9



Inspection of Earthquake and Fire Damaged Buildings Using Unmanned Aerial Vehicles

Falko Kuester
Director, CISA3-CHEI-DroneLab
Calit2 Professor for Visualization and Virtual Reality
Professor, Department of Structural Engineering

California Institute for Telecommunications and Information Technology (Calit2)
University of California, San Diego
http://chei.ucsd.edu/dronelab

Calit2 DroneLab

UAV Strengths

- Can deliver or collect data where and when needed
- Timely access to difficult to reach places
- Can put attention where it is needed most

- Enabler for rapid response
- Enabler for continuous monitoring

- Require streaming for situational awareness
- Require an ecosystem supporting innovation

Calit2

UAV Tasks

Pre-event, event, post-event imaging:

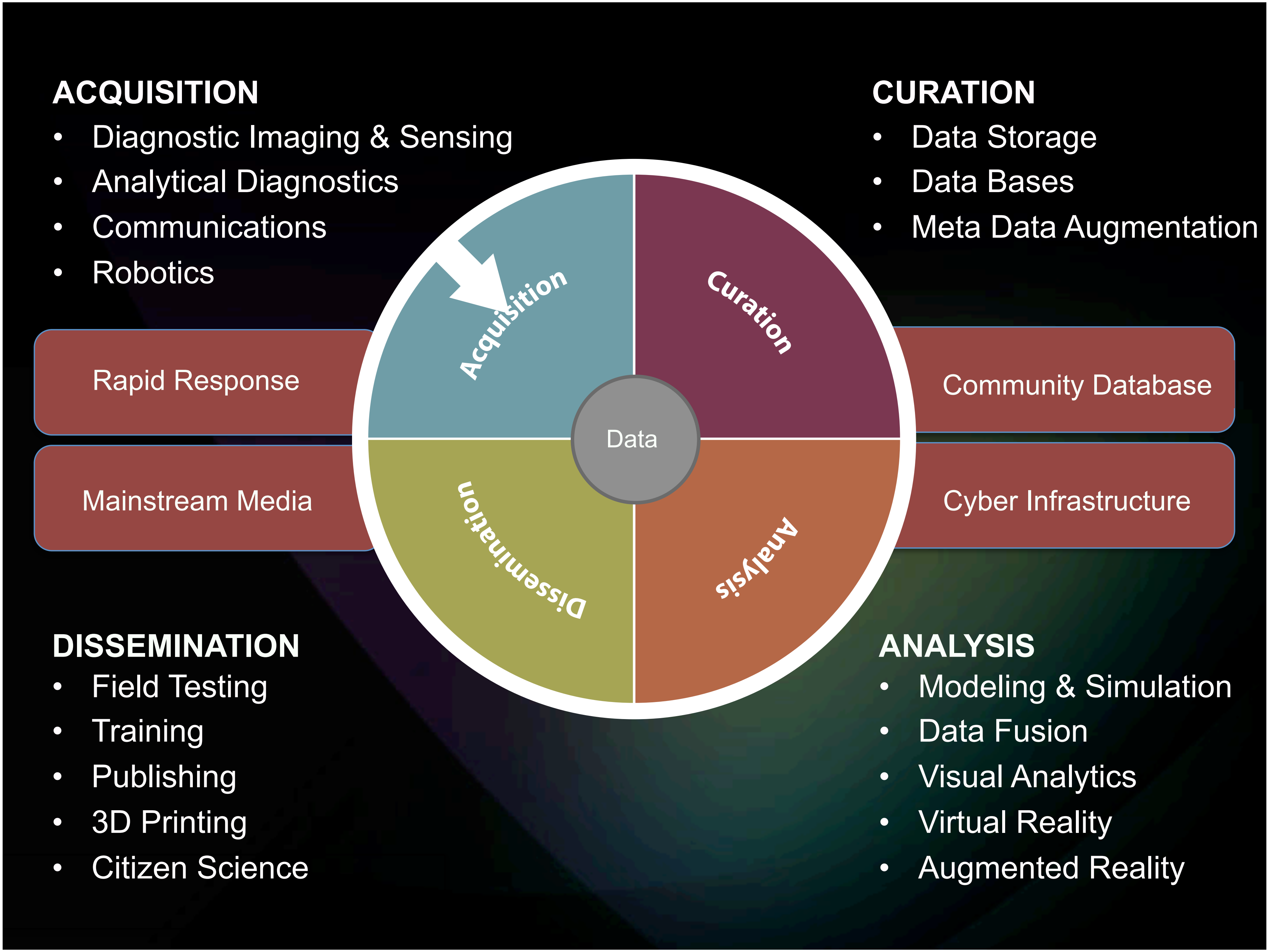
- Semi-autonomous UAV site survey with multiple sensor payloads
- Spot surveys using traditional terrestrial imaging techniques

Derivative data products

- 3D model creation using structure from motion (SfM) techniques
- Data synthesis and augmentation
- Explore and evaluate damage detection and classification strategies

Calit2

Rapid UAV Site Surveys


ACQUISITION
• Diagnostic Imaging & Sensing
• Analytical Diagnostics
• Communications
• Robotics
CURATION
• Data Storage
• Data Bases
• Meta Data Augmentation
Rapid Response
Mainstream Media
Acquisition
Curation
Data
Dissemination
Analysis
Community Database
Cyber Infrastructure
DISSEMINATION
• Field Testing
• Training
• Publishing
• 3D Printing
• Citizen Science
ANALYSIS
• Modeling & Simulation
• Data Fusion
• Visual Analytics
• Virtual Reality
• Augmented Reality

SfM-Based Model Creation from UAV Data

Calit2

UC San Diego
Jacobs School of Engineering

Earthquake & Post-Earthquake Fire Performance of Mid-Rise Light-Gauge Cold-Formed Steel Framed Buildings

Compilation of Select
Earthquake & Post-Earthquake Fire Scenarios

UCSD WPI

Calit2

Image Synthesis from 3D Model Data

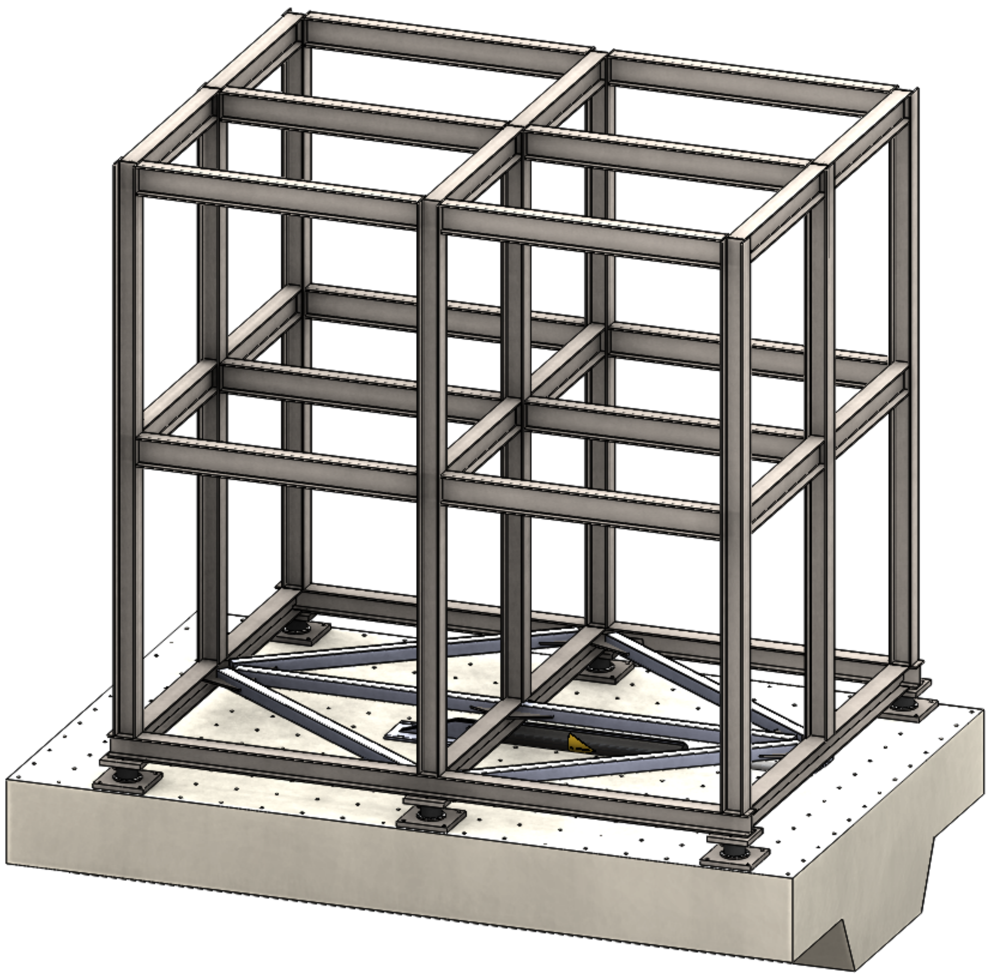
(a) Pre-completion (b) As-Built (c) Post-event

Calit2

Virtual Reality for Remote Presence and Inspection

Testbed Structure

- Testbed Structure
- Reconfigurable and reusable test frame that can be used to test a variety of structural and nonstructural components and systems
- Topic of discussion for Tuesday afternoon session
- Target applications in protective systems, nonstructural systems and hybrid simulation

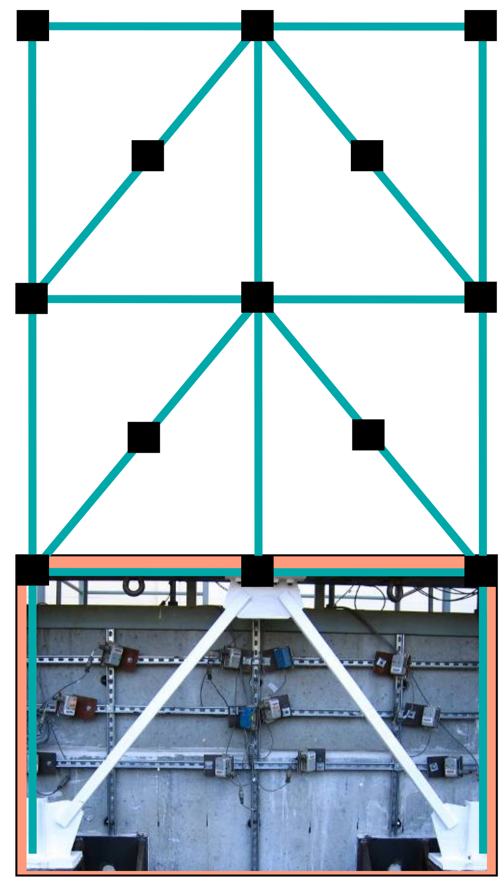


Hybrid Simulation

- Equation of motion for prototype structure

$$\boxed{ma + cv} + \boxed{r} = \boxed{f}$$

- Hybrid simulation combines:
  - Physical models of structural resistance
  - Computer models of structural damping and inertia
- Enables seismic testing of large- or full-scale structural models
- Solve equation of motion using numerical integration algorithms



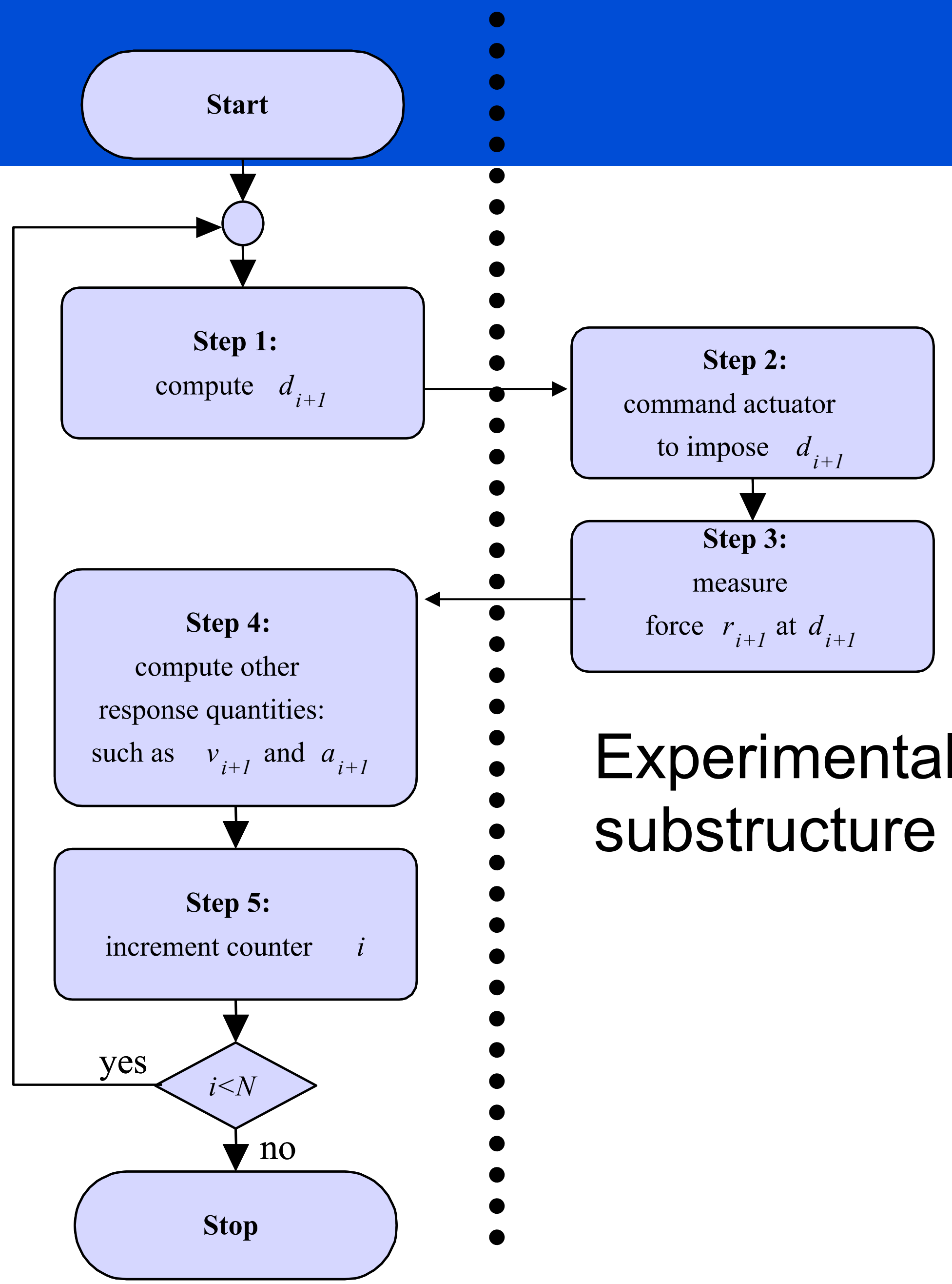
Test Procedure

Time-stepping integration algorithm e.g., Newmark Explicit

$$m a_{i+1} + c v_{i+1} + r_{i+1} = f_{i+1}$$

$$d_{i+1} = d_i + \Delta t v_i + \frac{1}{2}\Delta t^2 a_i$$

$$v_{i+1} = v_i + \frac{1}{2}\Delta t \left(a_i + a_{i+1} \right)$$



Implementation Issues

- Integration Algorithms
  - Implicit or explicit
  - Integration time step
  - Accuracy and stability
- Rate of testing
  - Time scaling
  - Pseudo-dynamic vs. dynamic
  - Material strain rate effects
  - Observation of damage
- Experimental Errors
  - Actuator tracking errors
  - Propagation of errors

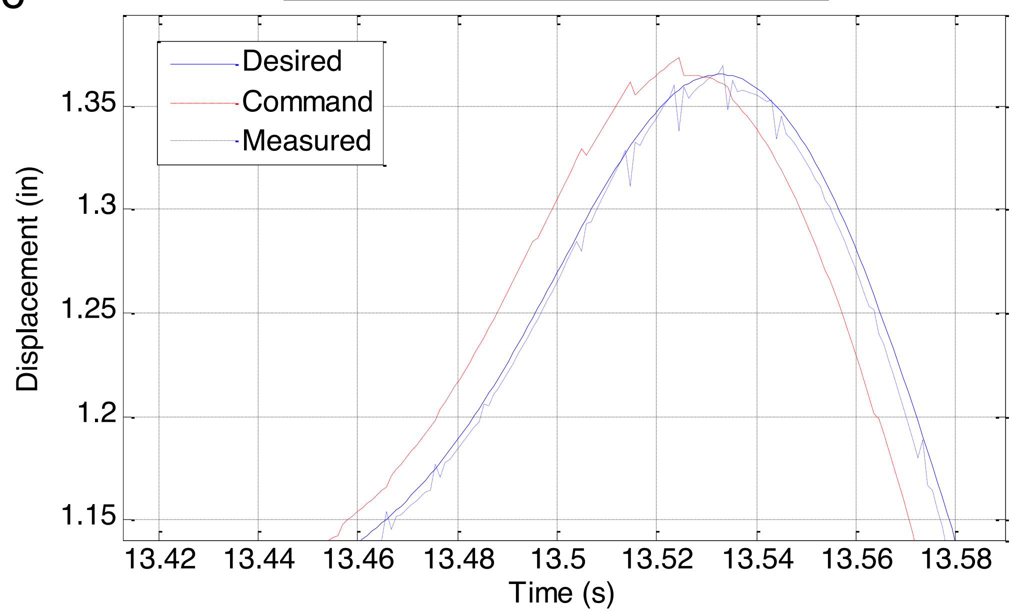
Central Difference

Newmark's Method

$$m a_{i+1} + c v_{i+1} + r_{i+1} = f_{i+1}$$

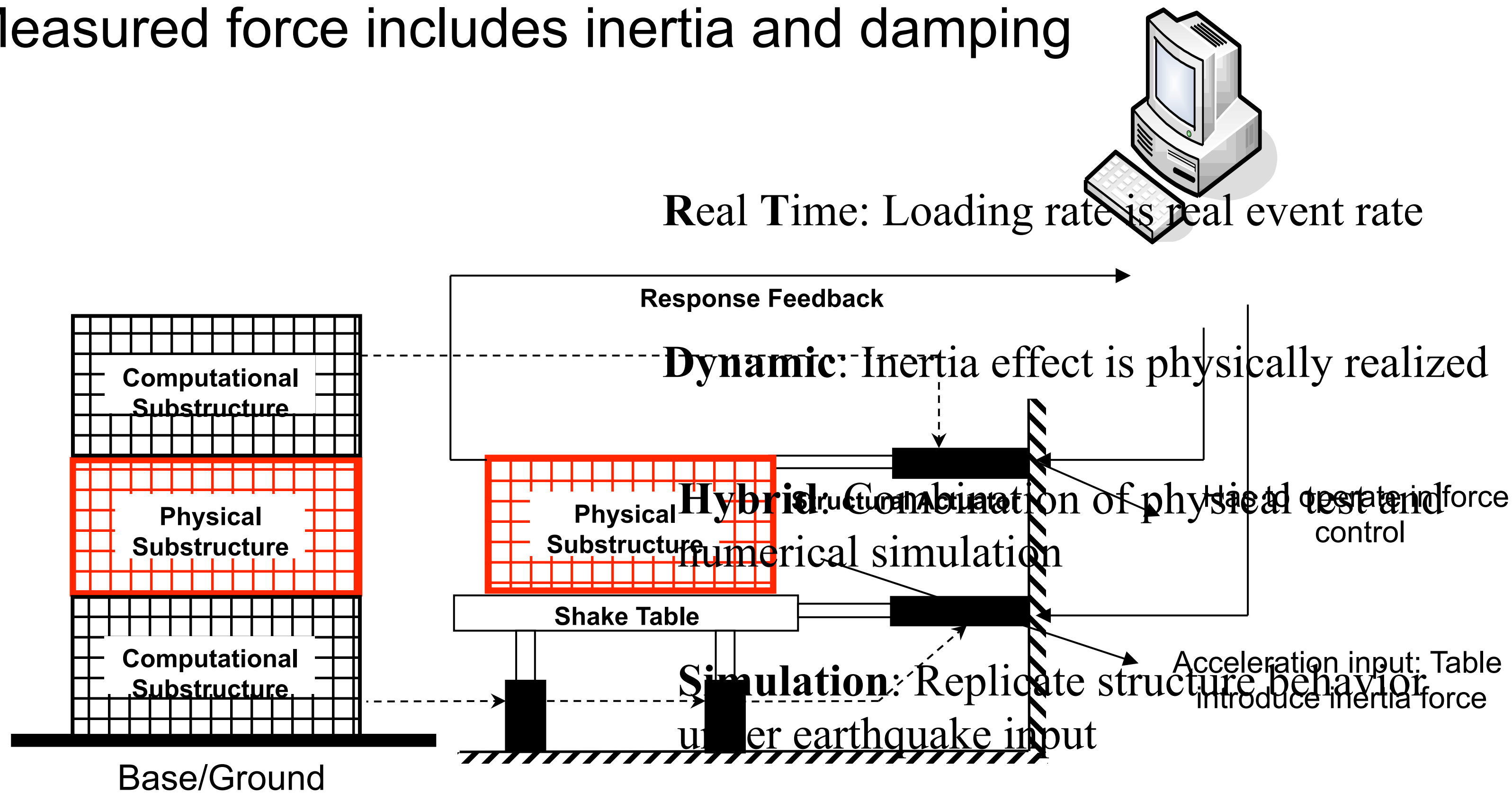
$$d_{i+1} = d_i + \Delta t v_i + \frac{1}{2}\Delta t^2 a_i$$

$$v_{i+1} = v_i + \frac{1}{2}\Delta t \left(a_i + a_{i+1}\right)$$



Real-Time Dynamic Hybrid Simulation

- **Real-time Dynamic Hybrid Simulation** combines use of shake tables, actuators and computational models
- Measured force includes inertia and damping



Real Time: Loading rate is real event rate

Dynamic: Inertia effect is physically realized

Hybrid: Combination of physical test and numerical simulation

Simulation: Replicate structure behavior under earthquake input

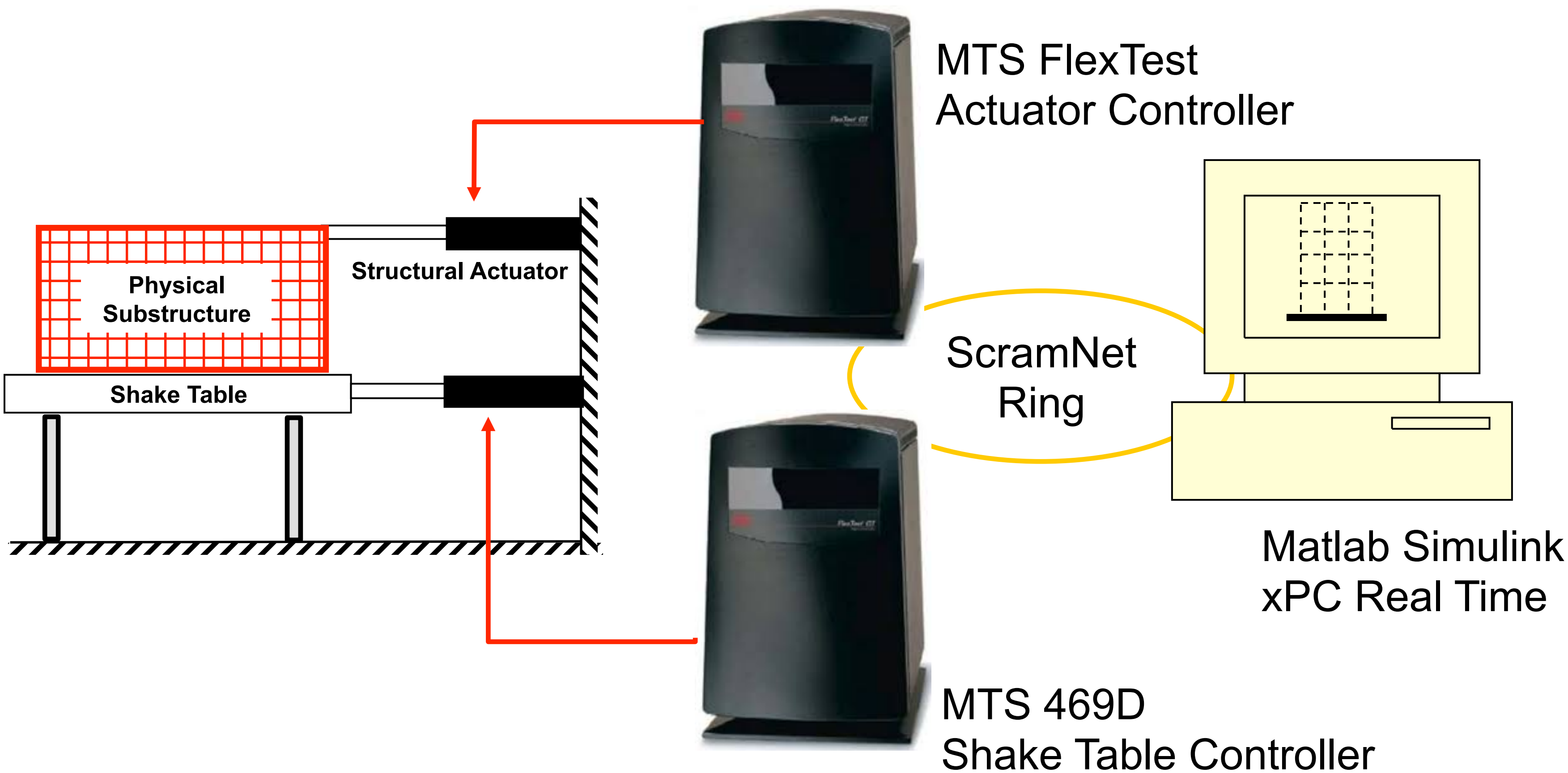
(Reinhorn and Shao)

Real-time Hybrid Simulation Control System

- **Hardware integrated through ScramNet Reflective Shared Memory for real-time communication between**
  - Exchange of data on the order of microseconds
- **MTS 469D Shake Table Controller**
  - Can be set to take control commands from ScamNet
- **Multi-channel MTS FlexTest Actuator Controller**
- **xPC Target/Simulink Real-Time**
  - User programmable environment using Matlab- Simulink that runs in real-time
  - Send commands and receive feedback from actuator controllers through ScramNet
- **50-ton dynamic actuator**

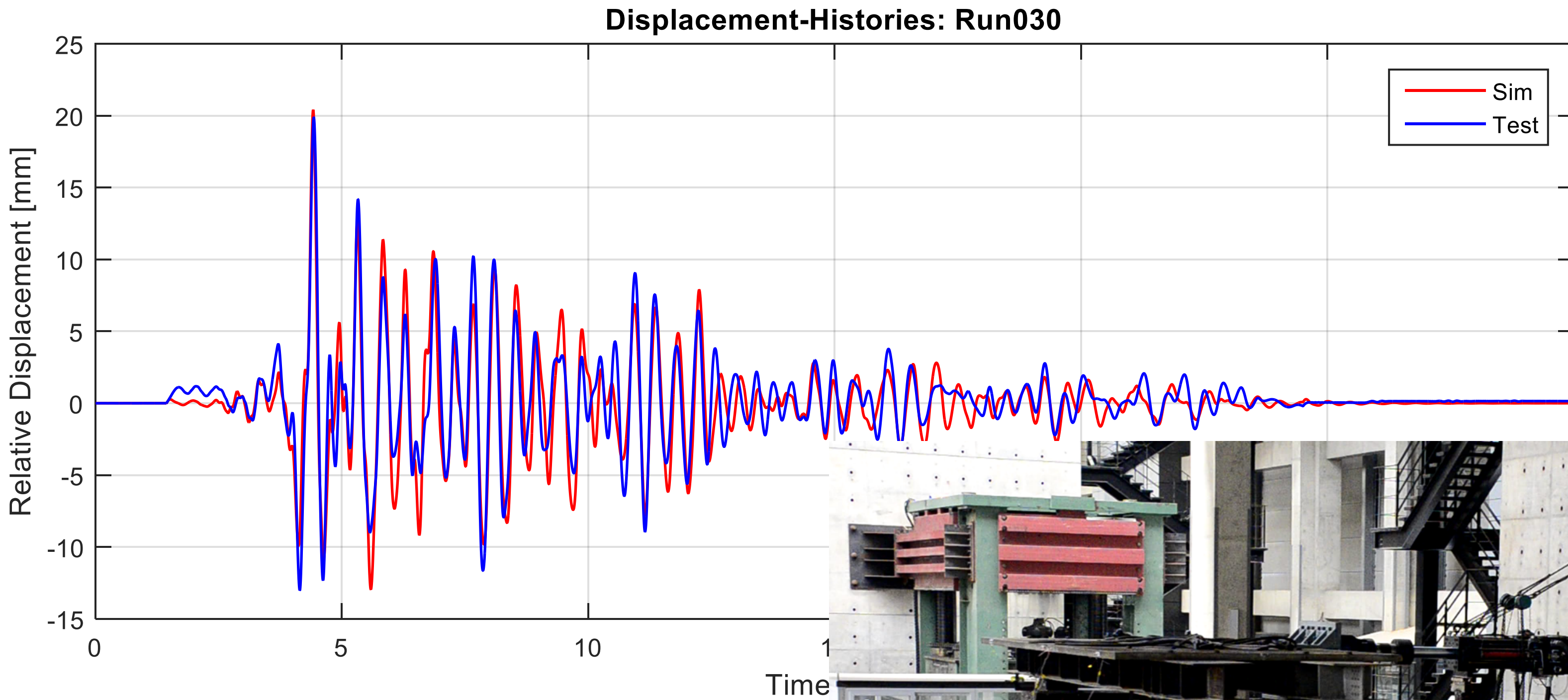
Hybrid Simulation Control System

- Real time integrated computational capabilities available at NHERI@UCSD

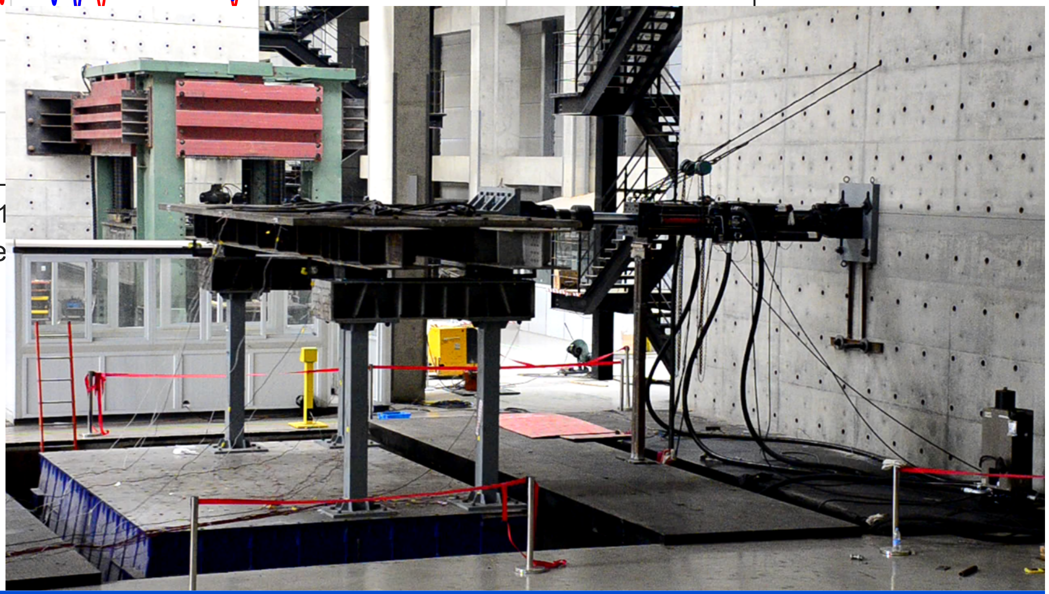


Real-time Dynamic Hybrid Simulations

➢ **Large scale RTDHS conducted at Tongji University**

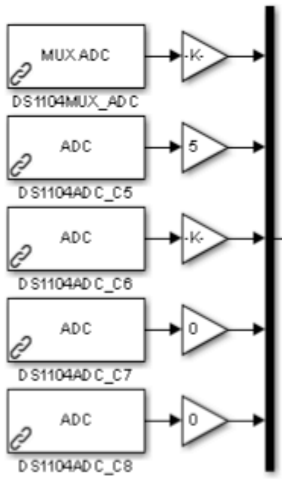


(Schellenberg et al.)



Real-time Hybrid Simulation Control System

- **User defined structural model and boundary conditions can be implemented in Simulink for ‘hard’ real-time**

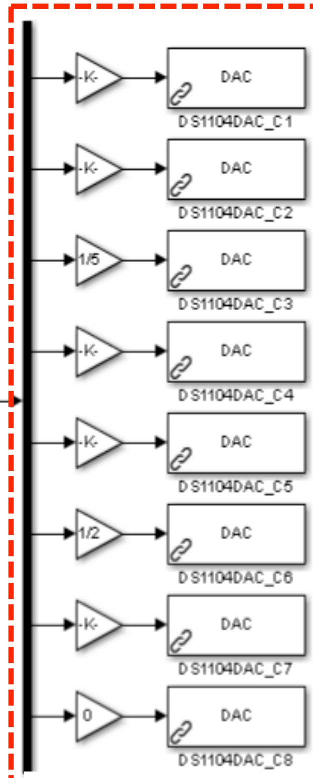


Feedback signals from ScramNet

Insert Custom Code Here
Numerical model
Integration algorithm
Compensation
Correction of feedback

Link to OpenFresco

Shake table commands can be displacement, velocity or acceleration



Commands to ScramNet

Real-time Hybrid Shake Table Testing

➢ Correction of online force measurements

- System identification of platen properties (Ozcelik et la. 2008)

Basic Least-Squares Formulation

$$F_{\mathrm{I}}(t) + F_{\mathrm{E}}(t) + F_{\mathrm{D}}(t) = F_{\mathrm{A}}(t)$$

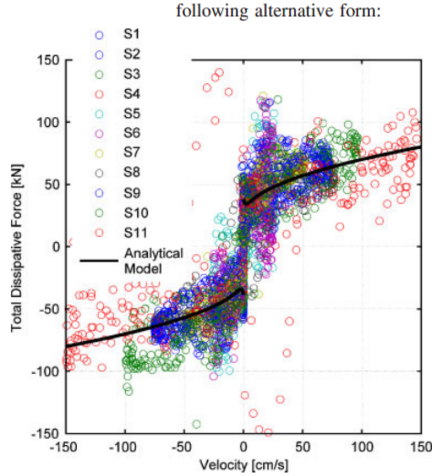
$$F_{\mathrm{I}} = M_{\mathrm{e}}\ddot{u}_x + 2\overline{M}'_{\mathrm{e}}\left(\frac{u_x}{h}\right)^2 \ddot{u}_x + 2\overline{M}'_{\mathrm{e}}\left(\frac{\dot{u}_x}{h}\right)^2 u_x$$

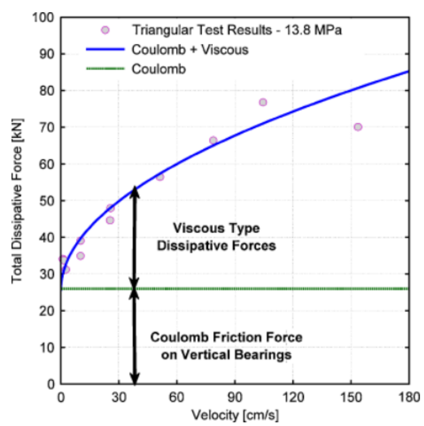
$$F_{\mathrm{E}} = K_{\mathrm{e}}u_x + K'_{\mathrm{e}}\left(\frac{u_x}{h}\right)^2 u_x$$

$$F_{\mathrm{D}} = \left[F_\mu + C_{\mathrm{e}}|\dot{u}_x|^\alpha + 2c_\beta\left|\frac{u_x}{h}\right|^{1+\beta}|\dot{u}_x|^\beta + \mu_{\mathrm{e}}^{(iv)}F_{\mathrm{hd}}\left(\frac{u_x}{h}\right)^2\right]\mathrm{sign}(\dot{u}_x)$$

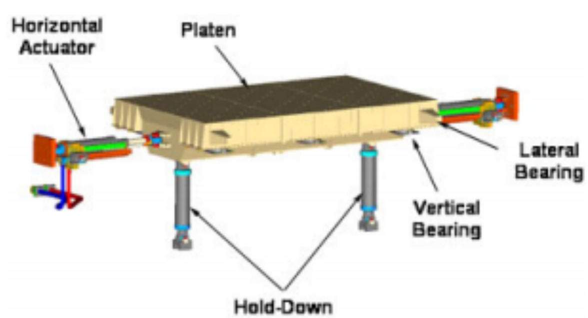
$$\bar{\in}^2 = \frac{\sum_{i=1}^{N}\lambda_i\int_0^{T_i}[F_{act}(t) - M_e\ddot{u}_x - K_e u_x - (C_e|\dot{u}_x|^\alpha + F_{\mu_e})\mathrm{sign}(\dot{u}_x)]^2 dt}{\sum_{j=1}^{N}\lambda_j\int_0^{T_j}F_{act}^2(t)dt}$$

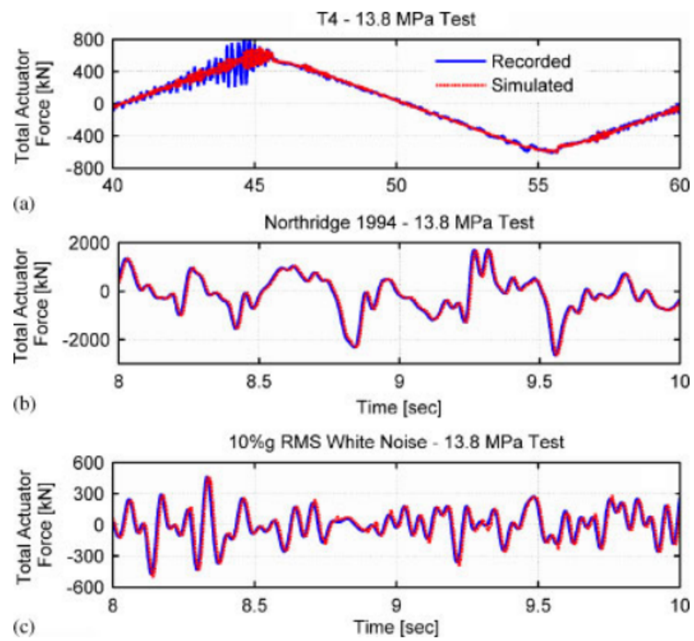
where $\bar{\in}$=normalized error to be minimized for a given value of α; N=number of tests considered; T_i=duration of the ith test; and λ_i=weight assigned to the ith test. Eq. (2) can be rewritten in the following alternative form:





NEES-UCSD SHAKE TABLE MECHANICAL SYSTEM





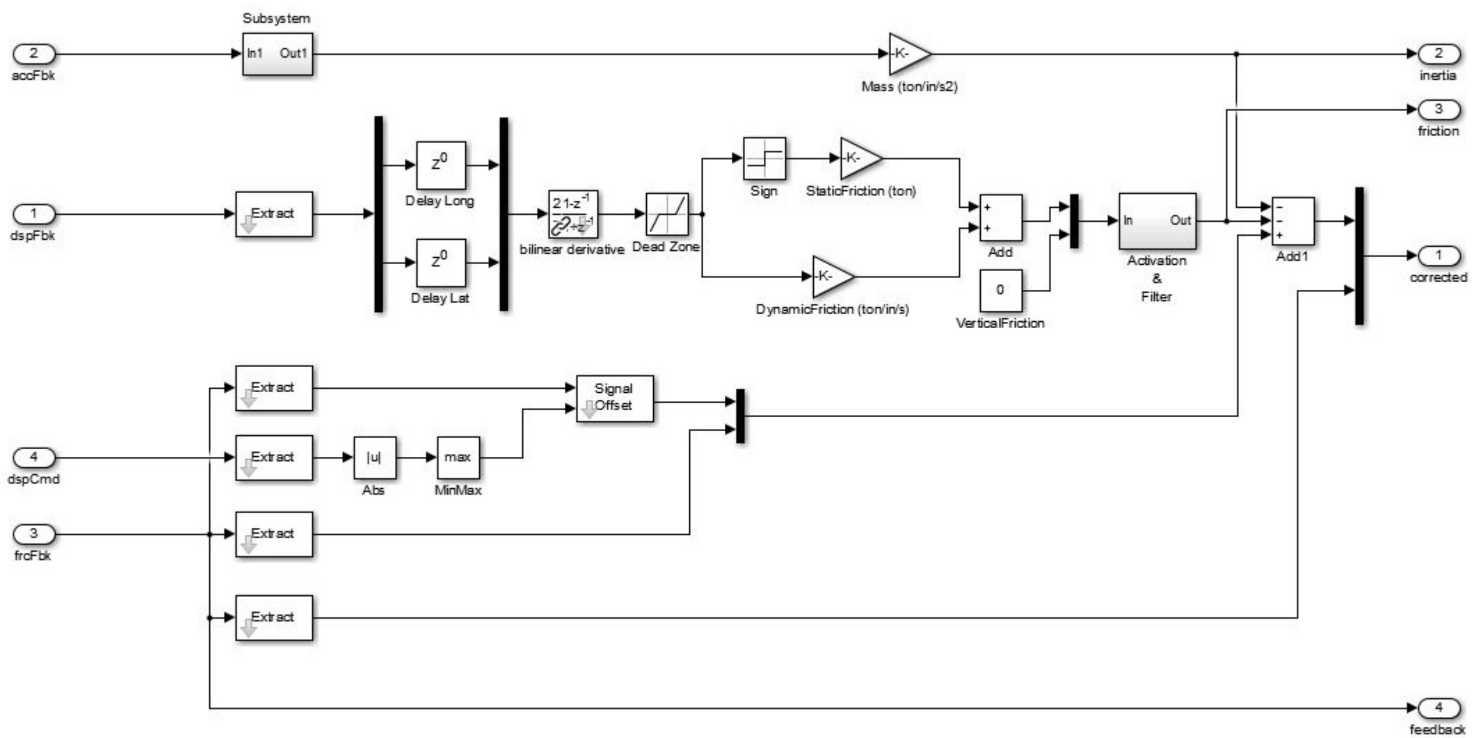
Real-time Hybrid Shake Table Testing

➢ **Correction of online force measurements**

- Measured forces using actuator load cells include inertia and friction

$$F = m_e u_x + F_{Friction}\, sign(u_x) + c u_x + d$$

Inertia *Static Friction* *Dynamic Friction*



Real-time Hybrid Simulation Control System

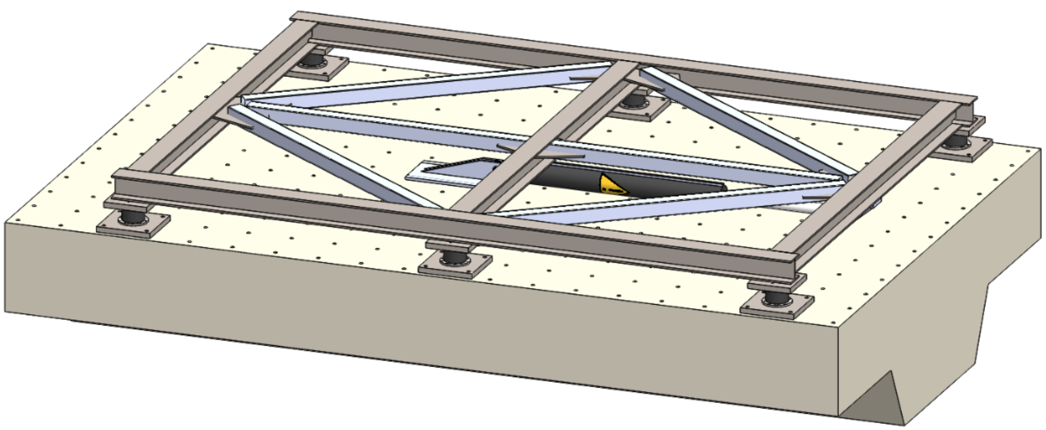
➢ **Planned Upgrades and improvements:**

- Update Simulink Real-Time computer and Simulink Host
  - ✓ High performance computers with multi-core processing
  - ✓ Enable more complex numerical models for real-time hybrid simulation
- Evaluation of delay compensation methods
  - ✓ Feed Forward and improved tuning for delay
  - ✓ Implementation of Adaptive Time Series (ATS) compensator (Chae et al. 2013)

Real-time Hybrid Simulation Control System

➢ **Planned Commissioning Test for Hybrid Simulation:**

- Experimentally evaluate hybrid testing capabilities and characterize system response (delays and other errors)
- Use of shake table and external actuator
- Scheduled for Spring 2016

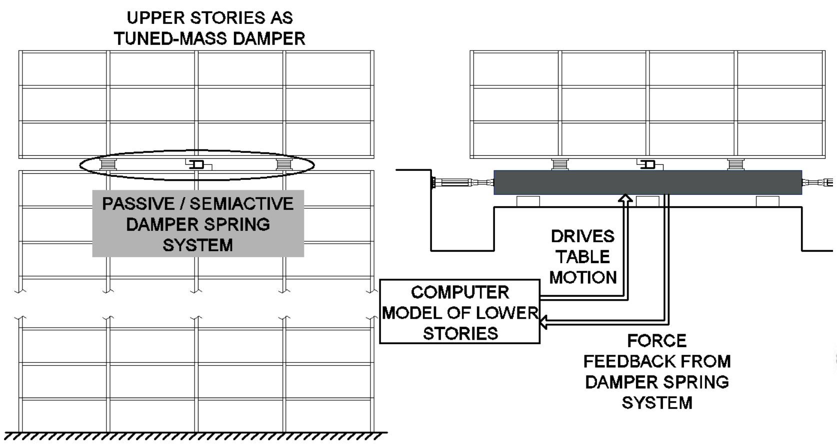


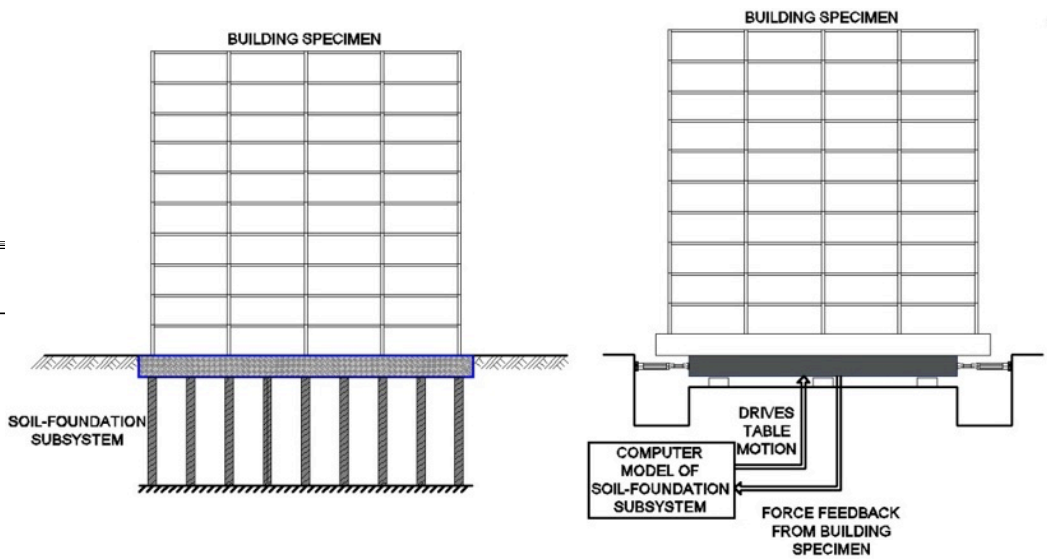
Real-time Hybrid Simulation Control System

- **For hard real-time, user can program numerical structural model in Simulink**
- **Potential to interface with real time programs for structural analysis through ScramNet**
- **Structural analysis software provides the advantage of access to libraries of integrators, elements etc.**
- **Delay compensation is critical to hybrid simulation**
  - Adaptive Time Series (ATS) delay compensators works well for shake tables and individual actuators (Chae, Kazemibidokhti, and Ricles)

Consideration of Dynamic Hybrid Simulation

- Simulate large and complex structures that exceed capabilities of the shake table such as long span bridges and tall buildings
  - Test a critical part of the structure at large scale
  - Numerically capture system level response and
- Some type of structures exhibit rate dependent effects and distributed inertial forces requiring dynamic testing





User Preparation

- Selection of structural model
  - ✓ Computer modeling, substructures and boundary conditions
- Design of experimental setup within capacity of facility
- Communication link between computer model and hardware for custom software
- Selection of integration algorithm and its implementation in real-time software if necessary
- Pre-test simulation with numerical model of test setup
- Low level simulations to verify system performance and feedback loops
  - ✓ Include some time for development and implementation of algorithms
- Execute test sequence

Concluding Remarks

- Hybrid simulation can be a cost-effective and reliable approach to expand testing capabilities
- Control of numerical and experimental errors is critical to accuracy and stability of a hybrid test
- NHERI @UCSD has the hardware in place to conduct real-time dynamic hybrid tests with shake table substructures and external actuator
- NHERI@UCSD can provide expertise to support the implementation of hybrid simulation
- Current efforts at UCSD to identify response characteristics of shake table for hybrid simulation