13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 1540

NEES EQUIPMENT SITE AT THE UNIVERSITY OF CALIFORNIA, BERKELEY

Bozidar STOJADINOVIC[1], Jack P. MOEHLE[2], Stephen A. MAHIN[3], Khalid MOSALAM[4], John F. CANNY[5]

SUMMARY

The *nees@berkeley* Equipment Site at the University of California, Berkeley is a part of the George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES). Our mission is to provide the means, both in terms of algorithms and hardware, to conduct geographically distributed hybrid simulation: a simulation that integrates physical and computer models of sub-structures to determine its response to an earthquake. The structural laboratory facilities, local area network, telepresence facilities and the hybrid simulation algorithms developed for the *nees@berkeley* Equipment Site are presented in this paper. More information about our facility is available at http://nees.berkeley.edu.

INTRODUCTION

The *nees@berkeley* Equipment Site at the University of California, Berkeley is a Phase 1 node of the National Science Foundation (NSF) George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES). The goal of NEES is to provide a geographically distributed collaboratory for an order-of-magnitude improvement in our ability to model behavior of civil infrastructure during earthquakes. This paper describes the principal features of the *nees@berkeley* equipment site.

The *nees@berkeley* Equipment Site is located at the University of California, Berkeley, Richmond Field Station. The centerpieces of the facility are the strong reaction floor and a reconfigurable reaction wall that, together with a 4-million pound compression-tension machine, enable testing of a great variety of structural components. The powerful hydraulic supply, 7 long-stroke high-speed actuators, 128-channel data acquisition system and a portfolio of instruments complete the traditional hardware side of the facility. The 1Gb/sec network split into two sub-nets, each headed by a NEESpop, forms the backbone of

---

[1] Associate Professor, Univ. of California, Berkeley, USA. Email: boza@ce.berkeley.edu
[2] Professor, Univ. of California, Berkeley, USA. Email: moehle@ce.berkeley.edu
[3] Professor, Univ. of California, Berkeley, USA. Email: mahin@ce.berkeley.edu
[4] Associate Professor, Univ. of California, Berkeley, USA. Email: mosalam@ce.berkeley.edu
[5] Professor, Univ. of California, Berkeley, USA. Email: jfc@cs.berkeley.edu

the computer hardware side of the facility. The video sub-net support the telepresence functions of the NEES network enabling users to remotely take part in the experiments at *nees@berkeley*. The data sub-net supports the computers necessary to do geographically distributed hybrid simulations. We developed and proof-tested a new control algorithm that combines our 8-channel MTS controller and digital signal processors with other NEES experimental and computer facilities and enables conducting a continuous pseudo-dynamic test in spite of random network delays. To maintain, operate and manage the *nees@berkeley* Equipment Site, we participated in the joint NEES Consortium effort and submitted a proposal to staff and manage our facility. More information about our facility is available at http://nees.berkeley.edu.

LABORATORY FACILITIES

The nees@berkeley experimental facilities are located in Building 484 at the Richmond Field Station and are shared with the Earthquake Engineering Center of the University of California, Berkeley. The overhead view of the facility is shown in Figure 1 **Location of the *nees@berkeley* Equipoment Site.**

Figure 1 Location of the *nees@berkeley* Equipoment Site.

The floor plan of the *nees@berkeley* facility is shown in Figure 2. The facility houses the test floor intended for larger-scale testing, a micro-NEES laboratory space intended for small-scale proof-of-concept testing, the control room, the electronic hardware room, a machine shop, a conference room and offices for facility personnel and visiting researchers.

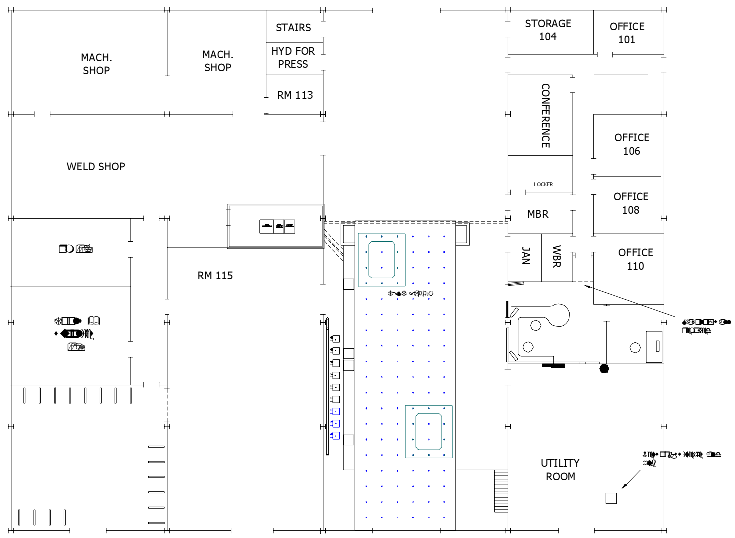


Figure 2 *nees@berkeley* floor plan.

The test floor, shown from overhead in Figure 3, consists of a main center bay and two side bays. The high main bay houses the test floor and the 4,000,000 LB Southwark-Emery Universal Testing machine. The full length of the main bay is serviced by an overhead bridge crane with capacity of 107 kN (12-tons). A paved area 15.2 x 30.4 m located on the east side of the laboratory is used as a construction area. The facilities include a fully equipped machine shop, 4 storage rooms, fabrication area (in addition to the construction area), 5 offices and a conference room. The controllers and data acquisition system used for testing are located in the instrumentation room at the southeast corner of the test floor. Operators and test participants are located in the control room just off the center of the north side of the test floor. The laboratory also has a micro NEES lab adjacent to the main test floor, which is intended for small scale testing not requiring a strong floor or a bridge crane.

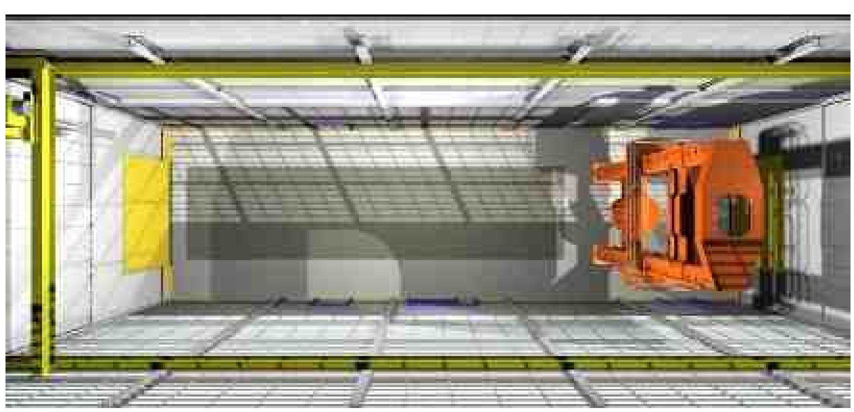


Figure 3 *nees@berkeley* test floor.

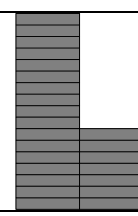
The structural tie-down floor is located on the east end of the main bay of the laboratory. The overall plan dimensions of the tie-down slab are 6.1 x 18.3 m. The slab has 63.5 mm diameter holes located in an array at 0.914m on center over the 6.1 x 18.3 meter area. The test floor provides a completely versatile facility for testing large structural assemblies. Static or dynamic loads may be applied to specimens using tie rods, hydraulic actuators, and the reconfigurable reaction wall. The test floor was designed to act as a hollow box girder in the longitudinal direction and as a Vierendeel girder in the transverse direction. The capacities are specified in Table 1.

Table 1 Reaction floor capacity.

Dimensions	Design load capacities					
Plan	Vertically @ 0.914m centers	Slab @ 457mm above floor. horizontal	Total moment of the box girder	Total shear in webs	Vierendeel action over a 0.914m cross section of the box girder. Vertical loads	
6.1 x 18.3 meters	+/-445 kN	1,330 kN	+/-843 kNm	6,670 kN	+/-667 kN over center web	+/-334 kN over outside webs

Reconfigurable Reaction Wall
The reconfigurable reaction wall or walls, is made up of 24 individual reinforced concrete blocks that are designed to be post tensioned to each other and to the test floor. The blocks are 3.05 m by 2.74 m in plan and 0.76 m high. Each block contains 10 vertical holes @ 0.91 m on center around its perimeter for post tensioning to the test floor. Similarly, each block contains horizontal holes for tying blocks together. The maximum stackable height of the wall is 12.8 m and the wall capacities for two principal configurations, assuming coefficient of friction of .5, are given in Table 2.

Table 2 Reaction wall capacities.

Wall Configuration	One-lock wall (total height = 13m)	Two-blocks wall with unequal height (total heights 5.33m and 13m)
Wall elevation view		
Load capacity at 12.2m	378 kN	601 kN
Load capacity at 10.7m	423 kN	756 kN
Load capacity at 9.14m	467 kN	912 kN
Load capacity at 7.62m	556 kN	1,090 kN
Load capacity at 6.10m	667 kN	1,330 kN
Load capacity at 4.57m	867 kN	1,760 kN
Load capacity at 3.05m	1,270 kN	2,560 kN
Load capacity at 1.52m	1,930 kN	3,870 kN

The reaction wall can be configured in many different ways to suite the experiment conducted by NEES researchers. Three principal configurations: 1) for simultaneous testing of two specimens, with a wall positioned in the center of the lab; 2) for high-axial load testing, with the wall positioned near the compression-tension machine; and 3) a two-policeman configuration suitable for realistic frame testing are shown in Figure 4. Also shown is a split-wall configuration that is being constructed for a pseudo-dynamic testing of a wall-and-frame specimen.


Configuration 1


Configuration 2


Configuration 3


Wall-and-Frame Test

Figure 4 Reaction wall configurations.

17.8 MN Test Machine

The 17.8 MN (four million-lb) capacity testing machine is one of the few large Universal Testing machines in the United States and the only one of its size on the West Coast (Table 3). This machine is used primarily for full scale structural component testing.

Table 3 Compression-tension machine capacities.

Capacity(MN)		Maximum Clearances(meters)		
Compression	Tension	Between support columns	Under compression head	Between tension grips
17.8	13.3	2.74	7.92	6.71

Hydraulic Actuators

There are 7 NEES hydraulic actuators, 4 for dynamic and 3 for static loading. The capacities of these actuators are listed in Table 4. The three static actuators are single ended and so have different piston areas for extension and retraction. The dynamic actuators are capable of providing a velocity of 20in/sec (508 mm/sec) enabling real-time dynamic testing. These new actuators, together with the old actuator of the UC Berkeley structures laboratories available at a recharge fee, can used on the reconfigurable reaction walls to accommodate a large variety of structural components and sections.

Table 4 Actuator capacities.

Actuator MTS model	Number	Stroke (mm)	Load static (kN)	Load dynamic (kN)	Velocity (mm/sec)
244.51S	2	508	979	667	508
244.50S	2	1,020	667	445	508
373.70T	3	1,830	961/1,460	-	-

Hydraulic Power Supply
The hydraulic power supply that supplies the NEES equipment consists of 4 high pressure pumps that can deliver a total of 1,210 liters per minute at 20.7 MPa and 1,890 liters of accumulators for peak demands. The hydraulic pressure is distributed to 9 individually controlled service manifolds, 6 high-flow and 3 low-flow, which are formed along one side of the laboratory. Sectional tubing and hoses are available to complete the connections to the actuators at various locations in the laboratory.

Controllers
There are two different and independent control systems available for operating the hydraulic actuators.

- **Hybrid controller:** The hybrid controller consists of an MTS design system that permits the user to completely design the control algorithms used through a Matlab/Simulink programming environment. The controller includes all hardware and cables to control up to 8 servo hydraulic actuators simultaneously at a system update rate of 1000 Hertz with a maximum of 5 degrees phase lag. This system is intended for conducting pseudo dynamic type tests involving the analytical computations of other machines either remotely through a network connection or locally.
- **MTS Flex Test GT controller:** The Flex Test controller is an MTS standard product which provides a wide assortment of pre-programmed functions for configuring and operating tests. The Flex Test hardware is designed to be completely cable compatible with the Hybrid Controller so that any of the seven actuators may be assigned to either controller and operated separately or together.

Data Acquisition
The DAS is a Pacific Instruments full-featured 128-channel system that includes transducer conditioning, A/D conversion, multiplexing, data storage/management, cabling and connectors. The user interface may be operated from several different environments such as Matlab or Labview or the OEM's stand alone software. All channels in the DAS are sampled at the highest sample rate, up to 15,000 samples per second. The recorded rates of individual channels may be programmed for any of 16 binary sub-multiples of the highest rate. The DAS includes a Scramnet and an Ethernet connection. The Scramnet connection can be included with the Hybrid control system so that all 128 channels are available to the hybrid control program. Approximately 80 different data acquisition instruments, summarized in Table 5 *nees@berkeley* instrument list., are available for NEES research use. More instruments, already used at the UC Berkeley EERC laboratory, are available at a recharge fee.

Control Room
Command and control of the test and observation of the acquired numerical and video data is centralized in the *nees@berkeley* control room, shown in Figure 5. This room is the home for computer that

provide the user interface to the controllers, the data acquisition system, the video camera systems, and the telepresence system.

Table 5 *nees@berkeley* instrument list.

	Total	Description
LVDT's	61	3-72", 2-40", 8-20", 12 each of 10", 4", 2" and 1" stroke
Accelerometers	8	2-8g, 4-4g, 2-2g span, variable sensitivity
Velocity meters	8	4-24" stroke, 4-48" stroke, 20 in/sec span,
Load cells	4	Multi-axial compression-tension-shear, 100 kips capacity
Tiltmeters	8	0.001rad sensitivity, uni-axial

Figure 5 *nees@berkeley* control room.

TELEPRESENCE FACILITIES

The telepresence facilities at the *nees@berkeley* equipment site are based on a 1Gb/sec local area network onnected to the Ethernet using a fiber optic cable that connects the Richmond Field Station to the University of California, Berkeley network. This service is purchased from the Comcast Corporation and provided to the *nees@berkeley* equipment site by UC Berkeley per the original cooperative agreement. A Cisco Catalyst router located at the Richmond Field Station is dedicated to the *nees@berkeley* equipment site. It routs traffic to two separate subnets, each having and Extreme Networks 1Gb/sec 28-port switch, as shown in Figure 6. Each subnet has a dedicated NEESpop Linux machine installed and maintained according to the NEES System Integrator instructions. A 1TB RAID array is attached to each NEESpop to serve for local data storage. Mirroring among these arrays provides for local backup and redundancy. Finally, a Network Time Protocol Tier 2 server is provided. This network configuration is shown in Figure 6.

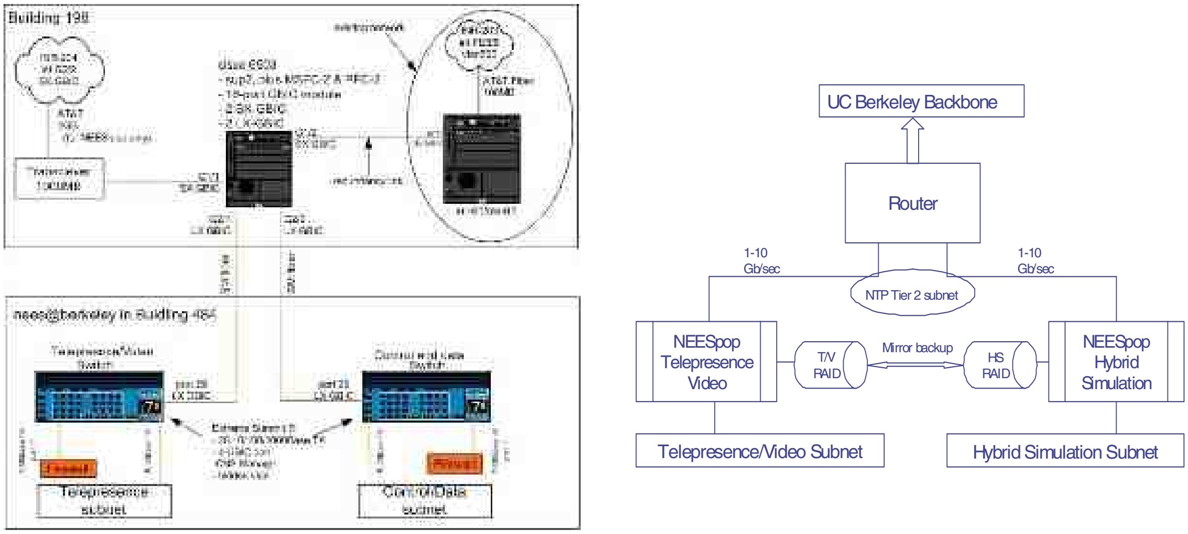


Figure 6 Local area network hardware and connectivity.

The hybrid simulation sub-net hosts the test controllers and the data acquisition system. A local shared-memory network connects the digital signal processors and personal computers that constitute the hybrid controller, as shown in Figure 7. This sub-net is separate from the telepresence sub-net because it requires low bandwidth (a small amount of data is exchanged) but high quality of service (data must be there quickly).

The telepresence/video sub-net, shown in Figure 7, hosts the video-as-data and telepresence components of *nees@berkeley* equipment site. The video-as-data component comprises 6 Canon XL1s video and 4 Canon D10 still digital cameras, a video mixer and storage device and a Zoomify software for high-resolution image analysis and web presentation (http://www.zoomify.com). The telepresence components of this subnet enable remote researchers to participate in their work at *nees@berkeley* equipment site. A Polycom Viewstation MP is provided for participating in conventional video-teleconferences. NEES Consortium is expected to provide and MCU unit for teleconferences involving more than 2 parties. An Axis/Broadware systems that enables teleopoeration of 4 video cameras for real-time observation of the goings-on in at *nees@berkeley* equipment site using the software provided by the NEES System Integrator is also on this subnet. An enhancement of the ability to remotely observe the tests is provided by the BeHere software and 360-degree lens cameras (http://www.behere.com). This system enables remote users to maneuver within a 360-degree picture of the facility. Finally, the Acivmedia Peoplebot robot is a mobile teleconference station that a remote user can steer around the laboratory and confer with the local researchers in real-time. The battery-powered robot is connected to the Ethernet using a wireless network, making it truly autonomous. Enhancing such remote presence is a remote-user driven laser pointer enabling the user to point to parts of the specimen she or he is interested in (http://www.activrobots.com/ROBOTS/peoplebot.html).

The 1Gb/sec wired local area network dedicated to *nees@berkeley* hybrid simulation and telepresence activities is supplemented by an independent 802.11g wireless network provided by the University of California, Berkeley (AirBears). This network is not on the *nees@berkeley* router (but it does share the 1Gb/sec fiber optic link to UC Berkeley). It provides password-controlled Ethernet connections for both *nees@berkeley* personnel and researchers working on NEES projects. The coverage of the wireless networkwas designed to provide NEES researcher with a wireless access inside the *nees@berkeley* facility (Building 484). While connections are possible outside the building (in the specimen construction area), they are not guaranteed.

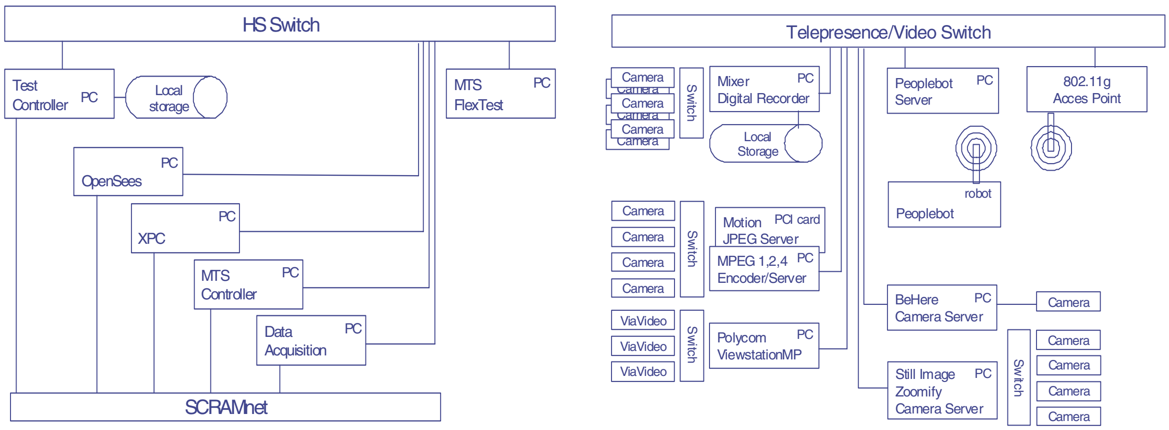


Figure 7 *nees@berkeleyi* hybrid simulation and telepresence sub-nets.

HYBRID SIMULATION METHOD

Response of a structure to an earthquake is the result of complex interaction of all elements of that structure. Today, our understanding of earthquake response of individual sub-structures is quite good. However, we do not fully understand how interactions among sub-structures define the response of the entire structure. The *nees@berkeley* equipment site is designed to enable modeling and simulation of the interaction among different sub-structures. A model in such hybrid simulation consists of sub-structures, many instantiated in powerful computers as finite element sub-models, and some instantiated as physical specimens in laboratories representing sub-assemblages of the prototype that are too complex to model numerically. Hybrid simulation is conducted using combined numerical analysis and test control procedures that smoothly integrate physical and computational sub-structures into a single model. The interaction among the sub-structures in a hybrid test occurs in the network that binds together the computers and laboratory facilities where the sub-structures are instantiated. Such simulation is rooted in the pseudo-dynamic testing method (PDTM) developed since the 1970's at UC Berkeley and elsewhere. Even though the hybrid simulation test is happening on the Ethernet, PDTM integration procedures and dynamic testing similitude rules still apply. Our challenge was to build the technology to enable such hybrid testing and test result interpretation on the NEESgrid network.

The technology for geographically distributed hybrid testing is based on a three-loop hybrid test control architecture. The innermost loop is the conventional PID actuator control loop updated at a 1kHz rate. The outermost loop is the conventional time-step integrator used in PDTM updated at 0.1kHz rate. The intermediate loop, comprising a predictor and a corrector, acts as a buffer between the inner and outer loops. When a hybrid test is run in a local mode (with all sub-structures connected using a high-speed shared memory network at *nees@berkeley* equipment site), the three-loop control architecture enables fast testing at real-time rates. However, the principal advantage of the three-loop architecture is that it lends itself to implementation on the NEESgrid network. The fast-rate communication between the inner and intermediate loops must be done locally using a shared-memory network, but the slower-rate communication between the outer and the intermediate loop may be shifted to NEESgrid relying on 1Gb/sec Ethernet spanning the NEES Equipment Sites.

However, such control architecture is not sufficient to enable geographically distributed testing. The time-delays or unexpected outages on the Ethernet introduce a random element into the control loop. An event-based control strategy, based on a finite state machine, was develop to encapsulate the logic required to make the geographically distributed hybrid test robust enough to be completed on the Ethernet. A proof-of-concept test using the sub-structure configuration, network deployment and event logic shown in Figure 7 was successfully accomplished during the May 2003 NEES Awardees Meeting at Park City, UT.

MAINTENANCE AND OPERATION

A proposal for maintenance, operation and management of the *nees@berkeley* Equipment Site has been submitted by the NEES Consortium. Equipment site operation is managed by the PI, Professor Nicholas Sitar, and the co-PI, Professor Bozidar Stojadinovic. An organization chart showing the reporting hierarchy of the *nees@berkeley* staff is shown in Figure 9. The budget for maintenance and operation in Year 1 is slightly more than $706,000 and covers the salaries of personnel in accordance with NEES Consortium use percentage rules, as well as maintenance and replacement of equipment. The proposed maintenance and operations plan is made for the first five years of planned facility operation, as requested by NSF, but continued maintenance and operation is expected to extend throughout the planned 10-year operation of the NEES Consortium. Maintenance and operation of the *nees@berkeley* upgrade proposed herein will be done within the *nees@berkeley* Equipment Site budget and staffing resources described above.

A potential NEES researcher will contact the NEES Operations Manager at *nees@berkeley* to prepare and submit a NEES proposal. When the proposals are funded, *nees@berkeley* facility manager will interact with the Consortium to schedule and organize the tests, while the remote NEES researchers and their students attend *nees@berkeley* training. Such training comprises a course on hybrid simulation methods, offered by the co-PIs, and lectures on safety and equipment usage at *nees@berkeley* provided by the staff.

FEEDBACK FROM NEESR 2004 PROPOSAL ROUND

Discussions with NEES researchers during the preparation of the first round of NEESR proposal (NSF 03-589) generated real, practical and most relevant feedback about the *nees@berkeley* Equipment Site. Potential NEES researchers found our facility quite suitable for conducting their work. In addition to a variety of local and geographically distributed pseudo-dynamic tests, a number of conventional quasi-static tests were discussed. While we can accommodate a majority of NEES researcher needs, we identified several principal groups of NEES user requests for upgrading our existing facility. They are:

1. Increase the number of available data acquisition channels from the existing 128 to 192.
2. Provide a data acquisition system to quantify and measure the damage on the surface of a specimen. This task can not be done using our existing equipment: the conventional uni-axial instruments, and conventional photo and video cameras.
3. Provide the means to record short-duration events, such as fracture propagation.
4. Provide a platform to enable repeated realistic testing of structural components to reduce the cost of building special-purpose test setups.

A proposal to purchase equipment to close the gaps identified by NEES researchers was submitted to NSF. In addition to purchase of additional data acquisition channels, this proposal outlines a system for surface damage measurement and observation comprising a high-definition laser imaging system, a high-speed high-resolution video camera and a 3-dimensioanl projection system for visualization. The proposal also request funding for components for a reconfigurable platform for earthquake testing (REPEAT) frame with clevis-pin connections.

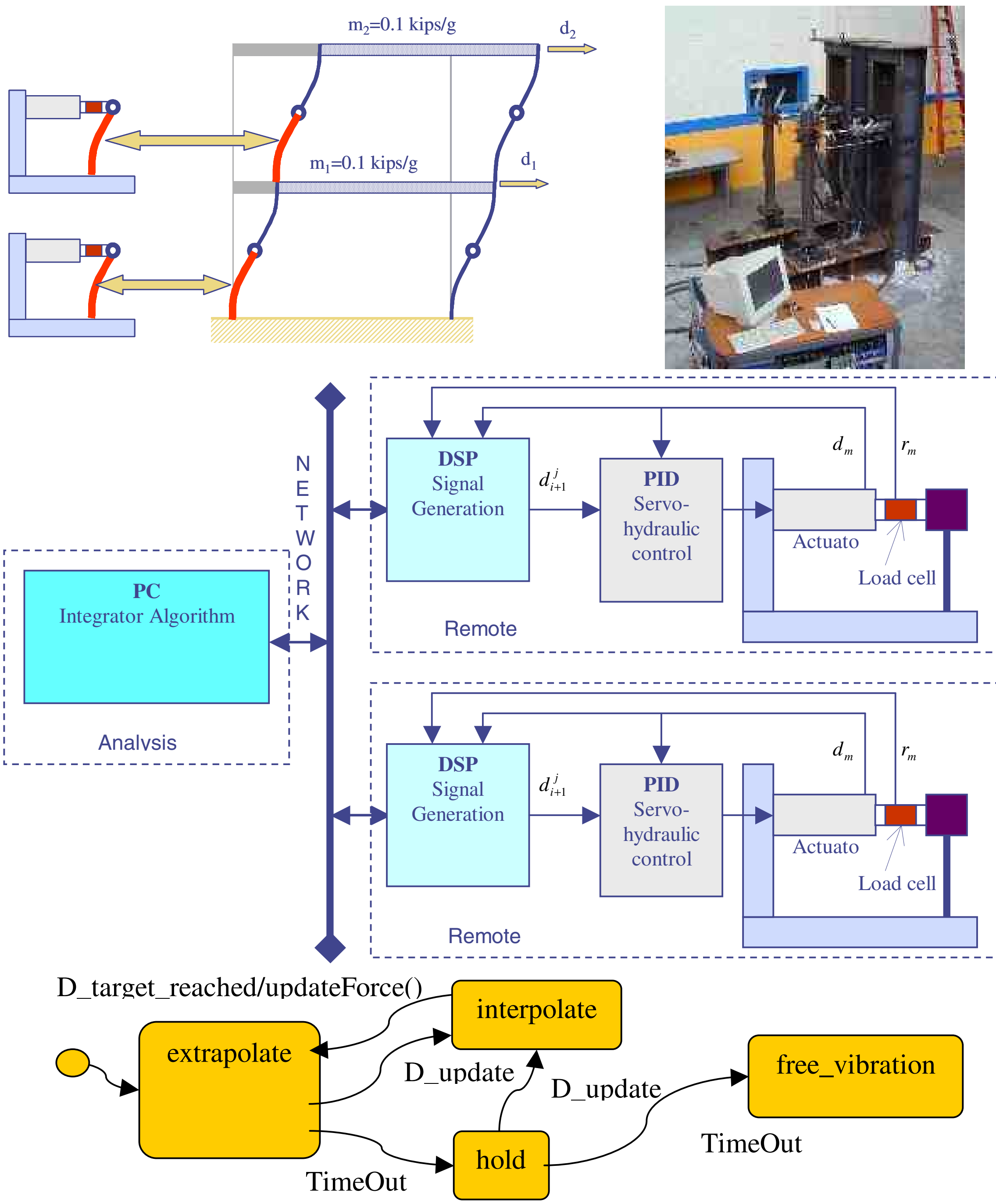


Figure 8 Proof-of-concept for geographically distributed hybrid simulation.

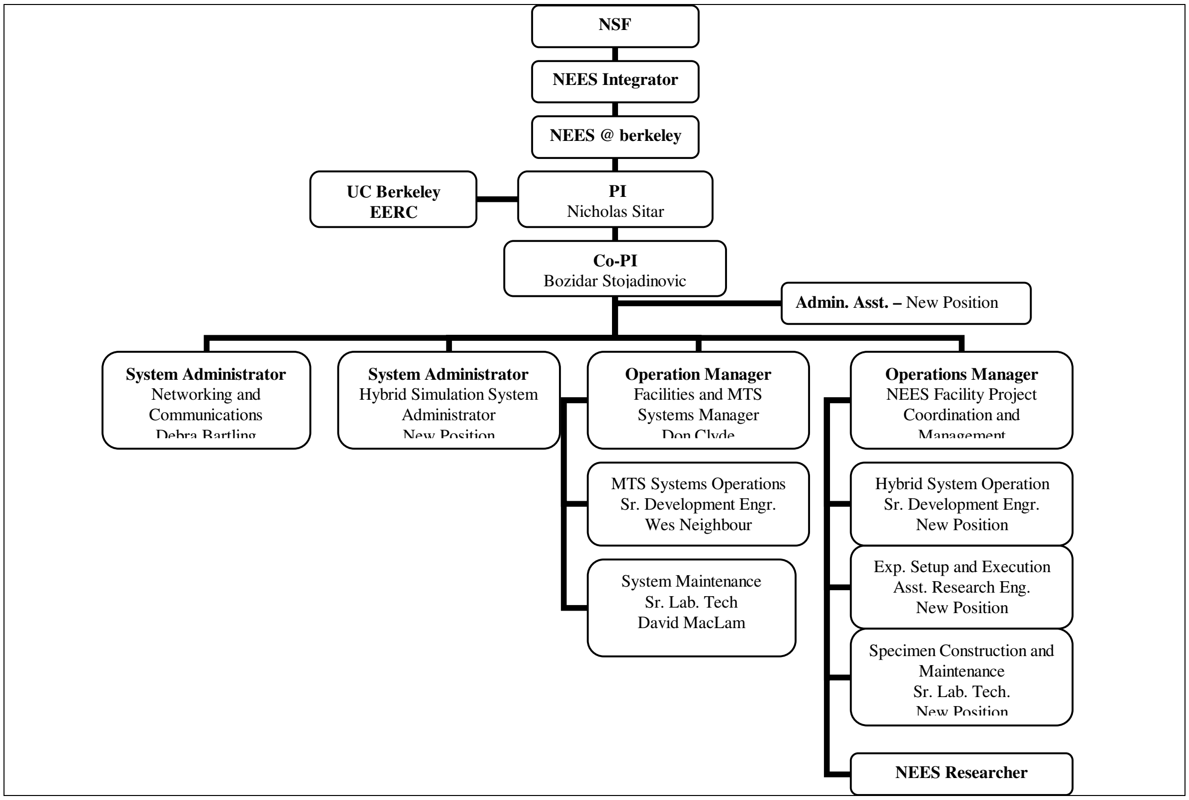


Figure 9 *nees@berkeley* management and organization chart.

CONCLUSION

nees@berkeley is a shared-use earthquake simulation facility at the University of California, Berkeley. It is an equipment site of the George E. Brown, Jr. Network for Earthquake Engineering Simulation. *nees@berkeley* equipment site leverages the capabilities of existing testing facilities located at the University of California, Berkeley Richmond Field Station. It builds on an existing 60x20-foot strong floor and an existing 4-million-pound axial compression-tension machine by adding a reconfigurable set of 24 reaction blocks, seven of dynamic and static actuators, a new 8-channel digital control system, and equipment and 1Gb/sec Ethernet connections to enable tele-observation and tele-operation. The reaction blocks may be configured to support: 1) multiply sub-structured pseudo-dynamic testing; 2) high-axial-load testing; and 3) frame collapse mechanism testing. A Matlab-based simulation model was developed to facilitate analysis of wall-actuator-specimen interaction and help in the design of stable hybrid simulation tests. The *nees@berkeley* controller is designed to support static, quasi-static cyclic, and various pseudo-dynamic test methods using stop-and-hold or continuous motions at range of rates from slow to real-time.

The facility is enhanced by teleobservation and teleoperation capabilities, and by data archiving and near-real-time data sharing. This capability will enable a broader pool of researchers to test more complex and realistic, large-scale physical specimens, thereby enhancing knowledge gained for earthquake risk reduction. The facility also includes a pseudo-dynamic digital control development bench-top dSpace-Matlab that will enable researchers to engineer, test, and validate new simulation procedures, thereby advancing testing capabilities for earthquake engineering research.

The most important feature of the *nees@berkeley* equipment site is the next-generation, dynamic hybrid simulation capability built around computer simulation and physical testing using a strong floor, reconfigurable reaction wall, and hydraulic actuators. The hybrid simulation method is designed to smoothly integrate physical and numerical simulations, using the pseudo-dynamic testing method, with capabilities to conduct simultaneously numerical simulations and multiple physical tests at geographically distributed sites connected through the Internet. Development of an algorithm that enables conducting a geographically distributed hybrid simulation test using NEES equipment site laboratories and computer facilities is presented by Mosqueda, Stojadinovic in Mahin [1].

ACKNOWLEDGEMENT

This research was supported by the National Science Foundation through a cooperative agreement with the University of California, Berkeley number CMS-0086621. This support is gratefully acknowledged.

REFERENCES

1. G. Mosqueda, B. Stojadinovic, S. A. Mahin, "Geographically Distributed Continuous Hybrid Simulation", 13th WCEE, Paper 959, Vancouver, Canada, August 2004.