

NSF/ESF WORKSHOP ON SMART STRUCTURES AND ADVANCED SENSORS

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STRUCTURAL ACTUATION AND ADAPTATION WORKING GROUP

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Abstract

This document is a result of discussions that took place during the workshop. It describes current state of research and development (R&D) in the areas of structural actuation and adaptation in the context of smart structures and advanced sensors (SS&AS), and provides an outlook to guide future R&D efforts to develop technologies needed to build SS&AS. The discussions took place among the members of the Structural Actuation and Adaptation Working Group, as well as in general sessions including all four working groups. Participants included members of academia, industry, and government from the US and Europe, and representatives from China, Japan, and Korea.

Introduction

Structural actuation and adaptation imply changes in structural properties for the purpose of achieving specific objectives. Adaptation is usually brought about through actuation (counterexample: materials that experience phase transitions in response to small temperature changes). General objectives of structural actuation and adaptation include: improved performance, avoidance of anomalies, delaying of time-to-failure, continued degraded operation with failed elements, etc. Adaptation may be implemented as changes in material properties (e.g., thermal conduction), in structural properties (e.g., architecture related strength), shape (e.g., aerodynamic surfaces), surface properties (e.g. hardness, thermal insulation), etc.

A futuristic view of smart structures should address the capability to deal with unplanned occurrences that may cause degradation/failure of a mission. This means that structures must adapt on-demand to changing conditions of operation.

Figure 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 (Liu, Tomizuka, Ulsoy, 2004). 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.

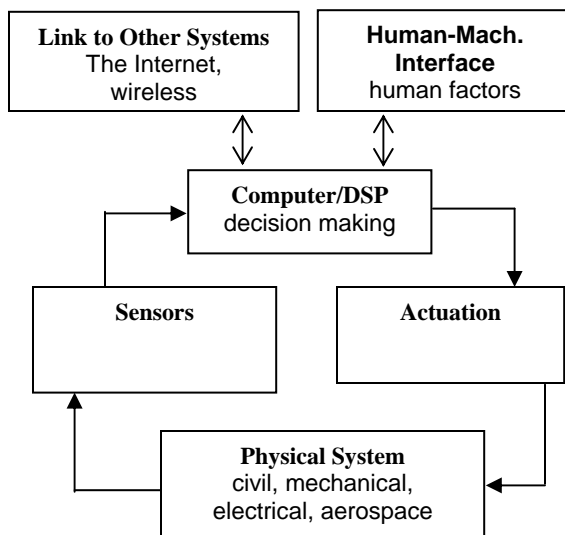


Figure 1. Modern Intelligent System

In the case of smart structures, actuation and adaptation encompass four primary elements: (1) materials and architecture (e.g., composite weavings, trusses), (2) sensors, (3) actuators, and (4) controllers. This report intends to establish the state of the art and challenges in existing actuation and adaptation systems for smart structures, and suggests future directions.

Review of State of the Art

Materials and Architectures

If one defines a smart structure to include embedded capability to determine its condition, and to minimize adverse effects of anomalous conditions on its own, then it is clear that materials to enable such functionality are not currently available.

Material selection invariably depends on the application. Civil structural materials traditionally include steel, wood, reinforced concrete, masonry such as brick and cement blocks, and, less frequently, aluminum and composites. Structural adaptation and

actuation have the potential to increase the time to an eventual anomaly (such as a collapse), minimize damage when certain anomalies do occur, avoid failure altogether, and, ultimately, to reduce life cycle costs.

Aerospace structural materials, on the other hand, primarily include aluminum, titanium, and composites of various types. Traditionally, aircraft are controlled through actuation of control surfaces such as flaps, ailerons, and the rudder, by electro-hydraulic actuators acting on them.

Other materials of potential interest from the standpoint of actuation (semi-active control) and/or sensing include bio-mimetic, piezoelectric, magneto-rheostatic, electro-rheostatic, and shape memory alloys.

A general view of the European development strategy for civil infrastructure can be found in the documentation presented by ECTP – the European Construction Technology Platform vision (ECTP Vision 2030, 2005). This Platform, which is now emerging, will bring together representatives from all stakeholders in the construction sector. Starting from an identification and analysis of the major challenges in the sector, the Platform will develop a “Vision 2030”, from which a corresponding “Strategic Research Agenda” (SRA) will be developed, the essential purpose of which will be to achieve the “vision” with its horizon set in 2030.

Aluminum: Aluminum is used as both structural elements and as surfaces (in sheets). Usually, strain and temperature sensors are glued to the surface. Actuation can be applied to modify orientation/position of plates that form part of a surface (Price et al, 2003).

Composite Materials: Composite materials have encountered a wide variety of uses (tanks, airplane surfaces and wings, building materials, bridges, etc.). An attractive quality of composites is that embedding sensors and actuators may be easier than with other materials.

Shape Memory Alloys: Shape memory alloys (SMA's) are metals which exhibit two very unique properties: pseudo-elasticity and the shape memory effect. Arne Olander first observed these unusual properties in 1938, but not until the 1960's were any serious research advances made in the field (F. Aurichio et al, 2001). The most effective and widely used alloys include NiTi (Nitinol), CuZnAl, and CuAlNi.

Magneto-Rheological and Electro-Rheological Fluids: These fluids can experience a dramatic change in their viscosity in the presence of electric and magnetic fields, respectively. The materials can change from a relatively thick fluid (similar to motor oil) to a near solid within the span of a millisecond when exposed to the magnetic or electric field; the effect is completely reversed when the field is removed. The composition of each type of smart fluid varies widely. The most common form of MR fluid consists of tiny iron particles suspended in light oil, while ER fluids can be as simple as milk chocolate or cornstarch and oil.

MR fluids have been developed for use in automobile shock absorbers, vibration dampers for washing machines, prosthetic limbs, exercise equipment, and surface polishing of machine parts. ER fluids have mainly been developed for use in clutches and valves, as well as for engine mounts designed to reduce noise and vibration in vehicles.

Nano Materials: Nanotechnology could play a very important role in developing materials for smart structures (e.g. materials with distributed controllable properties), but most developments have been at a small scale, and not focused on civil structure scales.

Sensors

The area of sensors has seen an impressive evolution with advances in the MEMS and Nano areas, as well as the optical systems area (e.g., fiber optic, imaging). Other complementary areas that enable development of multi-sensor systems are communications (wired and wireless), and miniaturized computational components (processors). These areas are contributing to development of small sensors (micro and nano scale), sensors that can communicate (Intel Research), "intelligent" sensors with embedded processing capability (Mahajan and Figueroa, 1995; Figueroa and Schmalzel, 2006; Schmalzel et al, 2005), and sensors embedded in materials and actuation systems. Piezoelectric sensors are suitable for simultaneous sensing and actuation, and can also be used as structural elements.

Smart structures should encompass distributed measurement of parameters such as stress, detection of cracks, deformation, corrosion, etc. In turn, these parameters should be used to effect control action as needed to accomplish a task.

Sensors used in structural applications have traditionally included classic strain gages, accelerometers, LVDTs, etc. Fiber optic and MEMS homologous to these classic sensors are gaining acceptance, but are not yet common practice.

Distributed embedded sensors, especially fiber optic gages, have been implemented in laboratory or test settings, but distributed measurements remain difficult to implement and the whole measurement system remains very expensive (F. Bourquin and J-M. Caussignac, 2005).

R&D on advanced sensors, networks of distributed sensors, and intelligent sensor systems has been emphasized in recent years by funding agencies (e.g. the US National Science Foundation).

Actuators

In general, the development of actuation systems is characterized by a rather slow but quite encouraging progress. Reliable devices with increasing tensing/traction force are

appearing on the market. They include mainly linear electric motors, compact servo-hydraulic systems, piezoelectric devices ... with better characteristics respective to the previous generation (size, power consumption, reliability...).

Servo-hydraulic devices have been used for the actuation part of an active tendon control system for use in a cable-stayed structure. The aim of the active control system is to upgrade the damping of the structure and consequently to mitigate the induced vibration of the stay cables (Bakule et al, 2005; Ikohuane and Rodellar, 2005; Ikohuane et al, 2005).

Advanced actuation technologies are not only appealing for active structural control but are at the origin of many new designs of semi-active devices, and we are just at the beginning of this take off. For example, piezoelectric actuation is (generally) not directly applicable in large civil structures but instead could be used as actuation elements of many new semi-active devices.

Piezoelectric actuation appears to be one of the most promising approaches for smart structures applications. These include piezo-actuators, piezo-motors and piezo-mechanisms.

Advanced Piezoelectric Actuators offer unique properties:

- Improved (larger) displacements per unit of length.
- Best mechanical energy density per volume and mass units.
- Large stiffness and force density.
- Low voltage power supply.
- Positioning with high precision.
- No backlash and no play.
- Very short response time.
- Low power consumption.

Piezoelectric motors use the friction between a mobile part and a vibrating part in order to create either a linear or a rotational motion.

The main advantages of piezomotors as compared to electromagnetic devices are:

- High force at rest with no power being applied.
- Low speed and high force without any gearing mechanism.
- High force-to-mass ratio.
- They can require low voltage (only 10V),
- They can be modular providing mainly a tangential velocity and a friction force.
- They can be integrated into both linear and rotating devices.

Time	Methodologies	Drivers/Applications	Remarks
1960's	<ul style="list-style-type: none"> Optimal Control & Estimation 	<ul style="list-style-type: none"> Aerospace & Military Power plants (DDC) 	<ul style="list-style-type: none"> Expensive computation
1970's	<ul style="list-style-type: none"> Stochastic Control Adaptive & Nonlinear Control; Sys Identification 	<ul style="list-style-type: none"> Process Controls Robotics & Automation 	<ul style="list-style-type: none"> LSI Technology DSPs; MEMS Uncertainties
1980's	<ul style="list-style-type: none"> Digital Control Robust & Multivariable Control Model Predictive Cont 	<ul style="list-style-type: none"> Automotive(e.g. engines) Mfg./machining Data Storage Semiconductor Mfg. 	<ul style="list-style-type: none"> Miniaturization Networking Information Technology Globalization
1990's	<ul style="list-style-type: none"> Intelligent Control Hybrid Systems Fault Detection Distributed Control Embedded Systems 	<ul style="list-style-type: none"> Communications Mechatronics Biomedical problems Energy problems 	<ul style="list-style-type: none"> Biotechnology Nanotech Broadening applications
2000's	<ul style="list-style-type: none"> Large Scale Computation 	<ul style="list-style-type: none"> Sensors/sensor networks Nano systems & devices Civil infrastructure 	<ul style="list-style-type: none"> Human-centric mechatronics

Table 1 - Timeline: Drivers/Applications and related Control Methodologies

Electrorheological (ER) fluids and magnetorheological (MR) suspensions are key words of many new semi-active devices. However, a great deal of R&D is needed to develop effective actuation systems. More work is needed on experimental characterizations, as well as theoretical prediction of the mesostructure resulting from field-induced phase separation and improved theories on the rheology of the fluids and its connection with microhydrodynamics and the structure of field-induced aggregates. The greatest attention must be devoted to new compositions of ER or MR fluids, polymer blends, magneto- or electroactive elastomers and gels.

Controllers

Table 1 provides a timeline, showing the important engineering applications that have driven the development of research in control systems (Liu et al, 2004). 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.

Table 2 gives a classification of structural control systems. Although it was established in the context of civil engineering, it may be general enough to apply to other areas such as aerospace and mechanical engineering.

Structural Control	Frequency Dependent	Resonant	Passive	Tuned Mass damper (TMD)
			Hybrid	Hybrid Mass Damper (HMD)
		Non-Resonant	Passive	Base Isolation
			Semiactive	Active Variable Stiffness (AVS)
	Frequency Independent	Passive		Viscous Damper
				Hysteretic Damper
				Joint Damper
		Active		Active Mass Damper (AMD)
				Active Tendon, Active Brace
		Semiactive		Variable Orifice Damper
				Controllable Fluid Damper (ER, MR)
				Variable Friction Damper

Table 2. Classification of Structural Control.

Structural control systems are classified according to frequency dependency. Frequency-dependent control type is sensitive to structural design (it makes effective use of natural frequencies) and shows effectiveness depending on frequency. It can be subdivided into resonant and non-resonant types. The passive tuned mass damper system (TMD) and the hybrid mass damper system (HMD) are examples of resonant types. The base isolation system is an example of non-resonant type which can avoid resonance, thus reducing the input energy of an earthquake-like excitation.

Frequency-independent control type in general dissipates energy applied upon a structure. It can be subdivided into passive, active or semi-active. Passive systems dissipate energy with various passive dampers. Active systems directly produce control forces using external energy-supplementing devices. Such examples are the active mass driver system, the active tendon system and the active bracing system. Semi-active systems of frequency-independent control type are classified into variable orifice damper system, controllable fluid damper system such as MR damper, variable friction damper, and so forth.

Two applications representing typical developments in course in Europe are:

- Active damping of cable stayed and suspension bridges
- Semi-active control of bridges

Detailed information can be found in (Bakule et al, 2005; Ikohuane and Rodellar, 2005; Ikohuane et al, 2005). Both applications were developed in the framework of European projects, funded 50/50% by the EU and industry. Other active control efforts are described by Auperin and other researchers (Auperin et al, 2001; Preumont, 2002; Marazzi and Magonette, 2001). Implementation of structural control is described by Bairrao and colleagues (Bairrao et al, 2005).

Because of the sensitivity of structural control to uncertainties, both in the models and the excitations, the emphasis of the control is put on the robustness. Most of the time simple local and decentralized controllers can be selected. However, control of smart structures will require further advances for systems with distributed sensing and actuation.

Facilities for experimental R&D of structure controls exist in many US and EU entities. Such facilities include physical structures, actuators, sensors, and modeling and computational capabilities. Earthquake simulation experiments are prevalent in these facilities.

Workshop Outcomes

Discussions focused on identification of R&D that could result in actuation and adaptation capabilities to enable development of smart structures for a variety of applications, but with emphasis on civil/mechanical structures.

The following general objectives for structural actuation and adaptation were specified:

- Improved performance.
- Avoidance of anomalies.
- Lengthening of time-to-failure.
- Continued degraded operation with failed elements.
- Manage unforeseen degradation/failure events.
- On-demand change to address operating conditions.

Materials and Architectures

The stated objectives could be achieved by producing changes in structural properties as a result of:

- Changing shape through actuation by conventional actuators (e.g. airplane ailerons).
- Changes in material properties.
 - Modulus of elasticity.
 - Thermal conduction.
 - Hardness.
 - Thermal insulation.

- Etc.

State of the art in the area of structures and materials focusing on smart structures includes:

- User selectable modulus: changing fiber composition (static, once fabricated it stays. Need dynamic modulus change)
- Continuously warping surfaces: embedded actuators in silicon rubber.
- Parametric control: semi-active vibration control. Smart damping materials.

Technology barriers in these areas include:

- Designs for dynamic control of structure properties. Need new combinations of materials and designs.
- Embedded actuators: Not easy to scale up.
- Embedding of distributed sensors.

Sensors

State of the art in distributed intelligent sensors (or in general intelligent components) includes standards (Basic Transducer Electronic Data Sheet Standards, and in general IEEE 1451.x). Implementations and integration software environments are not sufficiently adequate. Embedded sensors may be surface mounted, or machined into structure.

Technology barriers include the development/refinement of a core set of standards for distributed intelligent sensors capable of providing measurement value, quality of measurement value, and sensor health state; also, development of suitable software environments that support intelligent applications.

Actuation

State of the art in actuation includes:

- Shape memory alloys (SMA) for shape control: Small scale applications R&D. Not scalable to real applications.
- Piezo-electric actuators for higher frequency lower stroke vibration control are available.
- Constitutive behavior of SMA and piezoelectric material is adequately understood.
- Electro-rheological and magneto-rheological actuators for lower frequency and higher stroke vibration control: Experimental laboratory demonstrations.
- Biomimetic actuators: Not scalable to real applications.

Technology barriers for actuation needs in smart materials include:

- New materials with improved power vs. stroke trade balance.

- Compatibility with structural materials in terms of load and strain transfer, electrical insulation, and corrosion.
- New and innovative architectures, taxonomies, power management, and control for distributed actuation.
- Actuation embedded in structural elements.

Electrorheological (ER) fluids and magnetorheological (MR) suspensions are key words of many new semi-active devices. However, a great deal of R&D is needed to develop effective actuation systems. More work is needed on experimental characterizations, as well as theoretical prediction of the mesostructure resulting from field-induced phase separation and improved theories on the rheology of the fluids and its connection with microhydrodynamics and the structure of field-induced aggregates.

Controllers

A great deal of discussion revolved around controllers, from the stand point that advances are needed to control smart structures with distributed embedded sensors and actuators, and control of materials properties for new materials.

Scope for new Controllers

- A promising new class of actuators and sensors for smart structures is expected to be distributed.
- Distributed actuators may be capable to deliver high bandwidth and long stroke actuation.
- A unique new generation of actuators will change, in response to the control input, the material characteristics such as compliance and damping.
- Materials with variable damping coefficients, e.g. MR dampers, have been utilized for semi-active control of structures and suspension systems. Control theoretic approaches to the design of semi-active control exist.
- Materials with variable compliance or stiffness may apply fully active control, and a new breed of control theories will be required if we are to take maximum advantage of such new materials.
- One example of new exciting actuators is an artificial muscle, which acts like muscles in biological systems.
- The new generation of actuators is expected to exhibit strong nonlinear characteristics. Furthermore, the control input may not necessarily appear as an additive term in dynamic equations. Parameters defining material properties may be actually the control signal and may have to be manipulated.
- Desired features for new controllers should include adaptation, fault tolerance, intelligence (to make full use of capabilities associated with distributed intelligent sensors and actuators), graceful degradation etc.

Work to be done

Given the new generation of actuators in the scope above, a number of tasks must be performed. A non-exhaustive list of required tasks include:

- Modeling and identification; this topic will require multidisciplinary efforts by material scientists, applied mathematicians and control/mechatronics engineers.
- Optimal and adaptive control of parameters defining material characteristics. Control inputs will not appear as standard additive terms in the state equations but most likely parametric. The state equations will be nonlinear, and a new breed of nonlinear control theory needs to be developed.
- The new generation of actuators will be used in many ways. For example, a finite number of such actuators may be used as structural elements of a structure for vibration control and other purposes. Another example may be an airplane wing with a large or infinite number of the new generation of actuators for a variety of objectives such as vibration control and shape control. Modeling and control work must be performed for an array of structures that will utilize new actuators in different forms.

Required facilities and resources

Initial work will most be analytical with help of computer simulations. To verify new control theories for actuation materials with adjustable properties, it will be important to perform laboratory experiments. Such experiments will have to be coordinated with material scientists.

Milestones

There are several stages to pursue research in this focus area. Milestones will be attained when major accomplishments have been achieved in each stage.

First stage: At the initial stage, the new types of materials have not been developed. Thus, initial research will have to be based on postulated mathematical models. Inputs from material scientists should be sought to define such models.

Second stage: Functions of the new generation of actuators in various types of structures may be simulated by existing actuators plus any added characteristics implemented on computer software. Several possible structures utilizing new actuators were described under work to be done above. Such structures may be equipped with standard actuators to perform preliminary experiments.

Third stage: In this stage, structural and control engineers will have access to samples of materials with variable material properties.

Conclusions

The workshop provided a forum where experts from Europe, The United States, Japan, Korea, and China discussed topics to guide future R&D activity to support development of smart structures. The Structural Adaptation and Actuation Working Group organized the discussions into four areas: (1) materials and architecture (e.g., composite weavings, trusses), (2) sensors, (3) actuators, and (4) controllers. Given a definition of a smart structure as an element with embedded capability to determine its condition, and

to minimize adverse effects of anomalous conditions on its own, then it is clear that such structures do not exist now. The group focused primarily on materials and architectures, and controllers. However, materials for smart structures of the future should inherently include embedded distributed sensing and actuation. It was established that future direction of R&D efforts should address development of new materials with dynamically controllable properties, and related modeling and control methods for actuation of structures built using such new materials. Piezoelectric materials constitute the current option to enable distributed embedded sensing and actuation, while control of local properties such as friction or stiffness with Electrorheological (ER) fluids and magnetorheological (MR) suspensions hold promise for many new semi-active devices.

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