DOI: http://dx.doi.org/10.12989/sss.2005.1.1.001
Smart Structures and Systems, Vol. 1, No. 1 (2005) 1-12

Overview Paper

Challenges and opportunities in the engineering of intelligent systems[1]

Shi-Chi Liu†, Masayoshi Tomizuka†, and A. Galip Ulsoy‡

Division of Civil and Mechanical Systems, National Science Foundation, 4201 Wilson Boulevard, Arlington, VA 22230, U.S.A.

(Received September 22, 2003, Accepted November 2, 2004)

Abstract. This paper describes the area of intelligent systems research as funded by the Civil and Mechanical Systems (CMS) Division of the National Science Foundation (NSF). With developments in computer science, information technology, sensing and control the design of typical machines and structures by civil and mechanical engineers is evolving toward intelligent systems that can sense, decide and act. This trend toward electro-mechanical design is well-established in modern machines (e.g. vehicles, robots, disk drives) and often referred to as *mechatronics*. More recently intelligent systems design is becoming an important aspect of structures, such as buildings and bridges. We briefly review recent developments in structural control, including the role that NSF has played in their development, and discuss on-going CMS activities in this area. In particular, we highlight the interdisciplinary initiative on Sensors and Sensor Networks and the Network for Earthquake Engineering Simulation (NEES). NEES is a distributed cyberinfrastructure to support earthquake engineering research, and provides the pioneering NEES grid computing environment for simulation, teleoperation, data collection and archiving, etc.

Keywords: intelligent systems; mechatronics; automation; sensors.

1. Introduction

The National Science Foundation (NSF) celebrated its 50th birthday in the year 2000, and has been investing in the nation's future, through funding of basic research, with truly dramatic outcomes (NSF 2000). The Civil and Mechanical Systems (CMS) division of NSF focuses on basic engineering research related to machines and the constructed environment. Areas covered by CMS include mechanics of materials, surface engineering, infrastructure materials, structures, infrastructure systems, dynamic systems and control, sensors for civil and mechanical systems, geotechnical engineering, hazards and hazard response, etc. For example, past CMS investments have contributed to breakthroughs such as computer-aided design and the finite element method. Last year Paul C. Lauterbur received the Nobel Prize in Medicine for his contributions to the development of the magnetic-resonance imaging (MRI) medical imaging technique. Dr. Lauterbur was funded by the CMS division of NSF in the early 1980's to refine nuclear magnetic resonance into a routine diagnostic technique. The subsequent impact of that

†Program Director
‡Division Director
[1]This paper is an extended version of a paper presented at the fourth International Workshop on Structural Control, Columbia University, June 10-11, 2004

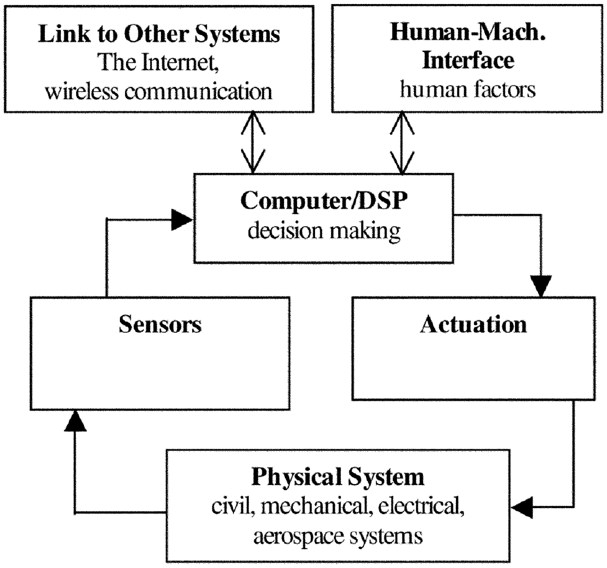

Fig. 1 Modern intelligent system

investment has been tremendous: in 2002, about 22,000 MRI machines were in use worldwide, and more than 60 million MRI examinations were performed.

The CMS division strives to achieve such beneficial results for the nation through a rigorous merit review process. In 2003, with a budget of over \$60 million, the CMS division was able to fund approximately 15% of the over 1400 proposals submitted, with a typical grant size of about \$100,000 per year and duration of 3 years. A growing area, over the past decade, in terms of proposals and grants, has been what we might broadly refer to as intelligent civil and mechanical engineering systems.

Fig. 1 schematically illustrates a modern intelligent engineered system, which includes a physical engineered system such as a machine or structure, as well as capabilities and components for sensing, actuation and decision-making. The decision-making capability is computer-based, the system is networked to other intelligent engineered systems, and includes a human-machine interface. With developments in computer science, information technology, sensing and control the design of typical machines and structures by civil and mechanical engineers is evolving toward intelligent systems that can sense, decide and act. This trend toward electro-mechanical design is well-established in modern machines (e.g. vehicles, robots, disk drives) and often referred to as *mechatronics* (Tomizuka 2002, Mehrabi, *et al*. 2002). Table 1 provides a timeline, showing the important engineering applications that have driven the development of research in this area. The development of new technologies, such as LSI and VLSI circuits, microprocessors and MEMS, in turn have lowered costs and increased the range of application of engineered intelligent systems. Sensing and computer control, while only practical for space and military systems 50 years ago, are now an integral part of every household device. The engineering of intelligent civil infrastructural systems is clearly one of the current significant drivers, and intelligent system design is becoming an important aspect of structures, such as buildings and bridges.

The purpose of this paper is to first briefly introduce the area of structural control research, and the

Table 1 Timeline of emerging research areas in engineering of intelligent systems and the motivating applications

Time	Methodologies	Drivers/Applications	Remarks
1960's	• Optimal control & estimation	• Aerospace & military	• Expensive computation
	• Stochastic control	• Power plants (DDC)	• LSI Technology
1970's	• Adaptive & nonlinear control; Sys identification	• Process controls	• DSPs; MEMS
	• Digital control	• Robotics & automation	• Uncertainties
1980's	• Robust & multivariable control	• Automotive(e.g. engines)	• Miniaturization
	• Model predictive cont	• Mfg./machining	• Networking
	• Intelligent control	• Data storage	• Information Technology
1990's	• Hybrid systems	• Semiconductor Mfg.	• Globalization
	• Fault detection	• Communications	• Biotechnology
	• Distributed control	• Mechatronics	• Nanotech
	• Embedded systems	• Biomedical problems	• Broadening applications
2000's	• Large scale computation	• Energy problems	• Human-centric mechatronics
		• Sensors/sensor networks	
		• Nano systems & devices	
		• Civil infrastructure	

role that NSF has played in the development of engineered intelligent infrastructure systems. Then we describe the on-going interdisciplinary research solicitation at NSF in the area of Sensors and Sensor Networks. NSF has also made a major infrastructure investment in developing the Network for Earthquake Engineering Simulation (NEES). We describe the NEES cyberinfrastructure, the research activities that NEES is envisioned to support. Finally, we present a summary and conclusions.

2. Structural control

Active, semi-active and hybrid structural control systems as a means of structural protection against wind and seismic loads are a natural evolution of passive control technologies such as base isolation and passive energy dissipation. The World Conference on Structural Control has been held three times (Housner, *et al.* 1994b, Kobori, *et al.* 1998, Casciati 2003), attracting over 1000 participants from nearly 20 countries and demonstrating the worldwide interest in structural control.

Table 2 Structural control research - milestones

Year	Event
1989	US panel on structural control research (US-NSF)
1989	First actively controlled building constructed in Tokyo
1990	Japan panel on structural response control (Japan-SCJ)
1991	Five-year research initiative on structural control (US-NSF)
1993	European association for control of structures
1994	International association for structural control (IASC)
1994	First world conference on structural control (Pasadena, CA, USA)
1998	China panel for structural control
1998	Second world conference on structural control (Kyoto, Japan)
2002	Third world conference on structural control (Como, Italy)
2004	IASC becomes International Association for Structural Control and Monitoring (IASCM)

This rapid growth of research interest and development of active/hybrid structural control systems is in part due to several coordinated research efforts, largely in Japan and US and partially funded by NSF, marked by a series of milestones listed in Table 2. One of the most challenging aspect of active control research in civil engineering is the fact that is an integration of a number of diverse disciplines, including computer science, data processing, control theory, material science, sensing technology, as well as stochastic processes, structural dynamics, and wind and earthquake engineering. These coordinated efforts have accelerated the research-to-implementation process. Control systems have been installed in more than 40 full-scale building structures in four countries, as well as have also been used temporarily in construction of numerous bridge towers or large span structures (e.g. lifelines, roofs).

Most recently, smart damping (also known as semi-active control) strategies have been shown to be particularly promising, offering the reliability of passive devices, yet maintaining the versatility and adaptability of fully active systems, without requiring the associated large power sources. Studies have shown that appropriately implemented smart damping systems perform significantly better than passive devices and have the potential to achieve, or even surpass, the performance of fully active systems, thus allowing for the possibility of effective response reduction during a wide array of dynamic loading conditions (Spencer, *et al*. 1997). Examples of such devices include variable-orifice fluid dampers, controllable friction devices, variable stiffness devices, adjustable tuned liquid dampers, and MR/ER dampers (Spencer and Nagarajaiah 2003). Recently constructed buildings in Japan have employed nearly 800 smart dampers.

Two recent full-scale applications of magnetorheological (MR) dampers were recently realized based on NSF sponsored research. In 2001, the first full-scale implementation of MR dampers for a building structure was achieved. The Nihon-Kagaku-Miraikan, the Tokyo National Museum of Emerging Science and Innovation, shown in Fig. 2, has two 30-ton, MR Fluid dampers installed between the 3rd and 5th floors. The dampers were built by Sanwa Tekki using the Lord Corporation MR fluid. The Dongting Lake Bridge in Hunan, China constitutes the first full-scale implementation of MR dampers for bridge structures (see Fig. 3). The extremely low damping inherent in such cables, typically on the order of a fraction of a percent, is insufficient to eliminate this vibration, causing

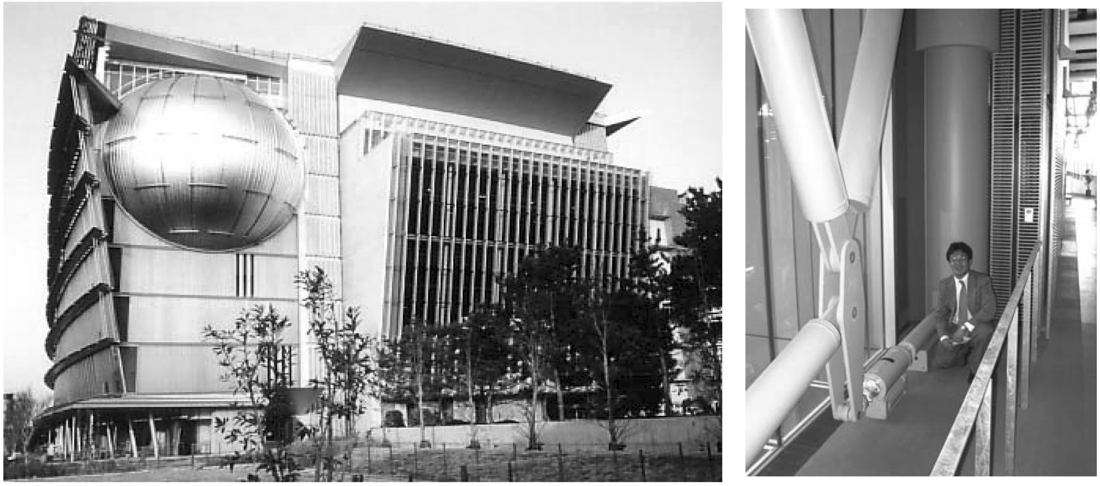

Fig. 2 Nihon-Kagaku-Miraikan, Tokyo National Museum of emerging science and innovation

Fig. 3 MR damper installation on the Donting Lake Bridge, Hunan, China

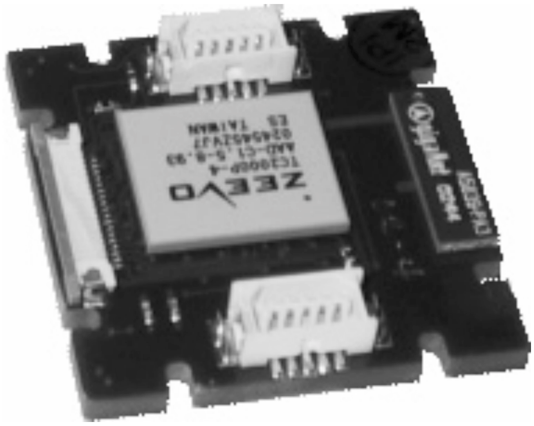

Fig. 4 Intel-mote smart sensor

reduced cable and connection life due to fatigue and/or breakdown of corrosion protection. Two MR dampers are being installed on each cable to mitigate rain-wind induced cable vibration (Spencer and Nagarajaiah 2003).

3. Smart sensors for monitoring civil infrastructure

The design, fabrication, and construction of smart structures is an important engineering research challenge, and one of the keys to smart structures technology is innovative sensors and sensor systems. Structural health monitoring and control systems (SHM/C) represent one of the primary applications for new sensor technologies. To efficiently investigate both local and global damage, a dense array of sensors is envisioned for large civil engineering structures. Dealing with the large amount of data that is generated by these monitoring systems, on-board processing at the sensor allows a portion of the computation to be done locally on the sensor's embedded microprocessor. Such an approach provides for an adaptable, *smart* sensor, with self-diagnosis and self-calibration capabilities, thus reducing that amount of information that needs to be transmitted over the network; however this represents a radical departure from the conventional instrumentation design and computational strategies for monitoring civil structures (Kurata, *et al.* 2003).

While substantial research has been undertaken to develop smart sensors for civil engineering applications (Agre, *et al.* 1999, Straser and Kiremidjian 1996, 1998, Straser, *et al.* 1998, and Kiremidjian, *et al.* 1997, Maser, *et al.* 1997, Brooks 1999, Mitchell, *et al.* 1999, Liu, *et al.* 2001, Lynch, *et al.* 2001), all of the previously mentioned systems are of a proprietary nature. To effectively move the technology forward, an open hardware/software platform is needed.

4. Sensors and sensor networks initiative (NSF 03-512, NSF 04-522)

Sensor technologies play a key role in intelligent engineering structures and systems. Research needs include the design and fabrication of sensors as well as the use of sensors as a part of intelligent engineering systems. Advances in the Internet, communications, information technologies and miniaturization technologies such as MEMS have set the stage for major growth in emerging sensor technologies that increase functionality and performance and reduce the physical dimensions at reduced cost. Important applications of sensors include but not limited to national security, civil infrastructures, various vehicles from automobile to space vehicles, the environment, energy, biomedical and health care, and manufacturing. In modern engineering systems, sensor technologies are utilized for diagnostics and prognostics of systems, failure detection and identification, system modeling and identification and real time control. Fig. 1 illustrates the use of sensors for closed loop decision making. As sensors become readily available and their costs reduce, the block labeled "sensors" may actually represent a large number of sensors: sensors may form a network and multiple sensors may be place in parallel for reliability and safety. On the other hand, certain types of sensors may still be expensive, and it is best from the viewpoint of system design to rely on intelligent signal processing so that the maximum amount of information may be extracted from a single sensor.

In 2003, the National Science Foundation announced a broad interdisciplinary program of research and education on Sensors and Sensor Networks. This multidisciplinary activity in its second year seeks to advance fundamental knowledge in new sensor technologies, including designs, materials and concepts for new sensors and sensing systems, sensor networking systems in a distributed environment, the integration of sensors into engineered systems, and the interpretation and use of sensor data in decision-making processes. Research may be carried out by individual investigators (II), as well as by small teams (ST) and larger interdisciplinary groups (IGR) that generate new concepts and approaches

Table 3 Sensors and sensor networks initiative statistics

Type of awards	Total NSF (# of awards/# of props)	CMS (# of awards/# of props)
Individual investigator	40/253 ~ 0.16	4/46 ~ 0.09
Small team	28/469 ~ 0.06	7/50 ~ 0.14
Interdisciplinary research group	9/128 ~ 0.08	1/15 ~ 0.07
Total investment	$45 M	$5.4 M

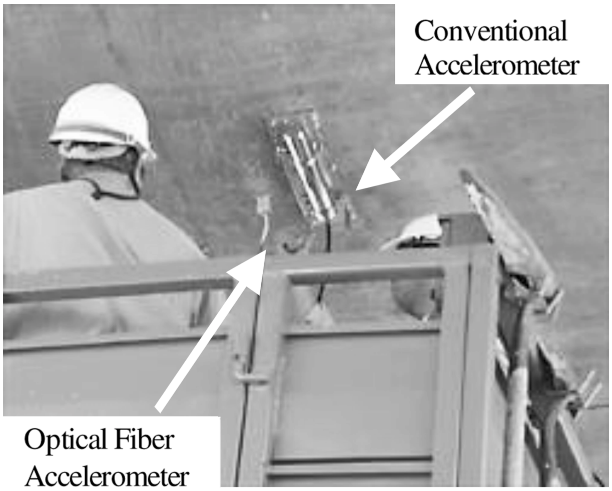

Fig. 5 Sensor systems for civil infrastructures

stimulated by the synergistic interaction of diverse disciplines. The funding limits were set $375 K ($125 K/year for three years) for II awards, $750 K ($250 K/year for five years) for ST awards and $2.5M ($500 K/year for five years) for IGR awards.

The NSF received an overwhelming response from the research community. In fiscal year (FY) 2003, the total number of proposals was 870. In spite of a sizable total investment of about $45 M in this program, the success rate was significantly low and the size of each award had to be reduced in many cases. Table 3 summarizes the submission statistics, both NSF as a whole and the CMS division.

The awards made by the CMS division included from research on new types of sensors to applications of sensor networks to monitoring and control. To provide some samples of research works on sensor technology at the forefront of the CMS community, we will provide below short descriptions of selected awards related to infrastructure systems.

4.1. Novel optical fiber sensors for civil engineering structures

M. Feng conduct research on development of a distributed optical fiber accelerometer system for civil engineering applications. The sensor system represents a novel integration of the Moire phenomenon and fiber optics to achieve a robust performance in addition to its immunity to EM interference, easy cabling, and multiplexing capability. All of these, impossible to achieve by the conventional sensors, make the proposed sensor system ideal for applications in civil infrastructure monitoring. The objective of this research is to investigate whether it is technically feasible to engineer the sensor concept into a high-performance and low-cost multiplexible optical fiber sensor system. The highly interdisciplinary nature and the international collaboration component of this project provide unique educational opportunities to students at all levels. The proposed high-performance optical fiber sensors will have a positive impact on the safety and reliability of the nation's civil infrastructure.

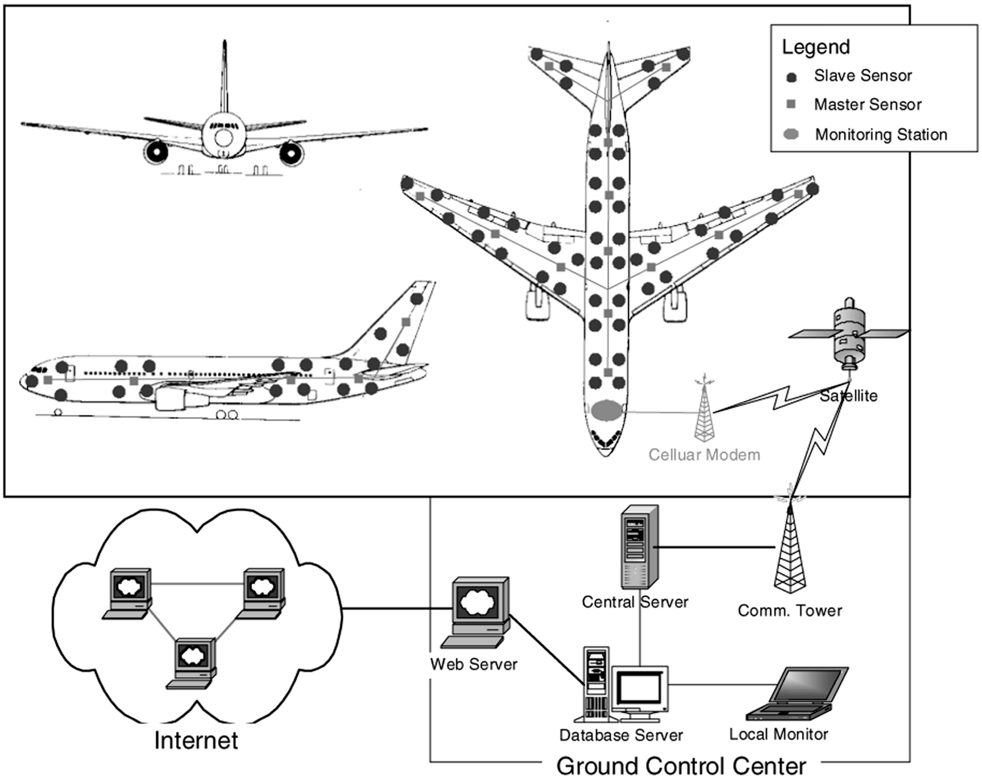

Fig. 6 Intelliegent health monitoring of aerospace structures using wireless sensor networks

4.2. Intelligent health monitoring of aerospace structures using wireless sensor networks

Research of F-G Yuan seeks to develop a multi-sensor data fusion information framework for aerospace structural health monitoring (SHM) using smart sensors (Fig. 6). The smart sensors are capable of exciting diagnostic signals, measuring physical parameters, interpreting and collaborating the data into information, and communicating with a monitoring station over a wireless link. The MICA platform developed at UC Berkeley is used as a basis of this research. The work is targeted at developing an active distributed smart sensing system for quantifying and visualizing location and sizing of damage in aerospace structures in near real-time. The proposed research will lay the groundwork for a novel wireless smart sensor network technology for near real-time intelligent monitoring of complex aerospace systems and a broad set of physical phenomena.

4.3. Self-monitoring structural composite materials with integrated sensing networks

The ultimate goal of this five year IRG research project under the direction of Sia Nemat-Nasser is the development of a new class of self-sensing materials, which have the ability to mange data flow from the sizable number of embedded sensors by use of local processing techniques. To be addressed first will be the fabrication issues to include the electronic, sensing and connection elements within a

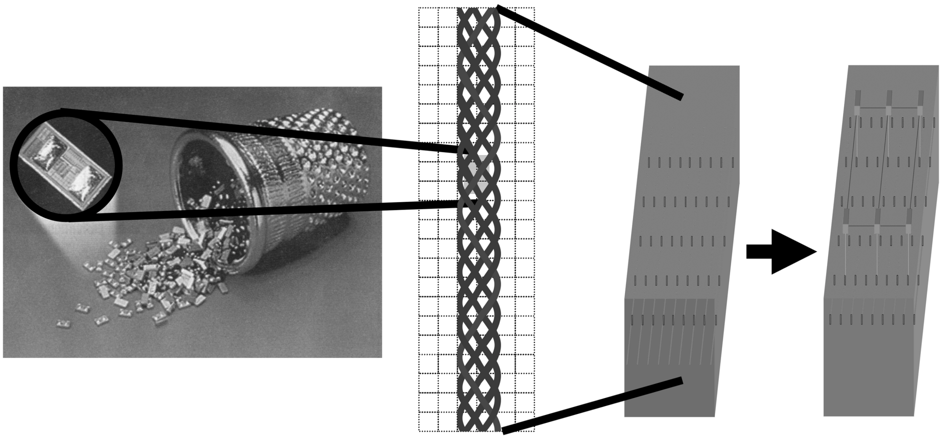

Fig. 7 Composite materials with integrated sensor networks

fiber-reinforced composite. Initially the work will be directed to demonstrating a proof-of-concept self-sensing material, capable of monitoring temperature flow patterns with the composite. Miniaturized MEMS based sensors capable of measuring such quantities such as acceleration, rotation and acoustic emission will be developed Hierarchical algorithms will be developed to manage the data expected from the sensor network (Fig. 7).

5. Network for earthquake engineering simulation (NEES)

The George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES) is a shared national network of experimental equipment sites and tools, a centralized data repository, and an archive of earthquake engineering simulation software, and linked together via the NEESgrid cyberinfrastructure (NSF 2003). It is named in honor of the late California Congressman who chaired the House Science Committee and was champion of engineering and science in congress for over 30 years. Under construction since 2000, NEES will become fully operational by October 2004 and will be managed, operated and maintained by the NEES Consortium, Inc. This $82 million investment by NSF will not only enable earthquake engineering research of unprecendented scale, complexity and completeness but is also the first pilot national cyberinfrastructure based upon advanced grid computing concepts (Fig. 8).

The grand challenges in earthquake engineering research that can be addressed by utilizing the NEES infrastructure have been detailed in a report from the National Academy of Engineering (NRC 2003). As illustrated in Fig. 9, the NEES facilities and cyberinfrastructure will enable the coordinated analysis of complex problems in their entirety by utilizing several experimental sites, together with simulation, and integration of the effort through NEESgrid. This approach entails testing the critical components of a substructure, while considering soil-structure interaction effects, and integrating the entire system via computer simulation. NEES will promote the integration of testing, sensor data and simulation. It will provide broad access to the entire research community to specialized facilities and curated data.

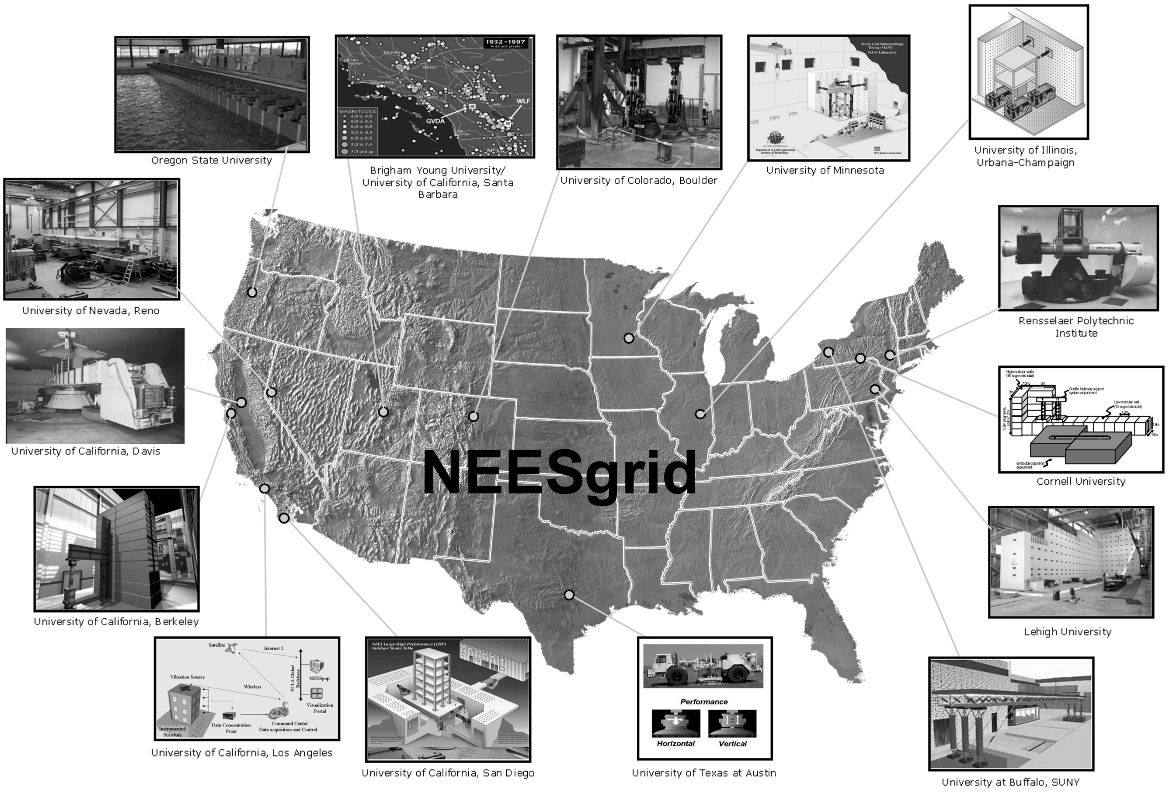

Fig. 8 Network for earthquake engineering simulation (NEES)

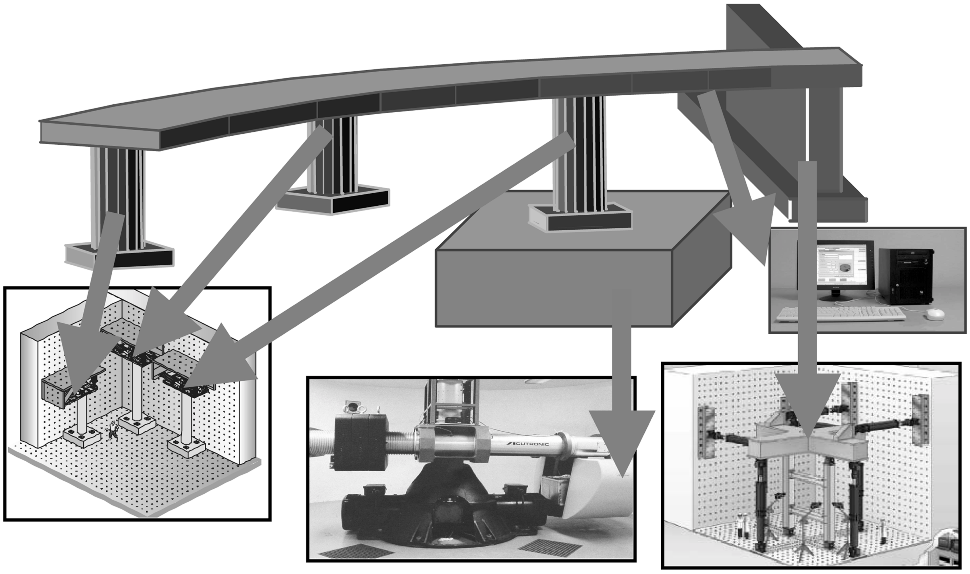

Fig. 9 Networked, distributed and hybrid simulation

6. Conclusions

In a variety of engineering applications, sensing, actuation, communication and computation capabilities are being integrated into the design of mechanical systems and structures. Consequently, there are many research opportunities and challenges associated with the engineering of intelligent systems. The CMS division of NSF has been investing in basic research in these areas through its programs, initiatives and infrastructure investments. This paper has provided a brief overview of structural control research, and the NSF role in its development. We have also highlighted the programs in Dynamics, Sensing and Control, the Sensors and Sensors Network Initiative and the NEES cyberinfrastructure investment for earthquake engineering research.

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