Innovative Characteristics and Opportunities of NHERI@UCSD

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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 & Kinematic 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)

- Transverse
- Vertical
- Longitudinal

MEMS
Kinematrics
GPS Antenna

15'-0"
19'-0"

Collocated with Kinematrics (2'-tall support)
GPS and Accelerometer Layout (Roof)

GPS stations on the roof
(UAV image)
Test Building before and after EQ9

- ~6% residual story drift ratio at level 2
- > 1% residual roof drift ratio (> 20 cm)
GPS Roof Measurement in EQ7 & EQ9

EQ-7: Pre-fire MCE motion
Residual drift < 0.1%

EQ-9: Post-fire MCE motion
Residual drift ~1.2%
Inspection of Earthquake and Fire Damaged Buildings Using Unmanned Aerial Vehicles

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Director, CISA3-CHEI-DroneLab
Calit2 Professor for Visualization and Virtual Reality
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http://chei.ucsd.edu/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
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
Rapid UAV Site Surveys
SfM-Based Model Creation from UAV Data
Earthquake & Post-Earthquake Fire Performance of Mid-Rise Light-Gauge Cold-Formed Steel Framed Buildings

Compilation of Select Earthquake & Post-Earthquake Fire Scenarios
Image Synthesis from 3D Model Data

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

\[ ma + cv + r = f \]

- 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

\[ ma_{i+1} + cv_{i+1} + r_{i+1} = f_{i+1} \]

\[ d_{i+1} = d_i + \Delta tv_i + \frac{1}{2} \Delta t^2 a_i \]

\[ v_{i+1} = v_i + \frac{1}{2} \Delta t (a_i + a_{i+1}) \]
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

\[
ma_{i+1} + cv_{i+1} + r_{i+1} = f_{i+1}
\]

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

\[
v_{i+1} = v_i + \frac{1}{2} \Delta t (a_i + a_{i+1})
\]
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

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- Numerical model
- Integration algorithm
- Compensation
- Correction of feedback

Link to OpenFresco

Feedback signals from ScramNet

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 al. 2008)

\[
F_l(t) + F_c(t) + F_{D}(t) = F_A(t)
\]

\[
F_l = M_0 \dddot{u}_x + 2\dot{M}_0 \dddot{u}_x \dddot{u}_x + 2
\]

\[
F_c = K_0 \dot{u}_x + K'_0 \dot{u}_x^2
\]

\[
F_{D} = \left[ F_0 + C_2[\dot{u}_2]^2 + 2\dddot{u}_2 \frac{[\dot{u}_2]}{\dddot{u}_2} \right] + \beta\dddot{u}_2 \dot{u}_2 + \mu_0 \lambda_0 \int \frac{[\dot{u}_2]}{\dddot{u}_2} \text{sign}(\dot{u}_2) dt
\]

\[
\bar{e}^2 = \sum_{i=1}^{N} \left[ F_{\text{act}}(t) - M_i \dddot{u}_x - K_0 \dot{u}_x - (C_2[\dot{u}_2]^2 + F_0) \text{sign}(\dot{u}_2) \right]^2 dt
\]

where \( \bar{e} = \) normalized error to be minimized for a given value of \( \alpha \); \( N \) = number of tests considered; \( T_i \) = duration of the \( i \)th test; and \( \lambda_i \) = weight assigned to the \( i \)th test. Eq. (2) can be rewritten in the following alternative form:
Correction of online force measurements

- Measured forces using actuator load cells include inertia and friction

\[ F = m\ddot{u} \downarrow x + F\downarrow \text{Friction sign}(u \downarrow x) + cu \downarrow x + d \]

- 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.