

## **A SYSTEM FOR MULTI-AXIAL SUBASSEMBLAGE TESTING (MAST): DESIGN CONCEPTS AND CAPABILITIES**

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### **ABSTRACT**

This document provides a brief summary of the capabilities of the Multi-Axial Subassemblage Testing (MAST) System at the University of Minnesota. The MAST system is one of the large-scale testing facilities awarded under the George E. Brown, Jr. Network for Earthquake Engineering Simulation program, funded through the National Science Foundation. The MAST system enables multi-axial cyclic static tests of large-scale structural subassemblages including portions of beam-column frame systems, walls, and bridge piers. The MAST system concept, employing a six-degree-of-freedom controller, can be used to apply realistic states of deformations and loading in a straightforward and reproducible manner. The MAST system advances the current state of technology by allowing the experimental simulation of complex boundary effects through its multi-axial capabilities, which can impose multiple-degree-of-freedom states of deformation and load. The system is unique in size and scope and will greatly expand the large-scale earthquake experimentation capabilities both nationally and internationally.

### **Introduction**

On October 1, 1999, the National Science Foundation (NSF) initiated the George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES). With this program, the U.S. federal government has provided an unprecedented commitment to the advancement of earthquake engineering research. The objective of the program is to develop a network of advanced integrated and interconnected facilities that will transform earthquake engineering research so that it relies on the integration and coordination of experimentation, computation,

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and model-based simulation. The development of the NEES facilities is a five-year, \$82 Million program that is intended to fund approximately thirteen equipment facilities in two phases.

Within Phase I of the NEES program, eleven sites throughout the U.S. have been awarded funding in five different categories. They include four large-scale structural testing, two shake table, two geotechnical centrifuge, one tsunami wave tank, and two field equipment sites. The University of Minnesota Multi-Axial Subassemblage Testing (MAST) system was selected as one of the four large-scale structural testing facilities. The equipment will be housed in a new structural engineering laboratory, the MAST Laboratory, currently under design and being planned for construction on the Minneapolis campus of the University of Minnesota. The national facility is scheduled to open October 1, 2004. The facility will be made available to researchers from across the country and around the world to conduct research both independently and in conjunction with University faculty and graduate students. With recent building code changes such as those implemented in the International Building Code (IBC 2000), broadening the requirements for seismic considerations in larger portions of the country, this facility helps to increase the ability of the engineering community to respond to the increased demand for earthquake engineering expertise nationwide.

The University of Minnesota MAST system enables multi-axial cyclic static tests of large-scale structural subassemblages including portions of beam-column frame systems, walls, and bridge piers. The MAST system concept, employing a six-degree-of-freedom controller, can be used to apply realistic states of deformations and loading in a straightforward and reproducible manner. The MAST system advances the current state of technology by allowing the experimental simulation of complex boundary effects through its multi-axial capabilities, which can impose multiple-degree-of-freedom states of deformation and load. The system is unique in size and scope and will greatly expand the large-scale earthquake experimentation capabilities both nationally and internationally.

### **Multi-Axial Subassemblage Testing (MAST) Concept**

In the (MAST) system installation, shown schematically in Fig. 1, a stiff steel crosshead in the shape of a cruciform will be controlled with six-degree-of-freedom (6-DOF) control technology. Two sets of actuator pairs with strokes of  $\pm 400$  mm ( $\pm 16$  in.) will provide lateral loads up to  $\pm 3910$  kN ( $\pm 880$  kips) in the orthogonal directions. These actuator pairs will be secured to an L-shaped strong wall with universal swivels. Four  $\pm 1470$  kN ( $\pm 330$  kip) vertical actuators, capable of applying a total force of  $\pm 5870$  kN ( $\pm 1320$  kips) with strokes of  $\pm 510$  mm ( $\pm 20$  in.), will connect the crosshead and the strong floor. Hydrostatic bearings will be used in conjunction with the vertical actuators to reduce friction loads. Vertical spacers can be mounted between the bearings and the vertical actuators for gross height clearance adjustment. The actuators will be powered by a combination of three hydraulic service manifolds, attached to a 680 LPM (180 GPM) hydraulic power supply. Each actuator is configured with 57 LPM (15 GPM) servovalves and will provide adequate flow of oil for quasi-static test modes.

Horizontal clear distance between the vertical actuators can accommodate specimens up to approximately 6.1 m (20 ft.) in length in the two primary orthogonal directions. The vertical

clearance extends up to approximately 7.6 m (25 ft.), and can be varied by repositioning the lateral and longitudinal actuator attachments to the reaction wall.

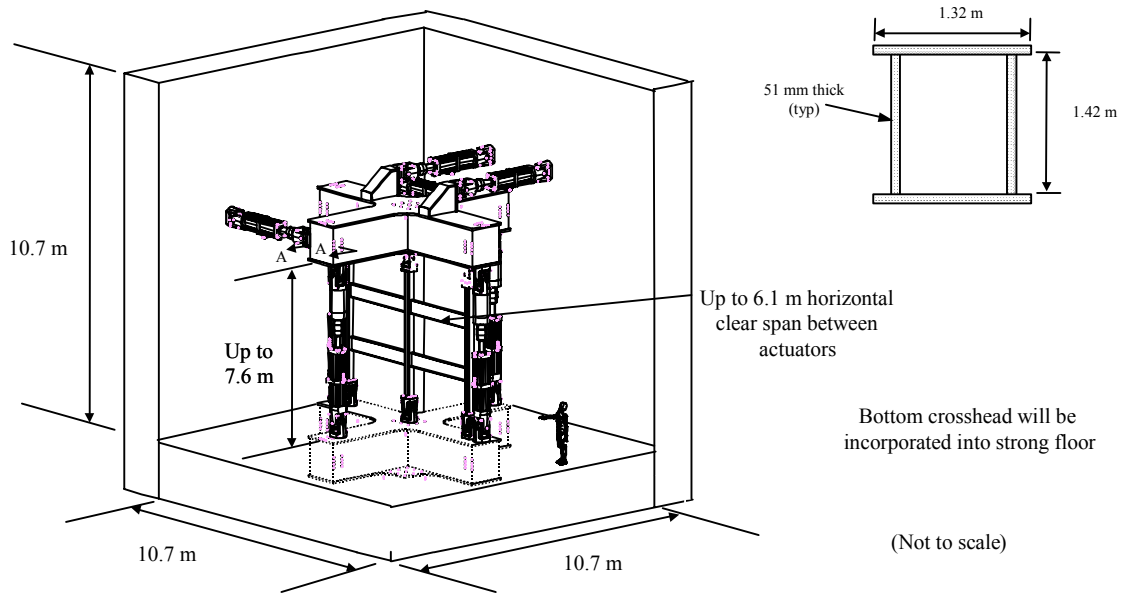


Figure 1. Schematic View of MAST System

Control of six degrees-of-freedom will enable application of complex biaxial load histories on subassemblies via control of the crosshead. The controller will be configured to provide closed loop control of the 6-DOF system. The controller includes two servo compensation techniques, one for geometric cross coupling compensation, and the other for force balance compensation.

With the MAST system, any degree-of-freedom may be programmed in either displacement control or load control, and degrees-of-freedom may be constrained in a master-slave relation to be a linear combination of the values of other degrees-of-freedom. For example, using the mixed-mode control capabilities of the MAST, it is possible to program any lateral displacement history, and at the same time specify overturning moment as a constant times the lateral force, while simultaneously maintaining an independent history of axial load on the test specimen. Another advantage of the MAST system is that it enables control of a plane in space rather than just a point in space. This feature, for example, enables application of pure planar translations, as well as the possibility of applying gradients to simulate overturning (e.g., axial load gradient in the columns of a multi-bay frame, or wall rocking).

In addition, the system will be equipped with four  $\pm 980$  kN ( $\pm 220$  kip) ancillary actuators with strokes of  $\pm 400$  mm ( $\pm 16$  in.). Each of the ancillary actuators will have the option of independent master/slave control combinations, with the flexibility of slaving the actuators to scaled master control signals off of the 6-DOF controller. Using the ancillary actuators to apply simulated gravity loading to test structures might be an example of a situation when one would employ independent control of the ancillary actuators. An example of slaving the ancillary actuators to scaled master signals off of the 6-DOF would be the case of using the ancillary

actuators to apply lateral displacements (or loads) to intermediate stories of multi-story subassemblages tested in the MAST system. Another example of this control combination would be the case of employing the ancillary actuators to control the beam end boundary conditions at assumed inflection points. In this case, the ancillary actuators would be programmed to maintain constant elevation based on the translational DOF's of the MAST system.

A solid floor and wall are shown in the three-dimensional view of the MAST system in Fig. 1. The strong floor will be 10.7x10.7 m (35x35 ft.) in plan with a regular grid of anchor points. The anchor points will most probably comprise single holes with a center-to-center spacing of 460 mm (18 in.). A plan view of the steel plate cruciform for the bottom crosshead is given in Fig. 2, including the pattern of anchor points. Within the bottom crosshead, each leg of the cruciform will be approximately 1.2 m (4 ft.) wide and will have two rows of threaded anchor holes at a 230 mm (9 in.) center-to-center spacing along the length of the cruciform legs. The rows of holes in the cruciform plates will have a center-to-center separation of 460 mm (18 in.), and the holes will coincide with the anchor points in the strong floor. The placement of the cruciform plates relative to the reaction wall is given in Fig. 2.

The capacity of each threaded hole in the strong floor is 1960 kN (440 kips) in the vertical (axial) direction and 560 kN (125 kips) in the horizontal (shear) direction. The reaction floor will have sufficient strength to develop the forces required to load eight adjacent anchor points to capacity 4450 kN (1000 kips). Threaded holes in the cruciform plates will also have 1960 kN (440 kips) capacities each in the vertical (axial) and horizontal (shear) directions, and any twelve adjacent holes may be loaded to capacity simultaneously. The cruciform will develop the force capacity of the vertical actuators, 1470 kN (330 kips), at each end of the cruciform (Fig. 2).

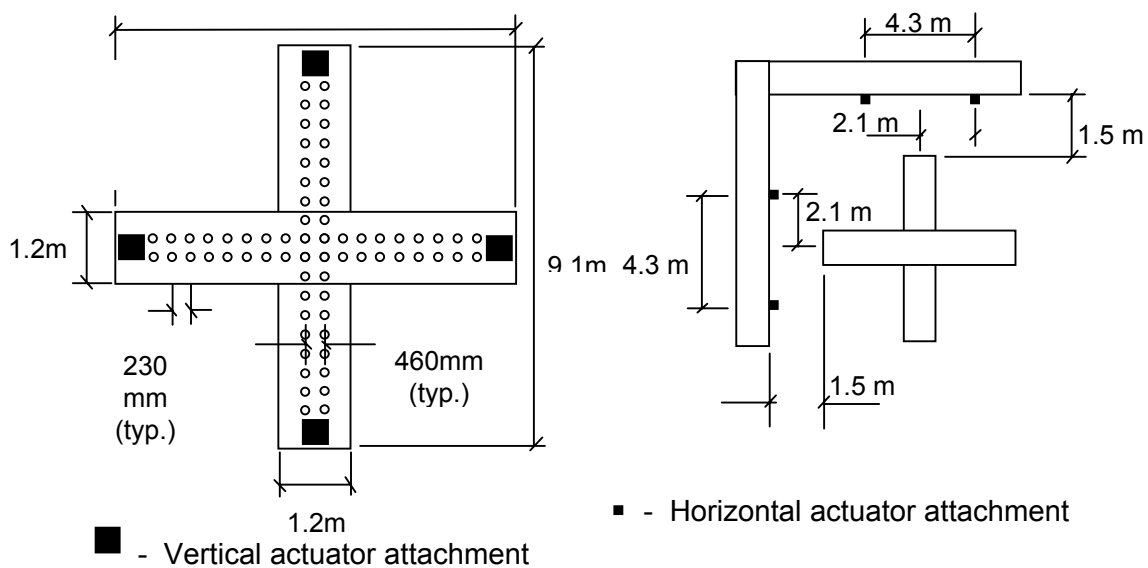


Figure 2. Plan View of Cruciform Plates and Reaction Walls

Each inside leg of the L-shaped reaction (strong) wall will be 10.7 m (35 ft.) wide and 10.7 m (35 ft.) tall. The wall will be post-tensioned to the foundation to increase its stiffness. A regular grid of anchor points will be provided at a 460 mm (18 in.) center-to-center spacing. Each anchor point will comprise a single through hole.

Each leg of the reaction wall will resist lateral forces of  $\pm 3910$  kN ( $\pm 880$  kips) each at two elevations along the wall height, 4.9 m (16 ft.) and 9.8 m (32 ft.) above the top of the strong floor), for a total of  $\pm 7830$  kN ( $\pm 1,760$  kips) (this configuration simulates that of a two story test structure, with the maximum lateral loads applied via the MAST top cross head and the four ancillary actuators). At each elevation, the  $\pm 3910$  kN ( $\pm 880$  kip) force is applied as a pair of  $\pm 1960$  kN ( $\pm 440$  kip) loads (Fig. 2), and these forces can generate maximum horizontal shear force, bending moment and vertical torsion equal to 7830 kN (1760 kips), 59,100 kN-m (43,600 kip-ft), and 52,600 kN-m (38,800 kip-ft), respectively, about the base of each leg of the wall. The maximum permissible lateral deflection for the reaction wall is  $\pm 12$  mm ( $\pm 1/2$  in.). The maximum vertical deflection for the strong floor is  $\pm 3$  mm ( $\pm 1/10$  in.).

A reference frame will be provided to allow for the monitoring of wall lateral deflection during testing. These deflection measurements will be incorporated in the control protocol for the MAST system to minimize deviations between actual and required absolute lateral deflection of test specimens.

### **Examples of Structures That May Be Tested within the MAST System**

The possibilities for structural testing with the MAST system are broad in scope. The following represent examples of types of structural configurations and variations on those concepts that could be tested with the MAST. The loading history, described below as “user-defined,” represents a multitude of options, including using an input from a multi-directional pseudo-dynamic testing system. In the case of pseudo-dynamic testing, the tests described below might represent one component of a structural system that is tested simultaneously at a number of NEES sites.

#### **Example 1 – Flanged Wall (Multidirectional Test)**

Post-earthquake reconnaissance often identifies building corners formed by intersecting concrete or masonry walls as vulnerable to seismic damage, and biaxial loading effects are often cited as one of the reasons for this damage. However, little has been done to quantify the biaxial loading and wall resistance characteristics at these corners, nor to systematically verify details to mitigate this damage. The MAST system would enable full biaxial testing of full-scale or near full-scale subassembly tests of wall sections. The sample reinforced concrete core wall shown in Fig. 3, typical of an elevator core, represents the lower two stories of a multi-story wall. To control the loading imposed on the wall through the boundaries, it is envisioned that rigid concrete blocks would be cast on the top and bottom of the wall to transfer the load from the cruciform-shaped crossheads to the flanged wall cross section. The 3/4 scale demands listed in Table 1 were scaled from a 10-story prototype with 3.7 m (12 ft. stories). Concrete strengths of 27.6 MPa (4000 psi) were assumed, along with a vertical reinforcement ratio of 2%, uniformly distributed throughout the cross section.

Assuming a moderate amount of inelastic behavior in the prototype structure, the centroid of the total lateral force distribution at maximum base shear is assumed at mid-height of the wall, resulting in a moment-to-shear ( $M/V$ ) ratio of  $H/2$ , where  $H$  is the height of the wall. Testing of this system could proceed with a prescribed lateral drift applied along each horizontal direction to define the biaxial load pattern (e.g., either from a user-defined source or from pseudo-dynamic input). At the same time, mixed-mode control could be employed to impose the desired moment-to-shear ratio at the boundaries in the two orthogonal directions. The procedure might be as follows: A prescribed lateral drift is imposed simultaneously in the two orthogonal horizontal directions. The resulting moment vectors in the two orthogonal directions, caused by the actuators applying longitudinal and lateral loads, apply an overturning moment to the structure. The distribution of lateral, longitudinal, and vertical loads would be controlled via the 6-DOF controller to ensure that the desired  $M/V$  ratio is maintained. The two remaining world DOF's (e.g., a twisting moment about the vertical axis and the resultant vertical force or axial load) may be suppressed or controlled as well. As an example, the vertical force might be specified as either constant or cyclically varying, and either independent or synchronous with the longitudinal/lateral drift histories.

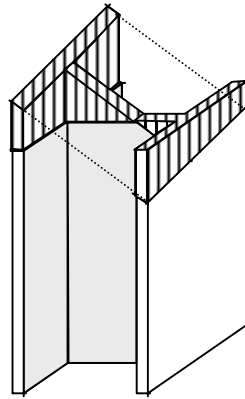


Figure 3. Flanged Wall with Biaxial Moment Gradient

### Example 2- Beam-to-Column Subassembly (Multidirectional Test)

A typical beam-to-column subassembly is shown in Fig. 4. The test specimen represents a portion of a structure modeled between inflection points assumed to occur at midheight of the columns and midspan of the floors. To represent the boundary conditions, movement of the top of the column would be controlled by the MAST top crosshead, and the bottom end of the column would be attached to the bottom MAST crosshead with a universal joint. Four ancillary actuators would maintain the story elevation of the beam ends as the column is subjected to a user-defined displacement history. The MAST 6-DOF controller enables complex biaxial displacement histories, while through mixed-mode control, the axial load on the column can be controlled as well. Table 1 shows the required load and displacement demands to test a biaxially loaded subassembly that would be similar in concept to one of the beam-to-column connections in the NSF Precast Seismic Simulation Systems (PRESSSS) Phase 2A project, in which case the lateral load resistance was assumed to be provided by perimeter frames. The demands listed in Table 1 are envisioned to be near the anticipated maximum limit for a large-scale biaxial subassembly test. The lateral/longitudinal loads and ancillary actuator

loads are based on the assumption that a beam-hinging mechanism develops. Maximum displacements are associated with extreme drifts (up to 8%). The axial load represents the gravity load on a lower story subassemblage in a 15-story building.

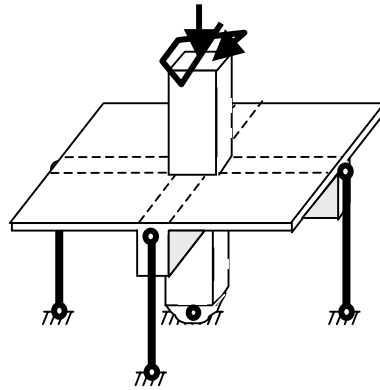


Figure 4. Beam-to-Column Subassemblage

### Example 3 – Multi-Story, Multi-Bay Frame (Unidirectional Test)

The third example is a two-bay, two-story steel structure shown in the schematic view of the MAST system in Fig. 1, and in more detail in Fig. 5. The bottom of the columns would be fixed to the strong floor. The top of the test structure, representing inflection points at midheight of the column story, would be attached to the top of the MAST crosshead with pinned connections. The columns could be loaded initially to simulate gravity loading in the lower stories of the structure. As the structure is displaced under cyclic lateral loads, a proportional amount of overturning moment could be applied via the 6-DOF control. The out-of-plane degrees-of-freedom would be constrained against displacement and twist at the top of the columns. Ancillary actuators (shown as arrows in Fig. 5) may be used to apply supplemental lateral loads (or displacements) at the individual story levels. The loads (or displacements) applied by the ancillary actuators may be scaled from the MAST crosshead. Another use of the ancillary actuators could be in the application of gravity loads to the test structure floor system.

With the 6.1 m (20 ft.) clear distance between the vertical actuators of the MAST system, the multi-bay structure as shown is limited to  $\frac{1}{2}$  scale [1:1 scale would correlate with W14x311 (50) columns and W33x150 (50) girders for a steel structure]. Typical loading requirements are highlighted in Table 1. These concepts could be expanded to include multidirectional testing capabilities.

The MAST system is not limited to particular types of building materials. The example specimens described above might feature reinforced concrete, precast concrete, steel, and masonry, or combinations of these materials. There may also be new building materials or structural configurations, not yet envisioned, that could be tested within the MAST facility, as well as energy dissipation and load control devices.

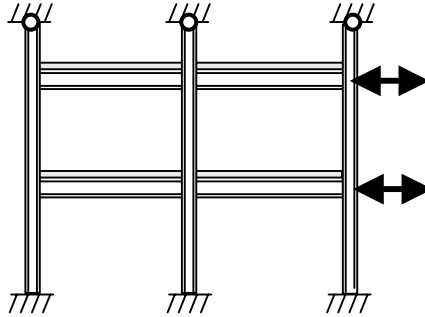


Figure 5. Multi-Story, Multi-Bay Frame Subassemblage

Table 1. Anticipated Specimen Load and Stroke Demands

Specimen Type	Dimensions		Longitudinal		Lateral		Axial	Ancillary	
	Column	Beam	Load (kN)	Stroke (mm)	Load (kN)	Stroke (mm)	Load (kN)	Load (kN)	Stroke (mm)
MAST <sup>1</sup> Capacity	6.1x6.1 m in plan, vertical 7.6 m (var.)		±3,910	±400	±3,910	±400	5,870	±980	±400
EX. #1 Scale 3:4	4.6x4.6 m in plan, 230 mm thick <sup>2</sup>		±2,890    to web	-	±670 ⊥ to web	-	4,000	Optional	
EX. #2 scale 1:1	1x1.1 m	0.5x1 m	±1,510	±330	±1,510	±330	5,340	±980	±200
EX. #3 Scale 1:2	W8x67 $F_y=345$ MPa	W16x31 $F_y=345$ MPa	±670	±380	Optional		4,500	Optional	

<sup>1</sup> Each actuator will be calibrated at three ranges, 10%, 25%, and 100%, for both stroke and load.

<sup>2</sup> Flanged wall dimensions are 4.6x4.6 m in plan, 230 mm thick, with longitudinal loading parallel to the web, and lateral loading normal to the web.

### Shared-Use Telepresence and Model-Based Simulation in the MAST Facility

In conjunction with the contributions of the NEES System Integrator (SI) at the University of Illinois at Urbana/Champaign, the telepresence infrastructure will provide all relevant information needed for both monitoring and interpretation of the experiments. As such, this facility will incorporate real-time telepresence of all visual monitoring information during an experiment and real-time transmittal of acquired sensor data (note that real-time implementation may for some components be near-real-time, with a typical latency constraint of 2-3 seconds imposed by processing, serving, and networking infrastructure). A summary of the equipment envisioned as part of the real-time telepresence capabilities in the MAST facility is shown in Fig. 6.

Teleobservation will be achieved primarily through a set of eight remotely-controllable high-resolution digital audio/video cameras and eight remotely-controllable digital still cameras spaced uniformly around the perimeter of the three-dimensional specimen, and through an array of sensors (e.g., strain gauges, position sensors). Limited real-time teleoperation of hydraulic equipment will also be developed where possible, under the assumption that an on-site research fellow will participate in the execution of all experiments to ensure safety and accuracy in execution of a remotely-operated experiment. Teleobservation and teleoperation of the video and still cameras will be through a set of high-end PC systems configured as Video and Camera Servers. Teleobservation of sensor data and teleoperation of the hydraulic system will be through a single high-end PC system configured as the Control and Data Acquisition Server. The information gathered during an experiment (including sensor data, streaming video/audio, and still images) will be collected on these associated servers and fed to a remote operator's Client Machine for real-time teleobservation and teleoperation. It is anticipated that an intelligent web browser on the Client Machine will serve as the primary graphical user interface for all real-time teleobservation and teleoperation functions of the MAST Facility.

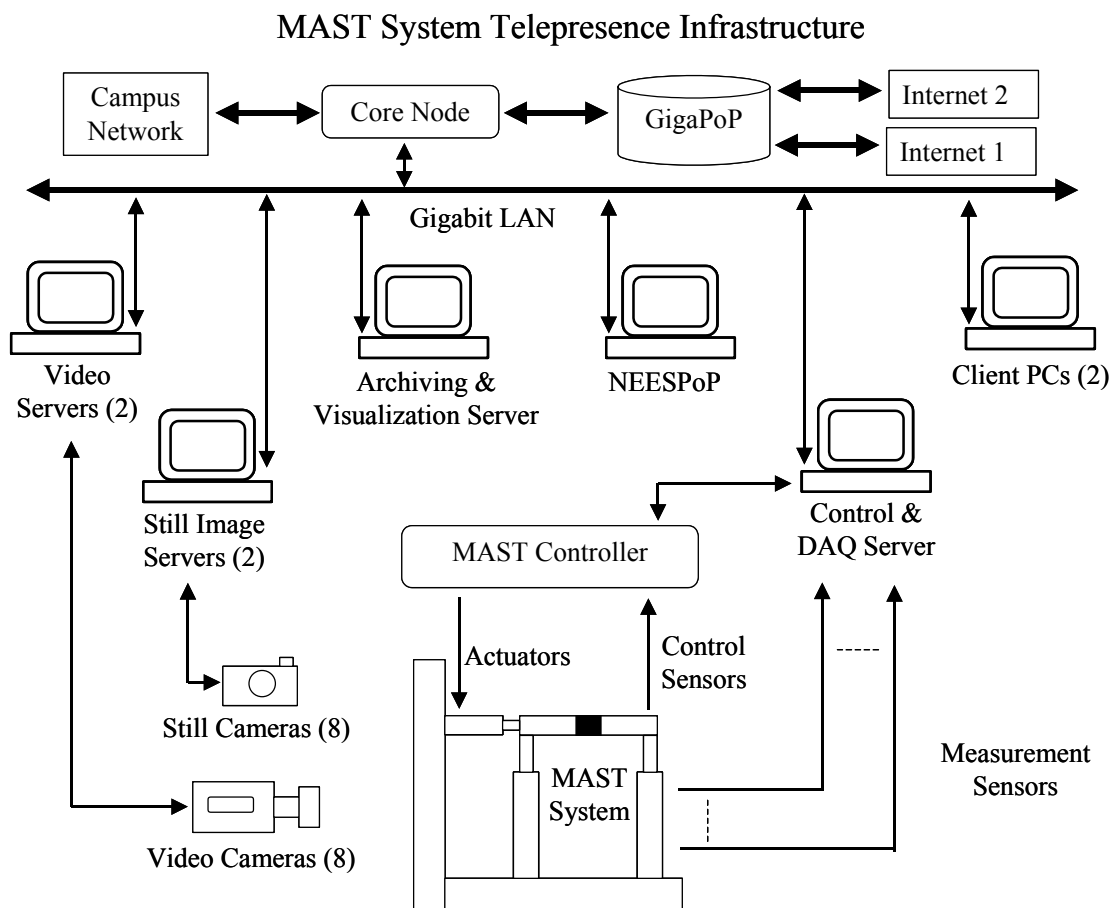


Figure 6. Schematic of Proposed Telepresence Capabilities in the MAST Laboratory

It is also envisioned that the MAST facility will fit into an integrated data-centric approach for experimentation, computation, theory, databases, and model-based simulation facilitated through the NEES System Integration. One of the most powerful features of this integrated approach to model-based simulation is an accumulated database of experimental results, which will feature the ability to “replay” tests and to couple experimental responses with computer simulations. To facilitate this integrated approach, a complete archive of all data (e.g., video, audio, still images, sensor responses, actuator settings, materials properties and measurement methods, structural dimensions) will be stored on a Visualization and Archiving Server for subsequent on-site and remote access. It is envisioned that the Visualization and Archiving Server will operate using the same graphical user interface intelligent web browser on the Client Machine for visualization, and will use software identified by the NEES System Integrator for archiving. The Visualization and Archiving Server, along with the intelligent web browser, will include video and audio streaming capability, multimedia authoring capabilities, remote accessibility to all playback functions, and multimedia synchronization capability. The latter feature is extremely important in a user-interactive environment where the captured data can be played back in an interactive manner.

### **Conclusion**

As part of the George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES) program, sponsored by the National Science Foundation, and coupled with the establishment of the national NEES Collaboratory in 2004, the Multi-Axial Subassemblage Testing (MAST) System at the University of Minnesota will be a national facility available for use by researchers for large-scale testing and computational research of structural subassemblages subjected to multi-directional loading. The MAST facility will fit into an integrated data-centric approach for experimentation, computation, theory, databases, and model-based simulation facilitated through the NEES System Integration. To house this facility, the MAST Laboratory is being constructed in a new building on the University of Minnesota Minneapolis campus, and is due to open October 1, 2004.

### **Acknowledgments**

Funding for this research was provided by the National Science Foundation under Grant No. CMS-0086602 as part of the George E. Brown, Jr. Network for Earthquake Engineering Simulation, and by the University of Minnesota. The authors would like to thank MTS Systems Corporation for their assistance with this research. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.