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INTEGRATION OF NEESGRID INTO THE NEES@UCLA FIELD TESTING SITE

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SUMMARY

Before the George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES) Program enters into the operational phase, the full *nees*@UCLA mobile field laboratory will be utilized to perform forced vibration testing of a four-story office building. The final task remaining to be completed before the *nees*@UCLA Site becomes fully operational is the integration of NEESgrid, a high performance internet network to support earthquake engineering research within the NEES community. The *nees*@UCLA Site has unique networking requirements given that it is field testing site, and that the NEESgrid system was originally designed for laboratory-based Equipment Sites. Consequently, the *nees*@UCLA Site has developed a High Performance Mobile Network (HPMN) to support real-time telepresence through the NEESgrid architecture for off-campus experiments. This paper describes the development and integration of the HPMN and NEESgrid networks, and the potential benefits it provides to future NEES researchers.

INTRODUCTION

The NSF-funded George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES) Program was established with the goal of transforming the nation's ability to carry out earthquake engineering research. In particular, NEES seeks to shift the emphasis from current reliance on physical testing to integrated experimentation, computation, theory, databases and model-based simulation. To support this goal, the NEES System Integration team is currently developing a high performance internet network, termed NEESgrid, to support collaborative experimentation, modeling and simulation across the 15 different NEES Equipment Sites. Once complete, NEESgrid will facilitate information exchange between researchers, enable remote shared access and provide a powerful collaborative space for modeling and simulation.

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The *nees*@UCLA Site is currently under development, and is preparing to become operational in October 2004. Before this occurs, the full *nees*@UCLA mobile field laboratory will be utilized to perform forced vibration testing of a four-story office building, termed the Four Seasons Project. The Four Seasons Project provides a valuable opportunity to collect a dataset that can provide insight into the dynamic response of a real building and its components. In addition to the technical merits of the project, the Four Seasons testing provides an opportunity to collaborate with the System Integration team to integrate the NEESgrid system to the *nees*@UCLA Site in what is termed an Experiment-Based Deployment. This paper describes the integration of the NEESgrid system into the *nees*@UCLA Site. In the sections that follow, we provide an overview of the *nees*@UCLA equipment and testing capabilities, describe the Four Seasons Building Project, and explain the system architecture of a High Performance Mobile Network to enable telepresence at field test sites. Next, we describe the integration of NEESgrid software and Application Program Interfaces (APIs) specifically customized for our application. We conclude by illustrating the potential benefits of NEESgrid as it relates to our Site.

NEES@UCLA PROJECT OVERVIEW

The *nees*@UCLA equipment site provides state-of-the-art equipment for forced vibration testing and seismic monitoring of full-scale structural and geotechnical systems. This equipment is useful for identifying system properties through system identification analyses of recorded data, studying the nonlinear responses of systems with limited mass, and evaluating the interactions of various system components for realistic sets of boundary conditions.

The major equipment components of the site are illustrated in Figure 1 and include the following:

A. **Eccentric mass shakers** that can apply harmonic excitation across a wide frequency range in one or two horizontal directions. These shakers can induce weak to strong forced vibration of structures. For small structures, excitation into the nonlinear range is possible when the shakers are operated near their maximum force capacity. The shakers can be operated in a wired or wireless mode.
B. **Linear inertial shaker** that can apply broadband excitation at low force levels. This shaker can be programmed to approximately reproduce the seismic structural response that would have occurred for any specified base-level acceleration time history (assuming the properties of the structure are known). The shaker can be controlled in a wired or wireless mode.
C. **Above-ground sensors** that can be installed at the ground surface or on building, bridge, or geo-structures to record acceleration or deformation responses. Accelerations are recorded with uni-directional or triaxial accelerometers. Deformations (i.e., relative displacements between two points) are recorded with LVDTs or using fiber-optic sensors.
D. **Retrievable subsurface accelerometers** (RSAs) that can be deployed below-ground to record ground vibrations in three directions. The sensors and their housing are specially designed to be retrievable upon the completion of testing.
E. **Wireless field data acquisition system** that efficiently transmits data in wireless mode from the tested structure to the high performance mobile network (see following item).
F. **High performance mobile network** that (a) receives and locally stores data at a mobile command center deployed near the test site; (b) transmits selected data in near real time via satellite to the UCLA global backbone; and (c) broadcasts data via the NEESpop server into the NEESgrid for teleobservation of experiments.

We anticipate several general categories of application for the *nees*@UCLA equipment site. The data retrieved from these applications will have the potential to significant impact our ability to effectively model complex geotechnical/structural systems and to manage and interpret data collected from dense field sensor networks, which will ultimately lead to improved seismic design procedures and significant reductions in the public's seismic hazard exposure. Example application areas are described briefly in the following paragraphs:

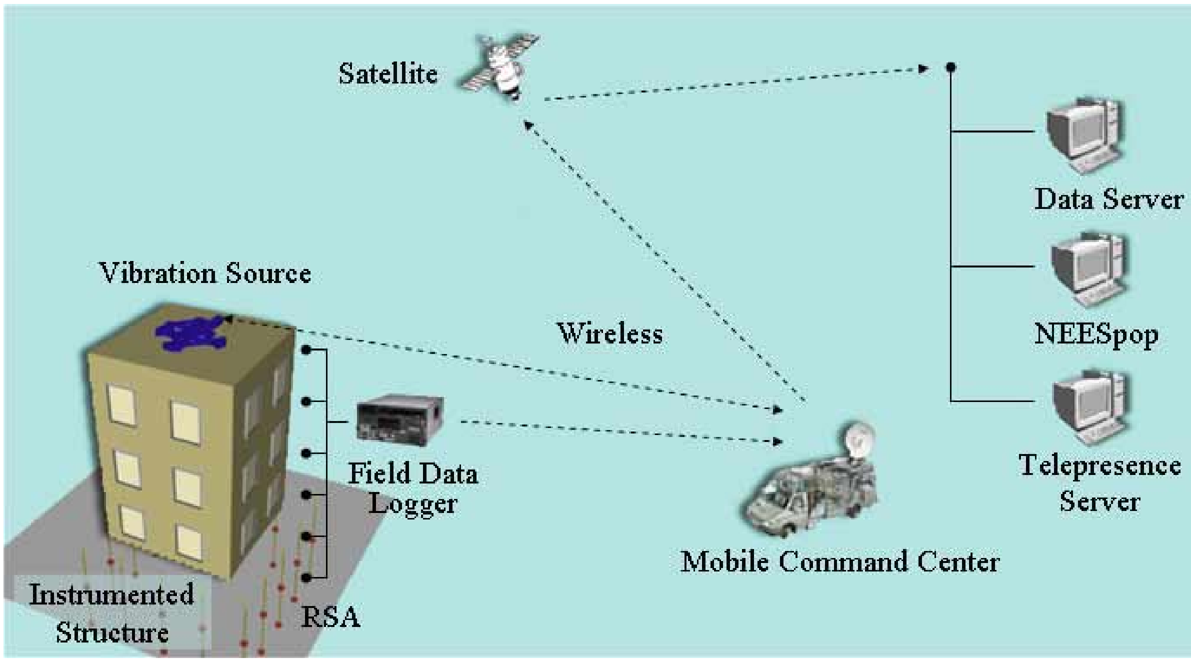

Fig. 1. Schematic illustration of deployed equipment from the *nees*@UCLA Site

Building or bridge structural response/performance studies. The equipment can be used to identify the modal responses of buildings (i.e., vibration periods, damping ratios, mode shapes), to evaluate the performance of non-structural elements within tested structures (i.e., HVAC, partition walls, equipment, etc.), and to evaluate the detailed response of structural components (e.g., beam-column connections, column-slab connections, etc.). Experiments can be performed at low levels of excitation from ambient vibration, micro-tremors, or over a range of excitation levels using the various shaker systems. For structures of small to modest size, the eccentric mass shakers can be utilized to excite structures into the nonlinear range. An important aspect of field testing is the ability to capture structural response and interactions without the shortcomings of scale and boundary conditions that commonly exist for laboratory testing. A unique feature of experiments performed using the *nees*@UCLA equipment relative to previous field testing programs is the potential for installation of dense instrumentation arrays that will provide more detailed insights into structural and non-structural response and performance characteristics. Potential applications might include forced-vibration studies of existing structures slated for demolition, full-to-moderate scale structures or sub-systems constructed specifically for testing, or use of the sensors and data acquisition system within structures during earthquake aftershocks.

Seismic health monitoring and sensor networks. A long-term vision for equipment use involves development of robust sensor networks for real-time seismic structural health monitoring by collaborating with other disciplines (e.g., computer science). Important issues to be addressed include: development of robust MEMS sensors, application of network time protocols in field sensor deployments, efficient transmission of data (e.g., multi-hopping or beam-forming), effective use of in-network processing, and development of efficient techniques for data management and interpretation.

Soil-foundation-structure interaction (SFSI) studies. The equipment can be used to apply forces and moments to foundation components, the response of which can be measured with acceleration and/or displacement sensors to evaluate SFSI effects. Load application to foundations is a natural consequence of vibration testing of buildings and bridges, so SFSI studies could be a component of any such experiment. Moreover, shakers can be directly installed on model foundations or simple structures mounted on model foundations to generate cyclic responses. Instrumentation would typically include an accelerometer array to record foundation motions and ground surface and below ground motions (using the RSAs). Specific research objectives of such work could include the evaluation of frequency-dependent stiffness and damping terms for foundation systems, as well as foundation-soil-foundation interaction effects.

Response/performance studies for geo-structures or soil deposits. As with building or bridge structures, geo-structures such as dams, embankments, and retaining wall systems can be tested though forced vibration or seismic monitoring. Such studies would typically be performed to evaluate seismic response characteristics (i.e., vibration periods, damping ratios, topographic amplification effects). Excitation at amplitudes that could induce soil shear failure is expected to not generally be possible. RSAs would enable measurements of internal response and deformations of geo-structures. Seismic monitoring of soil deposits is also possible with the RSAs. Monitoring of soil deposits might be of interest following a major earthquake, as data recorded from aftershocks could provide insight into wave propagation characteristics and soil pore water pressure generation.

FOUR SEASONS BUILDING EXPERIMENT BASED DEPLOYMENT

Project description

The Four Seasons building is a four-story reinforced concrete office building located in Sherman Oaks, California. This building was constructed in 1977 and the structural system includes a perimeter moment frame with an interior post-tensioned slab-column “gravity” system with drop panels, which represents a fairly common structural system used on the west coast of the US. The Four Seasons building was significantly damaged in the 1994 Northridge Earthquake, and post-earthquake studies of the building provide somewhat conflicting reasons for the observed damage. The building has since been yellow-tagged and is scheduled for demolition in approximately one year. Access to the building site has been granted by the building owner, and a series of forced vibration tests on the Four Seasons building have been planned.

The principal research objective of this project is to collect a detailed dataset that will be used to improve on our understanding of the dynamic response of real buildings using the *nees*@UCLA equipment. The data archived through the proposed research could form the basis of detailed analytical studies for many years. Both earthquake-type and harmonic force histories will be applied to the building and the building responses to these force histories will be recorded with a dense instrumentation array. The sensors used will monitor structural and non-structural responses (*e.g*., partitions, suspended ceilings, sprinkler system components), as well as foundation and soil responses through the use of accelerometers, displacement transducers, and concrete strain gauges. Approximately 60 channels of Episensor accelerometers, 40 channels of LVDTs and 96 channels of strain gauges will be deployed during the forced vibration tests.

Following the forced vibration testing of the Four Season building, two different time domain system identification techniques, the ARX (auto-regressive model with exogenous input) approach and N4SID (Numerical Algorithm for Subspace State Space System Identification), will be employed to identify the structural modal properties such as frequencies, damping ratios, mode shapes and the physical parameters of the building using the data generated throughout the testing.

The ARX approach is well known in electrical and system engineering field. In the case that the loading history of the shaker applied to a building is recorded, an ARX model can be used to construct the input-output relationship in the discrete-time domain. The coefficients of the ARX model are evaluated based on the least-square approximation. Once the coefficients of the ARX are determined, the transfer function of the system is completely known, which can be used to identify the modal properties of the building.

The N4SID is viewed as an alternative to the polynomial model but with a more complex numerical analysis. It can be applied when the excitation to a structure is measured or not measured. The key element of N4SID is the projection of the row space of the future outputs into the row space of the past outputs. It identifies the state space model of a structure based on the measurements and by using robust numerical techniques such as QR-factorization, singular value decomposition (SVD) and least squares. Once the mathematical description of the structure (the state space model) is found, it is straightforward to determine the modal parameters.

After using the ARX approach and N4SID to determine the state space model of the Four Season building, the second-order model of the building can be constructed based on the algorithm to determine some transformation matrices, which are used to transform the first-order state space equations to physical meaningful coordinates. Then, the physical parameters including the mass, stiffness and damping matrices of the building can be identified, which are useful for structural health monitoring and damage detection.

Aside from the potential societal benefits from improved understanding of dynamic structural response, the Four Seasons testing provides an opportunity to assemble and demonstrate the full *nees*@UCLA mobile field laboratory integrated with NEESgrid. The NEES System Integration team has been engaged in this effort, termed Experiment-Based Deployment.

HIGH PERFORMANCE MOBILE NETWORK

As previously mentioned, the NEES System Integration team is currently developing NEESgrid, a high performance internet network, to support collaborative earthquake engineering experimentation, modeling, and simulation using the NEES Equipment Sites. Once complete, the NEESgrid system will enable remote participation via telepresence[6], provide computational capabilities, and maintain a NEES data repository for the operational phase of NEES. The interface between NEESgrid network and the various Equipment Sites is through a dedicated, flexible platform called NEES Point-of-Presence (NEESpop). A NEESpop server connects to the global NEESgrid network through Internet2 via a gigabit backbone, and serves as the central system monitoring, authenticating, resource discovering, data caching, data browsing, data archiving, and associated services for collaborating for each NEES site. The *nees*@UCLA equipment site has two NEESpop servers (campus and field), and the campus-NEESpop provides the functionality as the primary point of contact with NEESgrid since it is directly connected to the campus gigabit backbone. The field-NEESpop provides temporary data, video, and metadata storage in the field. Additional details of the NEESgrid system are provided at http://www.neesgrid.org.

The *nees*@UCLA Equipment Site has unique networking requirements given that it is field testing site, and that the NEESgrid system was originally designed for laboratory-based Equipment Sites. Consequently, the nees@UCLA Site has developed a <u>H</u>igh <u>P</u>erformance <u>M</u>obile <u>N</u>etwork (HPMN) to

[6] real-time viewing of data and video

support real-time telepresence through the NEESgrid architecture for off-campus experiments. The following sections provide details on the HPMN system architecture as well as the software integration.

Wireless and Satellite telemetry

As shown in Figure 1, wireless telemetry is used to transmit data and video packets from the test structure to the mobile command center[7] located nearby to the test site. Wireless communication is performed using standard IEEE 802.11b and TCP/IP protocols and commercial off-the-shelf radios. Figure 2 shows the networking diagram and sequential data transfer through the various HPMN components. Analog sensor signals (e.g., from accelerometers, displacement gauges) are transmitted via cables to a Quanterra Q330 data logger node where they are digitized, GPS time-stamped and temporarily stored to local memory buffer. Each Quanterra Q330 comes equipped with an Enterasys Roam About™ radio card, which is used to transfer the digitized data packets to Wireless Access Points (WAP). Each WAP has two Enterasys radio cards, one of which is configured to communicate with other Quanterra Q330 radios (i.e., workgroup mode) and the other configured to communicate with other WAPs (i.e., wireless backbone). WAPs then relay data packets to a data concentration point located on the test structure with line-of-sight to the mobile command center. The data concentration point contains a Sun Microsystems Netra 120 server[8] running Antelope™ data acquisition software to centrally record data packets received from each of the various Quanterra Q330 nodes. Antelope synchronizes all of the data packets collected from the various Quanterra Q330 nodes using the GPS time stamps, and centrally records the data to an orb[9]. Afterwards, the Antelope orb2orb transfer protocol is used to transmit data packets from the Antelope server housed within the data concentration point to a Sun Microsystems Blade server running Antelope and connected to a data storage server in the mobile command center. A Yagi[10] long range antenna is used to complete this orb2orb transfer between the data concentration point and the mobile command center. Video streams are transmitted from the test structure to the mobile command center using the same system architecture although they bypass the data concentration point. The nominal wireless throughput using IEEE 802.11b is 11 Mbps, which is sufficiently large for 120 channels of data and 2 or 3 video streams.

Once data is received at the mobile command center, it is recorded locally by the Antelope server while selected channels will be streamed out to the NEESpop. Video packets will be streamed to the telepresence server on the UCLA campus for real-time observation while simultaneously recorded to DV tape for archival purposes. As shown in Figure 3, the mobile command center also contains a Very Small Aperture Terminal (VSAT) satellite system for the purpose of streaming both data and video packets back to the UCLA campus. NEESgrid services require a gigabit wide area network (WAN) connection, and accordingly, all field data and video must be routed through the campus-NEESpop.

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[7] mobile command center – a Chevrolet CC5500 truck with integrated mobile computing facilities and satellite system

[8] The Sun Microsystems Netra - a high density, thin, ruggedized server designed to withstand extreme levels of temperatures, humidity, radiation and vibrations.

[9] orb – object ring buffer where data is buffered and transported

[10] Yagi - a uni-directional antenna with high gain to enable long-range IEEE 802.11b wireless communication

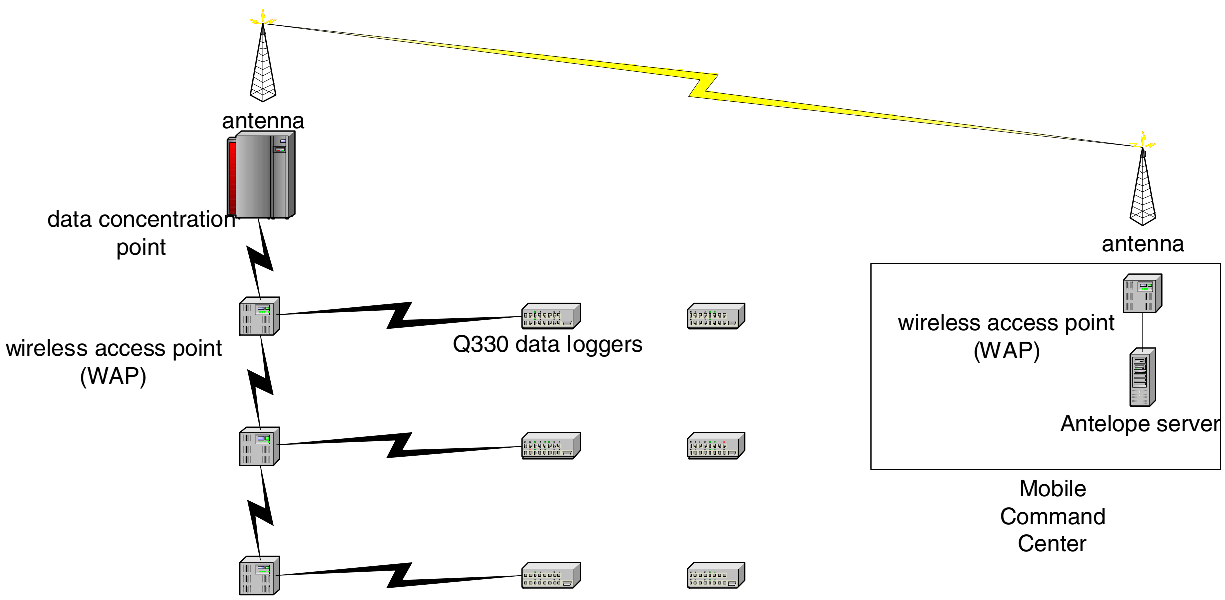

Fig. 2. Wireless network diagram

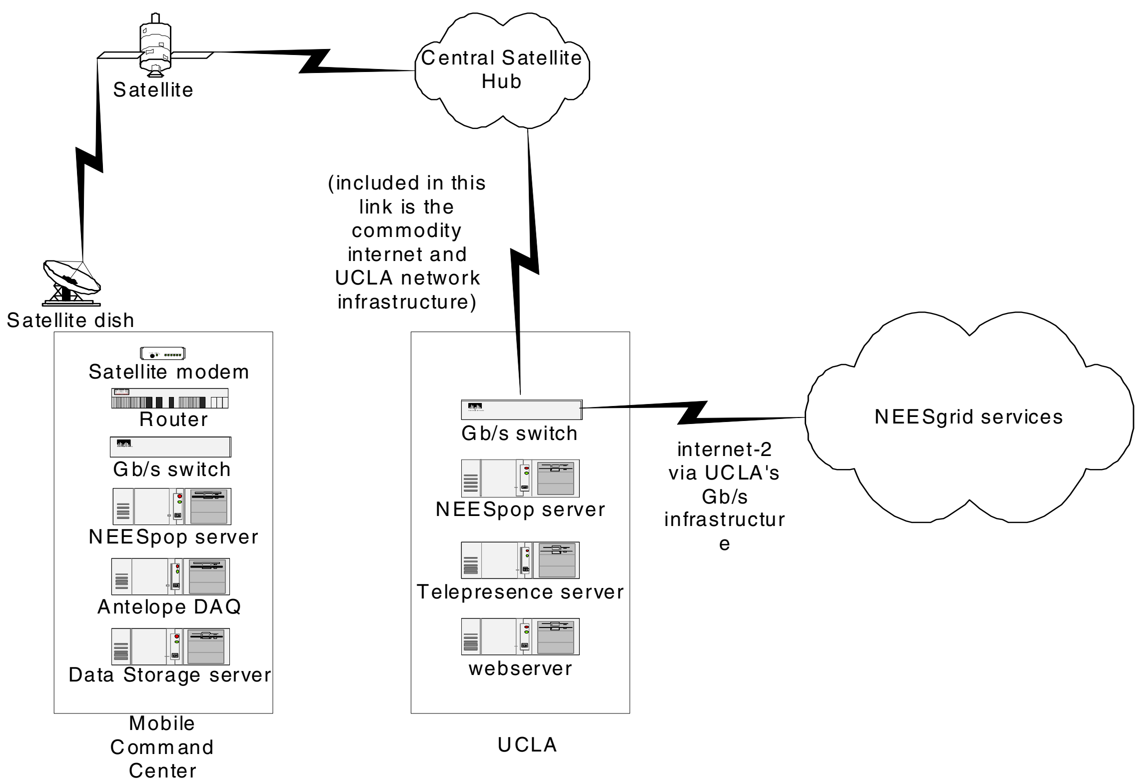

Fig. 3. Satellite networking diagram

The mobile command center transmits data and video streams to the campus-NEESpop via broadband satellite telemetry. The mobile command center contains a roof-mounted 1.8-m mobile VSAT satellite with auto-pointing and dual-bandwidth capabilities. The VSAT satellite system is capable of transmitting at uplink and downlink frequencies of 14 to 14.5 GHz and 11.7 to 12.2 GHz, respectively, which give nominal throughput performance of 1.54 Mbps which is equivalent to T1 connectivity. The satellite system employs standard TCP/IP protocol, and therefore requires no special software to transmit from the mobile command center to the campus-NEESpop. The packets are received at a central hub and sent to the campus-NEESpop over the commodity internet. Connections between the campus-NEESpop to NEESgrid are completely gigabit.

Time Synchronization Protocols

A critical issue with the HPMN wireless sensor network is to ensure that samples collected at the same time at different nodes can be temporally aligned at the data concentration point (i.e., time synchronized). One solution is to synchronize time in all the sensor nodes; this is also known as global time synchronization in sensor networks [1]. Mechanisms for global time synchronization via GPS signals have been proposed and implemented, and is currently available with all of our data acquisition systems. However, it is not always feasible to obtain a GPS signal within buildings. Furthermore, global time synchronization incurs overhead in terms of periodic beaconing to compensate for the clock skew (difference in clock rates) that may be present in the clocks of different sensor nodes. Consequently, we have implemented an innovative network time protocol recently developed by Elson et al. [1].

In Figure 4, suppose samples s_A and s_B are collected at the same time at nodes *A* and *B*, respectively. These samples, after compression and encapsulation into messages, are transmitted over multiple hops towards sink *S* (i.e., data concentration point) and take two different paths. s_A passes through nodes *A1*, *A2* and *A3* while s_B passes through *B1* and *B2* before reaching *S*. The total transmission times *i.e.,* spent by samples T_A (for s_A) and T_B (for s_B) in the network will be different and hence these samples will reach *S* at different times. The challenge is to align s_A and s_B at *S* after it has received them. In our implementation we take a different approach to avoid the overhead of global synchronization and at the same time enable synchronization of collected samples at the sink. Instead of attempting to synchronize time on all the sensor nodes we calculate the total time spent by the samples in the network and use this information to synchronize the samples.

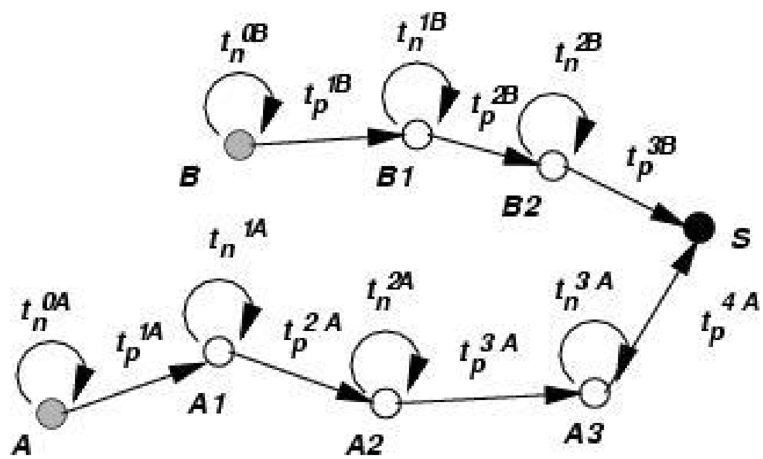

Fig. 4. Time synchronization example

We explain this new network time synchronization scheme through an example. In Figure 4, let t_n^{iA} be the time spent in at the i^{th} hop node and let t_p^{iA} be the propagation delay for the i^{th} hop. Then,

$$T_A = \sum_{i=0}^{i=2} t_n^{iA} + \sum_{i=1}^{i=3} t_p^{iA} \quad (1)$$

Noting that propagation delay (of radio waves) incurred over several hundred meters (path distance to sink) is in the order of nanoseconds, we neglect the second summation in Equation 1. The time spent at a node is generally on the order of milliseconds and cannot be neglected. Under this assumption, T_A can be calculated by summing up the times spent at each node. In our implementation each transmitted packet has a header field which carries the summed times spent at all the encountered nodes. As this packet reaches the base station *S*, the sink notes the time (its own local time) at which it received this packet say t_A. Hence, the sample must have been generated at t_A - T_A (T_A is obtained from the packet header) in the local time of the sink. The same procedure is applied for sample s_B. Now s_A and s_B can be aligned since $t_A – T_A = t_B – T_B$ and nodes do not require global time synchronization. We rely on the fact that while clock skews are not negligible of the scales of several tens of minutes, they are not significant over the time scales of multi-hop transmission delays. While this network time protocol was originally intended for wireless MEMS embedded networked sensors [2], this scheme can be extended to the existing Q330 data loggers.

Integration of NEESgrid software

NEESgrid software installed on the *nees*@UCLA NEESpop servers consists of the five major components, each of which provides different functionalities: (a) CompreHensive collaborativE Framework (CHEF) which serves as the primary graphical user interface for remote researchers, (b) NEES Streaming Data Service (NSDS) to provide a uniform interface for subscribing to and accessing streaming data originating from experiments and simulations during their execution, (c) Telepresence system which provides real-time data, video and audio feeds, (d) NEES MetaData Service (NMDS) for data management and ingestion into the NEESgrid data repository, and (e) the E-notebook, which is an electronic version of laboratory notebooks to enable lab notes to be entered by NEES researchers. Collectively, the components comprise the NEESgrid software platform developed by the System Integration team to provide online information sharing tools to facilitate collaboration between geographically distributed researchers.

CHEF enables researchers across the country to remotely access the *nees*@UCLA computational facilities using any supported thin-client web browser. During the pre-experiment phase, remote researchers can coordinate experiment configurations, instrumentation plans, testing protocols and project schedule using CHEF tools such as chat, threaded discussion board, and schedule. During testing, remote researchers can use the CHEF interface to tele-observe experiments in real-time by viewing subscribed data channels and video/audio streams as shown in Figure 5. Once an experiment is completed, researchers can download and query the data using CHEF analysis tools. Additional details regarding CHEF are provided at htttp://www.chefproject.org.

The NSDS, TPM and NMDS processes can be thought of as application programs supporting the CHEF interface. The NSDS is an Application Program Interface (API) which provides real-time data transfer from a data acquisition program to NEESgrid services. For our application, a customized NSDS driver was developed to enable real-time data transfer from the Antelope data acquisition server to the field-NEESpop server. Once data streams are received by the NEESpop and locally stored, selected channels are broadcast to remote researchers via the Telepresence system. The Telepresence system also streams live video and audio of the experiment, all of which are accessible through the CHEF interface. Supported TPM equipment at the *nees*@UCLA Equipment Site includes fixed and robotic video cameras with optional zoom-pan-tilt capabilities. Additional functionality includes remote viewing of high-resolution non-static images, remote audio connection for available sounds pertaining to experiments, and an electronic notebook. The electronic notebook is used for documenting and sharing experimental data integrated into NEESgrid services. It is a functional interface to both data and user notes and records. Lastly, the NMDS enables management, linking, discovery and ingestion of collected datasets in the NEESgrid data repository.

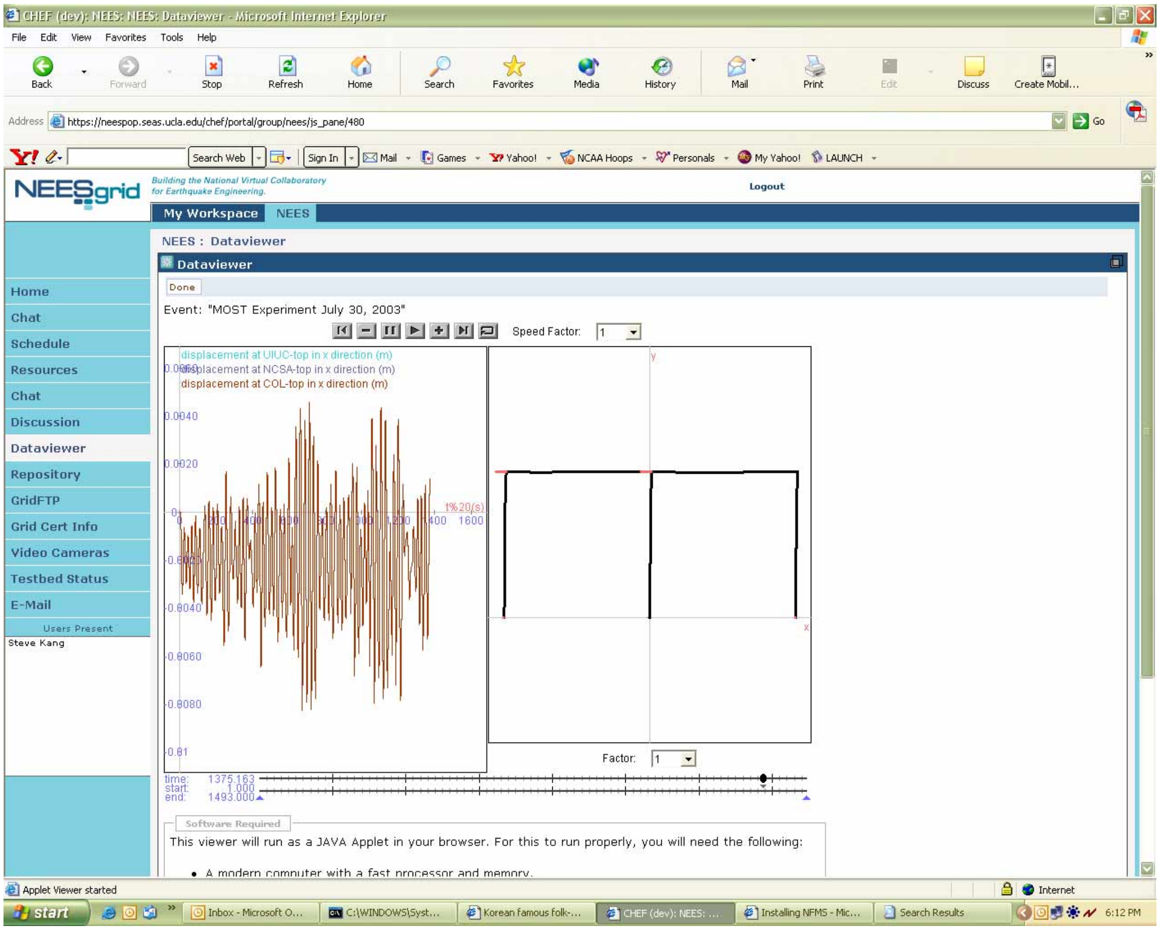

Fig. 5. Screen capture of the CHEF data viewer

To support the NMDS client, a *nees*@UCLA data model was developed for the Four Seasons Project in collaboration with the *nees*@UCSB Equipment Site. A data model is the structural decomposition of data/metadata into elements and relationships with real-world meanings. The *nees*@UCLA data model was developed using eXtensible Markup Language (XML) for easy ingestion into the NEESML data format which is currently under construction. XML is used to describe structured elements, such as metadata. Ironically, while XML provides the facility to define structured information, it has no semantic requirements of its own. All of the semantics of an XML document are defined by the applications that process them, namely NEESML. NEESML is an XML format for defining NEES metadata schemas and uploading metadata objects into the NEES metadata repository.

CONCLUSIONS

The George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES) Program is approaching completion, and the full *nees*@UCLA mobile field laboratory will soon be assembled and used to perform forced vibration testing of a four-story office building. The last remaining task in assembling the *nees*@UCLA Site is the integration of NEESgrid, a high performance internet network to support earthquake engineering research within the NEES community. The *nees*@UCLA Site has unique networking requirements given that it is field testing site, and that the NEESgrid system was originally designed for laboratory-based Equipment Sites. Consequently, the *nees*@UCLA Site has developed a High Performance Mobile Network (HPMN) to support real-time telepresence through the NEESgrid architecture for off-campus experiments.

Once integrated, the combined NEESgrid and HPMN network will enable remote participation in field experiments using the *nees*@UCLA Site. Geographically distributed NEES researchers will be able to collaborate through NEESgrid services to design, setup, execute an experiment, and post-process the data generated in the experiment. This will effectively reduce travel costs and time associated with field testing, thereby increasing the number of NEES researchers able to participate in a particular project. In addition, NEESgrid services enable digital documentation of the entire experiment through the E-notebook, NEES data model and various CHEF tools such as the discussion board, chat and scheduling features. The digital documentation is necessary for assuring data quality and data archiving into the NEES repository.

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