AIAA JOURNAL
Vol. 32, No. 8, August 1994

# Intelligent Structures for Aerospace: A Technology Overview and Assessment

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## Introduction

THIS article presents an overview and assessment of the technology leading to the development of intelligent structures. Intelligent structures are those which incorporate actuators and sensors that are highly integrated into the structure and have structural functionality, as well as highly integrated control logic, signal conditioning, and power amplification electronics. Such actuating, sensing, and signal processing elements are incorporated into a structure for the purpose of influencing its states or characteristics, be they mechanical, thermal, optical, chemical, electrical, or magnetic. For example, a mechanically intelligent structure is capable of altering both its mechanical states (its position or velocity) or its mechanical characteristics (its stiffness or damping). An optically intelligent structure could, for example, change color to match its background.[17]

### Definition of Intelligent Structures

Intelligent structures are a subset of a much larger field of research, as shown in Fig. 1.[123] Those structures which have actuators distributed throughout are defined as adaptive or, alternatively, actuated. Classical examples of such mechanically adaptive structures are conventional aircraft wings with articulated leading- and trailing-edge control surfaces and robotic systems with articulated manipulators and end effectors. More advanced examples currently in research include highly articulated adaptive space cranes.

Structures which have sensors distributed throughout are a subset referred to as sensory. These structures have sensors which might detect displacements, strains or other mechanical states or properties, electromagnetic states or properties, temperature or heat flow, or the presence or accumulation of damage. Applications of this technology might include damage detection in long life structures, or embedded or conformal RF antennas within a structure.

The overlap structures which contain both actuators and sensors (implicitly linked by closed-loop control) are referred to as controlled structures. Any structure whose properties or states can be influenced by the presence of a closed-loop control system is included in this category. A subset of controlled structures are active structures, distinguished from controlled structures by highly distributed actuators which have structural functionality and are part of the load bearing system.

Intelligent structures are a subset of active structures that have highly distributed actuator and sensor systems with structural functionality and, in addition, distributed control functions and computing architecture. To date, such intelligent structures have not been built. The ultimate realization of intelligent structures is a goal which has motivated this technology assessment.

### Development Background

Three historical trends have combined to establish the potential feasibility of intelligent structures. The first is a transition to laminated materials. In the past, structures were manufactured from large pieces of monolithic material which were machined, forged, or formed to a final structural shape, making it difficult to imagine the incorporation of active elements. However, in the past 30 years a transition to laminated material technology has occurred. Laminated materials, which are built up from smaller constitutive elements, allow for the easy incorporation of active elements within the structural form. One can now envision the incorporation of an intelligent ply carrying actuators, sensors, processors, and interconnections within the laminated material.

Exploitation of the off-diagonal terms in the material constitutive relations is a second trend which enables intelligent structures at this time. The full constitutive relations of a material include characterizations of its mechanical, optical, electromagnetic, chemical, physical, and thermal properties. For the most part, researchers have focused only on block diagonal terms. Those interested in exploiting a material for its structural benefits have focused only on the mechanical characterization, and those interested in exploiting its electrical properties have focused on the electrical characterization. However, much can be gained by exploiting the off-diagonal terms in the constitutive relations which, for example, couple the mechanical and electrical properties. The characterization and exploitation of these off-diagonal material constitutive relations has led to much of the progress in the creation of intelligent structures.

The third and perhaps most obvious advance comes in the electrical engineering and computer science disciplines. These include the development of microelectronics, bus architectures, switching circuitry, and fiber optic technology. Also central to the emergence of intelligent structures is the development of information processing, artificial intelligence, and control disciplines.

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Presented as the SDM Lecture at the AIAA/ASME/ASCE/AHS/ASC 33rd Structures, Structural Dynamics, and Materials Conference, Dallas, TX, April 13–15, 1992; received June 18, 1993; revision received Jan. 14, 1994; accepted for publication Jan. 18, 1994. 

The sum of these three evolving technologies (the transition to laminated materials, the exploitation of the off-diagonal terms in material constitutive relations, and the advances in microelectronics) has created the enabling infrastructure in which intelligent structures can develop.

The following discussion is limited to the theme of *mechanically* intelligent structures. An overview of the critical component technologies necessary to infuse distributed control functionality into structures is presented, followed by examples of synthesis into contemporary applications. The paper concludes with a summary of the state of the art and research needs and a vision of the developments of the future.

## Critical Component Technologies

There are four component technologies critical to the evolution and application of intelligent structures: actuators for intelligent structures, sensory elements, control methodologies and algorithms, and controller architecture and implementation hardware. Advances in these component technologies must be matched by a cost effective manufacturing technology which allows for the incorporation of the active elements and interconnections onto or into the structure in a structurally robust manner and in such a way that the inherent properties of the host structure are not degraded. The requirements, capabilities, and manufacturability of the four component technologies for mechanically intelligent structures are discussed in this section.

### Actuators for Intelligent Structures

Actuators for intelligent structures must be capable of being highly distributed and influencing the mechanical states of the structure. The ideal mechanical actuator would directly convert electrical inputs into strain or displacement in the host structure. Its primary performance parameters include its maximum achievable stroke or strain, stiffness, and bandwidth. Secondary performance parameters include linearity, temperature sensitivity, strength, density, and efficiency. These properties will be assessed and compared for several types of strain actuators.

The principal actuating mechanism of strain actuators is referred to as actuation strain, which is the controllable strain not due to stress. Actuation strains are produced by a variety of phenomena, with the most common but least controllable being temperature and moisture absorption. Other examples, less common but more useful for active control, include piezoelectricity, electrostriction, magnetostriction, and the shape memory effect. The latter four phenomena are desirable actuating mechanisms since they directly convert electrical signals into actuation strain.[35]

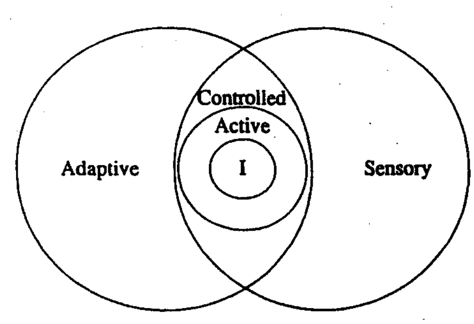


**Fig. 1 Intelligent structures as a subset of active and controlled structures.**[123]

#### *Strain Actuator Modeling*

The actuation strain enters into the constitutive relations in the same manner as do commonly modeled thermal strains. The constitutive relations dictate that the total strain in the actuator material is the sum of the mechanical strain induced by the stress plus the controllable actuation strain. Once the strain is commanded in the actuator, it must be converted into induced strain in the host structure. The strain in the host structure can be found by combining the constitutive models of the actuator and host material with the equilibrium relations and any one of a number of different assumptions about the local strain-deformation field.

The simplest deformation assumption for a surface mounted actuator is that of uniform strain in the actuation material and linearly distributed strain throughout the host structure.[27] Such a model captures the essential physics of the coupling and is moderately accurate for thin actuators. This model predicts that the strain induced in the host structure is proportional to the product of the actuation strain, which can be commanded in the actuation material, and the reciprocal of one plus the stiffness ratio (stiffness of the structure to that of the actuator). The latter term is an impedance matching effect which indicates that the stiffness of the actuator must at least be comparable to the stiffness of the structure for effective strain transfer. The induced strain in the host structure predicted by this model can be used as a figure of merit by which actuators are compared subsequently.

The most useful and general model for thin structural elements is based on the Bernoulli-Euler-Kirchoff assumption, in which the strain is linearly distributed throughout the actuator and host structure regardless of whether the actuator is surface mounted or embedded. Such modeling has been found useful for beams,[26,27,59] plates,[28,49,72,73,98] and shell-like structures.[62,113,114] Other models have been developed for the interaction between strain actuators and solid continua,[11] and of strain actuated structures coupled with aerodynamic and acoustic environments.[15,37,45,67,76]

If there is concern about the ability of the actuator to transfer the strain through a bonding layer, a shear lag analysis of the bonding layer can be performed. The principle result of this analysis is the identification of the shear lag parameter, which must be kept small to allow for efficient transfer of strain to the host structure.[27] The most general model includes local shearing of the host structure.[93] Fortunately, Saint Venant's principle makes such a detailed model unnecessary for predicting the overall deformation of strain actuated structures. However, such an analysis is necessary for accurately predicting the strain field near and around active elements.

#### *Comparison of Available Strain Actuators*

Commercially available strain actuating materials are listed in Table 1. There are four broad classes of materials which can create actuation strains. The first two columns represent two material classes (a piezoceramic and a polymer film) which use the piezoelectric effect. Piezoelectricity can be thought of as an interaction of the electrical field imposed upon the material with electrical monopoles in the material itself. When an electric field is applied, the monopoles are pulled in the appropriate direction, straining the material and creating a strain in the direction of the field. This fundamental relation of piezoelectricity between field and strain is lin-

**Table 1 Comparison of actuation strain materials**

| | PZT G-1195 | PVDF | PMN | Terfenol DZ | Nitinol |
|---|---|---|---|---|---|
| Actuation mechanism | Piezoceramic | Piezo film | Electrostrictor | Magnetostrictor | Shape alloy |
| $\Lambda_{max}$, μstrain | 1000 | 700 | 1000 | 2000 | 20,000 |
| E, $10^6$ psi | 9 | 0.3 | 17 | 7 | 4 m[b], 13 a[c] |
| $\varepsilon_{max}$,[a] μstrain | 350 | 10 | 500 | 580 | 8500 a[c] |
| Bandwidth | High | High | High | Moderate | Low |

[a]For a sheet of actuator bonded to aluminum beam ($ts/ta$ = 10) in bending assuming AC value of Λ.
[b]m = martensite.
[c]a = austenite.

Table 2 Comparison of strain sensors

| | Foil[a] | Semiconductor[a] | Fiber[b] | Piezo film[c] | Piezoceramic[c] |
|---|---|---|---|---|---|
| Sensitivity | 30 V/ε | 1000 V/ε | $10^6$ V/ε | $10^4$ deg/ε | $2 \times 10^4$ V/ε |
| Localization, in. | 0.008 | 0.03 | ~0.04 | <0.04 | <0.04 |
| Bandwidth | 0 Hz–acoustic | 0 Hz–acoustic | ~0 Hz–acoustic | ~0.1 Hz–GHz | ~0.1 Hz–GHz |

[a]10 V excitation. [b]0.04 in interferometer gauge length. [c]0.001 in sensor thickness.



ear to first order.[30,31,106,127] The third column represents a material which creates actuation strain through electrostriction, which can be thought of as an interaction between the electric field and electric dipoles in the material which is inherently nonlinear.[54,115–117] The fourth column is a magnetostrictor, which relies on a coupling between an applied magnetic field and magnetic dipoles in the material and is also inherently nonlinear.[47,120] The absence of magnetic monopoles explains the absence of a fourth effect, which would be the interaction between magnetic fields and magnetic monopoles in the material. Shape memory is a qualitatively different effect, in which heating in the material (e.g., by the application of electrical current) causes a phase change with an associated strain. In some materials the strain associated with phase changes can be recovered when the material cools; this is called the shape memory effect.[8,56,58,74,75]

All four of the material classes listed fulfill the basic strain actuator requirement of converting electrical inputs to strain in the material. Lead zirconate titanate (PZT) is a common piezoceramic material having a maximum actuation strain on the order of 1000 microstrain.[48,95] Other piezoceramics in development show promise of developing considerably higher actuation stains.[29,92] Polyvinylideneflouride (PVDF) is a polymer piezoelectric film which can produce about 700 microstrain,[65,122] and lead magnesium niobate (PMN) is a ceramic electrostrictor which can create about a 1000 microstrain.[13] PZT and PMN are generally available in transversely isotropic sheets and solids, which can be bonded to the surface of structures or embedded within laminated materials.[27] Orthotropic induced strain is possible by electrode arrangement,[64] bonding method,[9,10] or the fabrication of embeddable fibers.[124] PVDF is mechanically isotropic and piezoelectrically orthotropic, but its polymer nature limits it to low temperature and pressure environments. Terfenol, a rare earth magnet-like magnetostrictive material, can create about 2000 microstrain at its nonlinear maximum.[39] Its application as a distributed actuator is complicated by the need to provide a source of the large magnetic field necessary to reach these maximum strains. Nitinol (a shape memory nickel titanium alloy) can create up to 20,000 microstrain, or 2% strain.[43,78] Available in fibers and sheets, it can be embedded or applied to a surface.

As seen in Table 1, the modulus of each material is comparable to that of structural materials with the exception of the PVDF film, which is significantly lower. The next row in the table indicates the approximate strain which can be induced on the surface of an aluminum beam whose thickness is 10 times the thickness of the actuation material (calculated using the uniform strain model discussed earlier). This value indicates the range of strain which can be created in the host structure and is on the order of 3–500 microstrain with commercially available piezoelectric, electrostrictive, and magnetostrictive materials. In contrast, as much as 0.8% strain can be induced by the nitinol. However, the bandwidth of the nitinol is much lower than the other strain actuators because of the time constants associated with introduction and, especially, the removal of heat by cooling. Therefore, the trade which must be made in selecting an actuator is one of strain authority vs bandwidth. The piezoelectrics and electrostrictives have bandwidths beyond the frequency range of structural and acoustic control applications but small strain. Terfenol has a moderate bandwidth because of the difficulty of creating a rapidly changing magnetic field but slightly larger strain. Nitinol has large strain but very low bandwidth.

## Sensory Elements

Sensory elements of intelligent structures must be sensitive to the mechanical states of the structure and capable of being highly distributed. The ideal sensor for an intelligent structure converts strain or displacement (or their temporal derivatives) directly into electrical outputs. The primary functional requirements for such sensors are their sensitivity to the strain or displacement (or their time derivatives), spatial resolution, and bandwidth. Secondary requirements include the transverse and temperature sensitivity, linearity and hysteresis, electromagnetic compatibility, and size of sensor packaging. Although actuators are so large they must be explicitly accommodated in the built-up laminates, it is desirable to make sensors small enough to be placed in interlaminar or otherwise unobtrusive positions.

### *Sensing Mechanisms*

The two types of sensors which can be utilized in intelligent structures are those that do not require an external reference: acceleration and strain. The current competing technology for inertially referenced measurement of acceleration is based on integrated circuit chip-based devices. These have been fabricated using silicon cantilever structures with piezoelectric and capacitive detection mechanisms.[21,94,97,99] Another potential sensing mechanism for a chip-based device is electron tunneling.[128] Accelerometers can be packaged in a way which allows them to be embedded in a structure or highly distributed over its surface. The output of the acceleration can be integrated once or twice in a high bypass manner to provide an estimate of inertial velocity or displacement at the point of measurements. Accelerometers are capable of making measurements over wide frequency ranges, including nearly quasistatic.

The alternative sensing scheme is to measure the strain or strain rate in the structure (or the deflection or velocity of one point relative to another). Strain can be sensed at a point in the structure or averaged over a larger finite area to yield some particularly desirable output with the assistance of a weighting function.[18,24,77,84,89] Weighting functions can be chosen such that the output has frequency transfer function characteristics which are highly desirable and unobtainable from temporal filtering of discrete point sensors. An area averaging sensor can be thought of as a device which can sense incoming strain waves before they reach the center point of the sensors. The transfer function between the output of a discrete point sensor and an area averaging sensor centered at that point can appear to be noncausal and thus violate the causality assumptions of the Bode phase-gain theorem. In fact, this allows distributed strain sensors to recover some of the nonminimum phase associated with discrete point sensors which are not collocated with the actuators; as a result, they have more desirable gain/phase roll-off characteristics. Note that such weighting functions can be applied to the output of any sensing device, including fiber optic sensors, and do not rely on a shaped piezoelectric strain gauge sensor.

Two common weighting methods are modal sensors and discrete shaped sensors. Modal sensors use sensitivity weighting functions which are distributed in such a way as to mimic the strain pattern in one of the structural modes.[69–71,113] Therefore, modal sensors may be very sensitive to one mode and, through orthogonality, be relatively insensitive to other modes. Therefore, the frequency domain output is concentrated in bandwidths associated with modes of the system targeted in the sensor design. Discrete shaped sensors cover a finite portion of the structure.[5] By using relatively simple weighting functions, such as triangular weighting or the Bartlett window, discrete sensors can be made to roll off in frequency, effectively acting as low pass filters.

### *Commercially Available Sensors*

Current commercially available sensing devices are listed in Table 2. Available sensing devices, which can be embedded or distributed over host structures, include traditional foil gauges, semiconductor strain gauges, embedded fiber optics, piezoelectric films, and piezoceramics. Foil and semiconductor gauges rely on a change in resistivity associated with strain for their operation.[14] Piezoelectric and piezoceramic devices use a variation of the piezoelectric effect which relates the strain in the device and the voltage observed at its terminals.[7,65] Fiber optic strain gauges rely on mechanical/optical coupling effects to cause the optical output of the fiber to change with the strain.[12,19,33,81,107,108,112,119] The sensitivities, indicated in Table 2, range from approximately 30 V per strain for the foil gauges, through $10^3$ V per strain for the semiconductors, to $10^4$ V per strain for the piezoelectric and piezoceramic gauges. Fiber optics have a fundamentally different relationship between the output and measurement which is expressed in degrees per strain (fiber optics produce up to $10^6$ deg per strain). Note that the sensitivities listed in Table 2 are made for reasonable excitation voltage, gauge length, and sensor thickness assumptions needed to evaluate the various strain sensors using a common criterion. The bandwidths of almost all the devices extend over the range of conventional structural control.[23,60,61,102,103]

Considering that the available strain gauges are comparable in terms of their primary functional requirements of sensitivity, localization, and bandwidth, the choice of which to use in intelligent structures must be based on the secondary considerations. These considerations include embeddability (which eliminates the soft piezoelectric films), the ability to introduce weighting functions and electromagnetic compatibility issues (which generally reduce the attractiveness of foil gauges), and the bulk and power requirements of the associated electronics necessary to extract the strain signals. This last consideration tends to weigh against the fiber optics. Therefore, the preferable strain sensors are likely to be derivatives of the semiconductor based or piezoceramic devices, unless the signal conditioning electronics associated with embedded optics can be made small enough to accommodate widespread distribution throughout a structure.

### *Actuator-Sensor Synthesis*

With certain types of actuators and sensors a level of synthesis can be achieved in which the same device can be used for both actuation and sensing. Shape memory alloy fibers have been used in this application, as have piezoelectrics. In the case of piezoelectrics, the embedded material is modeled by combining the actuator and sensor constitutive relations.[51] The piezoelectric can be considered a generalized transformer between the structural states (stress and strain) and the electrical states (charge and voltage).[50] By making use of these properties, the same device can be used as both an actuator and sensor through a technique referred to as self-sensing actuation.[4,32,109] The circuit added to a piezoelectric to allow simultaneous actuation and sensing subtracts the charge which appears across a reference capacitor (effectively an electrical estimator) from the charge which appears across the piezoelectric (which is influenced by both mechanical and electrical effects). Nominally, the difference corresponds to the strain in the piezoelectric. Signal conditioning circuits can be designed to return either the strain or the strain rate as an output signal. Simultaneous actuation and sensing is advantageous for active control application since the actuator and sensor are a perfectly collocated pair.

Another aspect of actuator-sensor synthesis is the appropriate selection of actuators and sensors to simplify the structural control problem. In choosing a control scheme for a structure one can, in principle, select any form of actuator (i.e., applied force, applied moment, or applied distributed strain) and any form of sensor (i.e., displacement, velocity or acceleration, slope, slope rate or acceleration, or strain, strain rate or acceleration). However, it may be that there is an optimal combination of these nine possible sensor outputs and three possible generalized force inputs which simplifies the feedback in the structural control problem. To examine this issue, the tip displacement of a cantilever beam was controlled by a strain actuator over the region from the root to 10% of the length.[87] Assuming the displacement is known everywhere along the beam, a linear quadratic regulator (LQR) spatially distributed feedback gain function (or kernel) can be calculated. The function shows no regular pattern for displacement feedback. However, when expressed in terms of strain feedback, a much more regular function appears, diminishing approximately exponentially from root to tip.

In another example, the optimal output feedback was calculated for the sinusoidal flexural modes in an infinite beam for distributed moment actuators. It was found that if transverse inertial velocity and strain were measured, the optimal output feedback for flexural waves of a uniform structure (assuming uniform weighting functions of the error) was exactly collocated.[83] The simplicity of the strain feedback functions to strain actuation in these cases could imply that strain is a more natural input and output than displacement and force, and it is certainly more easily achieved in a distributed manner for real structural forms.

## Control Methodologies and Algorithms

The real intelligence of intelligent structures stems from their highly distributed control functionality. There are three levels of control methodology and algorithm design which must be considered for intelligent structures: local control, global algorithmic control, and higher cognitive functions. The objectives of local control are to add damping and/or absorb energy and minimize residual displacements. The objectives of global algorithmic control are to stabilize the structure, control shapes, and reject disturbances. These two levels are achievable within the current technology. In the future, controllers with higher cognitive functions will have objectives such as system identification, identification and diagnosis of component failures, the ability to reconfigure and adapt after failures, and eventually to learn.[111]

### *Local (Low-Authority) Control*

Considering that hundreds or thousands of actuators and sensors may be distributed throughout a structure, it may be desirable to use collocated or localized interconnections to introduce some level of control into the structure before attempting to close global (highly noncollocated) feedback loops.[6] The ideal choice for local control is to simulate the conditions of matched termination, in such a way that all of the impinging energy is absorbed by the controller.[86,96] However, simulating conditions of matched termination requires actuation and sensing of all independent cross-sectional variables, which is usually not feasible in a structural controller. For example, in the case of a flexural wave in a simple beam, such matched termination would require sensing of displacement and rotation, and actuation of moment and shear at a point.

For the case of a system with a single output, the optimal compensator is found by matching the impedance of the compensator to the reciprocal of the complex conjugate of the dereverberated frequency transfer function.[20,79,80] The dereverberated transfer function of a structure at the observation point is obtained by ignoring the effects of reflections from discontinuities and the boundaries in the far field. This can be calculated by smoothing or averaging the normally calculated frequency transfer function of the structure. In a limited number of cases, such dereverberated transfer functions can also be calculated from wave propagation theory. Unfortunately, the optimal single-input single-output compensator is unachievable because the resulting transfer function is usually noncausal. Therefore, it is necessary to use the best causal approximation. Approximations can usually match the amplitude and/or phase of the noncausal compensator over some specified frequency range of interest. Even though not ideal, such local loops improve performance and robustness of the global control.

### *Global (High-Authority) Control*

Although local control is useful for adding damping and low-authority control, high-authority control must be utilized for objectives such as global disturbance rejection, shape control, and stabilization of the structure. Aside from the usual questions concerning design of the compensator for robust performance (a topic beyond the scope of this review), the novel issue in the design of global controllers for intelligent structures is that of distribution of control. There are two limiting cases. The first is a completely centralized controller in which the outputs from all of the sensors are fed to a centralized processor which computes all of the control commands to the distributed actuators.[53] The other extreme is a completely decentralized design, which is essentially the same as the local control already discussed.[16] The centralized design would have the best performance but would be computationally inefficient. A single centralized computer would have to process signals at rates corresponding to the highest mode being controlled. Such computational requirements (typically on the order of $100 \times 100$ to $1000 \times 1000$ at speeds of 1000 Hz) cannot currently be met, even with dedicated real-time control computers (capable of computations on the order of $10 \times 10$ to $30 \times 30$ at a 1000 Hz). On the other hand, the decentralized scheme lacks some of the performance of the centralized scheme but is computationally trivial.

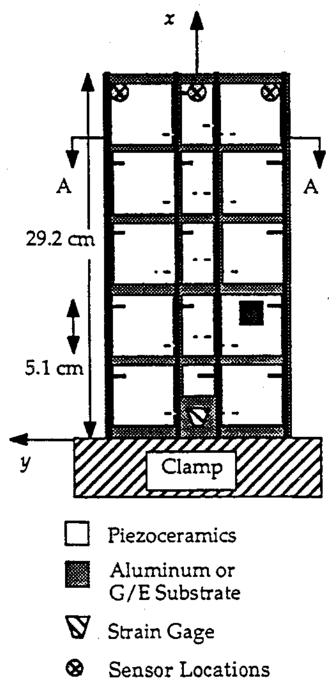


Fig. 2 Active aeroservoelastic wing.[66]

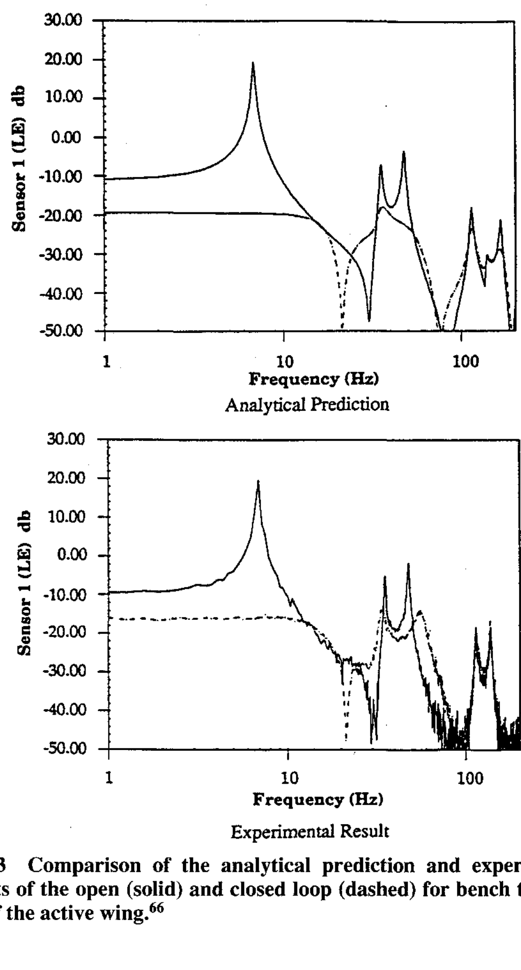


Fig. 3 Comparison of the analytical prediction and experimental results of the open (solid) and closed loop (dashed) for bench top testing of the active wing.[66]

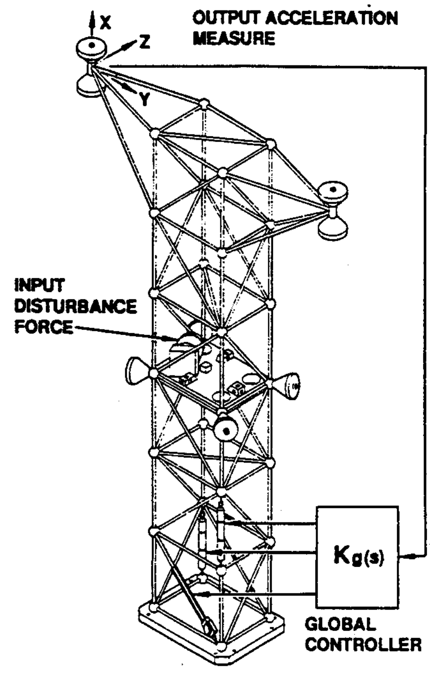


Fig. 4 Precision truss with dial-a-strut.[42]

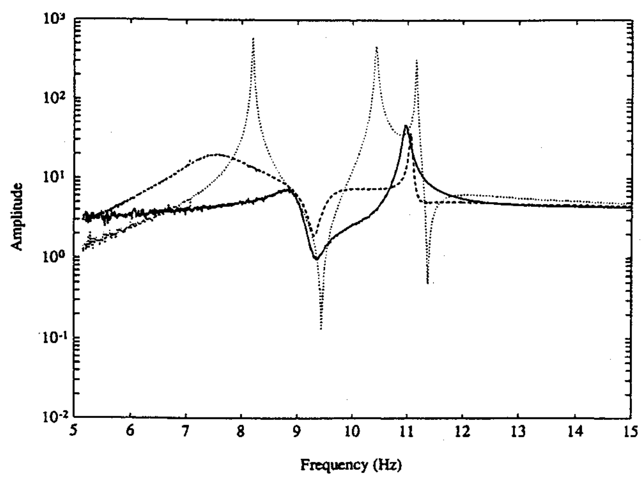


Fig. 5 Open loop (dotted) vs closed loop for one (dashed) and two (solid) dial-a-struts.[42]

A compromise must be made between the two approaches. One such compromise is to use a scheme, midway between a completely centralized and completely decentralized control, which is referred to as a hierarchic or multilevel control architecture.[52,57] In this scheme there would be two levels of control: a centralized controller for overall performance, and distributed processing for local control. The structure would be divided into finite control elements with local processors providing local control using measurements made within the element and commanding inputs of actuators within the element. An average representation of the shape within each element would then be passed on to the global processor, which would assume the task of high-authority control. This division of the control function into local and global control has been found to be practical and nearly reproduces the performance of a completely centralized structural controller.

### Controller Architecture and Implementation Hardware

The presence of actuators, sensors, and highly distributed control functionality throughout the structure implies that there must be a distributed computing architecture. The functional requirements for such a computing architecture include a bus architecture, an interconnection scheme, and distributed processing. The bus architecture should be chosen to yield a high transmission rate of data in convenient (probably digital) form throughout the structure. The interconnections must be suitable for connecting a (potentially) large number of devices, actuators, sensors, and processors with the least degradation of structural integrity. If the actuators and sensors are embedded within the structure, the interconnections should also be embedded within the structure to avoid the necessity of running the electrical connections through otherwise structurally important plies. The processing requirements are that the full functionality (signal conditioning, amplification, digital/analog (D/A) and analog/digital (A/D) conversion, and digital computation) be distributed throughout the structure. Secondary requirements for the computing architecture include minimizing electromagnetic interference, maintaining the mechanical strength and longevity of the structure and of the electronics components, and thermal and chemical compatibility of electronic components within the host structure.

*Bus Architecture*

Selection of the bus architecture will strongly reflect the hierarchic control architecture chosen. Typically, structures will have distributed actuators and sensors which report (probably analog signals) to a local processor where the local control is calculated. These local processors then communicate over (probably digital) busses to the global processor. Trade studies have shown that the use of a digital bus interface can simplify the overall interconnections in systems with more that 20 or 30 sensors and/or actuators.[125] Thus, a relatively small number of actuators and sensors move the design toward one of a bus architecture.[82]

*Processing Hardware and Material Integration*

There are state-of-the-art processors which can perform the functions of the local controller and are, therefore, candidates for distribution throughout the structure. One commercially available single-chip microprocessor (the Intel 87C196KB) has a central processing unit, A/D, D/A, sample and hold functions, multiplexors, a serial port, high speed digital input/output, and 16 kb of memory on a single chip.[1] This device operates at 12 MHz and integrates nearly all of the electronic functionality required to implement local processing for a hierarchic controller. With 16-bit precision, 10 inputs, and 10 outputs, this device can perform the calculations for an LQR controller at 3 kHz. Alternatively, for a 10-state linear quadratic Gaussian (LQG) controller, it can perform these calculations at 1000 Hz. Thus, the capabilities needed for the local processors are clearly achievable within the state of the art.

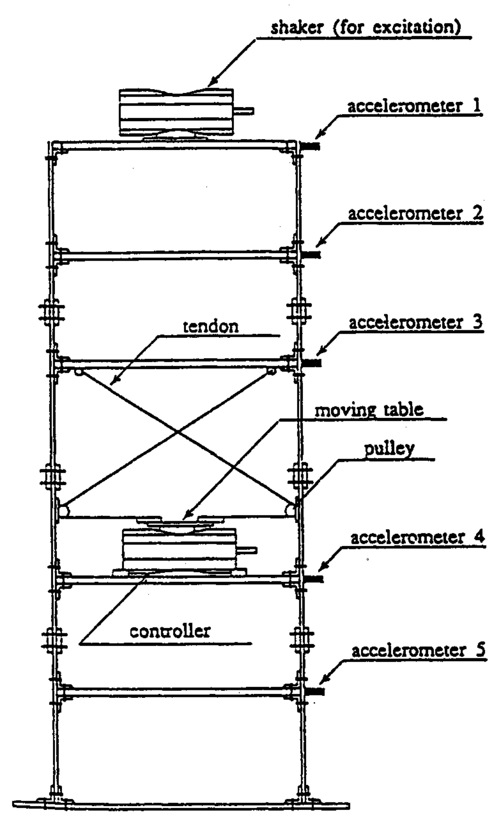


**Fig. 6 Building model for controlled seismic response.[90]**

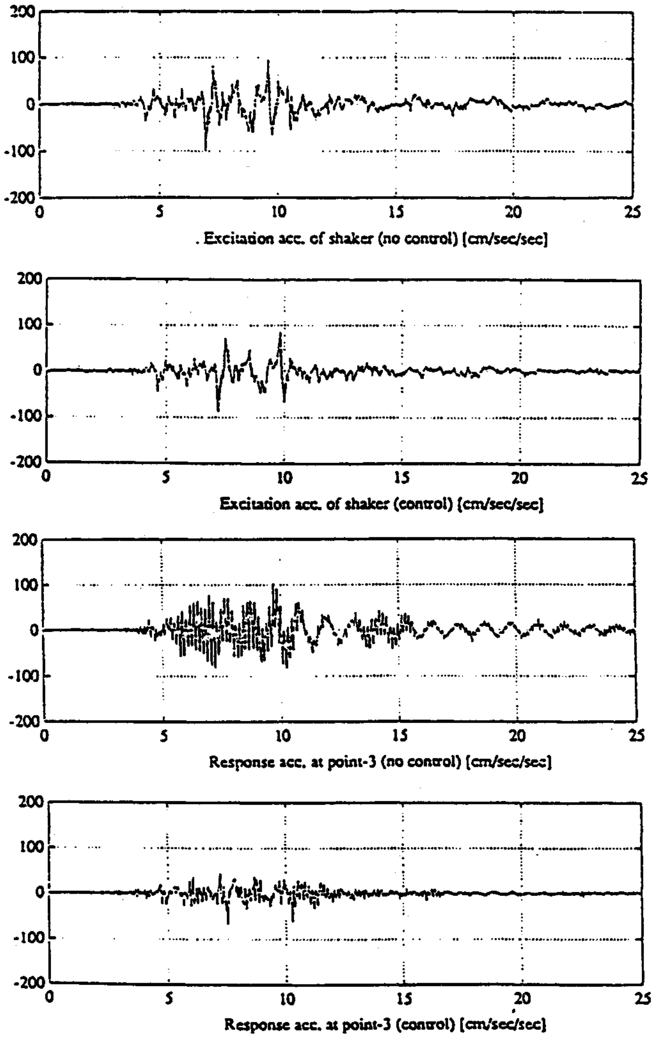


**Fig. 7 Comparison of open- and closed-loop response of midbuilding accelerometer under simulated seismic excitation.[90]**

Can such microdevices be embedded within a structural laminate? The issues here are: whether the device will survive the temperature and pressure cycles of the curing process, and whether it can survive the periodically applied strain of the operational environment as well as the temperature and humidity conditions of general operation. A preliminary investigation of this subject finds that the embedding of microdevices is feasible within common structural laminates.[126] Electronic devices without protective packaging have been embedded and cured in laminated test coupons. The electronic devices functioned normally up to failure of the laminate. The remaining challenges in this area are: the robustification of electrical contacts to the device, subject to fatigue and loading, on to and off of the device; the design for long-term reliability under adverse environmental conditions; and the design of signal and power conditioning electronics to minimize heat dissipation into the structure.

## Applications for Intelligent Structures

A wide variety of applications exist for intelligent structures technologies.[88] Despite the fact that truly intelligent structures (i.e.,

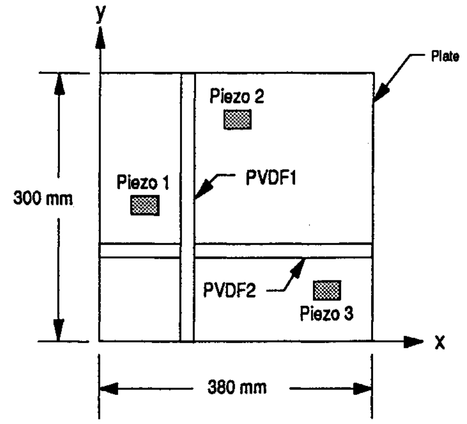


**Fig. 8 Actively controlled panel for control of sound radiation.[22]**

those with embedded controllers as well as actuators and sensors) have not yet been built, a number of experimental implementations of active structures (i.e., those with distributed actuators and sensors) have been successfully demonstrated. Notable experimental implementations include aeroëlastic control and maneuver enhancement,[110] reduction of vibrations and structure borne noise[46,85,104,121] and acoustic transmission,[2] jitter reduction in precision pointing systems,[34,40,41,44] shape control of plates[63,100] and mirrors,[3,101] trusses[36,118] and lifting surfaces,[55,68] isolation of offending machinery and sensitive instruments,[91] and robotic control.[25,105] To understand the potential and limitations of the current technology, four examples found in the recent literature are discussed subsequently: the aeroservoelastic control of a lifting surface, precision control of a truss, seismic control of a building, and the control of radiated sound.

In the first example, a typical high performance aircraft-like wing was built of a graphite epoxy laminate with piezoelectric actuators distributed over 71% of its surfaces.[66] The actuators were arranged into three banks which consisted of the vertical strips shown in Fig. 2. The actuators were wired so as to induce bending in the laminate. Three tip displacement measurements were used for feedback. The controller implemented was a reduced order, 14-state, LQG controller. The control objective was gust disturbance rejection and flutter suppression. Shown in Fig. 3 are the analytically predicted and experimentally measured open- and closed-loop transfer functions from disturbance to tip displacement. As can be seen, the static response of the structure was reduced by almost 10 dB, which corresponds to approximately a threefold stiffening in the structure due to the application of the closed-loop control. The first mode was virtually eliminated from dynamic consideration, being reduced 30 dB from an initial 1% damping. The second mode, which was torsional, was less strongly influenced, with a 10 dB reduction. This was due to the fact that this mode was less controllable than the first or third mode. The third mode achieved a 20 dB reduction. Overall the rms response in bandwidth up to 100 Hz was reduced by 15.4 dB. This is an example of the relatively high gain control which can be introduced into a structure, and is probably the largest control authority which has yet been reported on a structural test article in experimental implementation.

The second example of a prototypical intelligent structure is the "dial-a-strut" or locally controlled strut, which is part of a precision control truss experiment (Fig. 4).[42] In this case, the structure contains two active piezoelectric struts. Each strut has a collocated displacement and force feedback. By making measurements of the collocated displacement and force, the previously described localized optimal impedance matching can be implemented. The control objective of this experiment was rejection of disturbances due to onboard machinery, typical of a jitter reduction task in a precision interferemetric spacecraft. Figure 5 shows typical transfer functions (open loop and closed loop) for one and two of the dial-a-struts. By comparing the open-loop and two strut closed-loop responses, it can be seen that the first and second structural modes were significantly modified. Both the first and second mode response was reduced by 40 dB from an initial structural damping of a few tenths of a percent. Thus, the local collocated approximation to the optimal noncausal controller is seen to achieve good performance in a realistic structural configuration.

The seismic control of buildings is a considerably larger scale application of intelligent structures. Experiments were performed on a model building with a simulated large earthquake disturbance (Fig. 6).[90] Control was effected by an active shear brace incorporated into the structure. Five transverse accelerometers were used to monitor the control response of the structure, and two were used for feedback control. The control objective was to minimize building acceleration in response to the disturbance. Figure 7 shows the building excitation with and without the control system. As a result of the closed-loop control, the damping factor was increased from nearly zero to 20% in the first three modes, with significant reduction in the low frequency response.

The final example considers the reduction of sound radiated into a room or aircraft cabin by active control of the shell-like members which form the walls. To simulate this situation, a rectangular plate was placed inside a test chamber.[22] The plate was controlled by three piezoceramic actuators placed as shown in Fig. 8. Two PVDF piezoelectric film sensors were used to measure the vibration of the plate. The excitation source was an electromagnetic shaker which drove the plate at a known frequency corresponding to, for example, the excitation of an aircraft cabin wall from the rotation of an external propeller at a known rpm. In these cases, adaptive least-mean-square algorithms are likely candidates for the control scheme.[38] These schemes make use of knowledge of the frequency at which the primary excitation is occurring. The control objective in this example was narrow-band reduction of the radiated far-field noise. Figure 9 shows the radiated sound pressure level for the open-loop case, and the cases of one piezoceramic actuator with

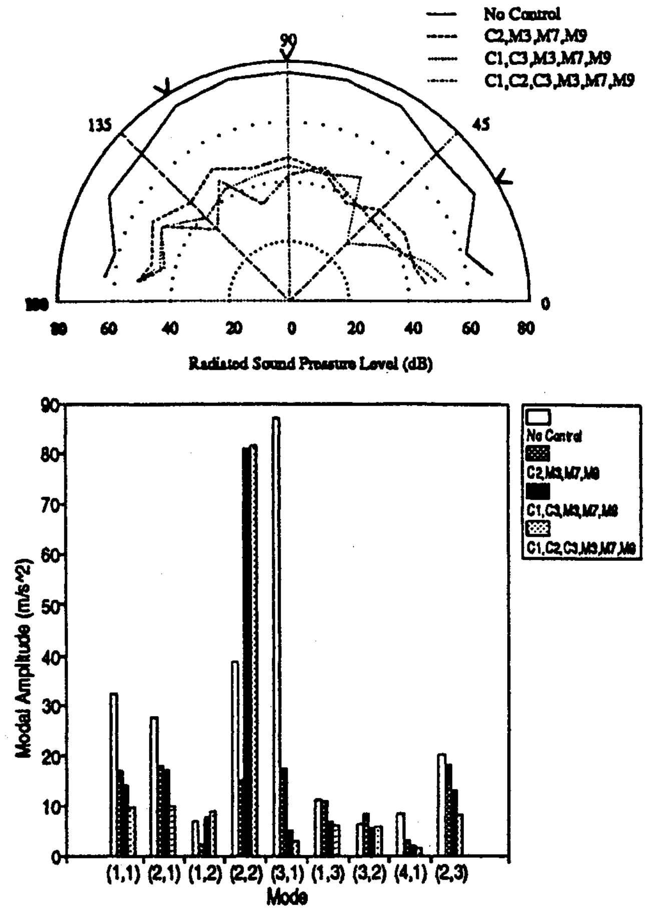


**Fig. 9 Spatial distribution and frequency content of radiated sound with no control and two arrangements of control actuators and sensors.[22]**

one sensor and two piezoelectric actuators with two sensors. As can be seen from Fig. 9a, the radiated sound pressure level was reduced by about 30 dB. Figure 9b indicates that this was achieved principally by reducing the response of the three-one mode, which corresponded to the frequency of the excitation source.

These four examples are but a few of the cases in which investigators throughout the world are now applying distributed actuation and sensing to a wide variety of control problems. It is encouraging that these early experiments show not only the feasibility of intelligent structures application but also remarkably good agreement between theory and experimental results as well. Of course, further experimentation is necessary to establish the technological limitations as well as the feasibility of distributing the processing and control architectures.

## Present and Future Needs

Currently, not all of the technologies needed for cost-effective application of intelligent structures have been sufficiently developed. There are a number of difficult problems which remain. Some of the more important of these problems are discussed next.

Better actuation materials: To truly achieve the desirable level of control for many structural applications, actuation materials which have 3–10 times larger strain than commercially available piezoelectrics and electrostrictives must be developed. Alternatively, materials should be developed similar to shape memory alloys, but with much higher bandwidth than those currently available.

Optimized sensors: The design of sensors must be optimized to alleviate problems such as spillover and to focus control effort on the bandwidths of interest through selective observability of the structure.

Inherently structural control algorithms: Much of the theory developed for controlled structures has been by control theoreticians who view the structure as an already discretized matrix system. However, structures are inherently distributed parameter systems. Gains must be made by considering this inherent distribution, as well as the inherent bandedness of structures in their parametrized form.

Distributed control: The proper distribution of control between a lower level and a higher level controller must be developed more completely, so that stability is guaranteed and robust performance is maintained.

Power conditioning and switching: Although it is conceivable that signal level electronics can be highly distributed through a system, power conditioning and switching requires dissipation of energy. This power conditioning and switching must be done in a way which minimizes the local heat load on the structure, so that the system can be embedded without thermally degrading the material.

Structurally robust very large-scale integration: Innovative packaging techniques must be developed in which the interconnections to the silicon devices are structurally robust, so that these devices can survive the strain and fatigue environments of typical structures.

Minimized impact on host structure: The presence of active elements (actuators, sensors, and processors) impact the host structure by interfering with the load path and potentially introducing discontinuities which must be accommodated. These changes in the fracture, fatigue, and toughness characteristics of host material must be understood and minimized.

Hermeticity of embedded components: The requirements for military microelectronic components are dominated by the need to isolate the electrically active surfaces from the ambient chemical and humidity environment. Once these devices are embedded in a laminate, the challenge becomes to isolate their surfaces from both the ionic contamination of the structural matrix material and from the chemical and humidity environment of the ambient conditions, which can penetrate the host material via the pathways created by the electrical connections.

Manufacturablity, reliability, and repairability: A number of practical implementation questions include the difficulty of manufacturing intelligent structures, their in-service reliability, and the feasibility of in-service repair. Such issues will have to be addressed before a widespread application of this technology is possible.

## Anticipated Research and Development

In the next decades, it is expected that there will be widespread application of the technology under development, in its current and evolutionary forms. The breadth of application of this technology is expected to not only span the aerospace industry but become widespread in the construction, automotive, and machine tool industries as well.

In the more distant future, the evolution of a new physical-biological technology is anticipated. This technology will have two trends which are complementary. The first is the natural evolution of the technology discussed earlier: the introduction of intelligence into the physical world, by the application of a machine electronic intelligence to otherwise unintelligent devices. The second is more revolutionary: the introduction of life into engineering application, i.e., the application of biological processes to the solution of engineering problems. Much as the steam engine drove the technology of the 19th century and electronics drove the technology of the 20th century, one can envision that the application of biological concepts to engineering will drive the technology of the 21st century. Engineering will cease to be the application of only the physical sciences for the betterment of mankind and become the application of all science, including both the physical and life sciences, for the betterment of humanity.

## Acknowledgment

The author wishes to acknowledge the technical assistance given in the preparation of this paper by his many colleagues and students in the Space Engineering Research Center at MIT. This work was prepared under Air Force Office of Scientific Research Grant AF F49620-92-J-0010.P00001 with Spenser Wu acting as grant monitor.

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