Concepts of Adaptronic Structures

Konzepte adaptronischer Strukturen

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For some time, engineers and scientists have been using the nature as an inspiration for their design of advanced robotics and mechanical systems. Today, nature has also become the inspiration for an entire new class of material systems – the *adaptronic structures* [1]. Using biological analogies and nature's ability to adapt a material's structure, morphology, shape, and properties to accommodate its changing environment and its aging process, present day engineers and scientists are designing material systems that can change their shape, control their vibrations, monitor their own health, and perform many other biological-inspired functions.

Über viele Jahre ließen sich Ingenieure und Naturwissenschaftler von der Natur anregen, um fortschrittliche Roboter und andere mechanische Systeme zu entwerfen. Heutzutage animiert die Natur darüber hinaus zu einer ganz neuen Klasse von Materialsystemen: *adaptronische Strukturen*. Durch Nutzung biologischer Analogien sind Ingenieure und Naturwissenschaftler nun in der Lage, Struktur, Gestalt, Form und Eigenschaften von Werkstoffen so zu designen, dass sie sich selbsttätig an Umweltbedingungen und Alterungsprozesse anpassen. Hierzu werden Materialsysteme entwickelt, die ihre Form verändern und ihre dynamische Belastung kontrollieren können sowie ihren eigenen Zustand überwachen und viele andere, durch die Biologie inspirierte Funktionen ausführen.

Keywords: Active materials, adaptive structures, piezoelectrics, magnetostrictive, morphing structures, structural health monitoring

Schlagwörter: Aktive Materialien, adaptive Strukturen, piezoelektrisch, magnetostriktiv, morphologische Strukturen, Strukturüberwachung

1 What are Adaptronic Structures?

Adaptronic structures (also referred to as smart materials or intelligent structures) are defined in the literature in the context of many different paradigms; however, two are prevalent. In the *technology paradigm*, adaptronic structures are seen as an "integration of actuators, sensors, and controls with a material or structural component" (Fig. 1). In the *science paradigm*, adaptronic structures are "material systems that have intelligence and life-like features integrated in the microstructure of the material in order to reduce the total mass and energy and produce an adaptive functionality". The vision and guiding analogy of adaptronic structures is that of learning from nature and living systems in such a way as to enable man-made artifacts to have the adaptive features of autopoiesis we see throughout nature. This leads to the description of the anatomy of an adaptronic material system: actuators or motors that behave like muscles; sensors that have the functionality of the "five senses" (hearing, sight, smell, taste, and touch); communication and computational networks that represent the nerves, brain, memory, and muscular control systems [2]. Although the leading analogy is that towards biological systems, it must be emphasized that adaptronic structures are designed by human beings in order to achieve human-related objective. Therefore, the system boundary of the adaptronic structures must necessarily be drawn to include the human end user.

What kind of life-like functions can we expect from adaptronic structures? Nature's systems have a few general attributes that we can aspire to instill in synthetic material systems. Many of nature's systems can change their properties, shape, color, and load paths to account for damage and allow for repair; and can also manage the graceful retirement of aged systems, to name a few. Engineers and

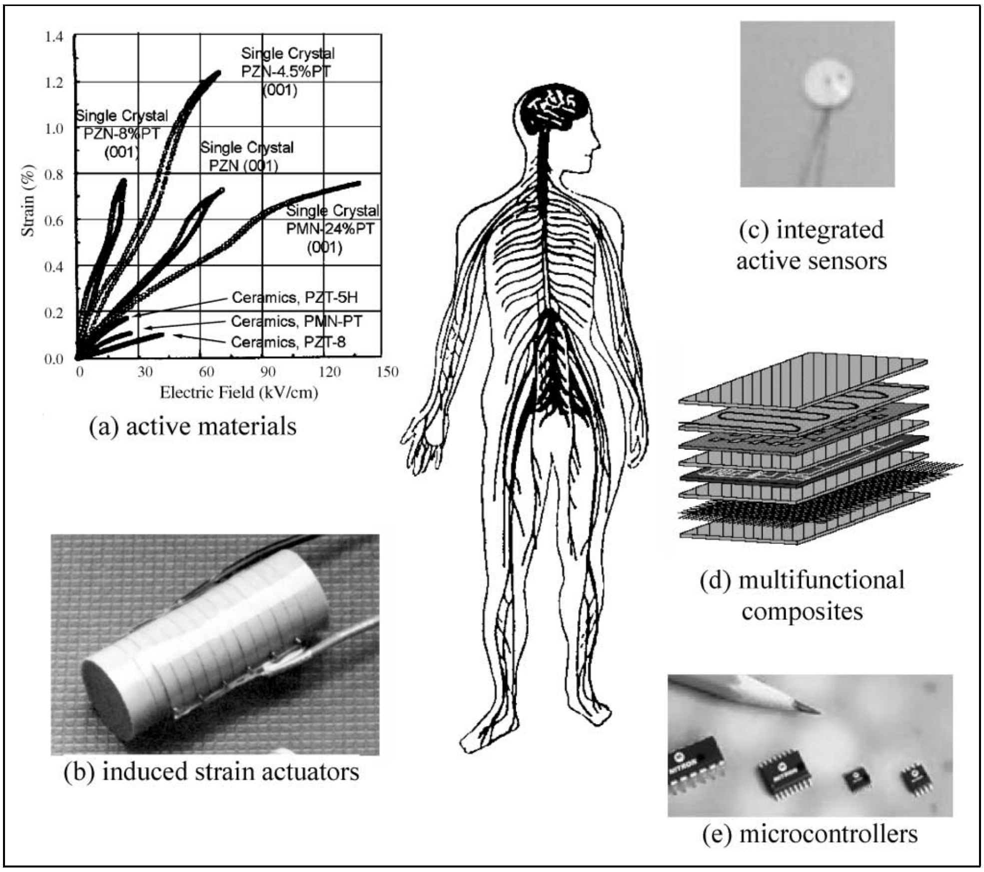

Figure 1: The biomimetic concept in adaptronic structures: (a) active materials, (b) induced-strain actuators; (c) integrated active sensors; (d) multifunctional composites; (e) microcontrollers.

scientists have developed a plethora of devices that have some of nature's capabilities; however, little has been accomplished towards realizing the integration of life-like functions at the system level to create materials systems that would be able to learn, grow, survive, and age with grace and simplicity. The survival of biological structures depends on nature's ability to balance the metabolic cost (economy of "construction" and "maintenance") with the required mechanical properties, such as strength, toughness, resistance to impact, etc. This balance is precisely what we aim for when we specify material and structural requirements in order to attain a design that simultaneously satisfies economic viability and mission-oriented performance. Besides, a particularly attractive feature of biological systems is their unique ability to diagnose localized damage (through a continuously 'distributed' sensor network) and to initiate a self-repair process. Such an attribute would be a most desirable function in an adaptronic structural system.

Although present day researchers are concentrating on adaptronic structures that may seem rudimentary when compared with mammalian systems, their efforts lay the foundation for the future engineered systems. Controlling the movement of an arm is a wonderful example of the seemingly effortless task that the biological creatures perform each day, but which has been quite difficult for engineers to mimic. Consider a situation in which you are sitting at a table that has one leg shorter than the others, and you wish to draw a straight line on a piece of paper that is resting on this table. Before you begin, you recognize that the table is unstable and that it will be difficult for you to draw such a line; in fact, you may have tried this task before and feel uncertain about the dynamics of the table. When you begin to draw the straight line, you will contract certain muscles to force movement of the pencil upon the paper. To draw a straight line, you normally need to contract no more than one muscle of an antagonist muscle group at a time; however, you will contract both your biceps and triceps simultaneously in an effort to better control the pencil. The biceps and triceps are antagonist muscles, meaning that they work against each other, resulting in a 'stiff' elbow joint. Activating both the biceps and the triceps is energy intensive; you are consuming a large of amount of energy to do no mechanical work (there is no work done if there is no displacement). However, 'stiffening' the elbow joint creates a more stable control system, i. e., minimizes the influence of an unknown disturbance (the rocking motion of the table) on the output (drawing a straight line).

Upon succeeding in drawing a straight line, you are asked to draw a straight line several more times on the same unsteady table. As you draw each line, you begin to formulate a sense of the dynamics of the table – and better understand the environment in which you are working –

and as this occurs, you begin to conserve energy by not co-contracting the biceps and triceps to the same degree as in previous attempts. When the environment has been sufficiently sampled and you have learned the dynamics of the table, your body will try to conserve as much energy as possible and tend towards no co-contraction of muscles. This has been achieved because a new response algorithm has been learned and stored in the neural networks of your brain, or of the local ganglions, as appropriate. If, however, someone wanders in the room and creates a disturbance in your task, e. g., bumps your arm or the table, then you will once again co-contract your muscles to again increase the accuracy. The "human arm" with the associate neural controls could be considered of a typical adaptronic system example drawn from the biological world.

The **classical engineering approach** to this same task would be to formulate mathematical models for the table dynamics, the mechanism that draws the line, the interaction between the table surface and the paper and the paper and the pen, and any other aspect of the problem that would seem important to an engineer. Using these models, a deterministic plan or control algorithm would be developed to control the movement of the pen upon the paper while calculating what is expected to happen to the unstable surface when the pen creates a force at various locations. The engineer would then measure the response of the table and the straightness of the line. Once implemented, this algorithm would perform the same function at each and every time – it never gets any better, and it never gets any worse. It uses the same amount of energy at each and every time.

In all likelihood, the mechanisms to be used would be conceptually different from those used in the human arm. Most robots that mimic arm motion use a rotary motor at the joint and do not have co-contraction capabilities. This basic difference in algorithm and architecture highlights one of the fundamental deficiencies of today's robot systems as compared to biological systems. When a robot arm in a manufacturing plant or the arm of the space shuttle moves quickly, the robot arm vibrates because of the sudden deceleration. The human arm can generally outperform a robot in this type of combined slewing (moving from one position to another) and vibration control. The arm will use only the muscles needed to quickly perform the slewing motion, and then use co-contraction to stiffen the structure and reduce any vibration that might be caused by decelerating the mass of the arm and the payload that it may be carrying.

The **adaptronic approach** would be one that would be inspired by the biological world. Materials that behave more or less like muscles can be used in adaptronic structures and are called *induced strain actuators*. When energy is applied to the actuators, they attempt to expand/contract and work against any load that is applied to them. The actuators are typically bonded to the surface of a structure, or embedded within the material. This means that the artificial muscles must now work against the inherent structural impedance of the component, just as human muscles are parallel to the skeletal structure or bone. However, whereas the arm has discrete joints about which rotation occurs, the adaptronic structure may be a continuum, thereby necessitating a distributed actuation system. For example, the tip motion of a beam will not occur by rotating the beam about a joint but by inducing its deformation by means of induced strain actuators placed on the beam.

A basic premise of adaptronic structures is the intelligent use of energy transduction principles. In a conventional design, a structure would be calculated to resist the worst-case scenario. This usually results in gross over design. A ladder designed for the worst-case scenario would be, 99% of the time, **too strong** and **too heavy** for its current use. However, an "adaptronic" ladder would be designed much lighter, and, through the energy transduction, would be able to modify its behavior to cover its utility envelope. For example, an adaptronic ladder that is overloaded could use electrical energy to stiffen or strengthen itself while alerting the user that the normal loading capacity is being exceeded. The overload response should also be based upon the actual 'life experience' of the ladder to account for aging or a damaged rung; therefore, the ladder would determine its current state of health and use this information in assessing when it has been overloaded. At some point in time, the ladder will graciously announce its retirement, as it can no longer perform even minimal tasks.

2 The Construct of Adaptronic Structures

Adaptronic structures are complex systems displaying motion, sensing, and artificial intelligence functions synergistically to duplicate life-like functions. In line with the biomimetic analogy, we will consider in turn the actuators (artificial muscles), the sensors (artificial senses) and the microcontroller-artificial intelligence network (artificial nerves, brain, and mind).

2.1 Artificial Muscles – Actuators

Materials that allow an adaptronic structure to adapt to its environment are known as actuators. These materials have the ability to change the shape, stiffness, position, natural frequency, damping, friction, fluid flow rate, and other mechanical characteristics of adaptronic structures in response to changes in temperature, electric field, or magnetic field. The most common actuator materials are shape memory alloys, piezoelectric materials, magnetostrictive materials, electrorheological fluids, and magnetorheological fluids [3].

Shape memory alloys (SMA) undergo solid-to-solid martensitic phase transformations, which allow them to exhibit large, recoverable strains [4]. Strains of up to 8% can be reversed by heating the SMA above its phase transformation temperature – a temperature that can be altered by changing the composition of the alloy. In the process of returning to its "remembered" shape, the SMA can generate a large force and thus enact actuation. Because actuation depends on heating and cooling, the response of SMA actuators is not as fast as that of the other types of actuator materials. Current developments in shape memory technology targets the use of magnetic shape memory alloys that have a better frequency response due to the rapid reversibility of externally applied magnetic fields.

Nickel-titanium, also known as Nitinol are high-performance shape memory alloy actuator materials. Nitinol wires embedded in composite materials yield adaptive composite structures with "muscle" similarities. They have been shown [5] to display large bending deformation when activated (Fig. 2). In addition to applying forces or changing the shape of the structure, the Nitinol wires can be used to change the modal characteristics of the composite by changing the stiffness or state of stress in the structure. Photoelastic damage control experiments have shown that embedded Nitinol actuators can also be used to reduce stress concentrations in notched tensile coupons by creating localized compressive stresses.

Piezoelectric actuators can enact deformation and mechanical forces in response to an applied voltage. Rather than undergoing a phase transformation, piezoelectric materials change shape when their electrical dipoles spontaneously align in electric fields, causing deformation of the crystal structure. Maximum strains of over 1000 microstrain are now possible at kHz frequencies. When these small deformations are constrained, large mechanical forces, energy and power densities are generated. Examples of systems using piezoelectric actuators are: optical tracking devices, magnetic heads, adaptive optical systems, micropositioners for robots, ink jet printers, and speakers. Recent research has focused on using piezoelectric actuators with sophisticated control systems in adaptronic structures to perform active acoustic attenuation, active structural damping, and active damage control.

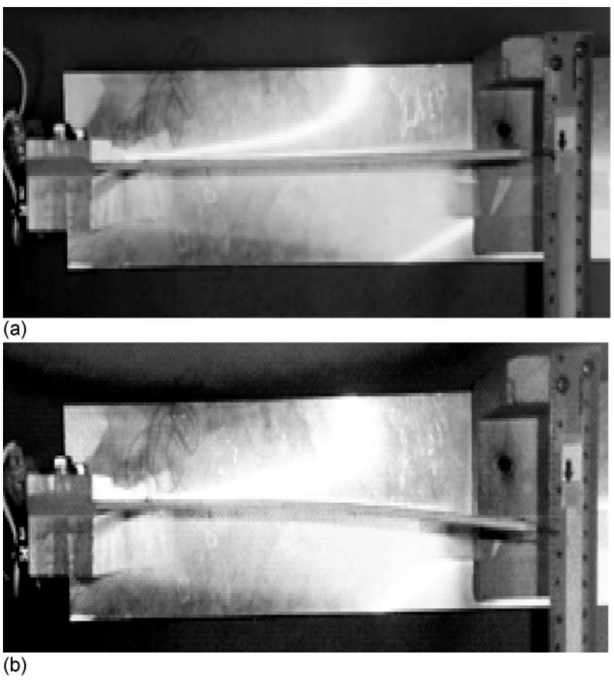

Figure 2: Polymeric composite with embedded Nitinol wires displaying large bending deformation when activated: (a) beam configuration before activation (b) deflected beam after SMA activation.

Magnetostrictive actuator materials are similar to piezoelectric materials, but respond to magnetic, rather than electric, fields. When placed in a magnetic field, the magnetic domains in a magnetostrictor rotate until they are aligned with the field, resulting in expansion of the material. Terfenol-D expands by more than 1400 microstrain due to alignment of its magnetic domains [6]. This material has been used in low-frequency, high-power sonar transducers; high-force linear motors; high-torque, low-speed rotating motors; and hydraulic actuators. Terfenol-D is also being investigated for use in active vibration damping systems.

Active fluids can also act as actuators in adaptronic structures. Electrorheological (ER) and magnetorheological (MR) fluids experience reversible changes in rheological properties (viscosity, plasticity, and elasticity) when subjected to electric and magnetic fields, respectively. These fluids contain micron-sized particles which form chains when placed in an electric or magnetic field, resulting in increases in apparent viscosity of up to several orders of magnitude. These fluids can be used to make simple hydraulic valves which contain no moving parts. Other applications include tunable dampers, vibration isolation systems, clutches, brakes, other frictional devices, and robot arms.

2.2 Artificial Nerves – Sensors

One of the critical functions instilled in adaptronic structures is that of sensing. Vibration detection and dampening, acoustic attenuation, intelligent processing, damage detection and control are just a few examples. Sensing capabilities can be given to structures by externally attaching sensors or by incorporating such sensors within the structure during manufacturing. Some of the sensing materials used for this purpose include optical fibers, piezoelectric materials, "tagging" particles, etc.

Piezoelectric materials have found widespread use as sensors in adaptronic structures [7]. Piezoelectric ceramics and polymers produce measurable electrical charges in response to mechanical stress. Because of the brittle nature of ceramics, piezoelectric polymers [8], such as Polyvinylidene fluoride (PVDF), are often used for sensing. PVDF can be formed in thin films and bonded to many surfaces. Uniaxial films, which are electrically poled in one direction, can measure stresses along one axis, while biaxial films can measure stresses in a plane. The sensitivity of PVDF films to pressure changes has been utilized in tactile sensors that can read the Braille alphabet and distinguish different grades of sandpaper. Tactile sensors with ultra-thin (200–300 micron) PVDF films have been proposed for use in robotics. A skin-like sensor that replicates the temperature and pressure sensing capabilities of human skin can be used in different modes to detect edges, corners, and geometric features or to distinguish between different grades of fabric. The pyroelectric effect, which allows piezoelectric polymers to sense temperature, also limits their use to lower temperature ranges.

Piezoelectric composite materials have been developed to overcome the brittleness of piezoelectric ceramics and the temperature limitations of piezoelectric polymers. Flexible composite sensors containing piezoelectric ceramic rods in a polymer-based matrix [9] have been widely used in hydrophones and medical ultrasonic transducers with improved sensitivity and mechanical performance over the original piezoelectric ceramics. Polymers containing piezoelectric powders have also been investigated for use as sensing materials. Piezoelectric paint and coatings are being developed that can be applied to complex shapes to provide information about the state of stress and health of the underlying structure.

Sensing with optical fibers can be done either extrinsically or intrinsically. When used extrinsically, the optical fiber does not act as a sensor; it merely transmits light. An example of an extrinsic fiber optic sensor is a position sensor which uses the fiber to collect light from a source. Breaks in the light beam are used to accurately determine the position of a work piece in robotics applications. Security systems also use this technique to detect intruders. Intrinsic sensing relies on changes in the light transmission characteristics of the optical fiber. The use of optical fibers to perform intrinsic sensing in smart structures has known an accelerated development in recent years in line with similar developments in the use of optical fiber for data transmission and communications. However, fiber optics sensors cannot perform an active interrogation of the structure; they can only record passively various structural parameters such as loads, strains, environment, vibrations, acoustic emission from cracks, and the like.

2.3 Intelligence – Signal Processing, Communication, and Controls

Tremendous efforts have been invested in developing theories, simulations, and hardware implementations for machinery control. Modern control approaches include adaptive control, neural networks and probabilistic control, to name only a few. However, the intelligence features that the adaptronic materials community is trying to create have constraints that the engineering world has never experienced before, but that the biological world seems to accept with simplicity and grace. Namely, the tremendous number of sensors, actuators, and their associated power sources compels us to supersede the conventional central processor architecture whereby every piece of sensor and actuator information must be stored and manipulated electronically.

Norbert Wiener defined *cybernetics* as the science of communication and control in animals and machines. Nature has used the natural selection to develop alternative architectural solutions that compensate for its quite restrictive and far-from-robust material selection; likewise, the natural selection has evolved more and more elaborate cybernetic architectures to facilitate signal processing, complex communication, and advanced memory via biological constructs. The electro-bio-chemical devices that we refer to as neurons are not nearly as fast as our silicon devices; however, nature has developed a wonderful way of processing information that allows rather complex tasks to be performed with amazing speed. The key appears to be a hierarchical architecture in which signal processing and the resulting action can take place at levels below and far removed from the central processor, the brain. Removing your hand from a hot stove to prevent getting burned ("damage to the system") need only be processed locally, i. e., in the spinal cord; whereas the less automatic behaviors are organized by successively higher centers within the brain. The information that you have touched a hot surface reaches the brain much later than the reflex action of contracting muscles in the arm and fingers to get away from it. This hierarchical approach not only yields control systems that are time-efficient, but yields systems that are fault-tolerant as well. Reliability is a critical factor in reducing energy costs. A failed system is a tremendous waste of resources and energy; and the control system is as important, if not more important, than the structural components in assuring a system that has a longer lifespan than any one of its components.

The control systems to be used in adaptronic structure will be able to learn, then change based on need; they will also be able to anticipate a need, and to correct a mistake. The architecture of control systems will remain an important element in the future manifestations of adaptronic structures, for it is the computational hardware and the processing algorithms that will determine how complex our systems can become – how many sensors we can utilize – and how many actuators we can use to effect change. Will all control systems be neural networks and modeled after biological systems? No. The same paradigm we use to design the material systems or structures is used to design the control system – the design that will reduce the mass and energy needs of the system to enable it to perform its adaptive functions.

3 The Use of Adaptronic Structures

Adaptronic structures are first and foremost hybrid material systems. The sensors, actuators, and artificial intelligence are reduced to the microstructure, be it nano level for artificial drug delivery systems, micron level for advanced fiber reinforced composites, or meter level for civil engineering constructions. Some may look like fluids with actuating particles that cannot be seen by the naked eye, but can manipulate molecules with grace and agility; others may look like materials that are hard and strong and in a moment, upon demand, can behave like Jell-O just long enough to deflect and absorb energy as a karate expert reacts to a punch. Yet others may have the mass of small mountains, but the perception to become one with nature to ensure the safety of the delicate and intricate human beings they have been designed to protect.

In the near future, adaptronic structures may start to affect our lives when they are being introduced commercially; but the most lasting impact will be that the philosophy of engineering design will begin to change. Engineers of the future will not have to add structural mass and cost to a structure to assure safety of structures that are used outside their initially intended envelope. Engineers will not have to learn from structural failures, but will be able to learn from the "life experiences" of the structure. Not only will adaptronic structures be of great utility to the consumer, they will have an even more profound influence on science and engineering. They will allow the silent systems we create to inform us, to enlighten us, to educate us of the physics, science, and interaction of the environment on our designs.

Already, solid-state actuation has found niche application in the aerospace industry. The aero-servo-elastic control of vibrations and flutter with solid-state actuated flaps, tabs, vanes, etc. for helicopter rotor blade and aircraft wings is currently being experimented. The challenge in these applications is to realize a capable amplification of the small-amplitude displacement produced by the active material driver of the solid-state actuator. Several concepts have been explored, starting with simple mechanical amplification based on lever principle and ending with elaborate designs utilizing various non-linear effects of structural deformation. A recent example of an actuation-intensive adaptronic structure is the Morphing Aircraft program. Morphing aircraft refers to the use of large shape changes to effect planform change and/or for flight control [10]. Early examples are the Wright Flyer, which used wing twist for flight control, and the F-14, which changes its wing sweep to capitalize on two distinct flight regimes. Unlike past efforts, current efforts in morphing aircraft focus on multiple, large planform changes in sweep, wing extension, wing folding, etc. and in chamber, twist, and asymmetric planform changes for flight control motivated by predator birds such as a hawk [11; 12]. This bio-inspired direction for morphing aircraft structures has lead to numerous research projects spanning flight dynamics, aerodynamics, structural mechanics, and control. The most common motivating example is the desire to have an unmanned aircraft that can morph from a long aspect ratio, straight winged plane for efficient loitering flight into a highly maneuverable short, swept wing aircraft that is effective in attack (Fig. 3). The second common example is the design of high altitude long endurance (HALE) aircraft that can take off and land on its own. Extremely long, highly flexible wingspans are required for long endurance and such wings tend to hit the ground during take off and landing. A morphing solution would be to fold or otherwise morph such wings into shapes more favorable for take off and landing.

Structural health monitoring, *condition-based maintenance* and *birth-to-retirement* refer to the capability of using sensors throughout the life or an adaptronic structure to monitor it state of "health" and act accordingly. The sensors would record the initial state of the structure, and would remember its *pristine state*. The network of sensors embedded in the adaptronic structure (Fig. 4) will be then used to monitor the structural behavior throughout its life. A structural health bulletin will be produced on demand and life history of the structure will be gathered in a database. If needed, active measures will be taken to control and reverse the evolution of structural damage or modify the structure's behavior or performance to elude damage. These sensors will monitor the structural aging process and will determine when the artifact should be repaired or even graciously retired. Thus, scheduled maintenance will be replaced by *need-based maintenance*, with associated savings in the life-cycle costs and increase in the structural safety and equipment availability. Piezoelectric materials offer the capability of performing active structural health monitoring, i. e., actively interrogating the structure with ultrasonic waves to detect damage such as cracks, disbonds,

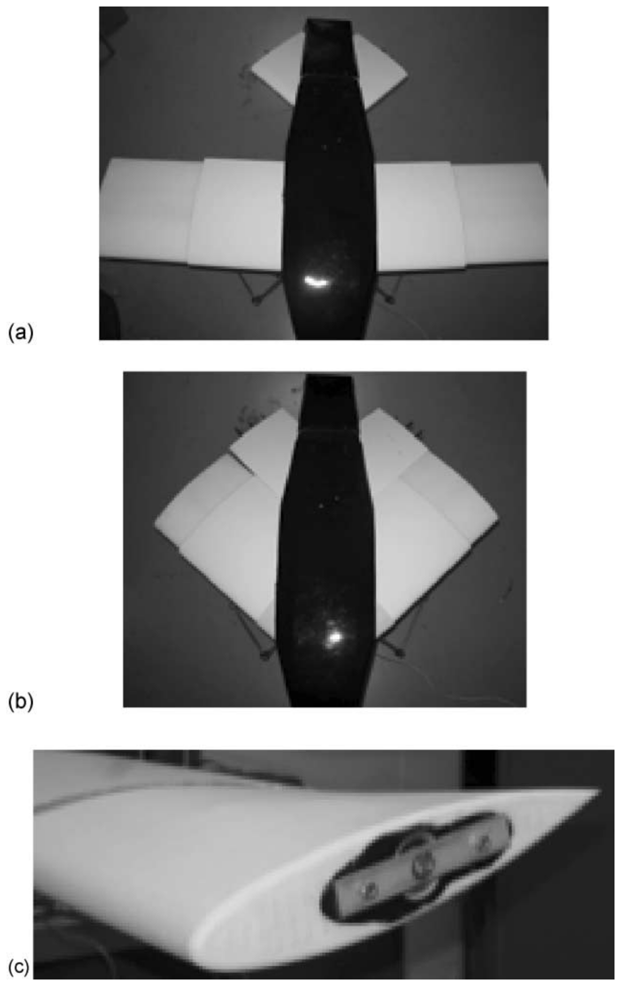

Figure 3: "Morphious", the Virginia Tech morphing wing simulator for wind tunnel experiments (a) cruise configuration; (b) attack configuration; (c) wing twist (Photos courtesy of the designer David A. Neal, III).

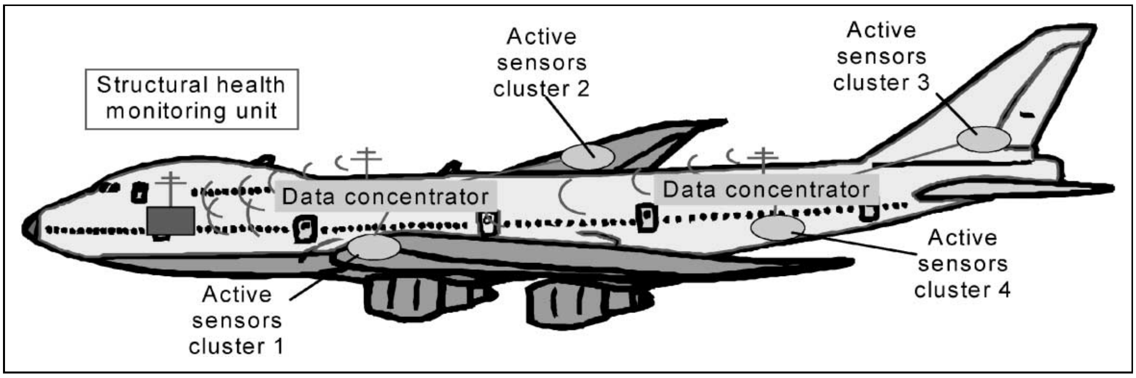

Figure 4: Concept of an aging aircraft instrumented with active sensors for structural health monitoring.

delaminations, etc. [13]. Recently, various nondestructive evaluation (NDE) methods have been successfully demonstrated with permanently attached piezoelectric wafer active sensors (PWAS) [14]. It is predictable that in the not so distant future, adaptronic structures will be permanently instrumented with an embedded NDE system that will allow on-demand structural interrogation to assess the state of structural damage, perform a structural diagnostic, issue a structural health bulletin, and even perform a prognosis of the future structural performance and remaining structural life.

Will adaptronic structures eliminate all catastrophic failures? No. Not any more than trees will stop falling in hurricane winds or birds will no longer tumble when they hit glass windows. However, adaptronic structures will enable man-made inanimate objects to become more natural and life-like. The future of adaptronic structures lies in developing a system with the ability to interface and interact with the network of sensors, actuators, and controls that allows the user/designer/builder to 'architect' a system to perform the function desired with the generic enabling system within the host material. An example can be postulated by focusing on one aspect of the material system, the sensor system. In this scenario, a sensor network is built into the system with many more sensors than are needed by any one application, but by means of adaptive architecture; these sensors can be connected together, or turned off, or turned on, to create the specific system desired. If a particular sensor fails, the adaptive architecture will replace the failed sensor with the next best alternative and reconfigure the interconnections and the control algorithm to accommodate this change. The sensor network, therefore, could look like the detail of a silicon microchip in which numerous sensors are spread about a polymeric sheet that can be used as the structural ply of a composite laminate. The sensor sheet can be mass produced by photolithography techniques, which are much like making a Xerox copy, for fractions of a cent per sensor. Similar 'pictures' can be painted for the other components of the system. It seems likely that a system with large arrays of sensors and actuators within a host will require three-dimensional interconnections between the power modulation devices, the control processors, and the sensors and actuators.

4 Summary and Conclusions

This paper has tried to give a brief account of the *adaptronic structures* concepts. This overview will be probably found by the readers to be both insufficient and incomplete. The author apologize for this shortcoming, but some of it has been intentional. It is hoped that this paper will just give to the readers a flavor of the adaptronic structures concepts, and then encourage them to explore further the other articles contained in this special issue dedicated to *Adaptronics*.

In summary, we can say that the adaptronic structures revolution to date has focused upon learning how to use energy as a structural component, how to make structures behave like nature's systems, how to make structures that are "soft", and how to better utilize the materials around us. New compositions of matter will begin influencing the manifestations of adaptronic structures. Scientists and researchers who are developing new materials, sensory materials, materials with actuator capabilities, energy storage and modulation devices that will allow the integrated system to be autonomous and self-supporting will add fuel to this movement. Adaptronic structures seem to have a bright future. However, before one gets overoptimistic, one should also consider the fact that adaptronic structures, in their current form, also have several limitations: such as higher costs, possible instability of the structures when the control is deactivated, negative influence of heat, dust, and humidity on their sensory systems, etc. Improvement of these aspects should be kept in mind along with the quest for continuous improvement of capabilities and performance.

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Manuscript received: 24th October 2005.

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