SMART MATERIALS:

STRUCTURES AND APPLICATIONS

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ADVANCED HIGHWAY MAINTENANCE & CONSTRUCTION TECNOLOGY

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PREFACE:

The purpose of this study and presentation was to familiarize the AHMCT group at the University of California-Davis with the evolution of Smart Materials and Structures, and their applications in various industries. Furthermore, it is aimed to study the possibilities of applying smart materials and structures in highway maintenance and construction. Such applications are believed to be original, and depending on the task they could very well be worthwhile. This is not a formal report, and it is basically a compilation of the previously reported materials and the author's thoughts and ideas on the subject.

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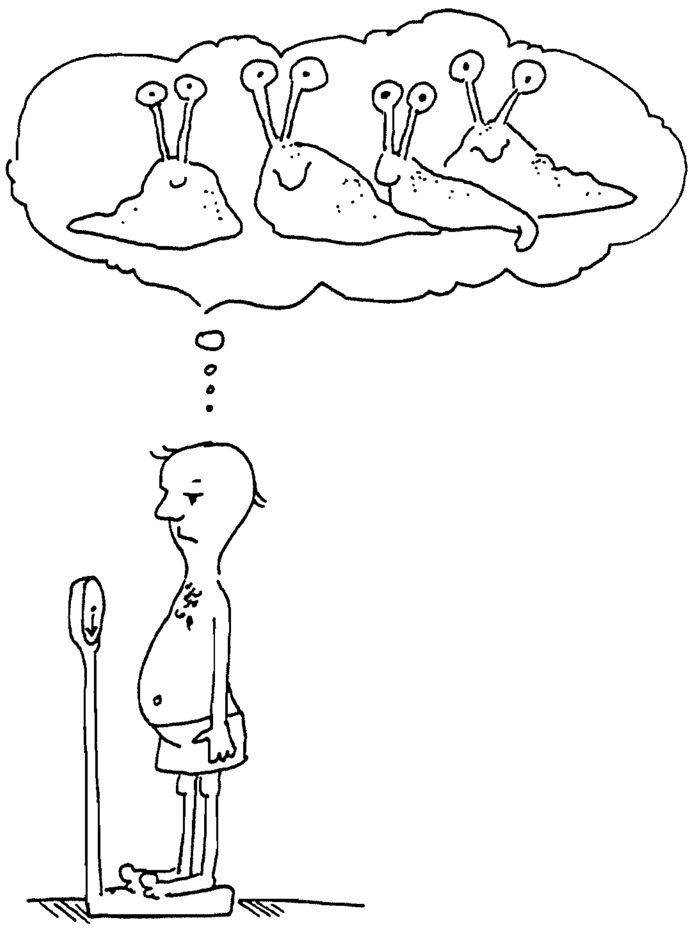

One possible reason why the British measurement system did not flourish.

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In the English System MASS is measured in SLUGS.

ONE SLUG = 32.2 Lbm

In the Metric System MASS is measured in GRAMS.

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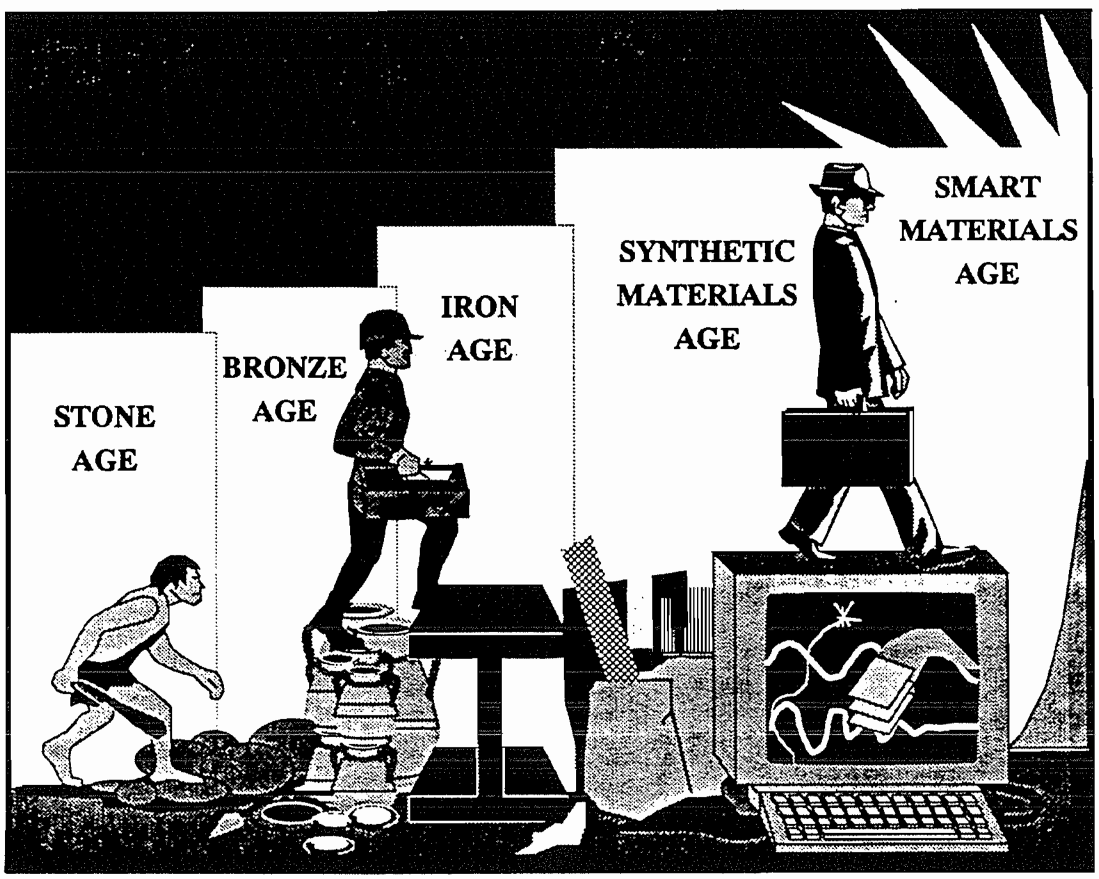
Human civilization has been profoundly influenced by materials technology that historians have defined distinct time periods by the materials that were dominant during these eras.

	* STONE AGE
PAST:	* BRONZE AGE
	* IRON AGE
PRESENT:	* SYNTHETIC MATERIALS AGE
FUTURE:	* SMART MATERIALS AGE



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STONE AGE: Is characterized as early as about one million years ago by the earliest humans "Homo Habilis". They used natural objects and materials such as skin, bone , horn , stone, flint to make pots & pans, knives, tools, and weapons.

BRONZE AGE: Is characterized by the period 3500 to 1000 BC. Tools and weapons were fabricated by bronze (an alloy of copper and tin). Hence, bronze is the oldest alloy used by mankind. Typical artifacts from this era were cups, urns, ornaments, helmets, swords, and shields.

IRON AGE: Began in approximately 1500 BC in Asia and continued to the 20th century AD. Resulting in technological innovations such as: pulleys, screws, levers, hydraulic devices, screw cutting machines, etc. Natural magnets based upon Iron Ore, Fe_3O_4 were employed for compasses by the Chinese between 500 BC to 1000 AD.
Iron was the dominant material during the roman empire, and continued to be the premier material exploited by civilizations until the emergence of Steel in the 18th century.

SYNTHETIC MATERIALS AGE: (Plastics, and Composites).
Synthetic Plastic Materials: Starting about1860's, synthetic plastic materials like Celluloid, and Xylonite were invented prior to the synthesis of Cellophane in 1908, and Bakelite in 1909. Now about thousand of different plastics are available in the marketplace, such that in 1979 the volume of plastics manufactured in the U.S. exceeded that of steels for the first time.
The Principal elements from which these advanced materials (plastics) are fabricated are: Carbon, Hydrogen, Oxygen, and Nitrogen that are normally obtained from Coal, Limestone, Petroleum, Salt, and Water.
Synthetic Composite Materials for Biological Systems: These engineered materials are synthesized with two distinct phases comprising a load-bearing material (or reinforcing material such as laminated fibers, or woven fabrics, particulates, whiskers) housed in a relatively weak protective matrix material to mimic the micro structure of biological structures. A characteristic of these advanced materials is that the combination of two or more constituent materials yields a composite material with engineering properties superior to those of the constituents.

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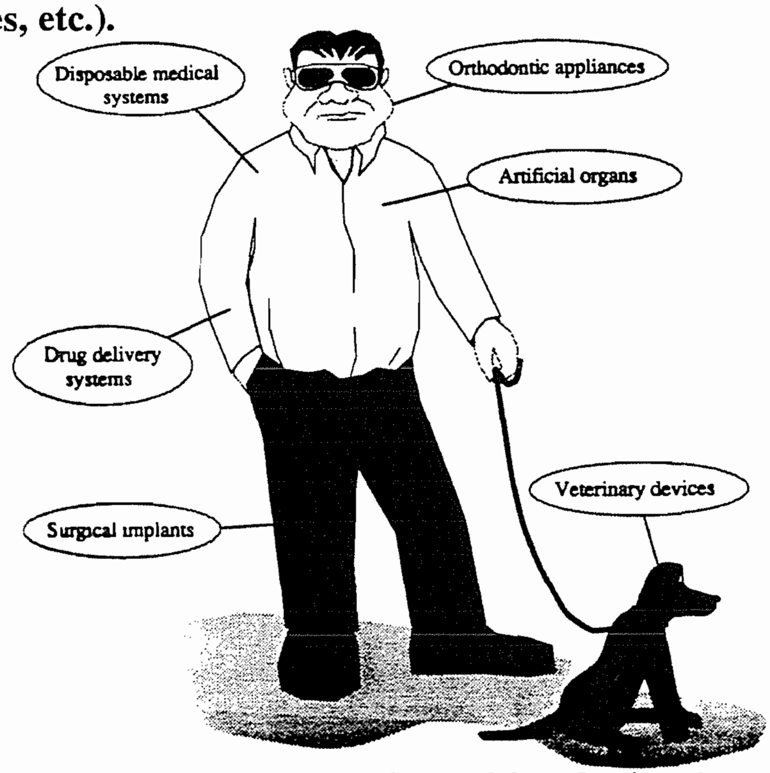
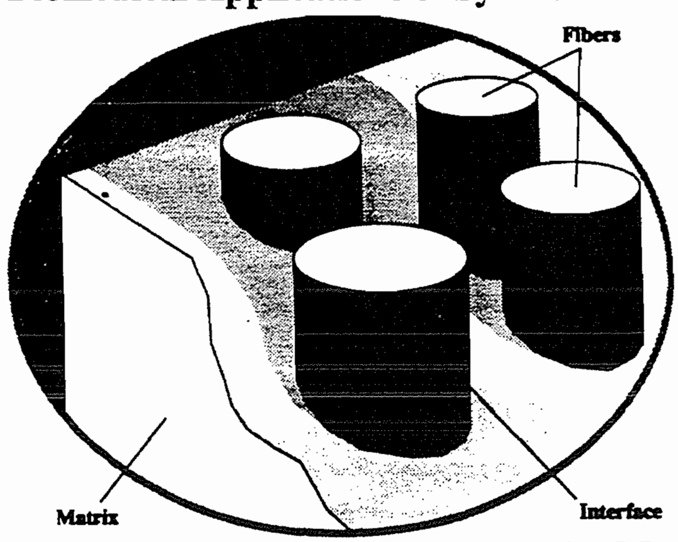
Applications of Synthetic Materials: automobiles, packaging, household appliances, biomedical implants, tools and instruments.

- **A car will save about 1/2 a liter of fuel for every 100 km's traveled if the weight of the vehicle is reduced by 100 kg's.**
- **A variety of artificial tissues and organs can be synthesized by employing plastics, composites, ceramics, and glasses that can harmoniously interface with or replace body tissues and parts (i.e., synthetic artificial human skin, dental structures, artificial larynxes, etc.).**



Sample Biomedical Applications of Synthetic Materials.



Principal Features of a Fiberous Composite Material.

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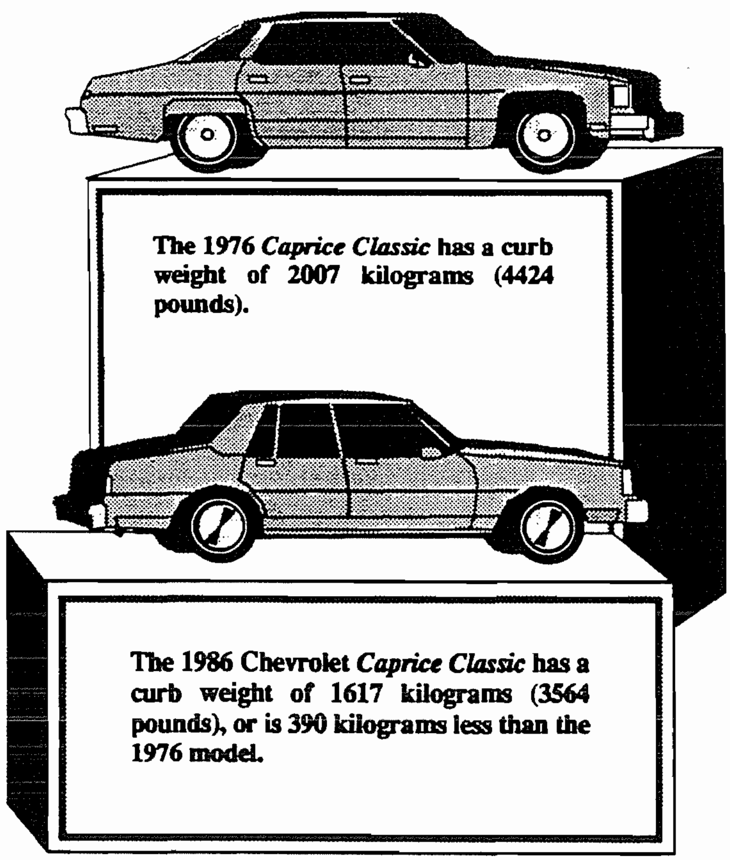
* Polymeric-Matrix Composites are currently employed mostly in Automotive Industry (Sheet Molding Compound-SMC used for the exterior body panels of vehicles). Examples: GM Pontiac Fiero, Ford Econoline, Chevrolet Caprice, and Mini-Vans.

The design of robot arms, and components of high-speed machinery in polymeric-matrix composite materials would greatly enhance the performance of these systems. Some of the benefits offered by the composites are: anisotropic properties, superior specific stiffness & strengths, and superior fatigue characteristics. Typically, these advantages are demonstrated in machines with fast-moving components whose speeds are limited by their own inertia rather than external surface tractions.

* Advanced composite materials are also applied in the sporting goods industry. Examples: Bicycles, Boats, Kayaks, Ski poles, etc..

* Advanced composite materials are also used in aerospace industry. Examples: Voyager aircraft which flew nonstop round the world without refueling, the "all plastic" corporate passenger airplane manufactured by Beech Aircraft Corp., and the recent version of British Aircraft Corp. Harrier Jump-jet (30% composites used in the wings & airframe structure).



Weight Reduction Trends in U.S. Automobiles.

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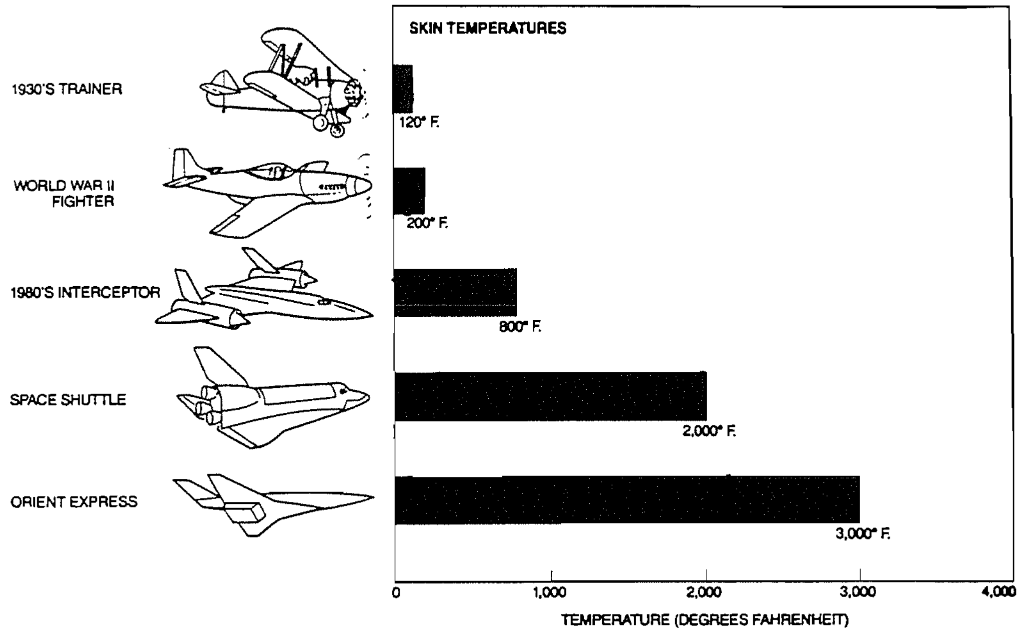

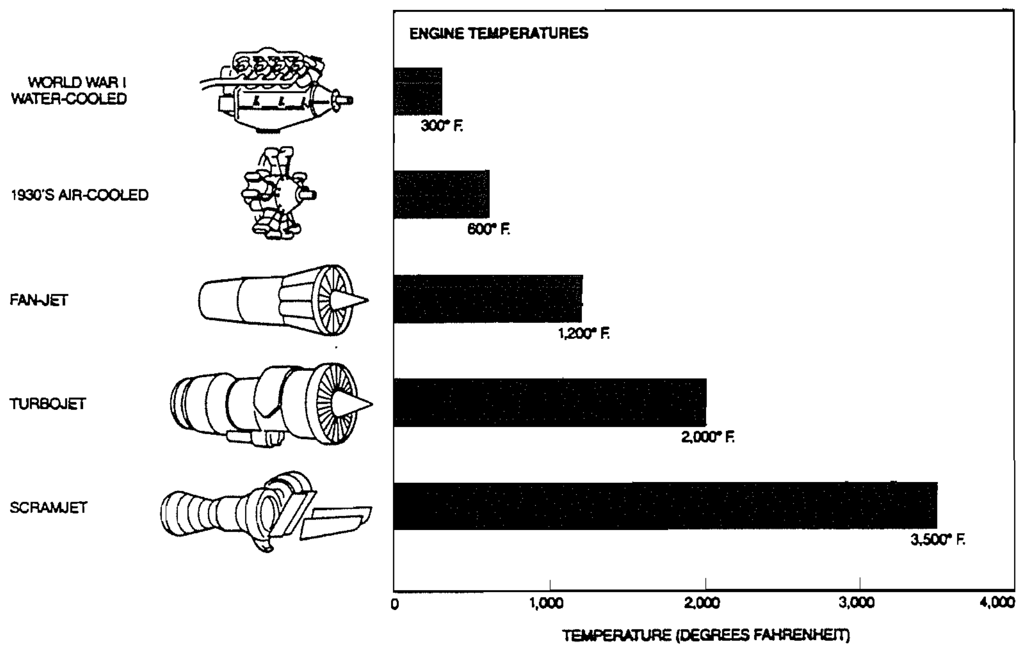

EVOLUTION OF AIRCRAFT has required continual improvements in materials, since increased speed raises the heating of the skin from friction with the air, and increased power raises the temperature of the engine. Skin materials have progressed from wood and fabrics to advanced alloys of aluminum, nickel and titanium, and composite materials based on graphite fibers in polymer matrix. In engines similar materials have replaced steel and aluminum.

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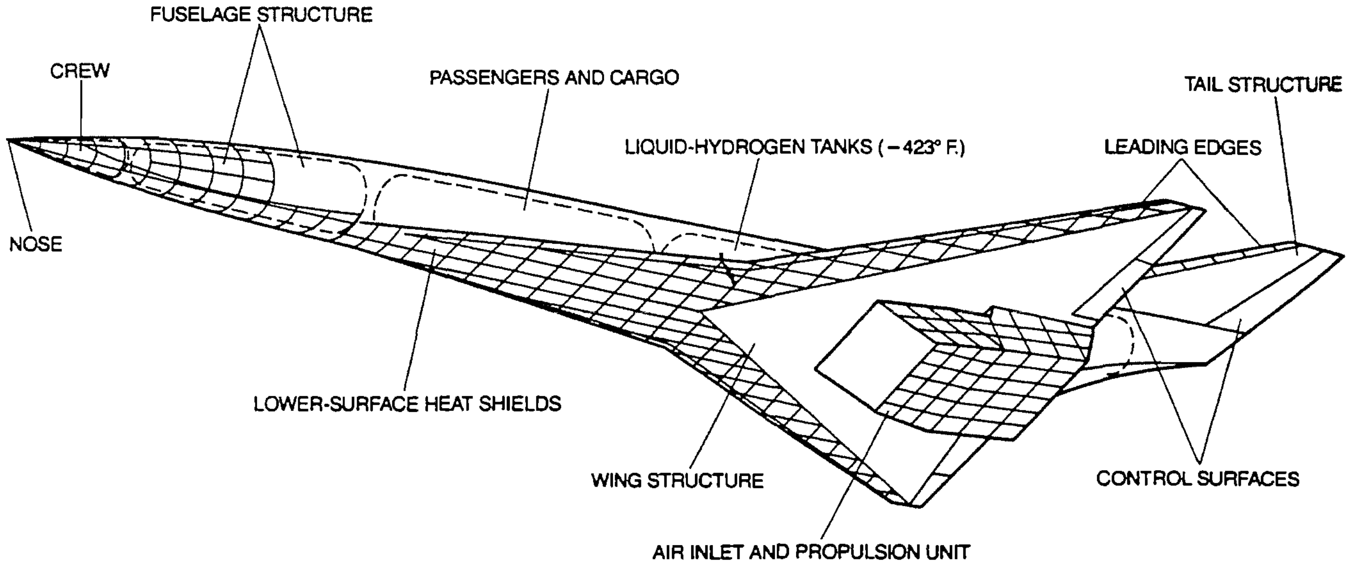

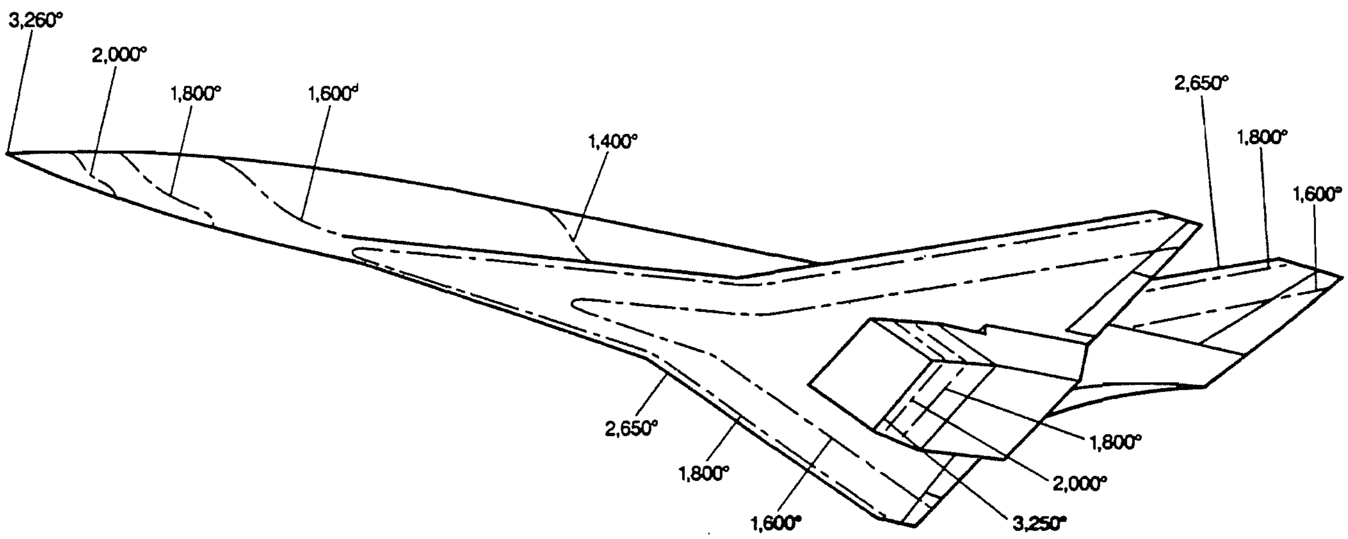

TRANSATMOSPHERIC AIRCRAFT has posed challenges for developers of advanced materials, since it shall move at high speed in both atmosphere and space. Configurations of the aircraft, and estimates of likely temperatures on the surface and in the propulsion system are shown. The aircraft is expected to cross the Pacific in less than two hours.

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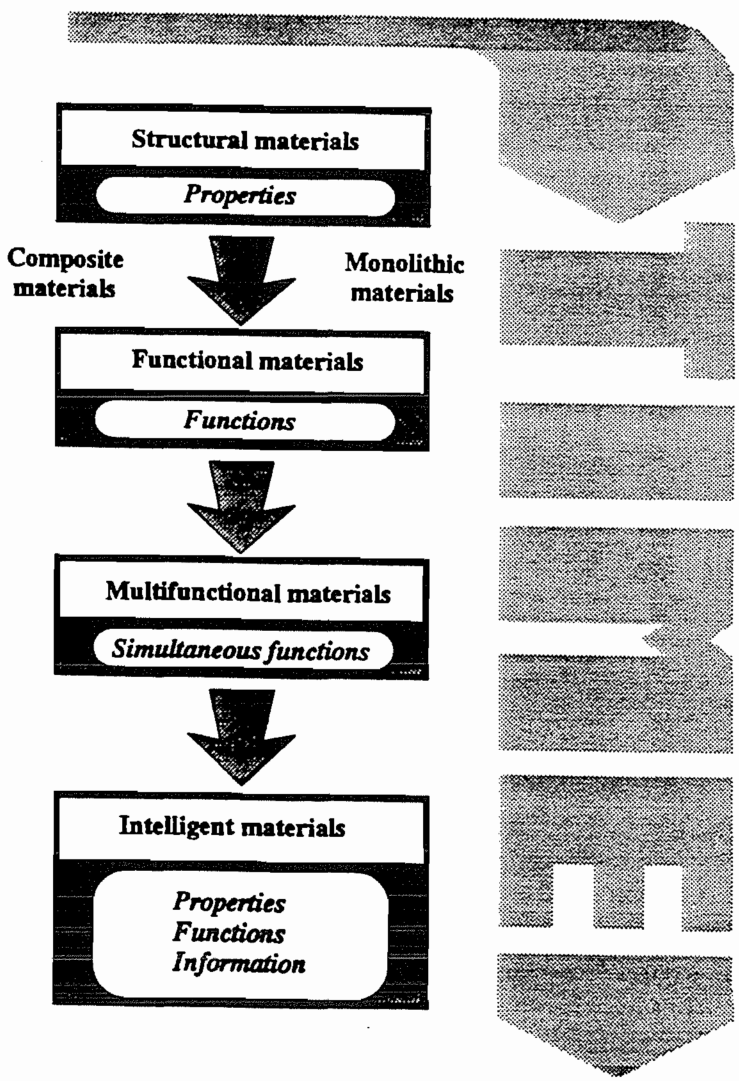
<< SMART or INTELLIGENT MATERIALS >>

Smart, Intelligent, Senseable, and Adaptive have all been used to describe and/or classify materials and structures which contain their own sensors, actuators, and computational/control capabilities and/or hardware.

* **A review of the historical evolution of materials science highlights the distinct transition from *Structural Materials* to *Functional Materials*, and now *Smart Materials*.**



Evolution of Materials Science.

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* <u>Structural Material</u>: are those materials that are principally characterized by their mechanical strength, and are generally employed in load-bearing situations.

Material
Steel
Polycarbonate
Wood
Iron
Concrete
Graphite-epoxy laminates

Structural Materials

* <u>Functional Materials</u>: are those materials whose principal functional characteristic is exploited in the fields of science & technology rather than the inherent structural properties of the material.

Examples:

- Vibration Transducers; typically feature a piezoelectric element, that, when fixed to a vibratory structure, is subjected to dynamical deformations and thereby develops an appropriate time-dependent electrical signal for measuring the vibrational response of the structure.

- Germanium; which is a photo-conductive material. When it is exposed to a light source it generates a small electric current as the photons of light are absorbed at the surface of the material and electrons are subsequently released from the atomic structure.

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Material	Properties
nickel-titanium	shape-memory
cadmium sulphide	piezoelectric
terbium iron	magnetostrictive
quartz	pyroelectric
electro-rheological fluids	viscoplastic
aluminum soap solution	viscoelastic
barium titanate	ferroelectric
copper oxide	photoelectric
potassium dihydrogen phosphate	electro-optic
selenium	photoelectric
germanium	photoconductive

Functional Materials

*** <u>Multi-functional Materials</u>: are materials characterized by several functional properties that are utilized in practice rather than their structural properties.**

Material	Properties
Lead Zirconate Titanates	Piezoelectric
Bone	Mineral Homeostasis Structural Homeostasis Piezoelectric Pyroelectric
Lead-Magnesium Niobate	Thermo-electrostrictive
Terbium-Iron-Dysprosium	Thermo-magnetostrictive

Multi-functional Materials

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* SMART MATERIALS:

Definition ; **Materials that possess adaptive capabilities to external stimuli such as load or environment with inherent intelligence. In other words, they have the ability to select and execute specific functions (or to change their physical properties such as Stiffness, Damping, Viscosity, Shape, etc.) intelligently in response to changes in environmental stimuli.**
The control or intelligence of the material could perhaps be "programmed" by material composition, processing, defect and micro -structure, or conditioning to adapt in a controlled manner to various levels of stimulus.

Examples: Optical Fibers, Piezo-Electric Polymers and Ceramics, Electro-Rheological Fluids, Shape Memory Alloys, Polymeric Gels, Mgnetostrictive Materials, etc.

* SMART STRUCTURES:

Definition ; **Structures that are simply constructed of smart materials with unique adaptive capabilities(or may contain integrated actuators, sensors, and intelligence in a more discrete form), providing them the ability to actively adapt to changing conditions.**

Features to be included in the definition are:

1- Sensors: Smart structures have embedded (or bonded) or intrinsic sensors that recognize and measure the intensity of the stimulus, which could be stress, strain, temperature, electrical voltage, magnetic fields, chemical compounds and concentrations, radiation, etc.
2- Actuators: Smart structures have embedded or intrinsic actuators to respond to the stimulus.
3- Control Mechanism: Smart structures have mechanisms for controlling the response to the stimulus according to a predetermined relationship, and are capable of selecting a response if more than one option is available.
4- Time and Nature of Response: Smart materials have fast response to stimulus. The system returns to its original state as soon as the stimulus is removed.

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Materials & structures having these features are indeed worthy of being described by the adjective "SMART", as defined by the Webster's dictionary:

having or showing mental alertness and quickness of perception, shrewd informed calculation, or contrived resourcefulness, marked by or suggesting brisk vigor, speedy effective activity, or spirited-liveliness.

*** Clearly materials featuring:**

- **control capabilities possess "mental alertness",**
- **sensing characteristics have the ability for an "informed" response along with "quickness of perception",**
- **actuator functions possess "spirited-liveliness" characteristics.**

Hence, "SMART" materials already exist today, but "INTELLIGENT" materials are an order of magnitude more sophisticated than smart materials, because "intelligence" is associated with learning, abstract thought, and the ability to think and reason, none of which has been demonstrated at this time and they shall be the focus of much research and development during the coming decades.

Webster's dictionary defines "INTELLIGENT" as:

the available ability to use one's existing knowledge to meet new situations and to solve new problems, to learn, to foresee problems, to use symbols or relationships, to create new relationships, to think abstractly; ability to preceive one's environment, to deal with it symbolically, to deal with it effectively, to adjust to it, to work toward a goal; the degree of one's alertness, awareness, or acuity; ability to use with awareness the mechanism of reasoning whether conceived as a unified intellectual factor or as the aggregate of many intellectual factors or abilities, as intuitive or as analytic, as organismic, biological, physiological, psychological, or social in origin and nature; mental acuteness.

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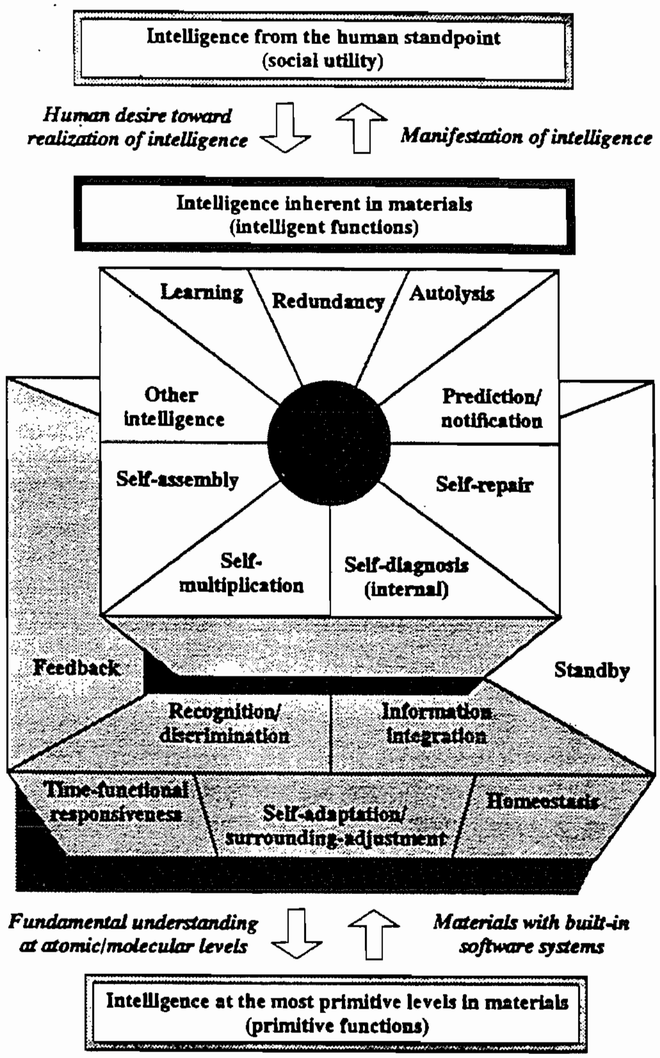

Intelligence Inherent in Materials.

Intelligence inherent in a naturally occurring material is typically a property unique to a material. Biological materials and systems are perhaps the best examples of smart materials.

Principal intelligence features in biological materials as well as the interpretation of their attributes in the context of materials science may be presented as follows:

* *AUTOLYSIS :*
When the tissues and cells of biological systems cease to receive nutrition and die, they decompose. Hence, intelligent materials with this attribute would immediately decompose upon completion of their useful life, and be assimilated within the environment.

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* *REDUNDANCY :*
Biological systems typically possess some degree of redundancy in their structures and functions. Hence, intelligent materials with this attribute would feature redundant functions that are not employed under normal working conditions.

* *SELF-MULTIPLICATION:*
Self-breeding, self-multiplication, or growth in a biological system involves a cell creating similar cells to replicate them. Thus, intelligent materials would be self-producing with the additional requirement of automatically halting this activity when prescribed conditions have been achieved.

* *SELF-REPAIR:*
The biological self-repair function involves various phenomena for restoring damaged living material to its state of normality. Typically, this involves processes associated with the DNA recovery. Hence, intelligent biomaterials must be able to autonomously perform appropriate self-repair functions in order to restore regions of degradation caused by extreme environmental conditions.

* *PREDICTION:*
Some biological systems can predict the future, by learning from the past experiences, and take appropriate actions based upon sensory data and knowledge. Some intelligent materials would also possess the ability to respond appropriately to changing environmental stimuli by capitalizing on knowledge from past experiences.

* *LEARNING:*
The predictive abilities of biological systems are closely associated with the ability of these systems to learn. While some of these abilities are inherent, others are developed through experience. Intelligent materials would also feature these abilities in order to respond appropriately to external stimuli.

* *SELF-DIAGNOSIS:*
The ability to self-diagnose problems, degradations, malfunctions and judgmental errors by comparing current and past performance or conditions , for example, is a health-monitoring feature of biological systems. Some intelligent materials would be able to monitor their state of well-being, or health, in order to determine the effect of a defective region on the materials performance.

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* *HOMEOSTASIS:*
Biological systems are usually subjected to dynamical external conditions and they feature continuously changing internal structures. These systems maintain stable physiological states by coordinated responses that automatically compensate for these ever-changing environmental conditions. Intelligent materials could incorporate innovative functions that permit them to automatically change their behavior in response to such dynamic conditions.

* *FEEDBACK:*
The state of homeostasis that is fundamental to the survival of numerous biological systems, depends upon closed-loop sensory feedback. This ability to use closed-loop feedback controls should be replicated in intelligent materials inorder to develop desired functions where sensors, processors and actuators are orchestrated in harmony.

* *INFORMATION INTEGRATION:*
Biological systems generally evolve by storing integrated experiences of time prior to transferring this information to subsequent generations of the species(ex., in the form of genes). Intelligent materials should mimic this evolutionary strategy by featuring functions that integrate and maintain memory-banks of information.

* *STANDBY:*
Biological systems frequently maintain a state of readiness for action. Intelligent materials should also maintain this condition of alertness.

* *RECOGNITION:*
Creatures frequently embody functions that permit them to recognize similar members of the species in a discriminatory manner. Some intelligent materials should be able to recognize and discriminate between information contained in different sensory data sets.

* *RESPONSIVENESS:*
Classes of intelligent materials should feature innovative functions, whose responsiveness is governed by the dynamically changing external conditions and the role mandated of the material.

* *ADAPTATION:*
The impact of changing environmental conditions on biological systems is apparent as the evolution of the physiological state to permit the system to adapt to the new environment. Hence, intelligent materials shall require functions that are able to change their behavior in response to environmental changes in an optimal manner.

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The current generation of smart materials and structures incorporate one or more of the following features:

1. ***Sensors*** **which are either embedded within a structural material or else bonded to the surface of that material. They measure the intensity of the stimulus associated with a stress, strain, electrical, thermal, radiative, or chemical phenomenon.**

2. ***Actuators*** **which are embedded within a structural material or else bonded to the surface of the material. These actuators are typically excited by an external stimulus in order to either change their geometrical configuration or else change their stiffness and energy-dissipation properties in controlled manner.**

3. ***Control Capabilities*** **which permit the behavior of the material to respond to an external stimulus according to a prescribed functional relationship or control algorithm.**

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EXAMPLES OF SMART MATERIALS HAVING ACTUATION & SENSING CAPABILITIES:

- **Shape-Memory-Alloys & Plastics**
- **Electro-Rheological Fluids**
- **Piezoelectric Materials**
- **Magnetostrictive Materials**
- **Electro-Mechano-Chemical Materials**
- **Fiber-Optics Sensors**

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Actuator / Characteristics	Electro-strictive Materials	Electro-Rheological Fluids	Magneto-strictive Materials	Nitinol Shape Memory Alloy	Piezoelectric Ceramic
Cost	Moderate	Moderate	Moderate	Low	Moderate
Technical Maturity	Fair	Fair	Fair	Good	Good
Networkable	Yes	Yes	Yes	Yes	Yes
Embedability	Good	Fair	Good	Excellent	Excellent
Linearity	Fair	Fair	Good	Good	Good
Response (Hz)	1-20 000	0-12 000	1-20 000	0-5	1-20 000
Maximum Microstrain	200	——	200	5000	200
Maximum Temperature (°C)	300	300	400	300	300

ACTUATOR CANDIDATES FOR SMART MATERIALS.

Sensor / Characteristics	Fiber-Optic Interferometer	Nitinol Shape Memory Alloy	Piezoelectric Ceramic	Strain Gauge
Cost	Moderate	Low	Moderate	Low
Technical Maturity	Good	Good	Good	Good
Networkable	Yes	Yes	Yes	Yes
Embedability	Excellent	Excellent	Excellent	Good
Linearity	Good	Good	Good	Good
Response (Hz)	1-10 000	0-10 000	1-20 000	0-500 000
Sensivity (Microstrain)	0.11 per fiber	0.1-1.0	0.001-0.01	2
Maximum Microstrain	3000	5000	550	10 000
Maximum Temperature (°C)	300	300	200	300

SENSOR CANDIDATES FOR STRAIN MEASUREMENT.

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	Actuators	Sensors
Acoustical Devices		X
Capacitive Devices		X
Electro-rheological Fluids	X	
Electrostrictive Materials	X	
Fiber-Optics Devices		X
Magnetostrictive Materials	X	X
Piezoelectric Materials	X	X
Shape-Memory Materials	X	X
Strain Gauges		X
X-ray Devices		X

ACTUATOR AND SENSOR CAPABILITIES FOR SMART MATERIALS AND STRUCTURES APPLICATIONS.

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Shape-Memory-Alloys are metals that, when plastically deformed at one temperature, will completely recover their original undeformed state upon raising their temperature above an alloy-specific transformation temperature.

*** Characteristics include:**

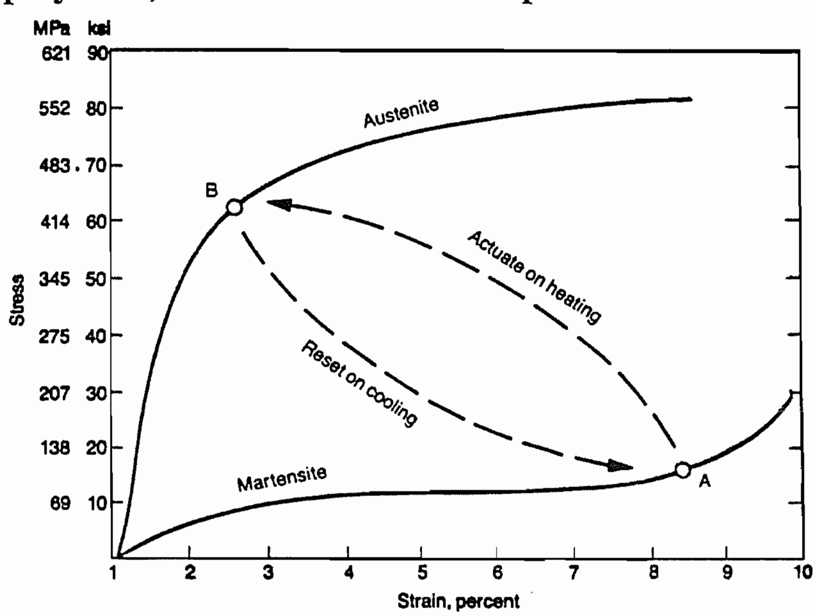
- **Their crystal structure undergoes a phase-transformation into, and out of , a martensite-phase when subjected to either prescribed mechanical loads or temperature.**

- **During the shape-recovery process, they couldbe engineered to develop prescribed forces or displacements.**

- **The transformation temperature of these materials can be selectively tuned over broad temperature range to suit each application, and plastic strains as high as 6% could be completely recovered by subjecting them to heat.**

- **They have been employed as both Actuators and Sensors in smart materials structures applications.**

- **Shape-Memory phenomena are not limited to the metals, and Shape-Memory plastics such as "Norsorex" (which features the polymer polynorbornene) and "Zeon Shable" (which is a polymer blend featuring polyester) have also been developed.**



Characteristics Above and Below the Transformation Temperature for the Nickel-Titanium Alloy.

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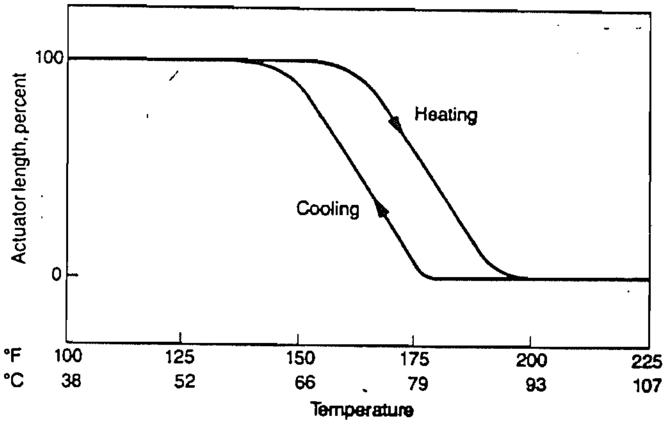
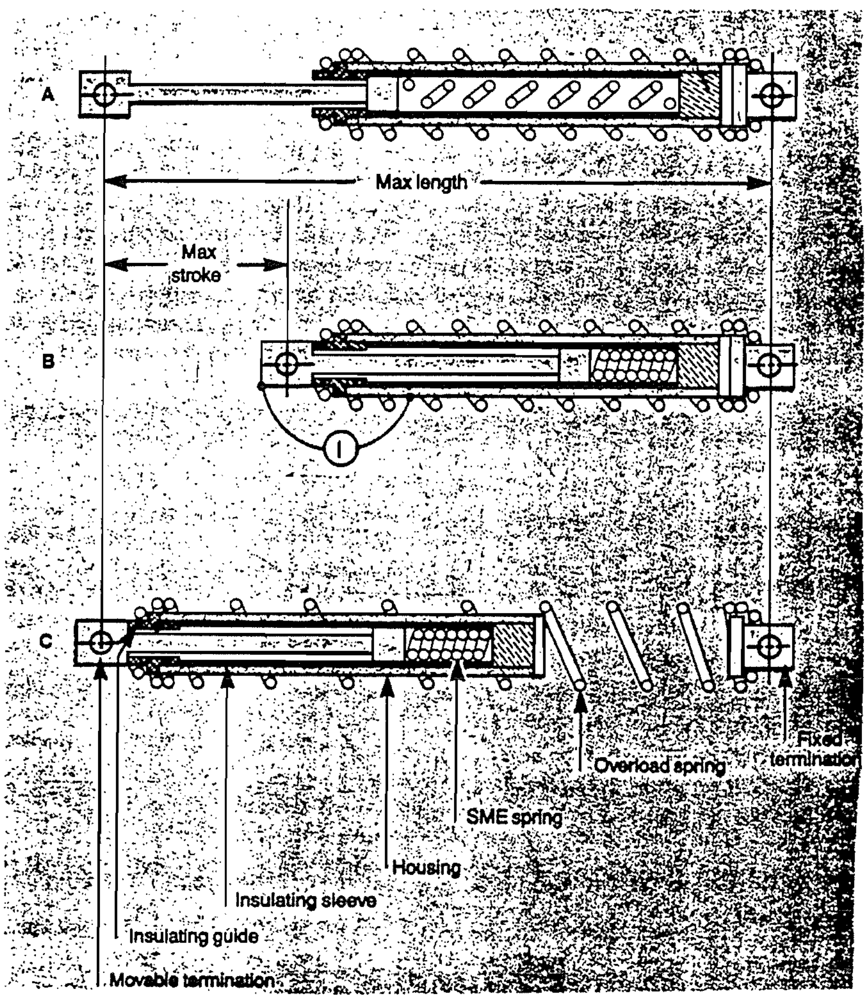


HYSTERESIS Exhibited by SMA Actuation. Parts actuate and reset at slightly different temperatures. The shape of this hysteresis curve, its width and slope, are dramatic functions of the chosen alloy.



ACTUATOR IN THE: (A) Ready or Reset Mode, (B) Full Actuation Mode, (C) Full Overload Mode.
Upon heating, the SMA part (Helical Spring) recovers to the lower strain and higher strength of the austenite phase at operating point B.

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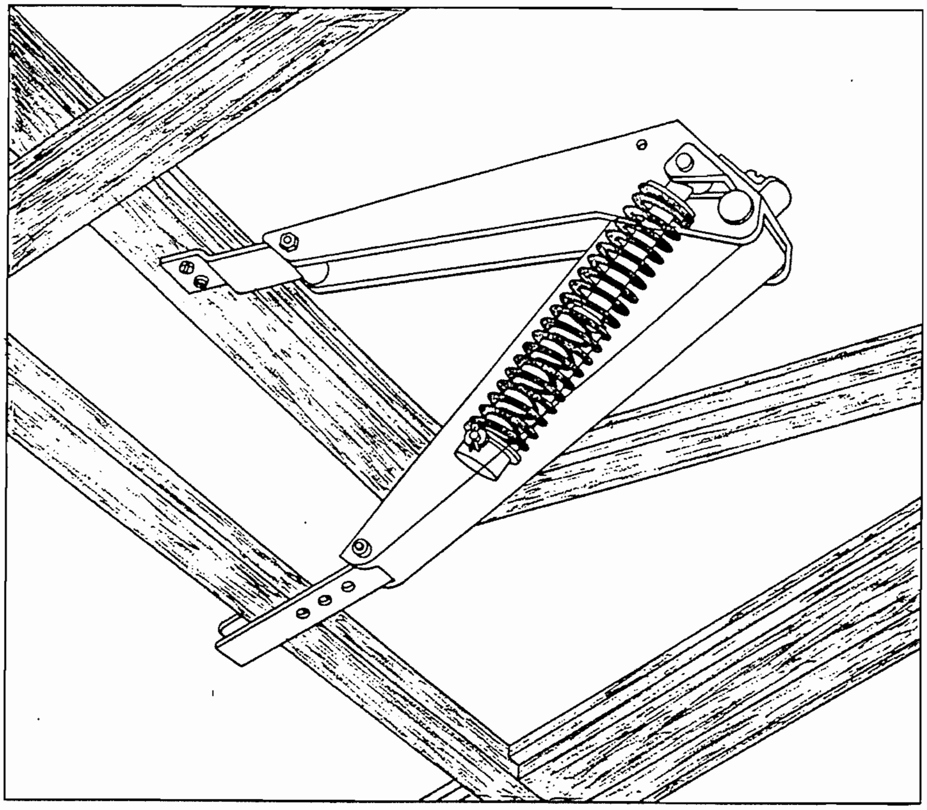
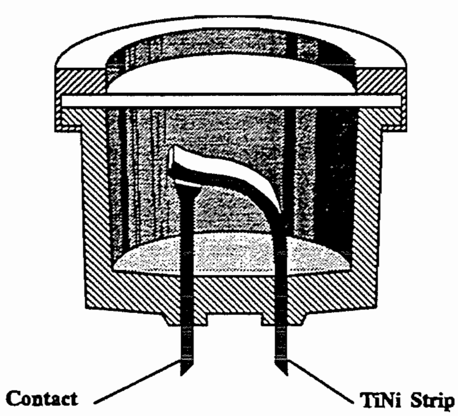


SIMPLE WINDOW OPENER that would be suitable for a greenhouse is actuated by a simple spring fabricated out of a Copper-rich Shape-Memory-Alloy. At temperatures below about 18° C (65° F) the spring is fully contracted and the window remains closed. When the temperature rises above 18 degrees, shape-memory spring overcomes the force of a bias spring and begins to open the window. At 25° C the actuating spring is fully extended.



A TEMPERATURE FUSE employing a Nickel-Titanium Shape-Memory-Alloy. This is a thermally activated switching device for the cooling systems of automobiles.

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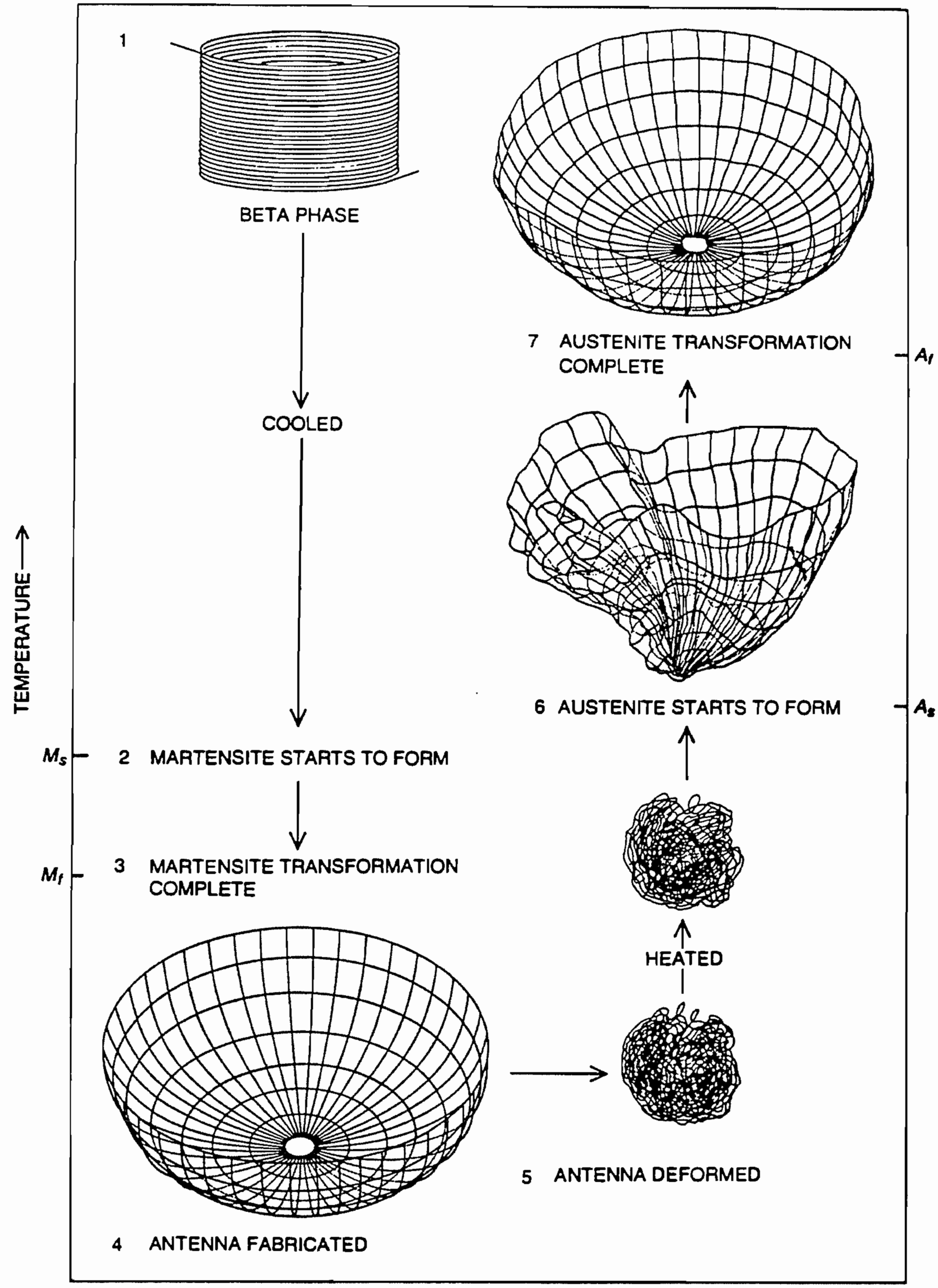

CRYSTALLOGRAPHIC HISTORY & SPONTANEOUS UNFOLDING of a wire hemisphere (it could serve as a small antenna for a spacecraft) made of an alloy of Nickel & Titanium (Nitinol) that shows the role of temperature in the Shape-Memory effect. The fully formed antenna has been crushed at room temperature into a tight ball. As the temperature of the mass of wire is increased the antenna gradually unfolds, and when it reaches 77 ° C, the structure assumes its original configuration.

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THE CRYSTALLOGRAPHIC HISTORY OF THE ANTENNA

1. **The construction material, Nitinol wire in a large coil, is raised to a temperature of 650° C, and is stabilized so that the crystal structure of the material is entirely in the beta or "parent" phase. This phase is often the crystal structure Austenite.**

2. **The wire is now cooled. At the temperature M_S (60° C) the new crystal phase Martensite starts to form, replacing the beta phase.**

3. **At temperature M_f (52° C) , the transformation to Martensite is completed.**

4. **While the Nitinol wire is held at a temperature below M_f it is cut into short lengths, which are gently bent to form the segments of the intended hemisphere. Where the segments cross one another they are fastened by tack welding.**

5. **One can now crush the antenna into a small volume.**

6. **In order to restore the original shape the crushed structure is heated. At temperature A_S (71° C), Austenite begins to replace Martensite.**

7. **Upon reaching A_f (77° C), the antenna has unfolded completely.**

Note that in this particular case what the shape-memory alloy (SMA) "remembers" is not the actual configuration of the antenna, but the gentle curves of the coiled wire from which the antenna was constructed. As the wire tries to straighten itself to the shape of a bowl, it is constrained by the multiple welds at the crossover points. The antenna was designed by the Goodyear Aerospace Corporation.

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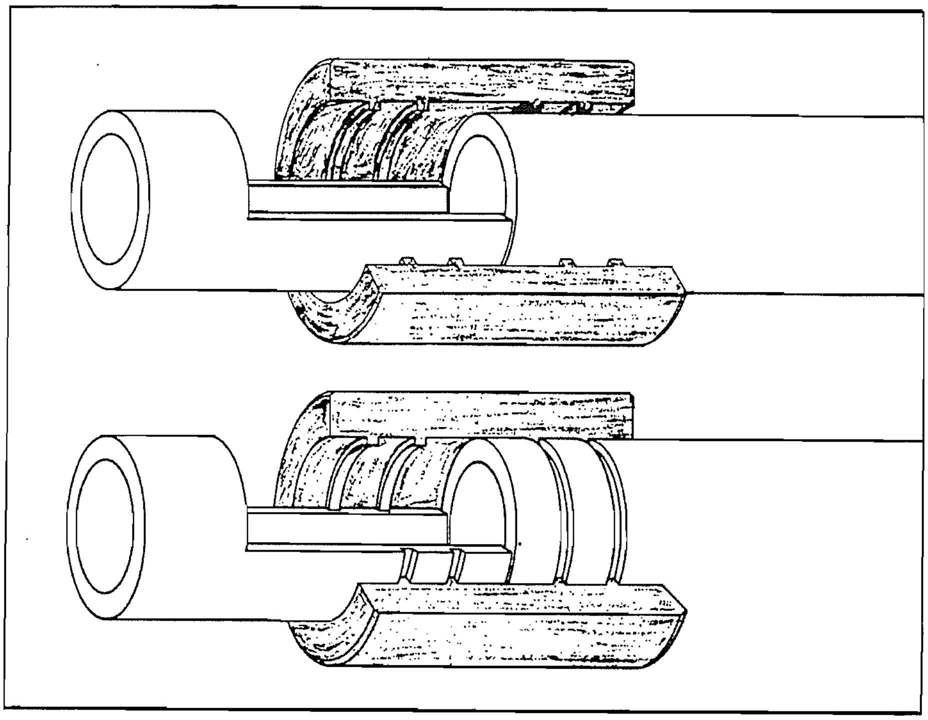
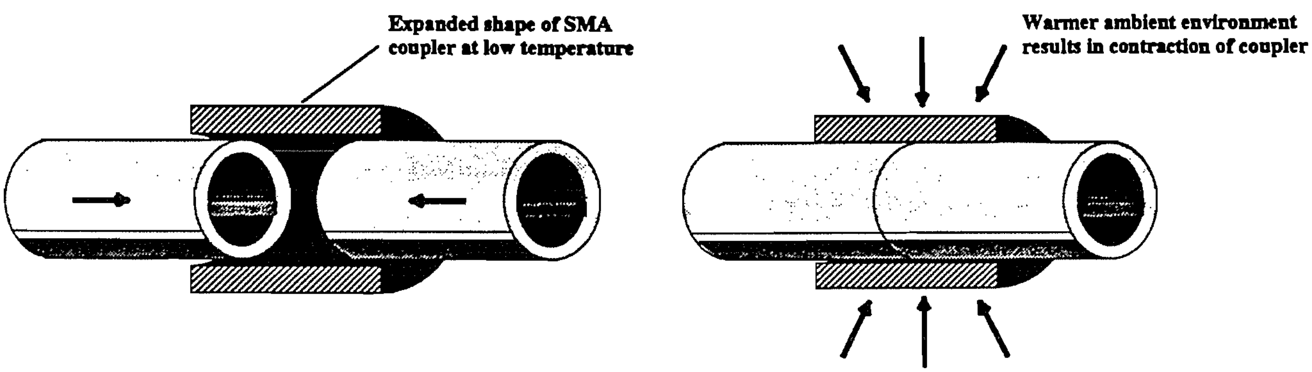


HYDRAULIC-TUBE COUPLINGS for the Grumman F-14 jet fighter are fabricated from a Nitinol alloy that a has a martensite-formation temperature, M_S, in the cryogenic region below -120° C. The sleeve-like coupling is machined at normal temperature to have an inner diameter 4% less than the outer diameter of the tubes to be joined. The sleeve is then cooled below the M_S temperature and is mechanically expanded to have an inner diameter 4% greater than the tube's outer diameter (top). When the coupling is warmed, it shrinks to form a tight seal (bottom). Ribs machined into the sleeve enhance seal by "biting" into tubes.



SMA PIPE COUPLINGS such as TiNiFe or AiZnAl are employed on the hydraulic systems of aircrafts, warships and submarines, and underwater oil pipelines laid on the seabed. This application involves fabricating the coupling in a SMA with a transformation temperature lower than the operating temperature of the hydraulic system.

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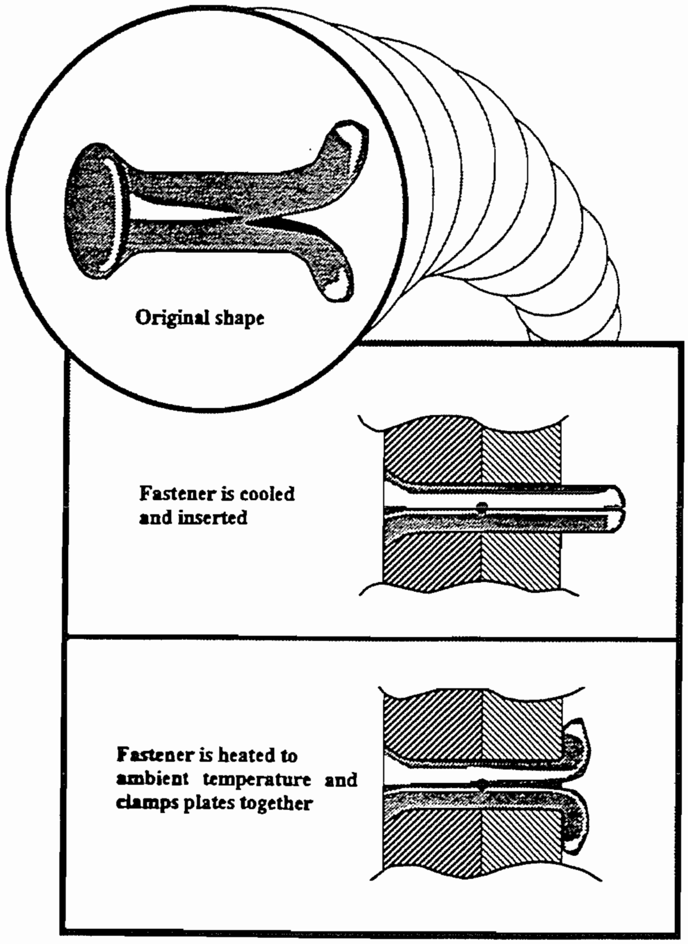

A SHAPE-MEMORY-ALLOY FASTENER is manufactured with the split ends of the shank memorized at the ambient temperature state. The fastener is cooled in liquid nitrogen so that the split ends of the shank deform to yield the classical rivet-like configuration. It is then inserted into the holes in the aligned plates and upon being heated by the ambient air, the split ends again deform to grip the two plates and prevent relative motion.

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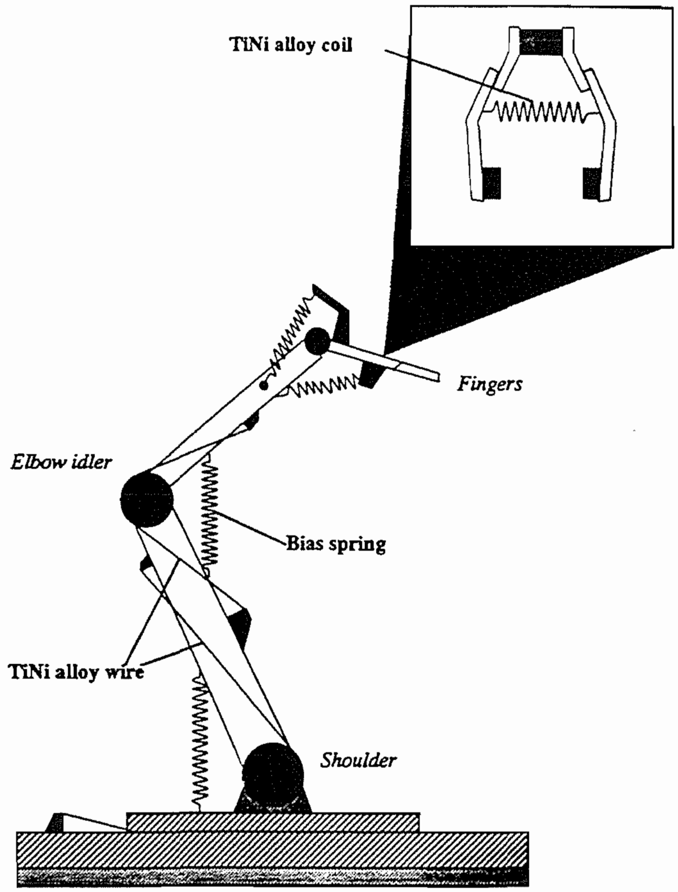
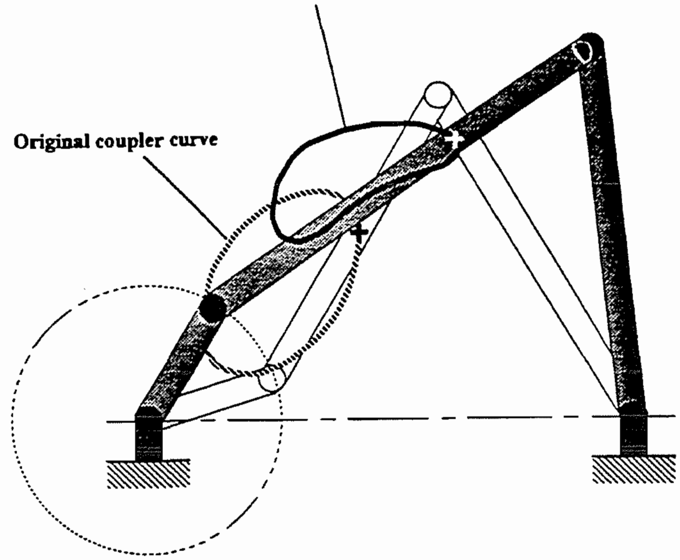


A MICRO-ROBOT ACTUATED BY SHAPE-MEMORY-ALLOYS.



ENHANCING THE COUPLER CURVE CHARACTERISTICS OF A FOUR-BAR MECHANISM BY USING SHAPE-MEMORY-ALLOYS.

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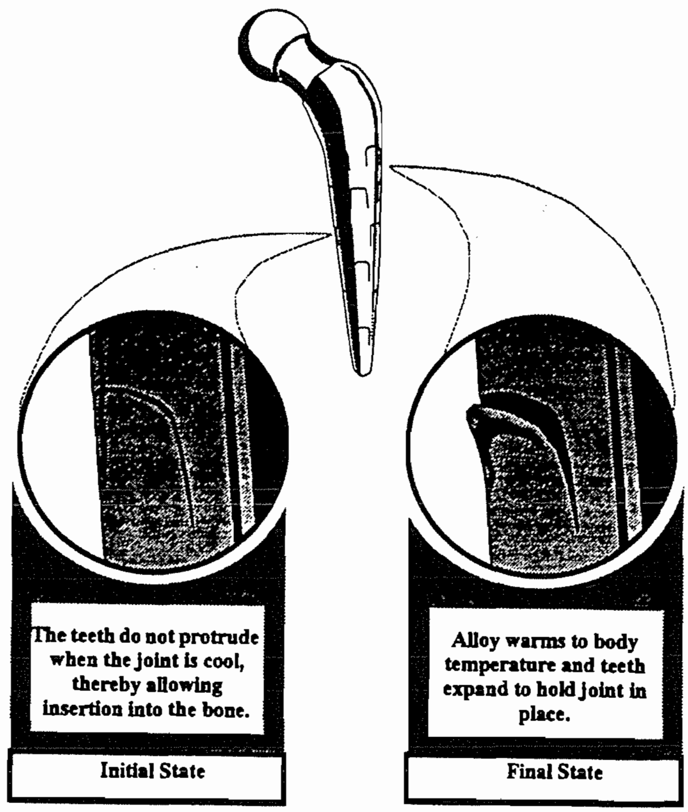

A SHAPE-MEMORY-ALLOY ARTIFICIAL HIP JOINT. The stems are cooled prior to insertion in the medullary cavity and the scales expand to exert a uniform force on the bone as they are heated by the body and return to their memorized shape. Trials involving sheep have been successfully completed and they clearly demonstrate that the scales function correctly within the adjacent bones, bone growth was good, and the stems were firmly fastened to the bones.

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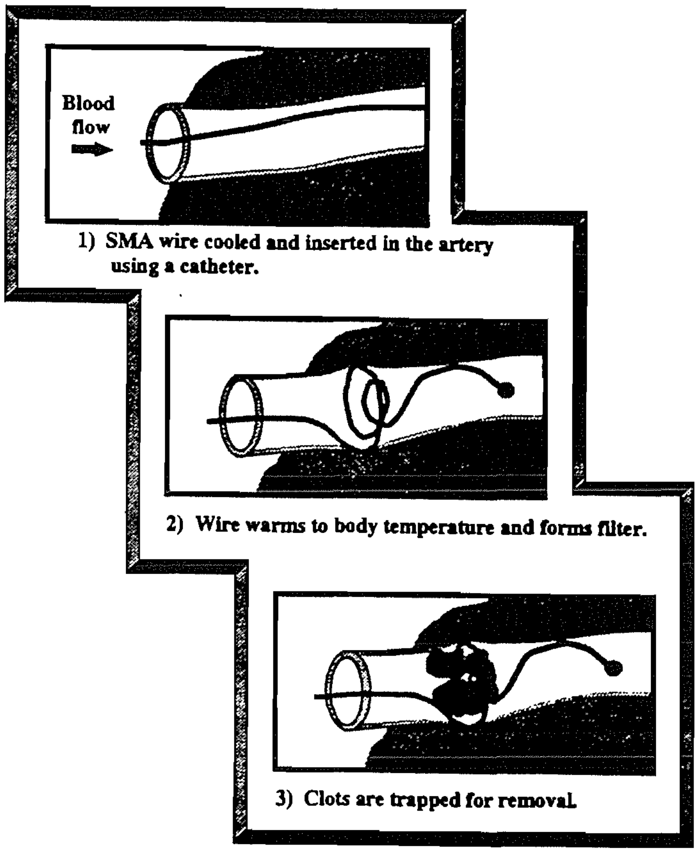

SHAPE-MEMORY-ALLOY BLOOD CLOT FILTER FOR TREATMENT OF PULMONARY THROMBOEMBOLISM(the obstruction of a blood vessel by an embolus that has broken away from a thrombus). The proposed exploratory procedure involving TiNi wire requires the wire to be first trained to the blood-clot trapping coiled configuration prior to cooling and straightening the wire. Subsequently, the wire is then inserted into the *vena cava,* with the aid of a catheter, where it is heated by the blood flow and then reverts to the original blood-clot filtering configuration. The procedure has been performed with animals using only local anesthesia and the results have been satisfactory.

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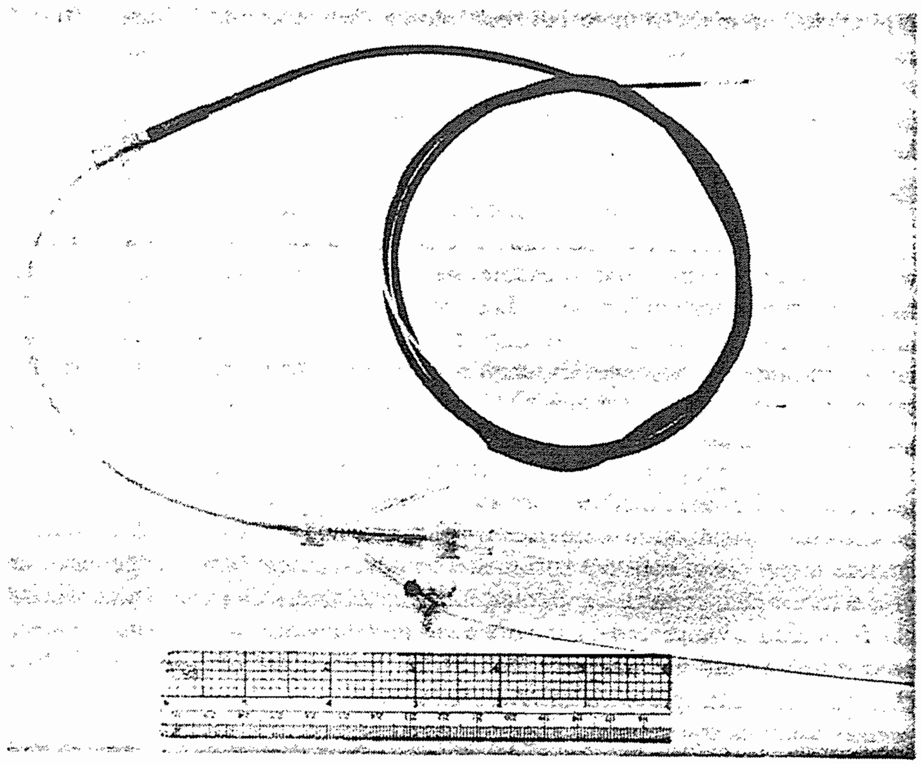

CURRENT GENERATION DISTENSIBLE CATHETER FOR ANGIOPLASTY OPERATIONS (techniques for repairing or replacing damaged blood vessels using surgery, lasers, or tiny inflatable balloons at the end of a catheter that is inserted into the vessel). The rationale behind the technique is to increase the diameter of the diseased region in order to increase the blood flow.

In the context of dilating coronary artery lesions, a 100 cm hollow guiding catheter is inserted into the brachial or femoral artery, prior to advancing the tip of the instrument until it is positioned in the region of the coronary artery to be dilated. The task of positioning the tip of the catheter in the orifice of the coronary artery is a challenging undertaking because of the uniform constant uncontrollable stiffness, and the significant variations in the curvatures of the vascular tubes and their surface roughness. A smart catheter with controllable properties could significantly enhance this procedure.

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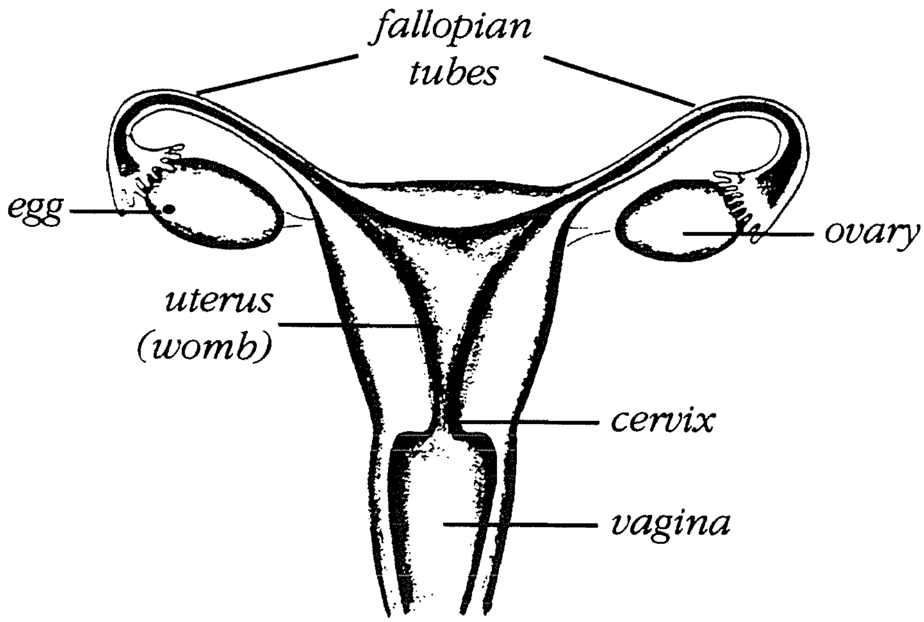

BLOCKED FALLOPIAN TUBES which are typically the result of endometriosis or inflammatory diseases of the fallopian tubes, or ovaries, cause an estimated 30% of female infertility by severing the connection between the uterus and the ovaries. A new procedure called Transcervical Balloon Tuboplasty is used to solve this problem. A series of balloon-tip catheters are inserted through the cervix into the fallopian tubes. The balloons are subsequently inflated to increase the diameter of the tube in the blockage region thereby reopening the natural tube-like structure connecting the uterus and the ovaries. Development of smart catheters featuring members with segmented variable-stiffness characteristics that are directly controlled by the physician would significantly enhance this process.

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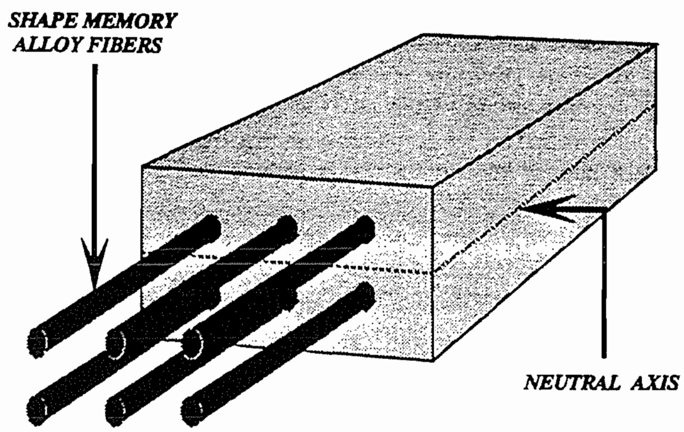

SHAPE-MEMORY-ALLOY-BASED SMART STRUCTURE. Fabricated with reinforced composite materials, fibers of SMA are embedded in a laminated fashion as shown. Changing the temperature of SMA fibers beyond the phase-transition point, changes the shape and mechanical characteristics of SMA, and hence changes the shape and global mechanical characteristics of the smart structure.

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<<< ELECTRO-RHEOLOGICAL FLUIDS >>>

Electro-Rheological (ER) fluids are typically suspensions of micron-sized hydrophilic particles suspended in suitable hydrophobic carrier liquids, that undergo significant instantaneous reversible changes in their mechanical properties, such as their viscosity /mass distribution, and energy dissipation characteristics, when subjected to electric field.

*** Characteristics include:**

- **When an electric potential is applied across the ER fluid, these hydrophilic particles arrange themselves in particle "trains" and cause an increase in the viscosity of the fluid.**

- **They could be embedded within a structure, allowing for variable internal damping of the structure, which may be actively controlled by controlling the mechanical properties of the fluid.**

- **The voltages required to activate the phase-change in ER fluids are typically in the order of 1-4 kV/mm of fluid thickness, but since current densities are in the order of 10 mA/cm2, the total power required to change the fluid properties is quiet low.**

- **The response-time of ER fluids to an electrical stimulus is typically less than one millisecond.**

- **Possible products based on ER fluids are: quiet car suspensions that automatically adjust to road conditions; engine and machine-tool mounts that dampen unwanted vibrations at all rotational speeds; small clutches, rotor blades for helicopters that automatically stiffen to compensate for precipitation and temperature variations; fishing rods that are flexible for casting but stiffen when a fish bites; sensitive actuators and robotic arms; and remote-control valves, etc.**

- **Their deficiencies are: still questions exit about their long-term stability while in use, possibility that they might erode or corrode the equipment in which they operate, need for high voltage.**

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COLLOIDAL DISPERSIONS

When a material (the solute) dissolves in another material (the solvent), to form a solution, the solute and solvent molecules are generally of comparable size and they are typically distributed uniformly throughout the solution. When these conditions are not satisfied, and the size of the solute particles are much greater than the size of the solvent molecules, then the system is termed as the *Colloidal Dispersion*.

SUBGROUPS ARE:

*** *SOLS*: Dispersions of Solids in Solids, or Solids in Liquids.**

*** *EMULSIONS*: Dispersions of Liquids in Liquids.**

*** *AEROSOLS*: Dispersions of Liquids in Gases, or Solids in Gases.**

*** *FOAMS*: Dispersions of Gases in Liquids, or Gases in Solids.**

<u>E.R. (Electro-Rheological) Fluids belong to the first category "SOLS"</u>.

- They exhibit large reversible changes in their rheological behavior when subjected to external electrical fields. They typically go through a phase-change from a liquid state to a solid state, or else a dramatic increase in flow resistance depending upon the flow regime and also the composition of the E.R. fluid.

- They often have Newtonian characteristics in the absence of an external electric field, and become Non-Newtonian when the electrical field is imposed upon the fluid domain.

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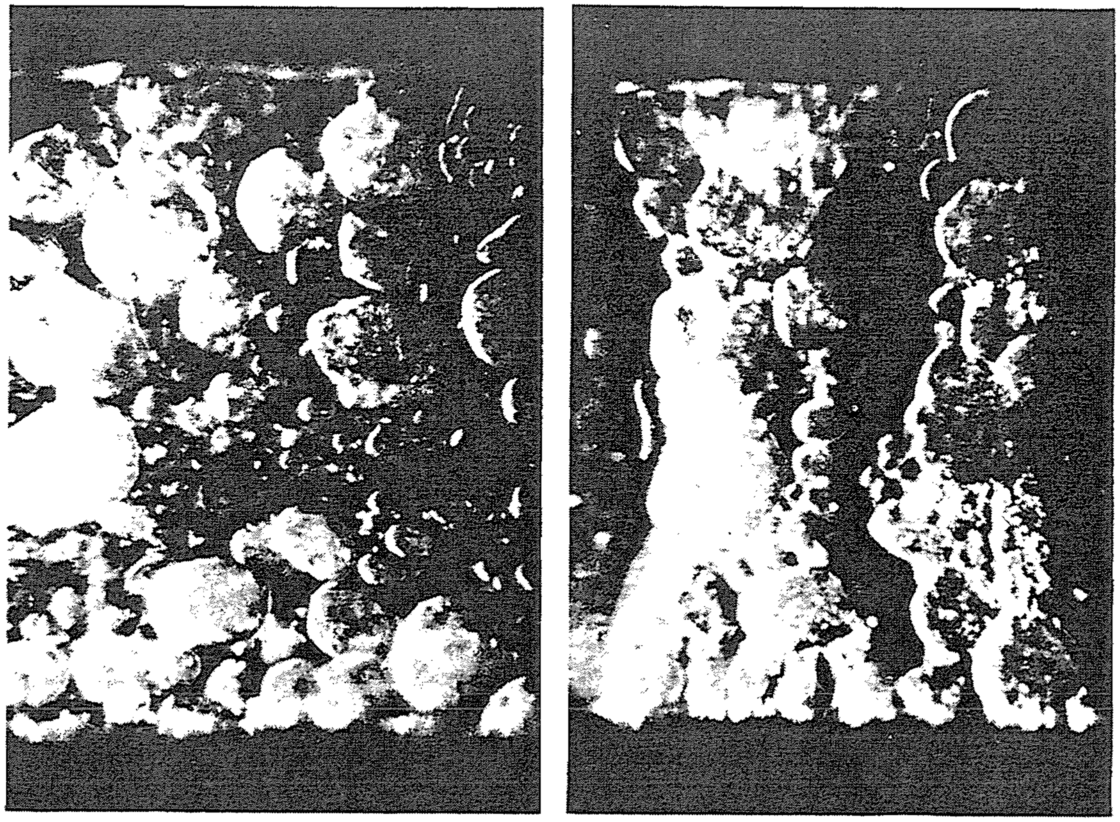
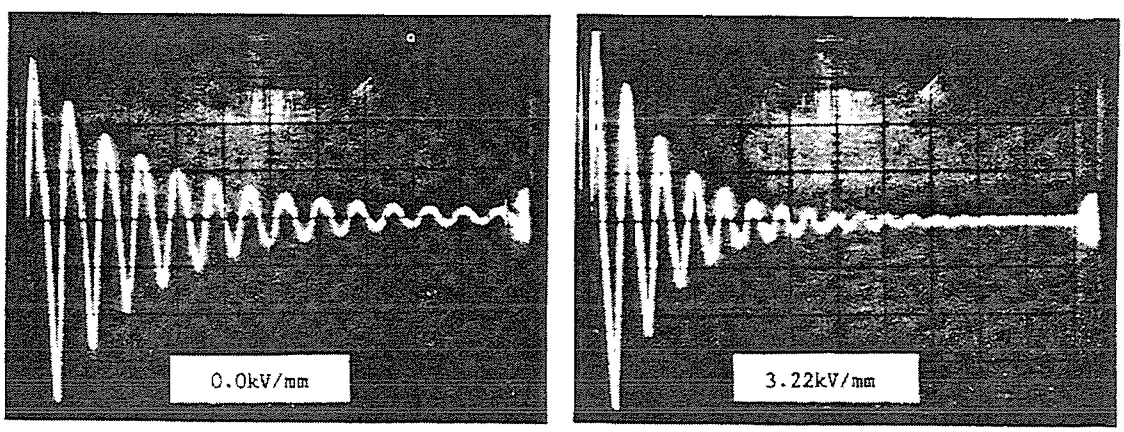


Photomicrograph of ER fluid microstructure at two discrete voltage states (0 kv/mm and 2 kv/mm, respectively). The current levels associated with the high voltage states are typically in the order of a few micro-amperes, consequently, the power consumption is minimal.



Experimental results demonstrating the controllability of a cantilevered beam vibrations (fabricated with graphite-epoxy material filled with an E.R. fluid) by employing constant voltage fields across the beam.

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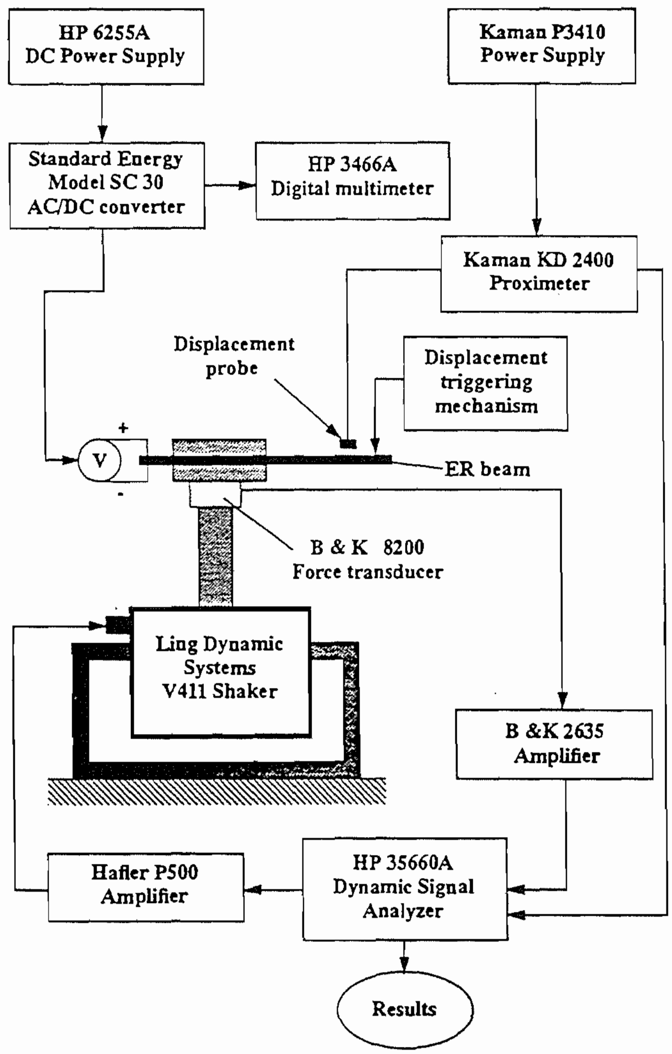
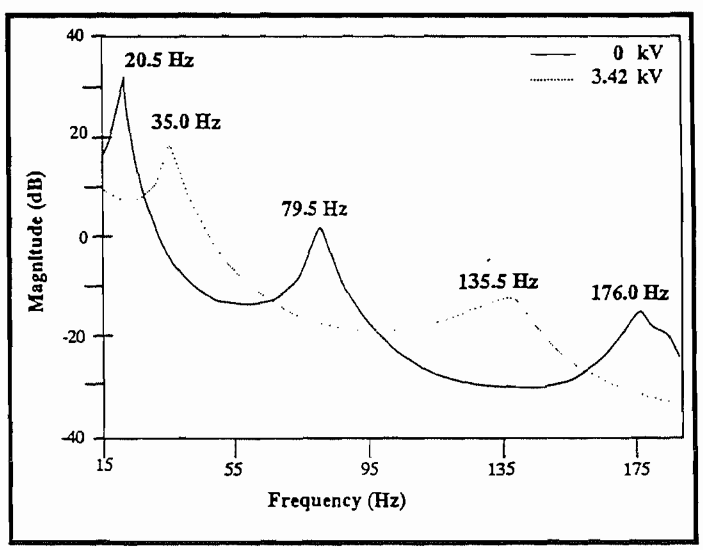


Experimental Apparatus for Dynamically Exciting a Smart Cantilevered Beam.



Frequency Response of a Smart Cantilevered Beam Featuring an E.R. Fluid.

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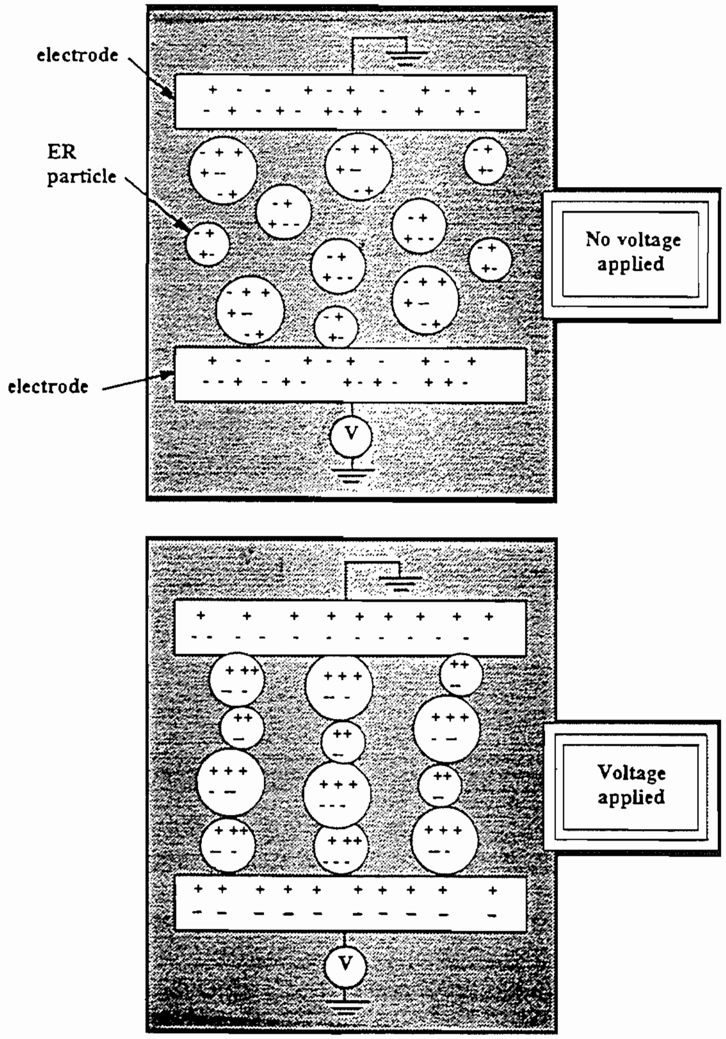

THE ELECTRO-RHEOLOGICAL PHENOMENON.

The particles align themselves parallel to the electric field, which is in the vertical direction for the two straight, parallel-sided electrodes (see photomicrographs). Initial conditions are that electric dipoles are induced in the particulate phase as a consequence of imposing the electrical field on the dispersion, so that there is interaction between the individual particles and they form columnar structures as schematically shown above.

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Solute	Solvent	Additive
Kerosene	Silica	Water and detergents
Silicone oils	Sodium carboxymethyl cellulose	Water
Olive oil	Gelatine	none
Mineral oil	Aluminum dihydrogen	Water
Transformer oil	Carbon	Water
Dibutyl sebacate	Iron oxide	Water and surfactant
Mineral oil	Lime	none
P-xylene	Piezoceramic	Water and glycerol oleates
Silicone oil	Copper Phthalocyanine	none
Transformer oil	Starch	none
Polychlorinated biphenyls	Sulphopropyl dextran	Water and sorbitan
Hydrocarbon oil	Zeolite	none

TYPICAL INGREDIENTS FOR ELECTRO-RHEOLOGICAL FLUIDS. (Provided by Block & Kelly, J. Physics, vol. 21, 1988, pp.1661-76).

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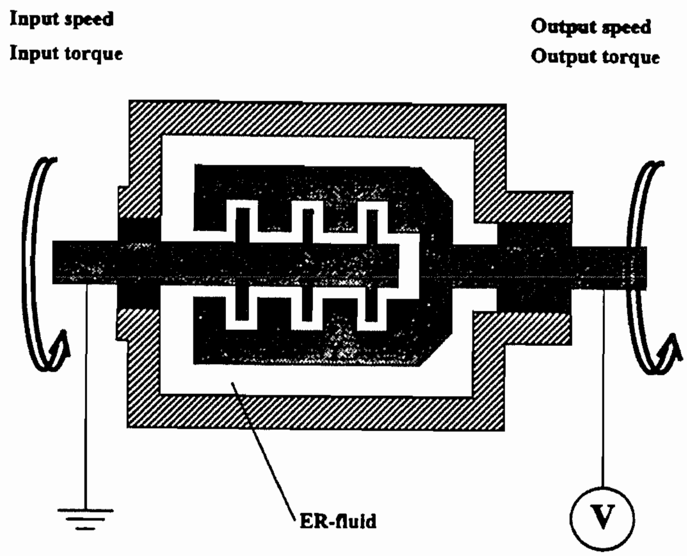
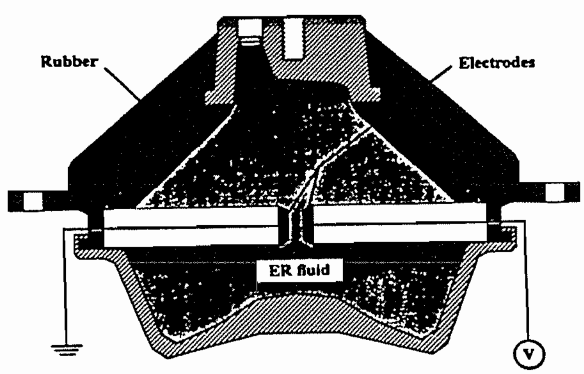


SCHEMATIC OF AN ELECTRO-RHEOLOGICAL FLUID CLUCH. It features a tailored slippage characteristic controlled by the time-dependent voltage profile imposed upon the fluid.



AN AUTOMOBILE ENGINE MOUNT FEATURING AN E.R. FLUID. The objective is to reduce the dynamic loads generated by the engine from entering the automobile structure in order to create enhanced ride characteristics.

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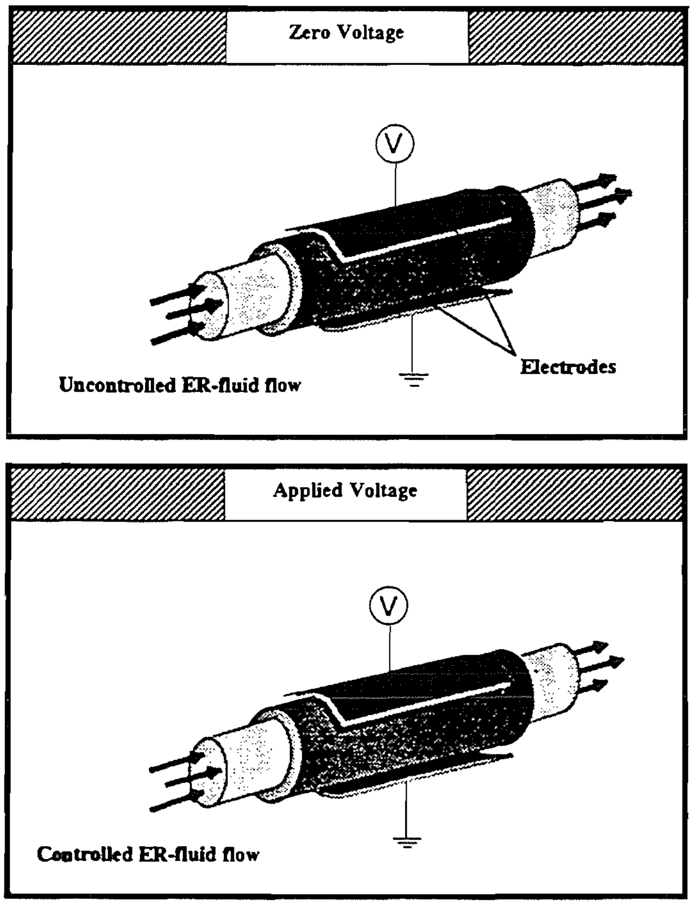

Schematic of a Valve Design for Controlling the Flow of Electro-Rheological (E.R.) Fluids by Controlling the Voltage Field, and Hence the Viscosity of the Fluid.

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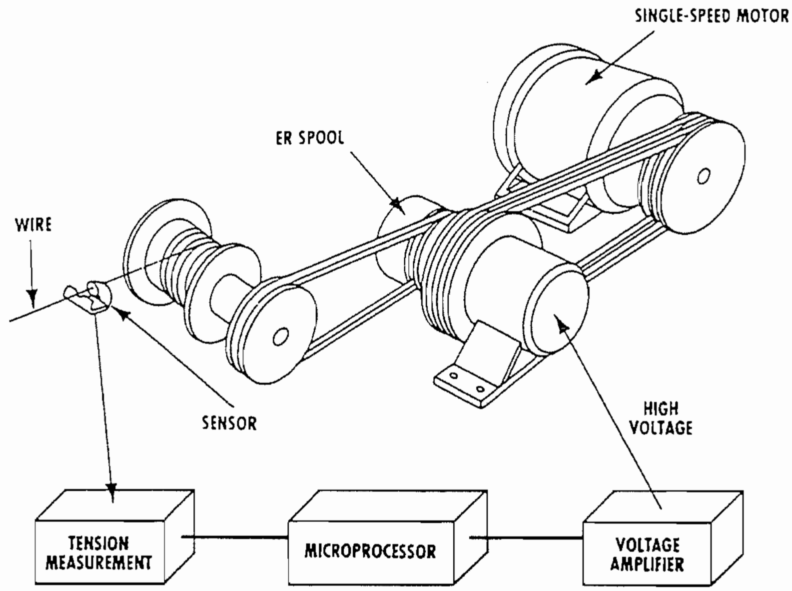
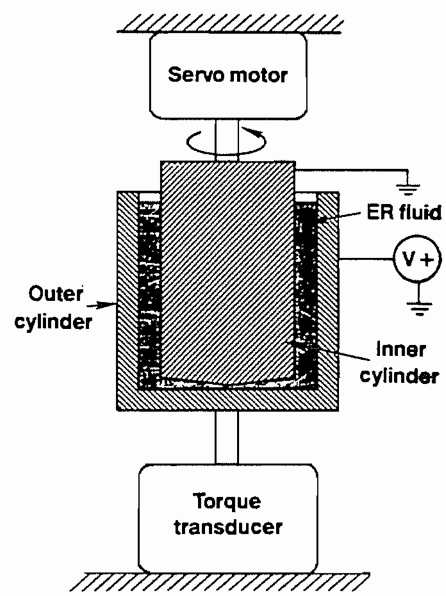


Power is transmitted from the motor to the wire reel through a spooler containing E.R. fluid. The spooler is controlled by a microprocessor linked to a tension sensor on the wire. The microprocessor controls the voltage, which changes the state of the E.R. fluid to keep the tension at the correct level. If the tension is too low, the voltage increases, the fluid becomes more solid, and the clutch transmits more power to the reel. The same apparatus could be used to spool textile, fibers, films, and thread.

Two concentric cylinders separated by a thin, fluid-filled space represent the element of a typical E.R. fluid device. With no electric field present, rotating the inner cylinder creates a shear stress between the two members but little or no torque/motion on the outer cylinder. When an electric field is applied, the E.R. fluid stiffens in proportion to the field strength, and stress is transferred to the outer cylinder as torque. If the field is great enough, the cylinders behave as though they were pressed together with no fluid between them.



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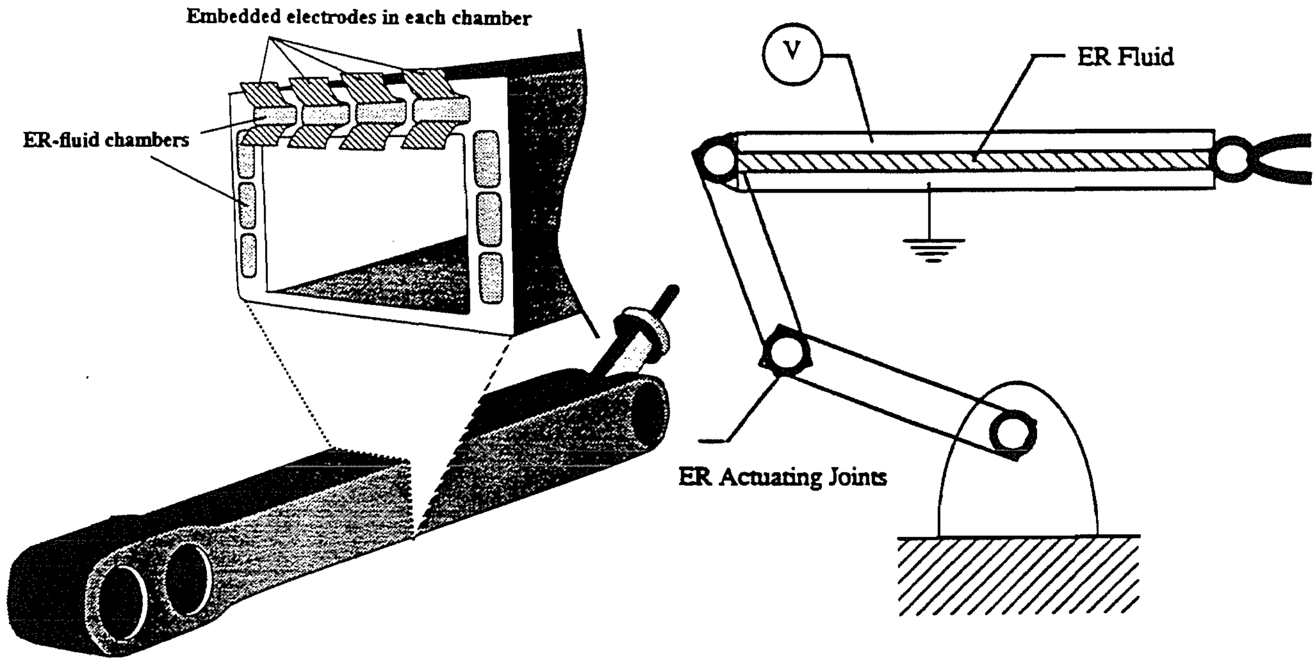

AN E.R. FLUID-ENHANCED ROBOT ARM. The objective is to actively control the energy-dissipation characteristics of robotic arms upon completing a series of high-speed maneuvers. Furthermore, to enhance productivity through the reduction of the vibrational settling-time when the robot motors are not powered upon completion of a series of maneuvers. It has been shown that the natural frequencies of robot arms containing voids filled with E.R. fluids have been actively changed as a function of the voltage imposed upon the E.R. fluid domains. This could avoid resonance conditions attributed to the excitation frequencies of loads imposed by production tooling at the end-effector.

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POTENTIAL APPLICATIONS OF SMART MATERIALS IN THE AHMCT PROGRAM:

COOLED CONFIGURATION

HEATED CONFIGURATION

PROPOSED SMART DOTS for Streets and highways made of shape memory alloys are capable of contraction to the pavement level when the roads are snowy (making it easier for snow plowing and preventing possible remove of the dots by the snow plow), and expand to its original shape when heated by the sun to a higher temperature.

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The are numerous applications for passive smart structures in the field of civil engineering. Dams, buildings, bridges and other large concrete reinforced structures in earth-quake zones are typical examples. Of the 576000 highway bridges in the US, at least 135000 are structurally defective in some way. Thus, for example, the sudden unexpected collapse of the Mianus River Bridge on the Connecticut Turnpike in June 1983 with the associated tragic loss of life is no surprise to the US Department of Transportation. Research is currently focused on the development of coatings for steel bars reinforcing concrete bridge decks, substitutes for metallic reinforcement and the deployment of sacrificial protection. A *Passive Sensory Smart System* to monitor the deterioration of critical regions of these structures may be another alternative.

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<<< PIEZOELECTRIC MATERIALS >>>

Piezoelectric materials are solids that generate a charge in response to a mechanical deformation, or alternatively they develop mechanical deformation when subjected to an electrical field.

*** Characteristics include:**

- **They are employed as either Actuators or Sensors in the development of smart structures.**

- **Piezoelectric ceramic materials are typically employed as actuators.**

- **Polymeric piezoelectric materials are typically employed as sensors for tactile sensing, temperature sensing, and strain sensing.**

****

<<< MAGNETOSTRICTIVE MATERIALS >>>

Magnetostrictive materials are solids that typically develop large mechanical deformations when subjected to an external magnetic field. This magnetostriction phenomenon is attributed to the rotations of small magnetic domains in the material, which are randomly oriented when the material is not exposed to a magnetic field. Orienting these small domains by the imposition of the magnetic field results in the development of a strain field (e.g., Terbium-Iron alloys, Terfenol-D).

*** Characteristics include:**

- **Terfenol-D is commercially available that offers strains up to 0.002, which is an order of magnitude superior to the current generation of piezoceramic materials.**

- **Deficiencies are: delivering a controlled magnetic field to a magnetostrictive actuator embedded within a host structural material, the material generates a much greater response when it is subjected to compressive loads, and the power requirement for this class of actuators is greater than those for piezoelectric materials.**

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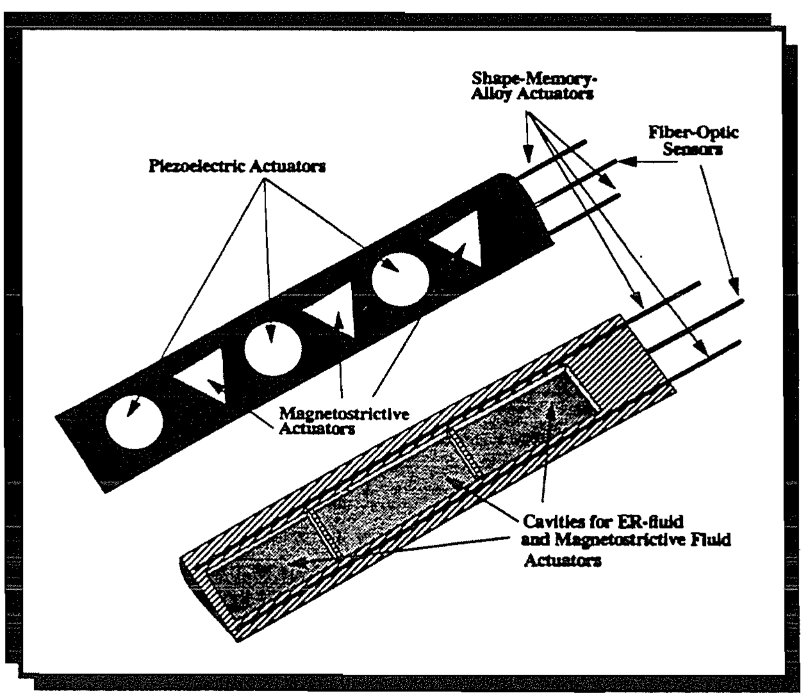
<<< ELECTROSTRICTIVE MATERIALS >>>

Electrostrictive materials are analogous to magnetostrictive materials since they develop mechanical deformations when subjected to an external electrical field. Electrostrictive phenomenon is attributed to the rotation of small electrical domains in the material when an external electrical field is imposed upon them. In the absence of this field, domains are randomly oriented. Alignment of these domains parallel to the electrical field results in the development of a deformation field in the material.

* Characteristics include:

- The ceramic compound lead-magnesium-niobate, PMN, exhibits a thermo-electrostrictive effect and is dependent upon the ambient temperature. This material, while exhibiting less hysteresis loss than piezoceramics, features a nonlinear constitutive relationship requiring some biasing in practice to achieve a nominally linear relationship over a limited range of excitation.

****



Conceptual Rotor Blade Featuring Smart Materials.

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<<< ELECTROMECHANOCHEMICAL MATERIALS >>>

These materials are "Polymeric Gels" (Gel is the intermediate between liquid and solid, consisting of a polymer network and interstitial fluid) that typically develop large and reversible contractions/expansions in response to small changes in external conditions such as temperature, pH, electric field, or solvent and ionic composition.

*** Characteristics include:**

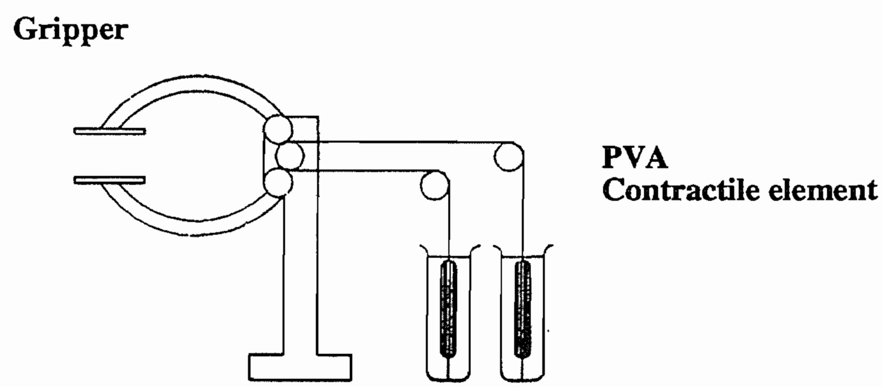
- **They can swell or shrink as much as 1000 times in response to an external stimulus (Tanaka 1987).**

- **They provide reversible changes such that restoration of the initial external conditions returns the gel to its original volume.**

- **In general, the rate of contraction is proportional to the square of the linear dimension of the gel. For example, micro sized gel fibers contract in milliseconds.**

- **Some gels support substantial loads. Polyacrylonitrile-Polypyrrole (PAN-PPY) and Polyvinylalchohol (PVA) gel fibers generate up to 10 kgf/cm^2, an order of magnitude above a human muscle, 1 to 2 kgf/cm^2.**

- **Possible applications are: Artificial Muscles, Robot Grippers, Micro-pumps, and Micro-actuators.**



A PROPOSED GRIPPER.

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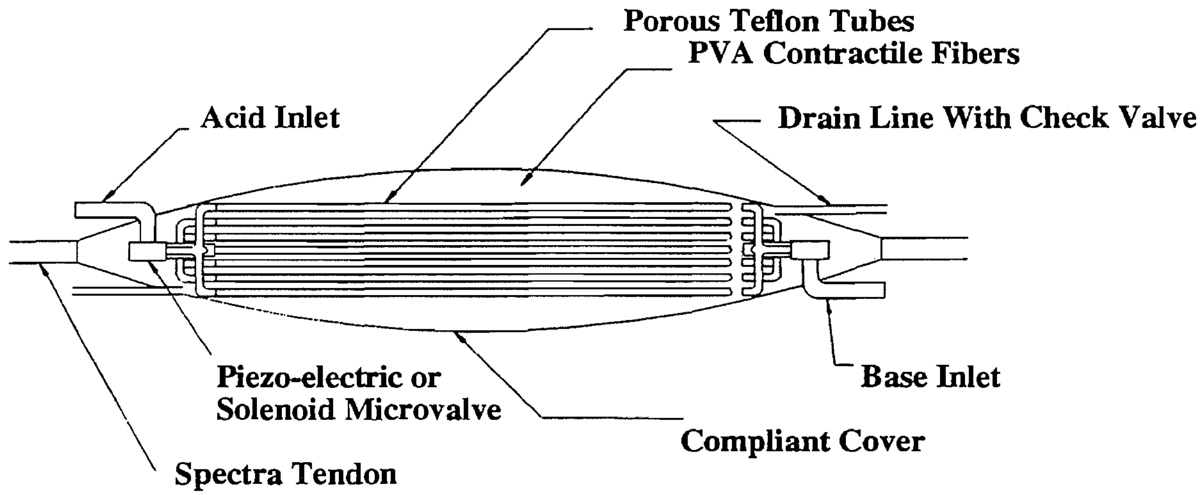
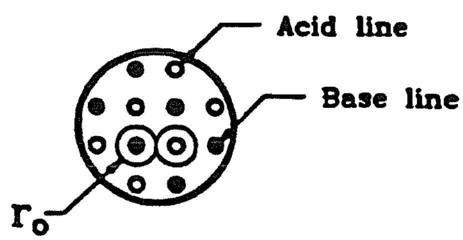
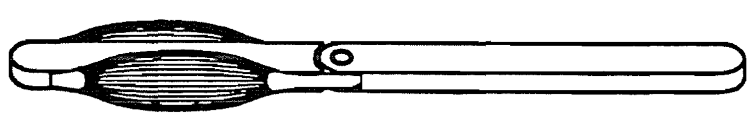


Two fluid microvalves meter desired amounts of acid or base through an irrigation system to a bundle of contractile fibers.



Arrangement of acid and base lines in the cross section of the muscle.



Two antagonist artificial muscles control a single arm.

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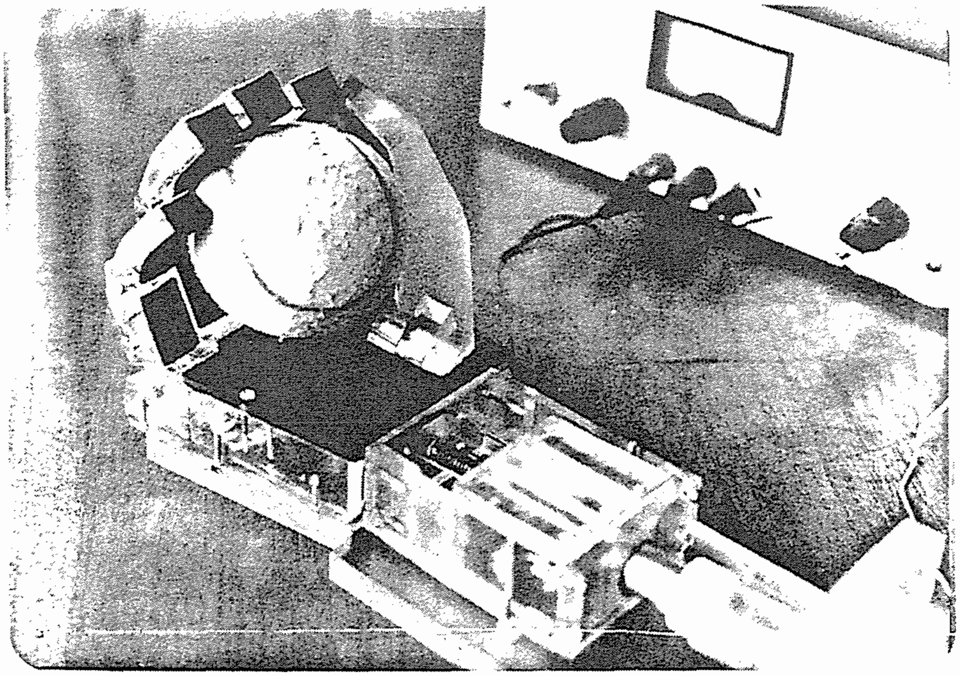
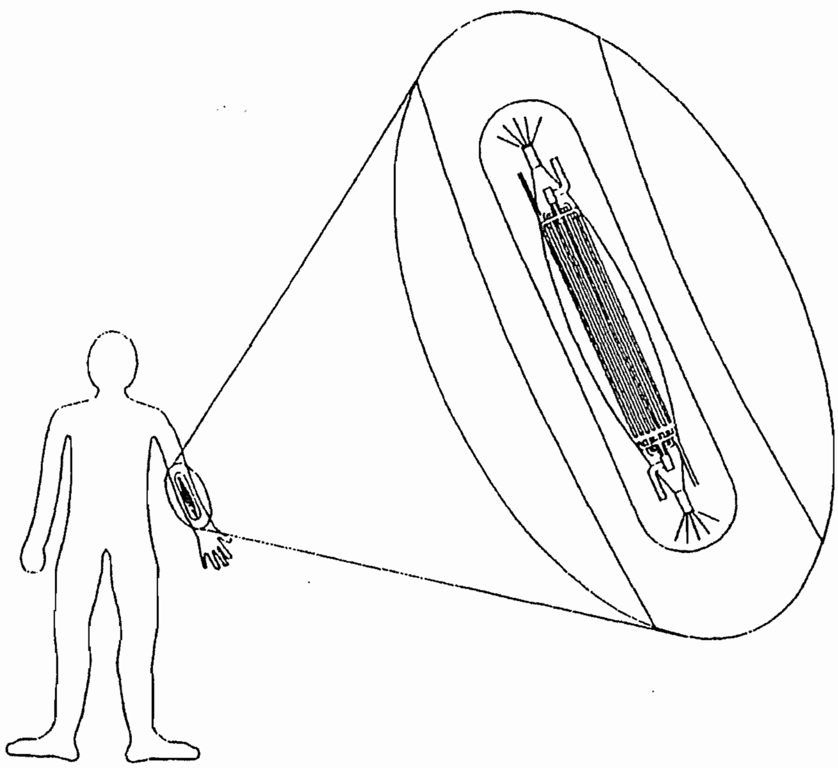


PROTOTYPE OF THE SHARIF ARTIFICIAL HAND.



POSSIBLE APPLICATION OF ARTIFICIAL MUSCLES TO PROSTHETIC ARMS & HANDS.

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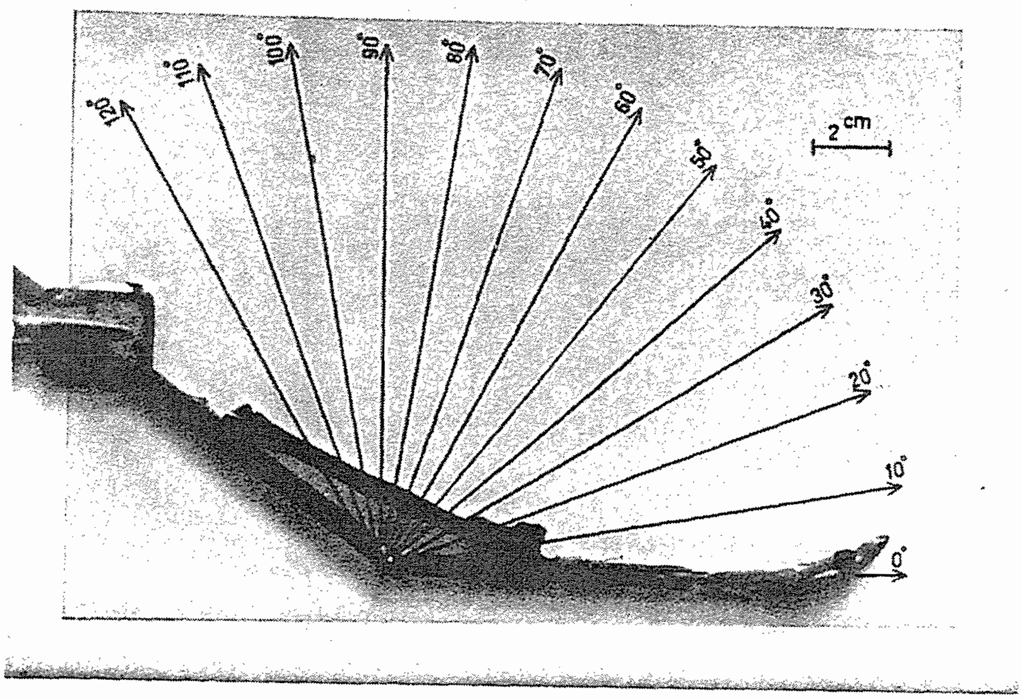
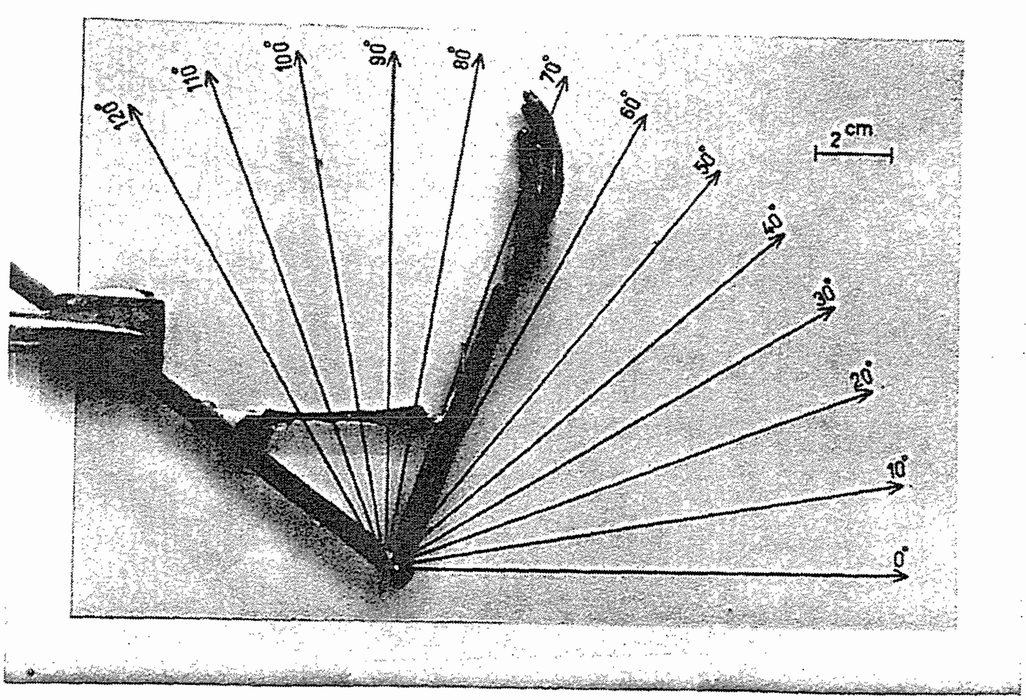


(A) - Relaxed Position.



(B) - New Position Immediately After Applying HCl (2M) to the Muscle.

GEL MUSCLES FABRICATED FROM PAN (Polyacrylonitrile) FIBERS ARE APPLIED IN A SIMPLE ARM.

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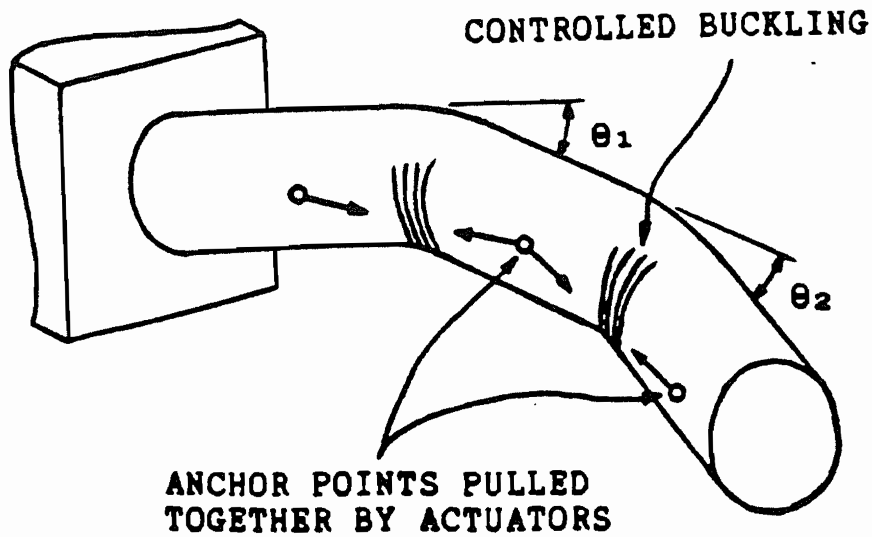
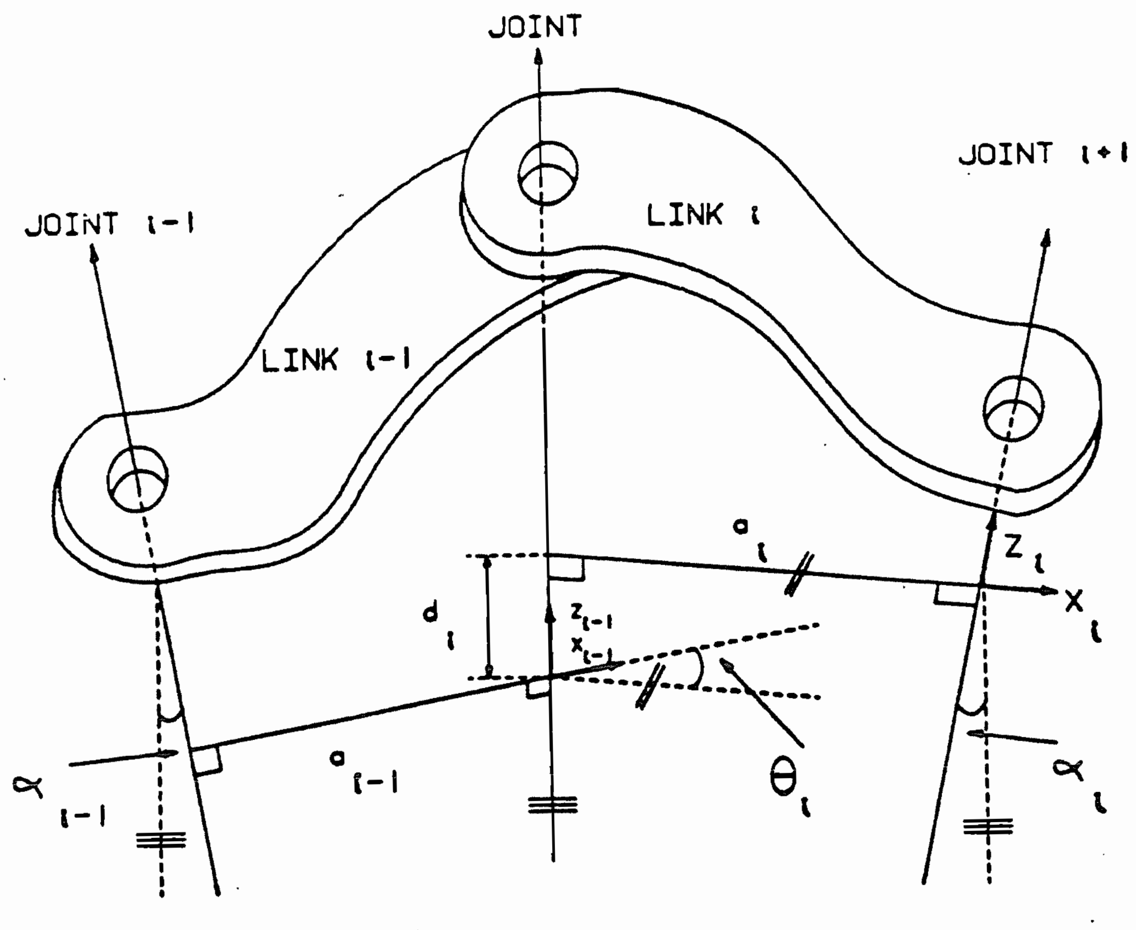


Fig. 3 Controlled Deformation of a Flexible Arm.(FINGER)



Generalized manipulators link representation.

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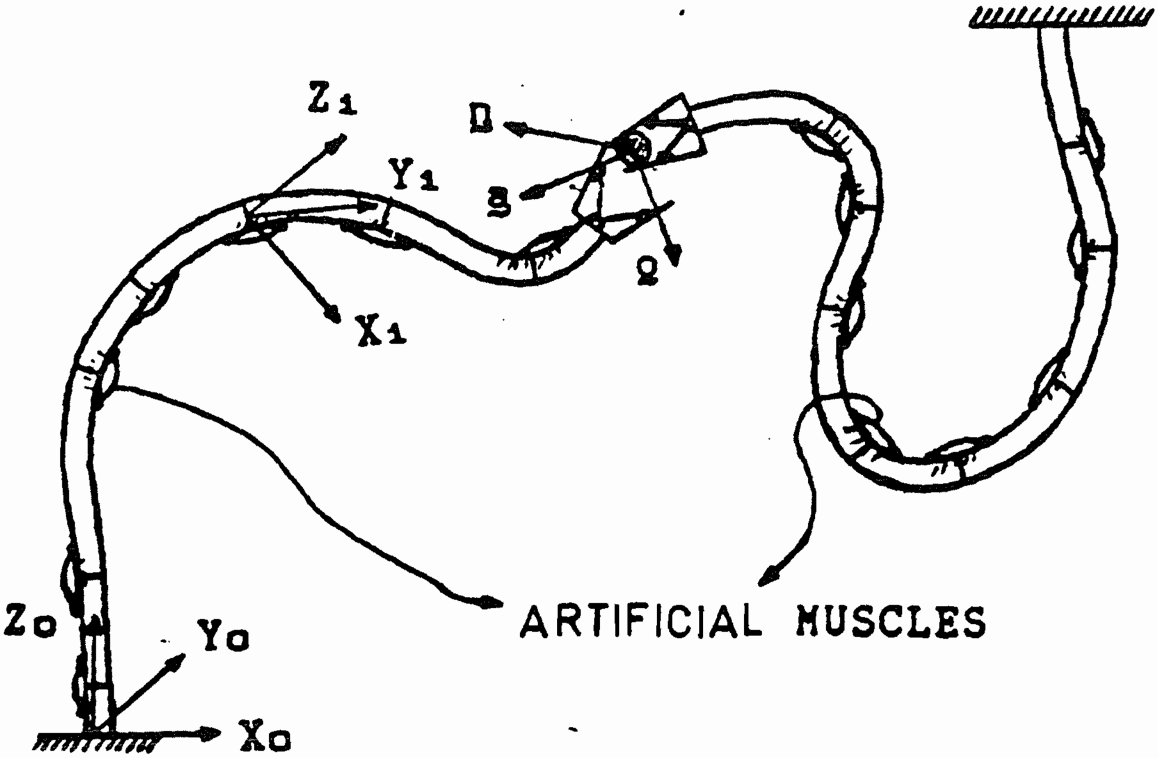

Fig. 1 A Planar Flexible Arm Actuated by Artificial Muscles.

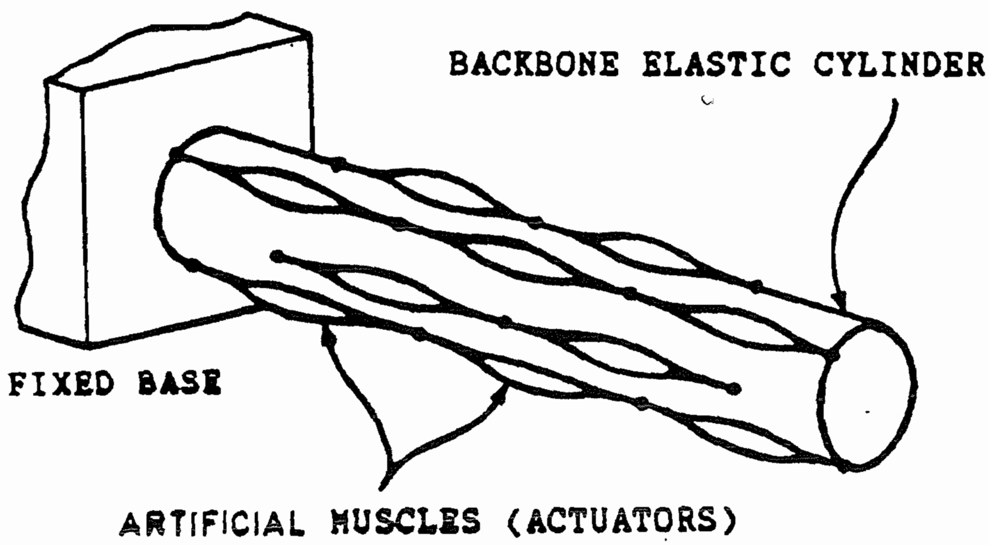

Fig. 2. Flexible Arm Surrounded by a Number of Actuators.

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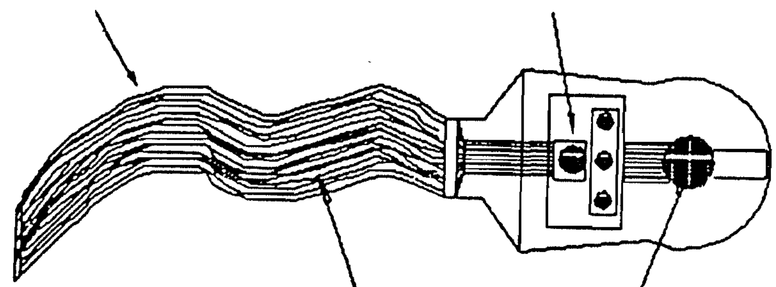
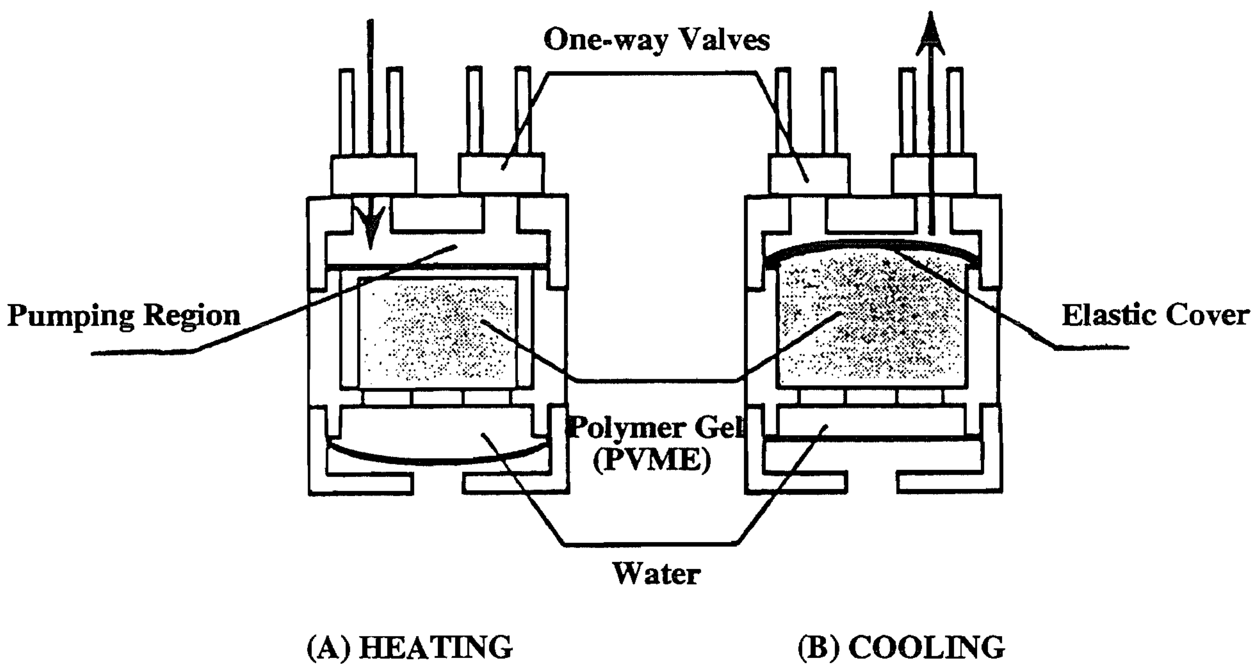


A SWIMMING ROBOTIC STRUCTURE UTILIZING IONIC POLYMERIC GEL MUSCLES. A change in the electric field results in a change in the bending direction of the polymeric gel fibers that are located at the robotic fish tail. Producing consecutive bendings with a continuous change in direction results in the motion of the fish in a fluid.



A MICROPUMP THAT EMPLOYS THERMO-SENSITIVE POLYMERIC GELS. Dimensions: Diameter=8 mm, Length=14.5 mm, Weight=3.2 grams [Hattori, 1992]. It employs the Polyvinyl Methyl Ether (PVME) gel. When the gel is heated, its volume decreases and consequently the fluid enters the pump. Then by cooling the gel, its volume increase and by pressing on the elastic cover some of the fluid is pumped out. Continuous heating and cooling of the gel results in a continuous pumping of the fluid.

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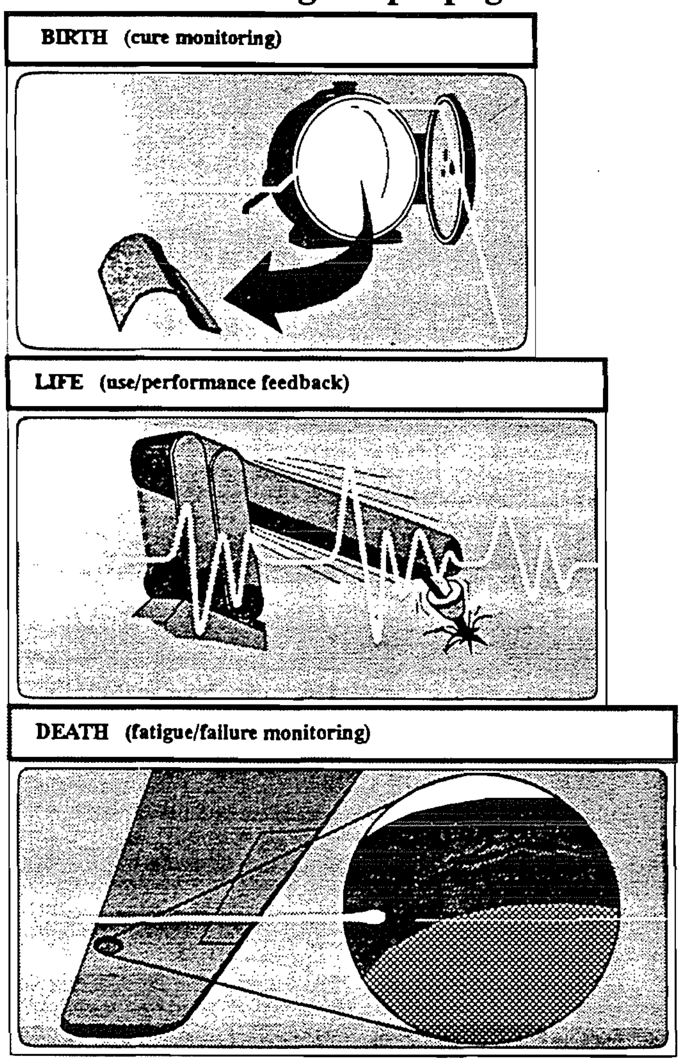
<<< PASSIVE SENSORY SMART STRUCTURES AND HEALTH-MONITORING OF PARTS BY EMBEDDED SENSORS >>>

A structurally integrated optical microsensor system for assessing the state of a structure is termed as a Passive Smart Structure. Such a structure employs these sensors throughout the part's manufacturing process as well as the service life of the part.

* **The embedded sensing system would be employed to monitor the state of cure during the fabrication of a smart component, in order to ensure that the part is processed correctly.**

* **Subsequently, the embedded sensing system would be employed to continously monitor a number of critical parameters within the part during service. (Dynamic stress characteristics of a robot arm due to the loading generated by the end-effector tooling could be monitored).**

* **The embedded sensing system would be employed to monitor the structural integrity of the component, such as aircraft wings (e.x., by detecting cracks and monitoring the propagation of these defects).**



The Health-Monitoring of Parts by Embedded Sensors.

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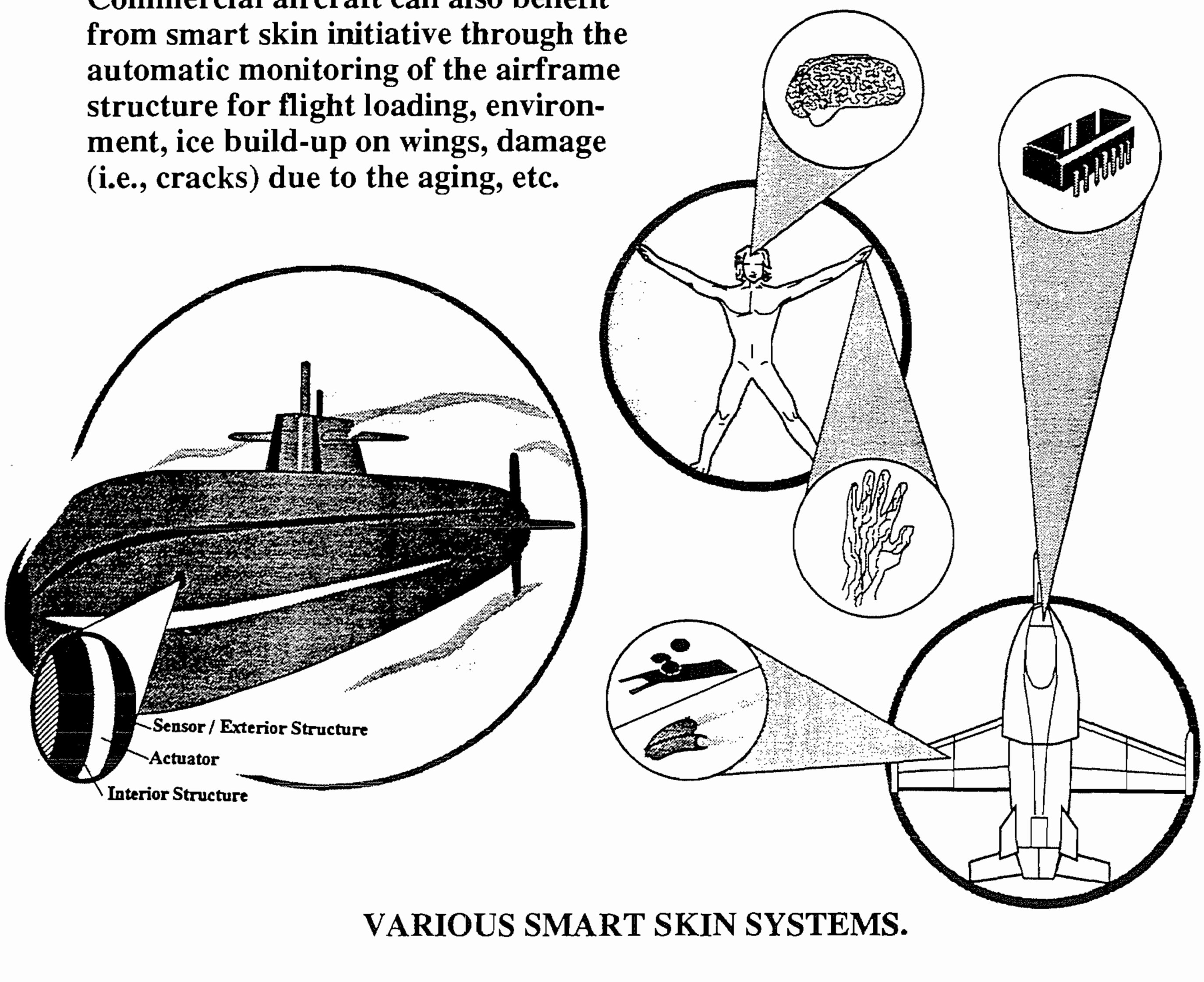
<<< SMART SKINS >>>

Aerospace products and naval vessels have typically shell-like structures featuring a thin skin whose structural integrity is generally mission-critical. The safe and optimal operation of the vehicle is dependent upon the environment to which the skin is subjected and the state of degradation of the skin. Hence, it is of critical importance to health-monitor the condition of this membrane within specified bounds in order the system function properly.

Smart skins have been developed which typically feature actuators, sensors, data-links and microprocessors embedded in the structural material in order to monitor the external loads and integrity of the structure prior to initiating corrective actions.

Corrective actions may involve the assessment of battlefield damage on an airplane immediately after sustaining a direct hit by ground fire, or else automatically adjusting the flight controls to ensure stable flight. Commercial aircraft can also benefit from smart skin initiative through the automatic monitoring of the airframe structure for flight loading, environment, ice build-up on wings, damage (i.e., cracks) due to the aging, etc.



VARIOUS SMART SKIN SYSTEMS.

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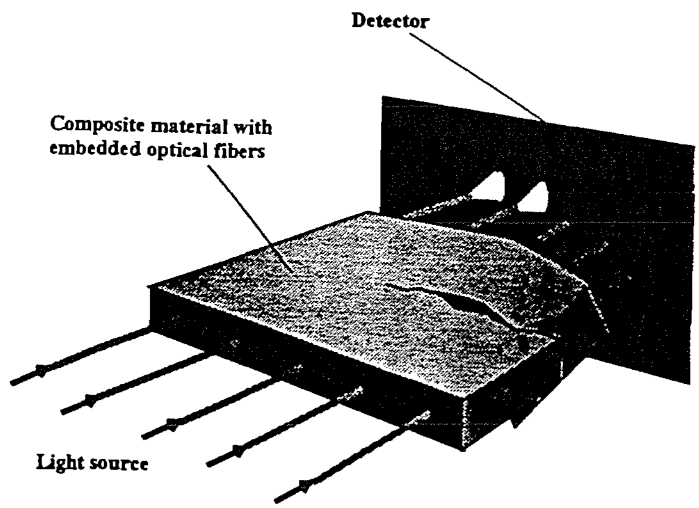
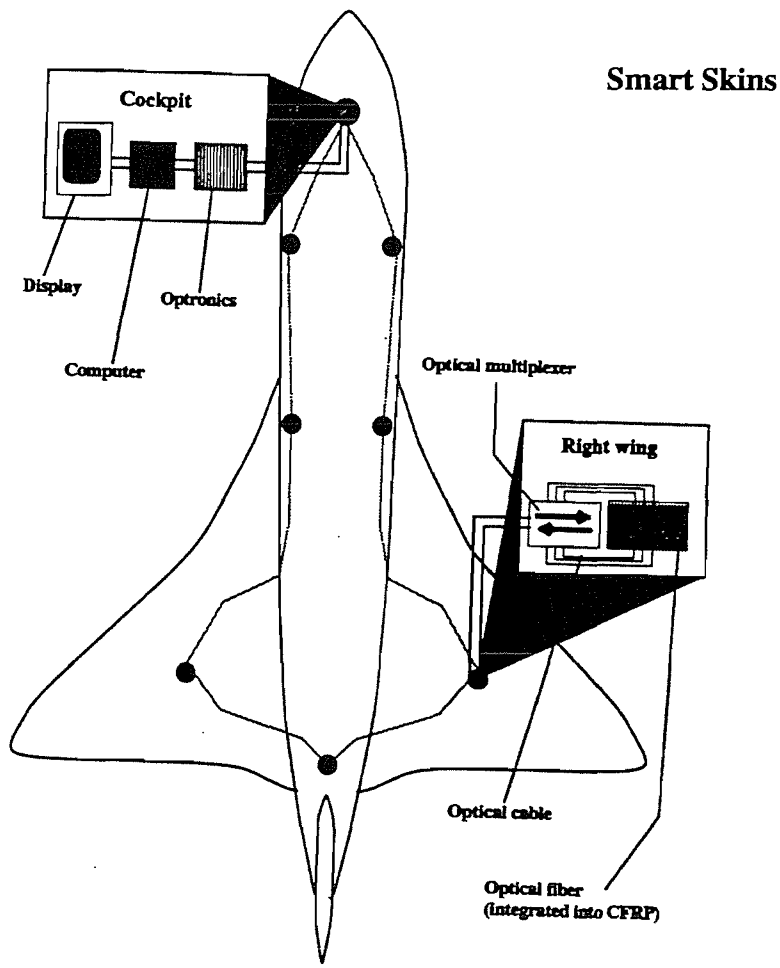


AN EMBEDDED OPTIC FIBER SENSING SYSTEM FOR DAMMAGE DETECTION. Embedded optical fibers break at the crack and prevent the light source from being received at the detector.



IN-FLIGHT STRUCTURE SURVEILANCE would require fiber-optic nervous system (FONS) channels in key structural regions of a plane. They would monitor the flight loading, the environment, and the structural integrity prior to initiating appropriate corrective actions.

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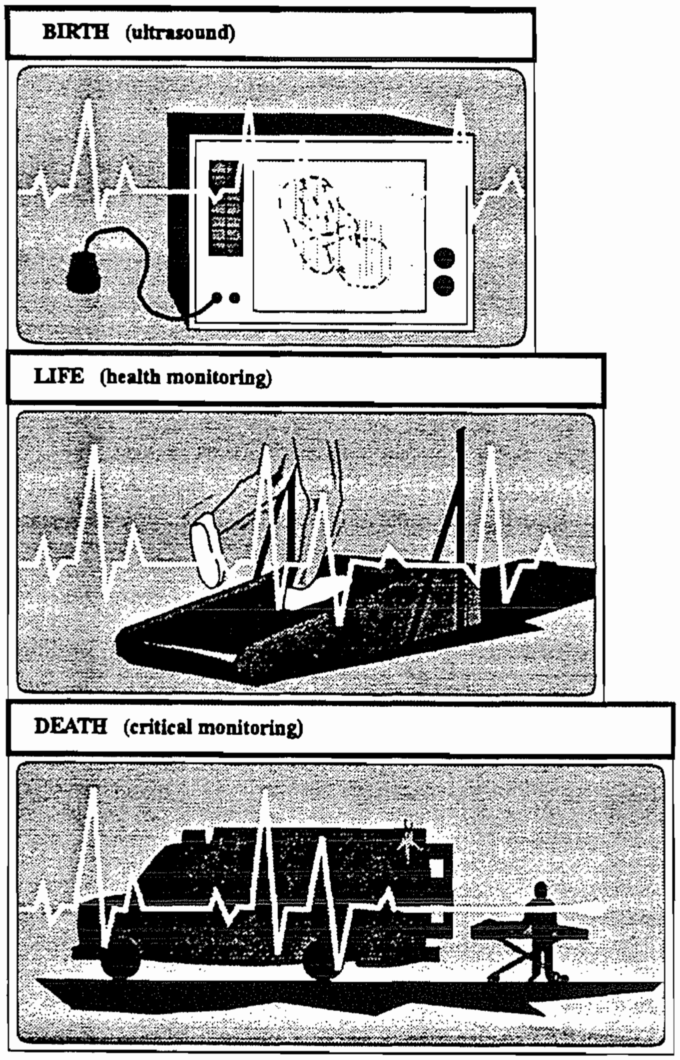
The notion of employing sensors embedded within a structural member in order to monitor the properties of the part has been termed as the "Health-Monitoring". This term is derived from the continual health-monitoring activities of the existing human species.

* Prior to birth, human beings are often subjected to non-invasive techniques to monitor the status of the fetus prior to embarking upon corrective courses of treatment.

* Subsequently, throughout life the health of human beings is monitored in response to external stimuli of various forms prior to being subjected to corrective treatments.

* Finally, as shown by the emergency care vehicle, the sensing system can be employed to monitor the vital signs and record the failure of principal organs such as the heart, liver, and kidneys.



The Health-Monitoring of Existing Human Beings.

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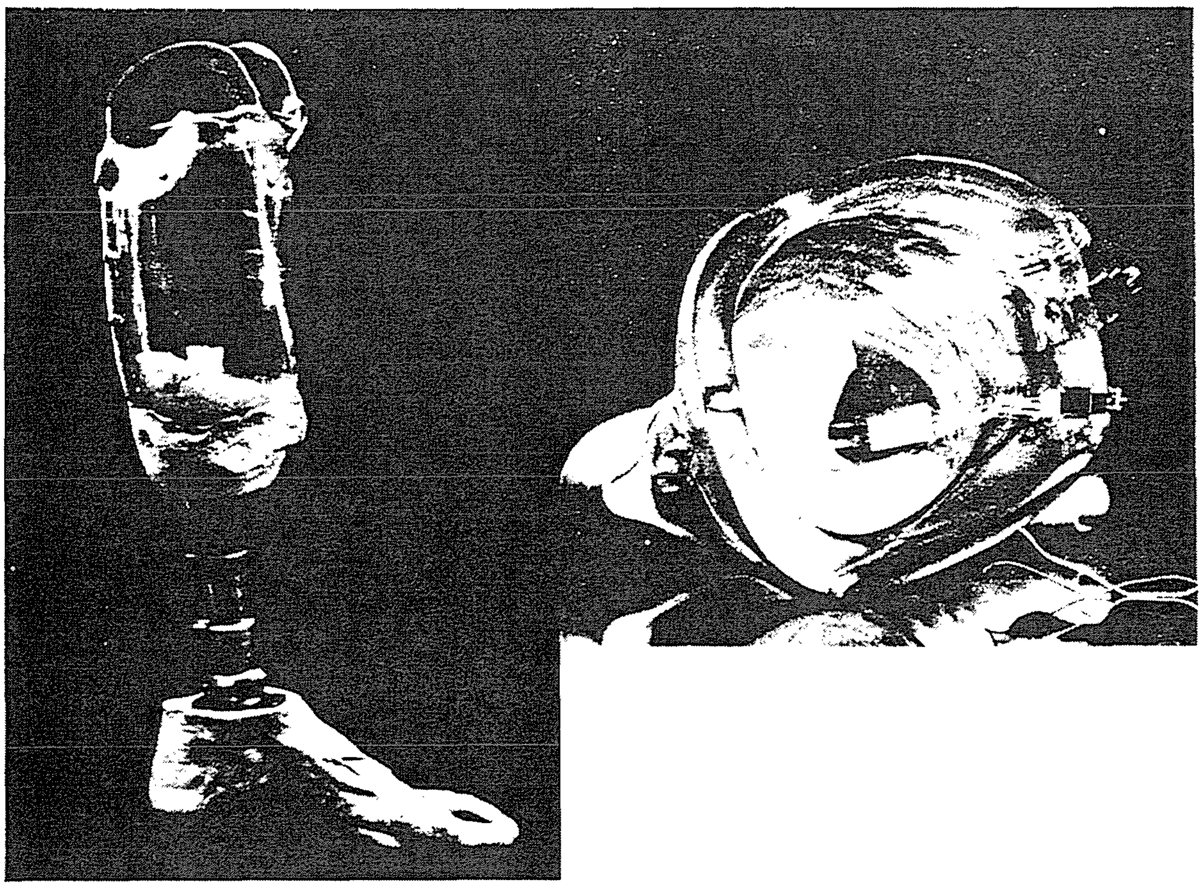
The task of fitting an artificial limb to a patient is an activity currently undertaken using experience and art rather than science in order to achieve the desired qualities of function, comfort and cosmetics.

* **An adaptable smart material that autonomously responds to the variable service conditions (due to the fluid retention properties of the human body associated with diet) in order to provide the optimal patient comfort in the interface region of the socket and the residual limb (stump) may be the ultimate choice.**



PROTOTYPE SMART LOWER LIMB PROSTHESIS.

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CONCLUSIONS:

The are numerous applications for passive smart structures in the field of civil engineering. Dams, buildings, bridges and other large concrete reinforced structures in earth-quake zones are typical examples. Of the 576000 highway bridges in the US, at least 135000 are structurally defective in some way. Thus, for example, the sudden unexpected collapse of the Mianus River Bridge on the Connecticut Turnpike in June 1983 with the associated tragic loss of life is no surprise to the US Department of Transportation. Research is currently focused on the development of coatings for steel bars reinforcing concrete bridge decks, substitutes for metallic reinforcement and the deployment of sacrificial protection. A *Passive Sensory Smart System* to monitor the deterioration of critical regions of these structures may be another alternative.

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