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Inventor(s):

Adrian Stoics
Sarita Thakoor

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JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY
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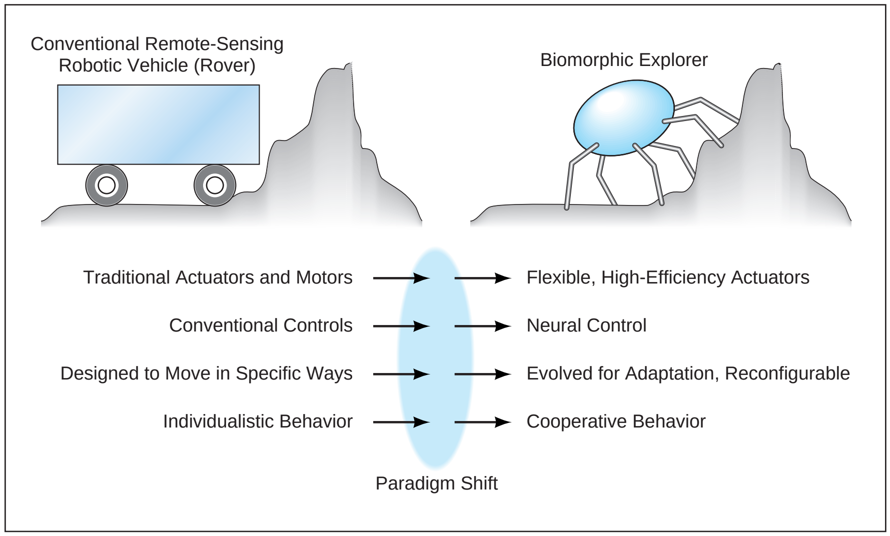
September 98

Biomorphic Explorers

Exploratory robots would feature animallike adaptability and mobility.

NASA's Jet Propulsion Laboratory, Pasadena, California



The **Development of Biomorphic Explorers** would be consistent with a current trend away from conventional, limited-mobility robots toward highly mobile, adaptive robots based partly on biological concepts.

"Biomorphic explorers" are a class of proposed small robots that would be equipped with microsensors and would feature animallike adaptability and mobility. These robots would capture key features, a specific design or function found in nature, taking advantage of general animal mechanical designs and neural functions that have evolved to enable animals to move through various environments. These robots are conceived for use in remote, hostile, and/or inaccessible terrestrial and other planetary environments, where they would be used to perform such diverse functions as acquisition of scientific data, law-enforcement surveillance, or diagnosis for precise, minimally invasive medical treatment. Depending on the specific environment to be explored, a biomorphic explorer might be designed to crawl, hop, slither, burrow, swim, or fly.

The biomorphic-explorer concept is a generalization and encompasses the nanorover concept reported in "Tetherless, Optically Controlled Nanorovers" (NPO-19606), *NASA Tech Briefs*, Vol. 21, No. 3 (March 1997), page 92. Like nanorovers, biomorphic explorers would exploit the emerging technology of microelectromechanical structures. Biomorphic explorers would be enabled by a unique combination of direct-driven, flexible, shape-reconfigurable advanced actuators and their adaptive control by fault-tolerant biomorphic algorithms. Typically, these actuators would consist largely of composites of thin piezoceramic films on strong polymeric substrates and/or combinations of shape-memory-alloy actuators. The actuators would generate forces and/or displacements in response to light or to applied voltage; that is, they could be controlled photonically or electronically. The desired combinations of mobility and adaptability, along with fault tolerance and a limited capability for "learning," would be achieved by integrating the actuators with very-large-scale integrated (VLSI) circuits that would implement neural-networks utilizing genetic algorithms.

Relative to conventional remote-sensing robotic vehicles, biomorphic explorers would be simple, inexpensive, and easy to fabricate; this raises the possibility of mass production of expendable biomorphic explorers that could be deployed in large numbers, possibly acting cooperatively under central control or distributed control. Such deployment would, of course, resemble the behavior of colonies of insects or other groups of small social animals engaged in cooperative activity.

This work was done by Sarita Thakoor and Adrian Stoica of Caltech for **NASA's Jet Propulsion Laboratory**.

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NTR Inventor's Report

Biomorphic Explorers

Sarita Thakoor and Adrian Stoics

1. Novelty:

A new paradigm in mobility combining flexible "limb-like" actuators and novel "bio-morphic" control strategies is described. Our approach is directed towards obtaining a new capability and significant Potential advantages, especially when traversing unusual and difficult terrain (such as loose granular surfaces/soft flour like soil or icy surface/subsurface oceans) by imitating the mobility attributes of animals. Mimicking biology, such "bio-morphic explorers" will possess varied mobility modes (be easily reconfigurable from one form to another): surface-roving, burrowing, hopping, hovering, or flying, to accomplish surface, subsurface, and atmospheric exploration. They would combine the functions of advanced mobility and sensing with a choice of electronic and/or photonic control. Preprogrammed for a specific function, they could serve as "no-uplink, one-way communicating" beacons, spread over the exploration site, autonomously looking for/at the object of interest. The biomorphic controls promise an excellent approach to capture learning and adaptivity in the behavior of the actuator(s) assembly to autonomously match with the changing ambient/terrain conditions.

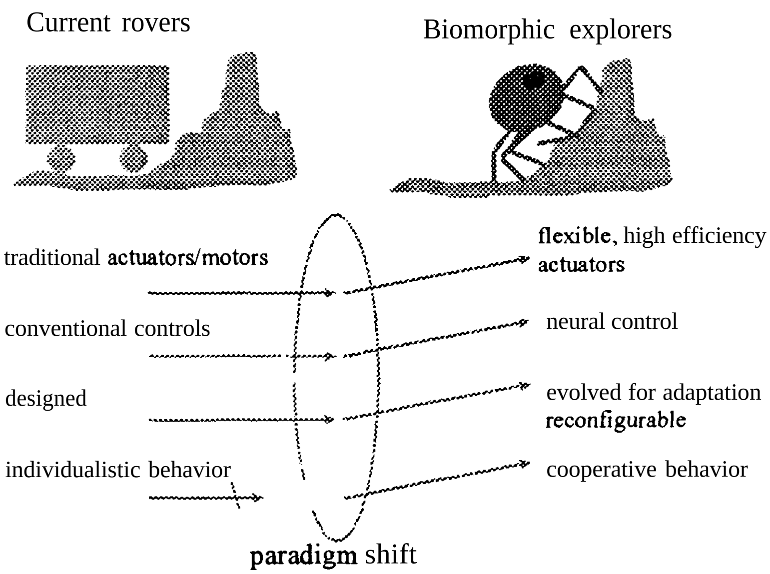
2. Technical Disclosure

A. Problem

Small low cost, mobile platforms are required for hazardous or scouting activities for a variety of exploration, surveillance, or security need. To obtain mobility, motors are generally used to drive wheels/legs/mobile segments. Reduction of size of motors is a continuing need which is approaching its own limits due to the intricacies involved in designing smaller motors. Assembly of small motors tends to become an intricate and expensive process. Direct driven advanced mobility with features of low mass, low cost, low power in small volume is in great demand for a variety of mobility needs including autonomous miniaturized mobile platforms (as transport mechanisms for a variety of sensors) and medical diagnostic tools for precision minimally invasive treatment.

B. Solution

In-situ, autonomous exploration and intelligence gathering from surfaces, subsurfaces, and environments will benefit from the new capabilities offered by a totally new class of exploring vehicles : "the bio-morphic explorers": with **animal-like mobility/adaptability, scaleable in size, equipped with dedicated microsensors**. For example, a mission to Mars/Europa in search of life or evidence of prebiotic materials would benefit immensely from such explorers. Large number of such inexpensive, therefore dispensable explorers would enable a new paradigm in exploration[1] that will enrich our capability for exploration site selection/sample collection by providing a much wider horizon of areas for inspection/testing. Their dedicated sensing functions and maneuverability would be invaluable in hazardous or difficult-to-reach territories for scouting missions. Combining the flexible actuators and biomorphic controls would offer for the first time a new direction in ***ADVANCED MOBILITY WITH NEW CAPABILITIES*** of adapting to terrains, enhanced spatial access owing to flexibility, and ease of multiplicity due to reduced complexity.



C. Detailed Report attached

EXHIBIT A

*PROPOSAL TO **TRIWG FY'98***

ADVANCED MOBILITY: BIO-MORPHIC EXPLORERS

PI: **Sarita Thakoor,** *Jet Propulsion Lab (Div. 34);* ***CO-I:*** **Adrian Stoica,** *Jet Propulsion Lab (Div. 34)*

ABSTRACT

Development and demonstration of "bio-morphic explorers" based on a unique combination of direct-driven, electrically/photonically stimulated, strong, flexible actuators and their control by adaptive, fault-tolerant biomorphic algorithms is proposed. The composite piezoceramic/polymer materials-based flexible actuators, employing innovative amplification techniques to provide the desired combination of *high force and displacement characteristics*, will form the legs, muscles, or mobile "limbs" of the explorer. The biomorphic controls promise an excellent approach to capture learning and adaptivity in the behavior of the actuator(s) assembly to autonomously match with the changing ambient/terrain conditions. Based on selected mobility mechanisms emulating biology, this 3-year effort will involve the development, design, and demonstration of a multi-limb explorer system. This demonstration will be done, first in a CAD-based simulation and subsequently in hardware, highlighting its new capabilities of learning and adaptive response to a variety of terrains (not possible with the current conventional approaches to mobility). Other features of the bio-morphic explorers include a substantial reduction in system complexity, enhancement in its survivability, and power efficiency.

I. OBJECTIVE

The overall objective of the proposed effort is: (1) to develop flexible "limb-like" actuators (based on smart materials offering high force/efficiency, high deflection and robust cyclability) and (2) to combine them with novel "biomorphic" control strategies (neurocontrol evolved by neural/genetic algorithms). This will lead to demonstration of the "bio-morphic explorers" exhibiting adaptive mobility mechanisms with learning ability, especially suitable for a variety of future exploration environments. For example, multipod inchworm/crawling/undulatory mechanisms or innovative swimming mechanisms will address the unique exploration challenges offered by the loose gravel/sandy areas on Mars terrain and icy surface/subsurface oceans of Europa respectively, to enrich and enable exploration with NEW capabilities.

II. JUSTIFICATION AND BACKGROUND

In-situ, autonomous exploration and intelligence gathering from surfaces, subsurfaces, and environments will benefit from the new capabilities offered by a totally new class of exploring vehicles : "the bio-morphic explorers": with **animal-like mobility/adaptability, scaleable in size, equipped with dedicated microsensors**. For example, a mission to Mars/Europa in search of life or evidence of prebiotic materials would benefit immensely from such explorers. Large number of such inexpensive, therefore dispensable explorers would enable a new paradigm in exploration[1] that will enrich our capability for exploration site selection/sample collection by providing a much wider horizon of areas for inspection/testing. Their dedicated sensing functions and maneuverability would be invaluable in hazardous or difficult-to-reach territories for scouting missions.

Some of the most influential recent approaches to mobile robotics are discussed in the following. In the *behavior-based approach* introduced by Brooks[2], the robot behaviors are developed gradually, from simple to more complex. The approach puts an important accent on embodiment and situatedness (real robots performing in their target environments). A primary purpose in robot life is its survival in the environment. The *neuromorphic* approach illustrates the power of neural models using artificial neural networks for sensory-motor control. A good example of an application oriented system using neural networks is the vision guided vehicle NAVLAB, which drives autonomously at 55m/h under neural control[3]. The *evolutionary* approach ("evolve by a natural selection mechanism") makes use of evolutionary techniques (such as genetic algorithms or genetic programming) to shape robot controls and sensory-motor maps. A variety of insect-like robots have been evolved[4] to exhibit different gait patterns, adapted to the particular environments in which they behave. *Bio-hybrid* robots combine natural and artificial parts. One such hybrid from Shimoyama's[5] lab is the roboroach, hybrid cockroach-robot which has no motor or gears but two real cockroach legs actuated by electrostimulation. *Biorobotics*[6-13] is the area of robotics in which robots can either utilize, mimic, or are inspired from, the biological functions, morphology, or behaviors of plants and animals.

We propose herein, a new paradigm in mobility combining flexible "limb-like" actuators and novel "bio-morphic" control strategies. Our approach is directed towards obtaining a new capability and significant potential advantages, especially when traversing unusual and difficult terrain (such as loose granular surfaces or icy surface/subsurface oceans) by imitating the mobility attributes of animals. Mimicking biology, such "bio-morphic explorers" will possess varied mobility modes (be easily reconfigurable from one form to another): surface-roving, burrowing, hopping, hovering, or flying, to accomplish surface, subsurface, and atmospheric exploration. They would combine the functions of advanced mobility and sensing with a choice of electronic and/or photonic control. Preprogrammed for a specific function, they could serve as "no-uplink, one-way communicating" beacons, spread over the exploration site, autonomously looking for/at the object of interest. The following comparison table highlights the new capabilities of the proposed approach:

Table 1: Comparison of Conventional Approaches and Proposed Approach

	Conventional Robots with Conventional Controls	Conventional Robots with Bio-morphic Controls	Proposed Bio-morphic Explorers with Bio-morphic Controls
Actuator Shape	Wheels (Legs - experimental)	Wheels (Legs - experimental)	Any Shape: (Legs, Limbs) Modifiable
Actuator Type	Conventional actuator materials, mostly Rigid flexible ERfluids/gels, Elastomers[9]:experimental	Conventional actuator materials: Rigid	Novel Flexible Actuators Low power, mass and volume
Drive Mechanical Motion	Electrical Motors, Complex Transmission	Electrical Motors, Complex Transmission	Direct-Driven Flexible Actuators
Control Strategy	Control Rules Based on Terrain Models	Learning, Adaptive, Neural (Biomorphic) Controls	Learning, Adaptive, Neural (Biomorphic) Controls
Control Sequence	Pre-determined Designed	Adaptively Evolvable, Generalizable	Adaptively Evolvable, Generalizable Re-configurable
Terrain Adaptability	No	Partial, Limited by the Actuator Type / Rigidity	Yes
Fault Tolerance	No	Partial, Limited by the Actuator Type / Rigidity	Yes
Scale Independent supports miniaturization	No	No	Yes
Spatial Access Narrow crevices	No	No	Yes
Complexity/Cost	High	High	Low

Key new features of the new paradigm in mobility proposed here in include:
(1) "Limb-like" flexible actuators: A limitation of current wheeled/jointed-legged mobility mechanisms is that only certain terrains that they are designed for can be accessed. Complex drive mechanisms for "transmission" of motion make them highly vulnerable. On the other hand, flexible actuators based active mobile limbs in this new paradigm would be direct driven, higher efficiency, with substantially lesser mechanical vulnerability.
(2) "Bio-morphic Control" : We will utilize, the recent emerging neuro-reflexive control, a powerful paradigm that offers for the first time real time adaptivity, generalizing and learning ability with fault tolerance that can be implemented in hardware. Combining the flexible actuators and biomorphic controls would offer for the first time a new direction in ***ADVANCED MOBILITY WITH NEW*** *CAPABILITIES* of adapting to terrains, enhanced spatial access owing to flexibility, and ease of multiplicity due to reduced complexity.

III. CONCEPT: BIOMORPHIC EXPLORERS - A NEW PARADIGM

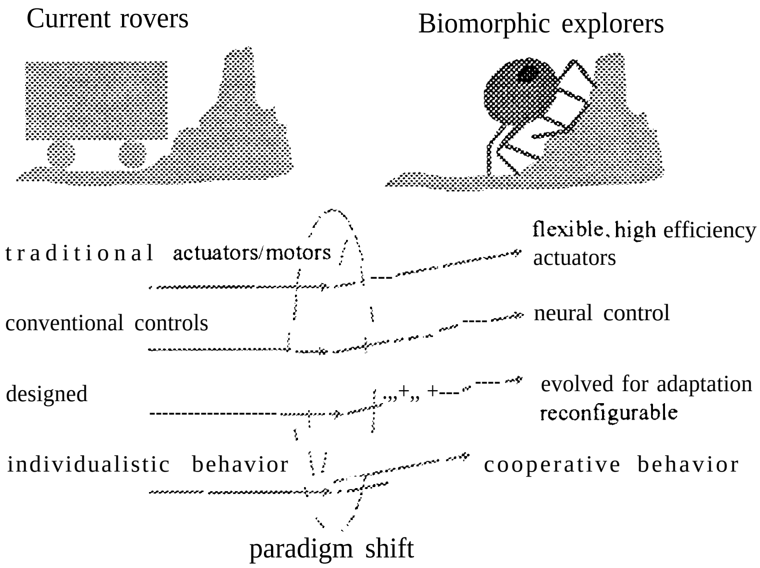


Figure 1. A paradigm shift for robotic explorers

The proposed effort is in line with an on-going paradigm shift: from rigid, mobility-limited traditional robotics to adaptive, bio-morphic explorers. We discuss in the following some important contributors to this paradigm shift, illustrated in Figure 1.

III. A. Advanced flexible actuators will allow design of direct-driven **"limbs" (legs/muscles/appendages)** bypassing the need for complex chassis (motors and transmission systems). The limbs will possess the added advantage of reconfigurability within a certain phyla/domain of mobile systems . Figure 2 illustrates four different kinds of biomorphic explorers[14] that could be constructed using such flexible actuators.

1. Multipod[15] crawlers/burrowers for surface/subsurface explorations maneuvering through soft soil and difficult terrain, adaptive to the environment (e.g. for Mars Exploration).
2. Ciliary / Flagellar Explorers[16] for navigation through fluids (e.g. for Europa Exploration[17])
3. Hopping Mechanisms for surface and aerial exploration
4. Hovering Explorers for aerial exploration

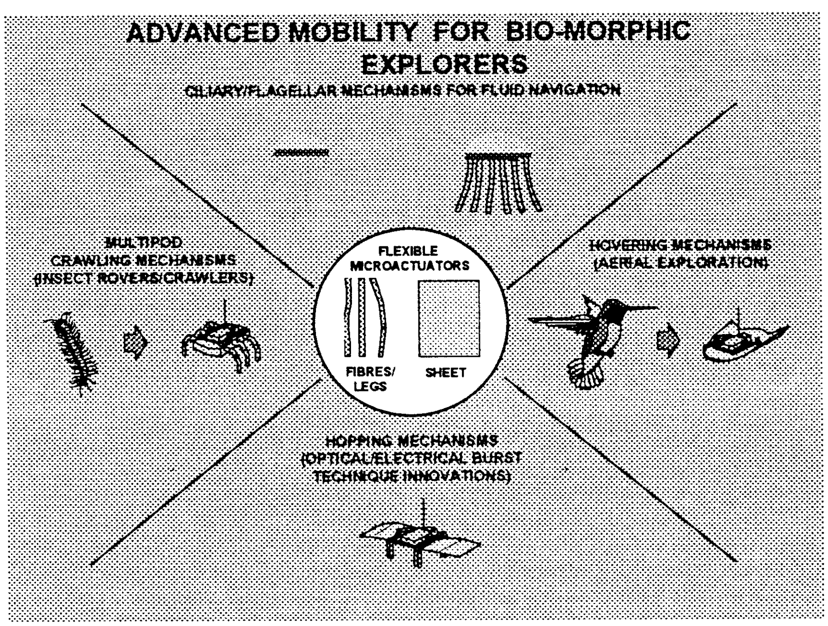


Figure 2: Advanced mobility for biomorphic explorers - lessons from biology

III.B. Inspired from biological neural networks, artificial neural networks (already available in VLSI implementations) possess unique ability of learning non-linear controls.

III.C. Evolutionary mechanisms for adaptation enhance traditional fixed designs. For example, control sequence to the legs may be determined for optimal ways to move in a particular environment.

III.D. Cooperative behaviors enable new types of missions, allowing distributed exploration with groups of robots, each of which could be dedicated to specific tasks.

We address in the proposed work first three out of the four mentioned characteristics of the biomorphic explorers, leaving the cooperative behavior issue for future work.

IV. ROADMAP-TASKS AND APPROACH

This work will focus on technology development in the areas of advanced mobility and bio-morphic control. The four main tasks, their implementation time schedule, and the approach proposed is detailed as follows:

Table 2: Tasks and Time Schedule

	Tasks	Year 1	Year 2	Year 3
1	Advanced Mobility			
	a) Animal mobility survey	<===>		
	b) Selection/optimization of smart actuator material(s)	<==============>		
	c) Down-selection of a specific bio-mobility mechanism(s) for simulation/hardware realization	<=======>		
	d) Simulation /demonstration of the selected Bio-mechanism(s) - limb design	<=========>*		
	e) Preliminary Explorer System Design with Payload options	<=======>		
	f) Bio-morphic Explorer Concept feasibility Demonstration	<======	==>*	
2	Bio-morphic Controls			
	a) Selection of bio-morphic algorithm/architecture for adaptive control	<====>		
	b) Development of software simulation	<=======>*		
	c) Demonstration of adaptive neurocontrol of the selected bio-mechanism in a CAD-based simulation		<=========__	
3	Flexible Mobile Limb Demonstration			
	a) Individual limb hardware design/fab	<=======	====>	
	b) Interface bio-morphic control software with the mobility test structure	<==	============>	
	c) Demonstration of individual mobile limb operation		<===========>*	
4	Multilimb Explorer Design			
	a) A CAD-based design of a multi-limb mobility system	<======	=======>	
	b) Feasibility demonstration of the biomorphically controlled multi-limb system in a CAD-based simulation		<=======	====>*
	c) Biomorphic Explorer Demonstration in Hardware		<====	============>*

The key milestones are indicated by *

IV.1. Advanced Mobility:

This task will involve the following four closely interrelated work items as described below.

a) **Animal mobility survey:**

Natural evolution of the world of insects has clearly experimented with virtually infinite mechanical designs, selecting some (e.g. legs and wings) for their effectiveness, and discarding others (e.g. wheels) due to the system integration difficulties. Legged designs are also capable of negotiating much more varied terrains than wheeled vehicles as demonstrated by Tilden[13]. Although an artificial mobile system does not have to exactly mimic any specific real animal, a systematic study of naturally successful mobility mechanisms, in conjunction with the rapidly advancing composite materials with interesting/useful properties (for e.g. a combination of high force and displacement at low power) will lead to hardware-implementable designs for bio-morphic explorers. Clearly, such study would not rigorously "copy" any natural designs (e.g. airplanes do not have to flap their wings). On the other hand, the study would not rule out incorporation of "unnatural" mechanisms (e.g. joints with full 360 degree rotation, are generally avoided by the natural evolution). The study would therefore focus on the mobility traits, physiology and mechanics of the bio-systems, their potential ease of implementability, and applicability to desired/conceptualized exploration scenarios. Such a comparative study in conjunction with evolving "in-situ exploration needs/scenarios" will lead to down-select one or more specific biological mobility design for further detailed analysis.

b) **Selection/optimization of Advanced Flexible Actuators** :

The PI has recently done a survey[18] of emerging/advanced actuation technologies. **Selection/optimization of smart actuator material(s)** from the rapidly advancing knowledge-base of advanced composite materials and innovative amplification techniques with interesting/useful properties (e.g. combination of high force and displacement at low power), will lead to hardware-implementable designs for the bio-morphic explorer. As an option, for example **flexible actuators** may be fabricated[18] by depositing tailored thick (~ 2-10 micron) films of active(piezoceramic) materials on strong flexible (polymeric) substrates. Not only such **flexible actuators could be tailored to provide a combination of high force and displacement, but would also be operable over a wide temperature range based on material composition selection**. Potential advantages of flexible actuators are:

1) low power (low voltage operation, < 5 V), low mass, low volume

2) low cost, batch production of the components compatible with VLSI processing

3). high force/volume even with low voltage operation

4) higher deflection

5) flexible, miniaturizable from meter scale down to microns: readily scaleable for MEMS/MOMS

6) excellent cyclability -more than million cycles

7) amenable to both electrical or optical activation.

In addition to the high energy density offered by piezoceramic thin films (up to 5 times enhanced ratio of output force per unit volume for a film bimorph with operation at the Si-VLSI compatible low voltage of < 5V), they promise two to three orders of magnitude enhanced conversion efficiency in a piezoceramic flexible bimorph when activated optically accompanied with up to 200 times higher ratio of output force to input power (refer Table 3). Flexible actuator can be formed in the form of fibers or sheets.

b.1 **Fabrication of flexible actuator structure:** Flexible actuator test structures would be fabricated by depositing tailored thin (2-10 micron thick) films of selected composite piezoceramic material (e.g. PLZT) films on suitably selected flexible film substrates. The substrate must have high temperature stability, high strength (Young's Modulus ~ 4.9×10^{10} N/m^2), a close match of thermal coefficients of expansion with the piezoceramic film, and a tailorable crystal orientation in order to provide a desired template for growth of oriented PLZT. Earlier work has shown[19] that ferroelectric quality PZT could be crystallized at ~ 550°C. Polybenzoxazole (PBO) has been validated[16] to work well up to ~ 550°C and extensively characterized for operation at 460°C. Yavrovian et al provide[20] the comparative data for a variety of substrate films and fibers. PBO stands out as the leading candidate for its high tensile strength, high Young's Modulus, low heat shrinkage and coefficients of thermal expansion and hydroscopic expansion to provide such a high temperature substrate for forming flexible microactuators by this technique. As an alternative, piezoceramic films deposited on the known high temperature substrates (e.g. alumina or silicon) would be delaminated after crystallization and mounted on the selected flexible substrates.

b.2 **Optimization of the Piezoceramic films: The** technique[19] of multiple-sequential-target sputter-deposition of films with tailored composition compatible with low temperature microelectronic processing for deposition of the multicomponent oxide piezoceramic films of lead lanthanum zirconate titanate (PLZT) is already leading to fruitful collaborations with industry. The film quality improvement will be achieved by combining the following:

(i) <u>Optical quality enhancement:</u> The defect density in a thin film could be lowered by over an order[21,22] of magnitude, thus reducing scattering losses that are common in the ceramic wafer. Also the optical absorption coefficient in a thin film could be tailored to be almost 20% higher than that in the bulk materials. **An order of**

magnitude better absorption is expected in the thin film compared to the ceramic wafer leading to a correspondingly higher efficiency.

(ii) Polarization direction & intensity optimization: Photoresponse from ferroelectric thin films is shown[23, 24] to be maximum when the electric field vector associated with the incident light is parallel to the c axis in the material. In fact, the observed small effect from the edges of the ferro-capacitors (with c axis predominantly perpendicular to the substrate) was primarily attributed to the domains which had some angular variation (estimated to be in the range of +/- 10 to 15 degrees) with respect to the substrate perpendicular. Such photoeffects are known[22] to exhibit enhancement by over an order of magnitude when the alignment of the incidence E field with the c axis changes from nominally 10 degrees to ~ fully parallel. Therefore the photodeflection effect is expected to be maximum when the photonic electric field is parallel to the spontaneous polarization in the ceramic (namely, the c axis), optimization of the angle of incidence and tailoring the direction of spontaneous polarization in the ferroelectric will lead to maximum interaction with photon incidence and thereby maximum photodeflection. **This optimization will allow design of an actuator with another order of magnitude enhancement in efficiency.**

(iii) Optimization of the optical penetration effect: Since the absorption of the illumination occurs in at the most 1 to 10 micron skin of the piezoelectric material facing the illumination, the photovoltage generation is expected[25] to be entirely located in this thin top skin layer. Using a film thickness equal to this penetration depth ensures that the entire film is active. In a ceramic typically ~ 200 micron thick, almost 95% of the bulk is an inactive mass to be moved. In films, therefore significantly larger displacements are expected.

Table 3: Flexible film actuators. matrix of improvement

		Current Status Ceramic Actuator	Projected Improvement Film Actuator
ELECTRICAL ACTUATION PARAMETERS	Thickness	200 microns	2 microns: Thickness reduced, material tailored
	Operating Voltage	100 V	5 V : Operational voltage reduced
	Energy Density	1 x	25 X : Inherent advantage of reduced thickness
	Force/Volume	1 x	5X enhancement for film actuator
OPTICAL ACTUATION PARAMETERS	Optical Power	80 mW/cm^2	8 mW/ cm^2 : Illumination Intensity reduced by 10 times
	Photonic to Mechanical Energy Conversion Efficiency	0.1 %	1 % - 10 % : significant enhancement in overall efficiency
	Force /Energy	1 x	2X to 20X : Multifold enhancement in the film actuator
	Force /Power	1 x	20X to 200X

Table 3 shows the projected parameters of improvement. The numbers in this table are evaluated based on using a 200 micron thick typical ceramic wafer as the current state of the art and a 2 micron thick film as the flexible film actuator projected[18] to deliver about 25 times higher energy density

We have recently demonstrated in collaboration with Penn State, a deflection amplification technique tha enhanced the deflection of an actuating device (based on bulk piezoceramic PZT wafers) from 2 micron to millimeter (sponsored by **the Advanced Concepts Research Program Office**). Further step and repe techniques and multilayer stacking that we are working on with our Industry/University partners can provide hi force in combination with the high displacement tailored for a specific application. With such ability to tailor t desired force and deflection combination, advanced flexible actuators will enable the innovative mobility desi conceived in subtask 1a.

c) **Down-selection of a specific bio-mobility mechanism(s) for simulation/hardware realization**:

Determination of hardware implementability (using advanced actuators) of any effective, miniaturized, mobility system akin to biology will be dictated by a variety of engineering factors. This will include a systematic analysis and comparison of the selected bio-examples, to address the feasibility and optimization of hardware embodiment and the control algorithm, with respect to their characteristics such as: [i] range of possible speed, [ii] load bearing capacity, [iii] degrees of freedom for mobility, [iv] power requirement, control requirement, [v] mechanical complexity, [vi] configuration scalability [vii] candidate material and mechanism choice [viii] durability/ longevity/ cyclability [ix] adaptability to different terrain types, for example soft granular soil or icy terrain [x] re-configurability and [k] manufacturability- cost analysis This analysis would lead to candidate materials and mechanism choice(simple or composite) for the promising design(s). A biological mechanism from subtask la will be down selected for further emulation to demonstrate the potential of such flexible advanced actuators in forming a "limb" (articulated centipede leg / undulating body muscles (snake)/contractile muscles of the bell for jet propulsion in aquatic animals).

d) **Simulation and demonstration of the selected Bio-mechanism(s)**: A CAD-based software simulation will combine the selected bio-mobility mechanism(s) and the chosen smart material(s) with their relevant physical properties to assess and demonstrate the projected performance of one or more limb-like structures. The simulated limb structure design(s) will incorporate realistic geometrical configuration(s) and physical dimensions, as well as relevant (chosen) ambient conditions, to evaluate the projected performance of the structure(s) and establish their superior mobility potential compared to the current state of the art.

e& f) **Bio-morphic explorer concept feasibility demonstration:** The design of a biomorphic-explorer, equipped with the selected/optimized miniaturized mobility mechanism would also involve consideration of an appropriate utilization of a natural/artificial power source (to make the explorer self-sufficient or remote controlled) as well as a candidate payload, representing a dedicated sensor and communication subsystem to extract the significant information collected by the explorer. Another part of this activity will be to identify functions/payloads for the biomorphic-explorer and develop a mission scenario that demonstrate the full impact of utilization of the low cost expendable explorers. For example focus on the Mars exploration requirements may lead to a centipede[15]/snake[26] combination mobility mechanism that can burrow/run through sandy/gravel terrain at high speeds with a exobiological tool on its back beeping back information if and only if it finds what it is programmed to look for. An Europa exploration scenario may consist of a three pronged mission including (i) a ice trailing crawler, (ii) a large screw drill penetrator to negotiate in and out of the thick ice surface (iii) carrying within it tiny jellyfish like explorers/swimmers that will be released into the subsurface ocean, to obtain the three levels of exploration.

IV.2. Bio-morphic Controls:

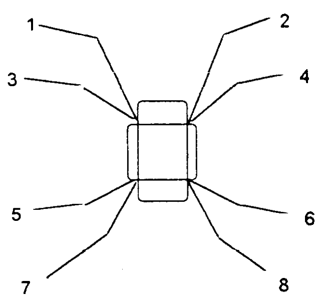
Biology tells us that the control of periodic limb motion sequences are generally delegated to a lower level controller (e.g. spinal cord in humans) than the powerful CPU (e.g. the brain). Obviously, this relieves the brain resources to attend to the higher level cognitive functions including sensory information processing (e.g. vision, hearing, etc.). This arrangement does not of course rule out a higher level command from the brain to the spinal cord to modulate/change the ongoing periodic motion whenever necessary, based on sensory input received and processed. For example, decision to turn or run in a specific direction rather than walk on the sight of a prey/predator.

This subtask is composed of three essentially sequential work items as described below:

a) **Selection of biomorphic algorithm/architecture for adaptive control:**

This will initiate with simple neural controls and will gradually evolve into an optimum architecture desired. Biological mobility systems have two important characteristics which could be used in the development of increased performance engineering systems: they are controlled by neurons, and they have evolved by natural selection to highly adapted solutions. The most popular "evolutionary engineering" mechanism are genetic algorithms (GA). GAs are a search/optimization method using principles of natural selection to obtain systems adapted to their environment. GAs perform a parallel search, operating on a population of individuals, each individual having a unique genotype (information coded in "chromosomes") and fitness, which is a measure of phenotype's (external behavior determined by genotype) success in meeting some objectives. GAs aim to improve the general fitness of the population by selective breeding, merging the genetic material of most fitted individuals, (and also some random mutations) to obtain the genotypes of offspring in a new generation. The fittest member of the final generation is taken to be the optimum. In evolving robots, our approach would be behavior-based[1] in the sense that the robot behaviors would be developed gradually, from simplest to more complex.

In a first stage, simple mobility mechanisms, such as gait would be evolved. As an example the control of the leg motion can be evolved into several types of gait pattern. Consider the schematic of an artificial insect, modeled after a spider, with 8 legs. A neural network controller is associated with each leg, the controllers being interconnected. The neural weights are randomly initiated and accordingly a sequence of leg movements is produced. Scoring the walk of the robot in several trials with different parameters (for example giving higher score to those who move further), and applying a genetic algorithm reproducing the genetic code with a selectionist bias on most fittest individuals lead to a insect-like gait pattern. An example of a gait pattern evolved in simulation is:



At time= t1, simultaneously trigger legs 1, 2, 5, and 6;
At time= t2, simultaneously trigger legs 3.4, 7, and 8.

A variety of insect-like robots have been evolved to exhibit different gait patterns, adapted to the particular environments in which they behave. Examples of evolved locomotion controller for insect-like robots are given earlier[4, 8]. The evolutionary approach is scale-invariant. The same evolution mechanisms apply for both big and small robots. Miniature robots can be ideally paired with small sensors and built at lower cost.

In a second stage, simple behaviors would be coordinated into more complex ones (such as moving in some direction, while actively looking for the home-target and balancing a load). *A third stage* would address the development of collective behaviors of several individual robots tasked with the same mission. The selected biomorphic/neural algorithm then would be simulated as a versatile software package under the next subtask

b) **Development of software simulation:**

When appropriately interfaced with the CAD based bio-mechanism selected in the task 1, the software simulation will lead to the next subtask

c) **Demonstration of adaptive neurocontrol of the selected bio-mechanism in a CAD-based simulation:**

For developing mobility mechanisms, evolutionary algorithms would shape the type and position of actuators, and the neuro-motor control signals to the actuators and sensory-motor maps. Previous evolutionary robotics approaches consisted of determining control commands to electric motors that powered legs or wheels. Based on advanced actuators, our approach eliminates motors from the system, the controlled electric signals to the active limbs, directly produce forces used for locomotion. Tolerances in the characteristics of the actuator materials are accepted by the method, evolution through trial and error compensates for them.

A successful conclusion of the first year's activity therefore would lay an excellent foundation for undertaking actual development of a prototype biomorphic explorer by providing a full quantitative 3D visual/mechanical design and kinematic model of the explorer mobility and its controls. Demonstration of the Bio-morphic explorer concept feasibility in simulation will be the key milestone of Year 1.

IV.3. Flexible Mobile Limb Demonstration:

a) Individual limb hardware design/fab based on the flexible advanced actuators selected, characterized and optimized in Year 1.
b) Interface biomorphic control software with the mobility test structure.
c) Demonstration of individual mobile limb performance with order magnitude higher efficiency will be the key milestone of Year 2.

IV.4. Bio-morphic Explorer Demonstration :

a) A CAD-based design of a multi-limb mobility system.
b) Feasibility demonstration of the biomorphically controlled multi-limb system in a CAD-based simulation and characterization of multi-limb hardware.

c) Biomorphic Explorer Demonstration in hardware will be the key milestone for Year 3.

V. COST ESTIMATE: Total Cost Estimate : $ 103 OK. Duration:3 Years

	Year 1	Year 2	Year 3
Cost Estimate	$250 K	$ 350 K	$ 480 K
Work Year Effort	1.36WY	12. 0 WY	2.6 WY

VI. DUAL USE POTENTIAL:

Main application of this bio-morphic explorer concept is seen in robotics (robots highly adapted to specific environments, available in multitudes at low cost (for example Mars/Europa for NASA missions, earthquake rubble or hazard area exploration for Industrial/DoD needs etc. environmental clean-up, security and intelligence purposes, Navy and geologic exploration has need for such explorers for under-water and hazardous area exploration respectively) such as navigation adaptable to terrains, swimming, hovering, etc.. Additional uses are seen in instrumentation (microinspection, flow control valves, adaptive control, motion/load sensing instruments, etc.) and medical diagnostics/precision surgery.

VII. PARTICIPANTS:

Division 34: Sarita Thakoor, Adrian Stoics

Consultants: Steve Saunders, Joy Crisp, Bruce Banerdt, Sue Smreker (JPL, 32): **Science Applications**; Frank Carsey(JPL): **Application Specific System Design**; Prof. C. Brennen/J. Burdick (*CALTECH)*: **Mechanical Engineering Design**; Prof. Robert J. Full/Bruce Anderson, Prof. M. Koehl/J. Jed (*Universitv of California, Berkeley):* **Biological Inspiration and Bio-inspired design**; **Andre** Yavrouian (JPL, 35):**High temperature Polymeric Substrates**; Steve Townes (JPL,33): **Telecommunications**; Prof. Dave Rutledge, *CALTECH* **: Telecommunications;** S. Surampudi (JPL, 34): **Small Power Sources**.

This effort will leverage with the concurrent work ongoing on actuator development at JPL alongwith Industry collaborators, and other University collaborators such as Penn State, and MIT.

VIII. USER ADVOCACY*:*

Sam Gulkis, *Advanced Concepts Office, Program Manager;* **Dan McCleese,** *Mars Exploration, Chief Scientist;* **R S. Saunders,** *In-situ Exploration COE, Chief Scientist;* **Lynn Lowry,** *Technologist, Mars Exploration Directorate*

IX. INVESTIGATORS:

Sarita Thakoor, MS, MPhil in Physics from Univ. of Delhi India (1977, 1979), Member of the Technical Staff at JPL will lead this effort. She has been involved at JPL/CALTECH for the last twelve years in the R & D of a variety of novel thin film memory devices for neural networks, non-volatile ferroelectric memories, and microactuators for robotics and active control. Within the last six years, she has taken a lead role in piezoceramics/ferroelectrics and created/conceptualized innovative designs of piezoceramics based devices/applications, in particular flexible microactuators. She holds five patents including three on device designs for ferroelectric memories and electro-optically addressed devices with non-destructive readout. She has published over 18 refereed articles and made over 30 conference presentations. She serves as a member of the editorial board of the journal "Integrated Ferroelectrics" and a member of IEEE and Materials Research Society. She is a recipient of over twenty certificates of recognition/awards from NASA for new technology innovations. She earlier organized a very successful conference on Non-volatile memories for the advanced concepts office at JPL and led a workshop discussion for the DARPA sponsor on the same subject. Her current research interests include ferroelectric and piezoceramics for robotics, innovative concepts of mobility, biologically inspired advanced mobility, microactuators for shape control and biomedical applications, sensors, and non-volatile memories.

Adrian Stoics is a Member of Technical Staff at JPL. He received his Ph.D. from Victoria University, Melbourne, Australia, with a thesis in robot learning. His expertise is in learning and adaptive systems, fuzzy logic, neural networks, and evolutionary computation. He has published over 30 papers in these areas. His robotic research addressed learning sensory-motor control for anthropomorphic robots. His most recent work focuses on evolvable hardware. He is a member of IEEE, AAAI, ACM.

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*Please obtain references from the sources listed.

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RECONFIGURABLE, ADAPTABLE, MOBILE SYSTEMS
"BIO-MORPHIC EXPLORERS"

JPL

Sarita Thakoor and Adrian Stoics

EXHIBIT B

1b

March 4,1997

JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY
PASADENA, CALIFORNIA 91109

Presentation to DARPA:
Dick Urban, Asst. Director, TECHNOLOGY INTEGRATION

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RECONFIGURABLE, ADAPTABLE, MOBILE SYSTEMS "BIO-MORPHIC EXPLORERS"

PURPOSE OF THE MEETING:

- TO UNDERSTAND DARPA's/DoD's NEEDS IN THE AREA OF RECONFIGURABLE, ADAPTABLE, MOBILE SYSTEMS

- TO DISCUSS THE JPL CONCEPT OF "BIO-MORPHIC EXPLORER"

2b

DARPA'S INTEREST

- SMALL INEXPENSIVE MOBILE SYSTEMS THAT CAN TRAVEL OVER A VARIETY OF TERRAINS
  - BEING ABLE TO AUTONOMOUSLY CHANGE THEIR PHYSICAL CONFIGURATION IN FIELD/ IN-SITU
  - TO ADAPT TO THE CHANGES IN THE TERRAIN CONDITIONS, AS REQUIRED

................00000 Synergistic with NASA's interest in autonomous rovers for scouting missions/planetary exploration

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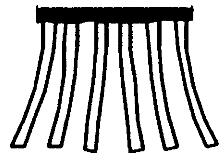
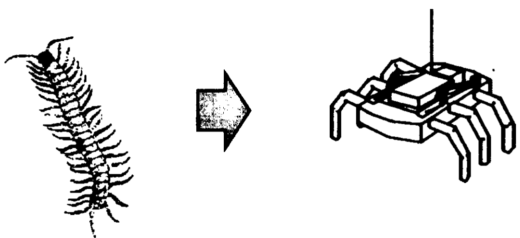
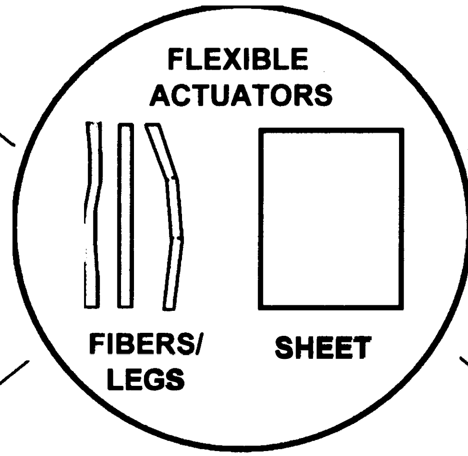
ADVANCED MOBILITY FOR BIO-MORPHIC EXPLORERS

CILIARY/FLAGELLAR MECHANISMS FOR FLUID NAVIGATION

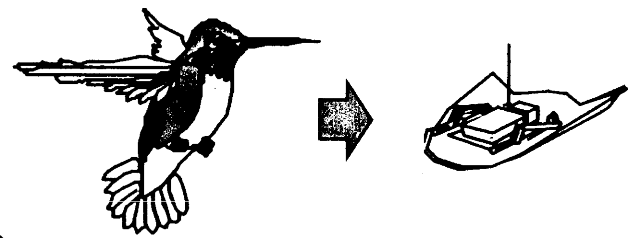


MULTIPOD
CRAWLING MECHANISMS
(INSECT ROVERS/CRAWLERS)

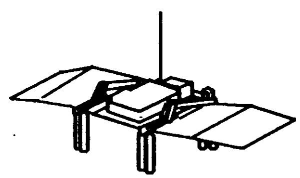




HOVERING MECHANISMS
(AERIAL EXPLORATION)



HOPPING MECHANISMS
(OPTICAL/ELECTRICAL BURST
TECHNIQUE **INNOVATIONS)**



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RECONFIGURABLE MOBILE SYSTEMS

- **TRULY SUCCESSFUL "RECONFIGURABLE" SYSTEMS WITH RESPECT TO MOBILITY TODAY COME FROM NATURE....... ANIMALS/INSECTS**

  e.g. animals **have the** ***ability*** **to adapt their** ***mobility as the terrain changes. They effectively "transform" their mobility*** **attributes to** ***be*** **ah/e to** ***walk on*** **hard** ***surface*** **or** ***soft soil,*** **or** ***to s wim in water. They*** **use the same** ***limbs,*** **spread around** ***differently*** **to** ***obtain*** **the desired mobility** ***and*** **adapt the** ***motion*** **parameters to suit the** ***ambient needs.***

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RECONFIGURABLE MOBILE SYSTEMS

- **FEATURES OF RECONFIGURABLE SYSTEMS**

  DIRECT DRIVEN, FLEXIBLE ACTUATORS forming legs, arms, and multitude of muscles

  HIGHLY ADAPTIVE, TRAINABLE , “bio-control” of the actuators.

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CONCEPT

BIO-MORPHIC EXPLORERS

- BIOMORPHIC EXPLORERS: a unique combination of direct-driven, electrically/photonically stimulated, strong, flexible actuators and their control by adaptive, fault-tolerant biomorphic algorithms

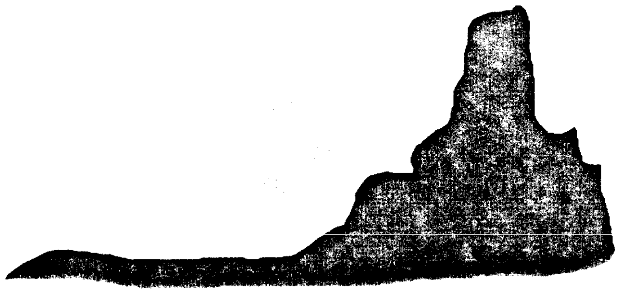
- biomorphic controls promise an excellent approach to capture learning, fault tolerance and adaptivity in the behavior of the actuator(s) assembly to autonomously match with the changing ambient/terrain conditions

PAYOFF:

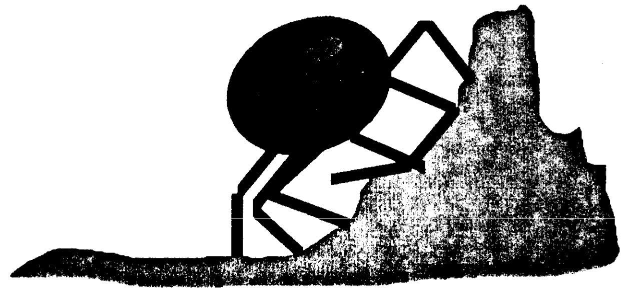
- ADAPTABLE TO VARIETY OF TERRAINS
- HAZARDOUS AREA DUTIES
  - ENVIRONMENTAL CLEAN up/inspection
- SCOUTING MISSIONS
- SECURITY/SURVEILLANCE

CONCEPT: BIO-MORPHIC EXPLORER

Current rovers



Bio-morphic explorers



traditional actuators/motors → flexible, high efficiency actuators

conventional controls → neural control

designed → evolved for adaptation reconfigurable

individualistic behavior → cooperative behavior

paradigm shift

8b

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NEW PARADIGM FEATURES

FEATURE	TRADITIONAL	NEW PARADIGM
LIMB	PASSIVE	ACTIVE
DRIVE MECHANISM	INDIRECT	DIRECT
CONTROL	RULE BASED	BIOMORPHIC
DESIGN	FIXED	RECONFIGURABLE

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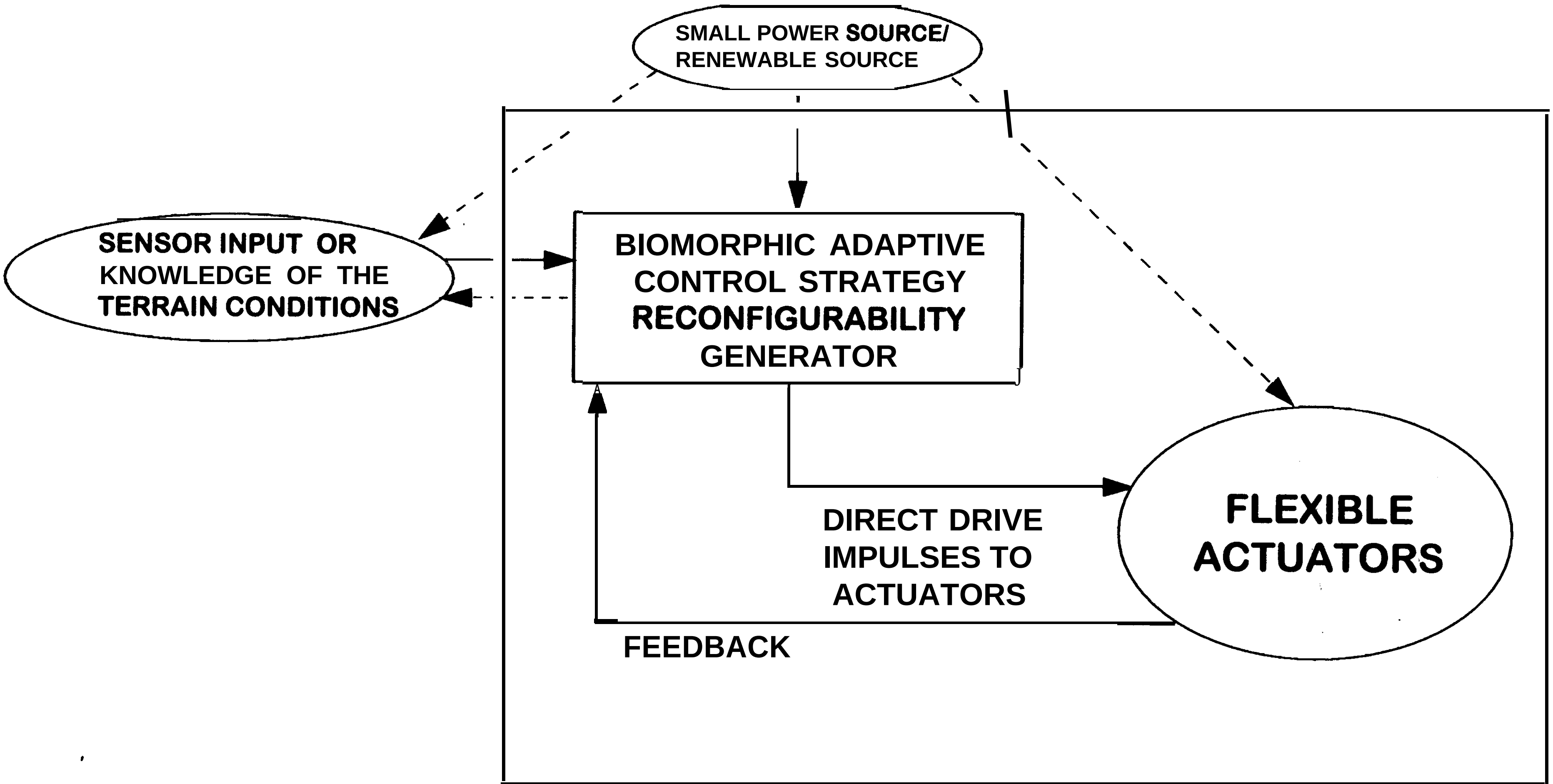
BIO-MORPHIC EXPLORER SCHEMATIC



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BIO-MORPHIC EXPLORER IMPLEMENTATION SCHEMATIC

Advanced Mobility

- Mechanism emulating biology
- Flexible actuator selection/optimization
- Preliminary Explorer Design with Payload
- Demonstrate feasibility of concept

Bio-Morphic Control

- Algorithm/architecture selection
- Develop software simulation
- Demonstrate adaptive Bio-Control

Individual Mobile Limb Demonstration

Multilimb Explorer Concept Demonstration

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RECONFIGURABLE MOBILE SYSTEMS

- WHAT IS RECONFIGURABILITY?

When signal comes in that *the ambient* has changed from *A* to *A'*, then you want response *signals* generated that *would* reconfigure *the* actuators to *behave* different*ly*

e.g. legs -----------> fins

straight legs --------> webbed feet

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RECONFIGURABLE MOBILE SYSTEMS

- HOW WILL IT BE ACHIEVED?

  If solid surface for example *changes* to *soft flour-like soil, the legs would change* continuously *wrt the* distance between *them, the* gait of *motion, the* position in *which* they *will contact the* ground

  e.g. vertical stick to arms bent at elbows in order to change from a pogo stick configuration to a webbed feet configuration

JPL WHY PIEZOCERAMIC ACTUATION?

(AS WE SCALE DOWN TO THIN FILM PIEZOCERAMICS)

			POLYMERIC MATERIALS		
	PIEZOCERAMIC	SHAPE MEMORY ALLOY	**PVDF** and **PVDF** copolymers	**Polymides PMMA Polyurethanes**	**MAGNETO-STRICTIVE**
MECHANISM	**PIEZOELECTRIC & ELECTROSTRICTIVE**	**THERMAL: MARTENSITIC → AUSTENITIC** PHASE CHANGE	**PIEZOELECTRIC,** PHASE **TRANSITION**	ELECTRO-**STRICTIVE**	MAGNETIC FIELD INDUCED BY COIL
STRAIN	**10^{-4}** TO **0.3×10^{-2}****	**10^{-5} TO 10^{-1}**	**10^{-6} TO 10^{-1}**	**10^{-9} TO 10^{-2}**	**10^{-5} TO 10^{-2}**
DISPLACEMENT	LOW TO **HIGH***	MEDIUM TO **HIGH*****	LOW TO HIGH	LOW TO **MEDIUM**	MEDIUM
FORCE	**HIGH ~100 kgm** FORCE	LOW-MEDIUM **~1 kgm** FORCE	SMALL	SMALL	HIGH
HYSTERESIS	**TAILORABLE** BY COMPOSITION	SMALL	LARGE	SMALL TO MEDIUM	**LARGE**
AGING	COMPOSITION DEPENDENT	VERY SMALL	LARGE	LARGE	SMALL
TEMPERATURE RANGE OF OPERATION	**−196°C → 300°C** WIDE	**−196°C → 100°C** WIDE	**−50°C → 150°C** MEDIUM	**−10°C → 80°C** LIMITED	**-273°C → 100°C** WIDE
RESPONSE SPEED	**μsec-msec**	seconds	**msec**	**msec**	**μsec-msec**
ACTIVATION MODE	BOTH OPTICAL AND ELECTRICAL	THERMAL AND ELECTRICAL	ELECTRICAL	ELECTRICAL	MAGNETIC
POWER REQUIREMENT	LOW	LOW	MEDIUM	LOW TO MEDIUM	HIGH
RADIATION HARDNESS	**YES**	**TBD**	**TBD**	**TBD**	YES
CYCLABILITY	EXCELLENT	GOOD	FAIR	FAIR-POOR	GOOD
PROSPECT OF MINIATURIZATION	GOOD	GOOD	GOOD	GOOD	FAIR

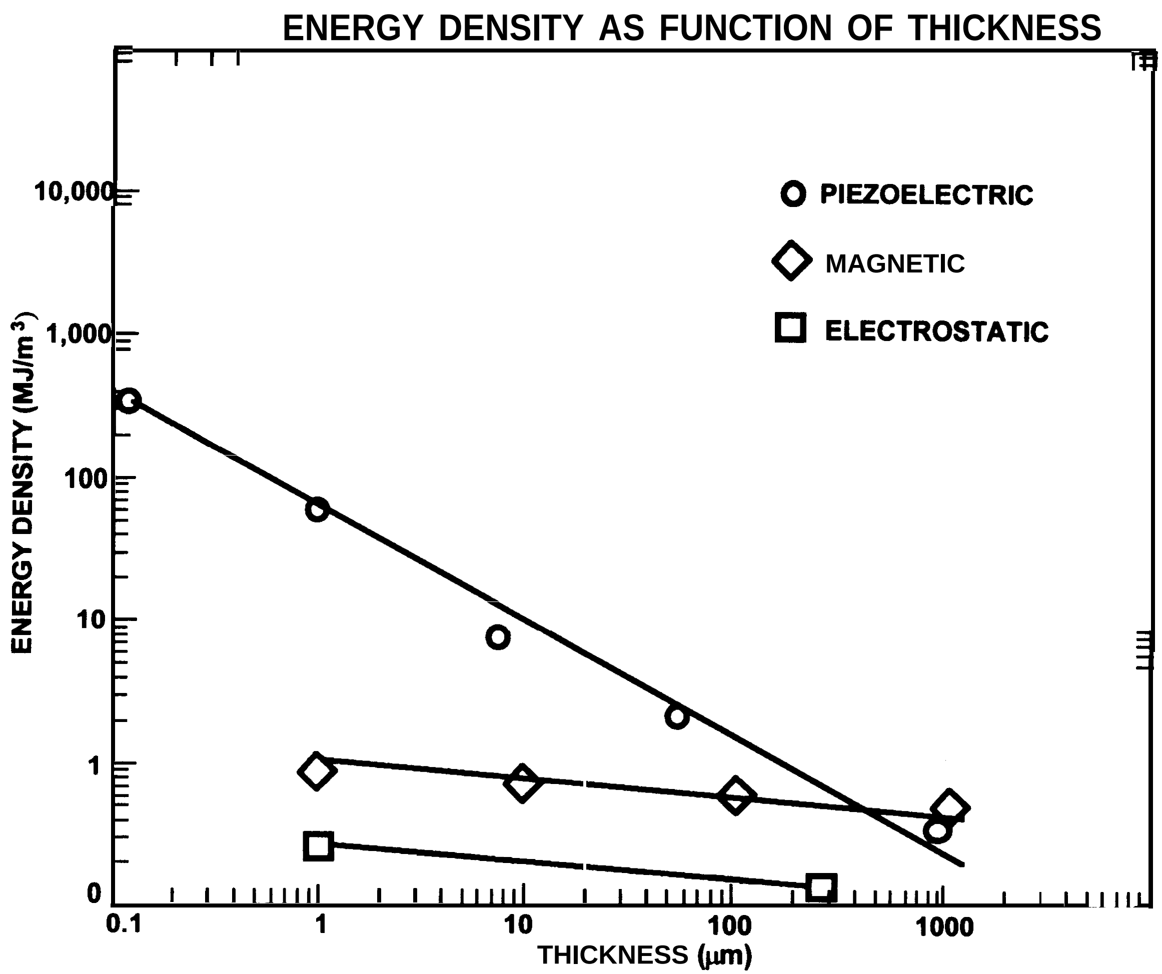
PIEZOELECTRICS REPRESENT A LEADING CANDIDATE FOR ADVANCED **MICROACTUATION**

* With amplification techniques (**e.g.** optically or electrically activated **bimorph, flextensional** elements and combination thereof to obtain double **amplification)**

** **Antiferroelectric** phase transition materials

*** Limited by Thermal Energy Input

JPL COMPARISON ACTUATION TECHNOLOGIES



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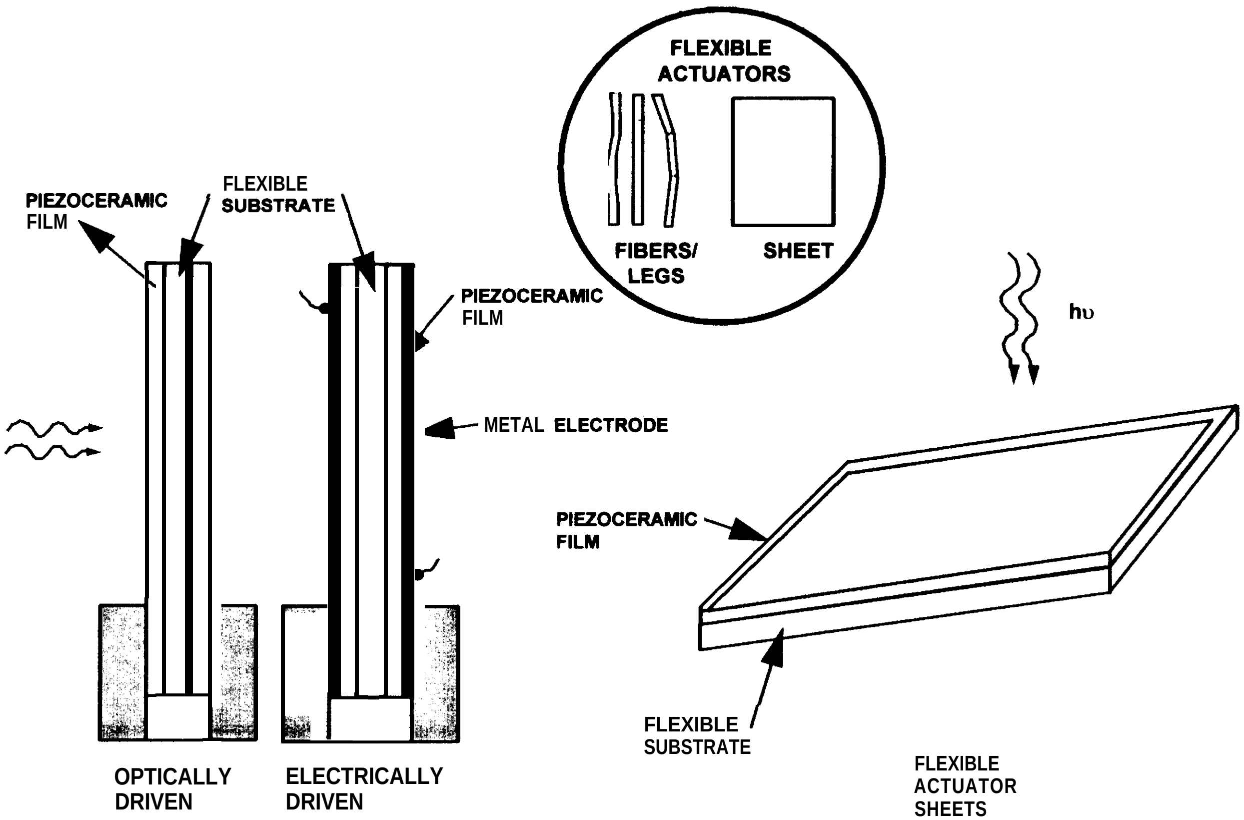
Flexible Actuators For Advanced Mobility



Flexible actuators are envisioned by depositing tailored thick (~ 2-10 micron) films of active materials on judiciously chosen, strong flexible substrates.

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BIO-MORPHIC EXPLORERS TEAM

- **Sarita Thakoor, JPL:** *Advanced Flexible Actuators,*
  Optical Actuation
  Integration of Biomorphic Explorer
- **Adrian Stoica, JPL:** *Reconfigurable, Evolvable Electronics*
  Biomorphic Controls
- **Surampudi Rao, JPL:** *Small Power Sources*
- **CALTECH:** *Mechanical Design, Telecommunication*
- **UC Berkeley:** *Biologically Inspired Mechanical Design*
- **Penn State:** *Actuation, Amplification techniques*
- **INDUSTRY:** *Manufacturing of film actuators*

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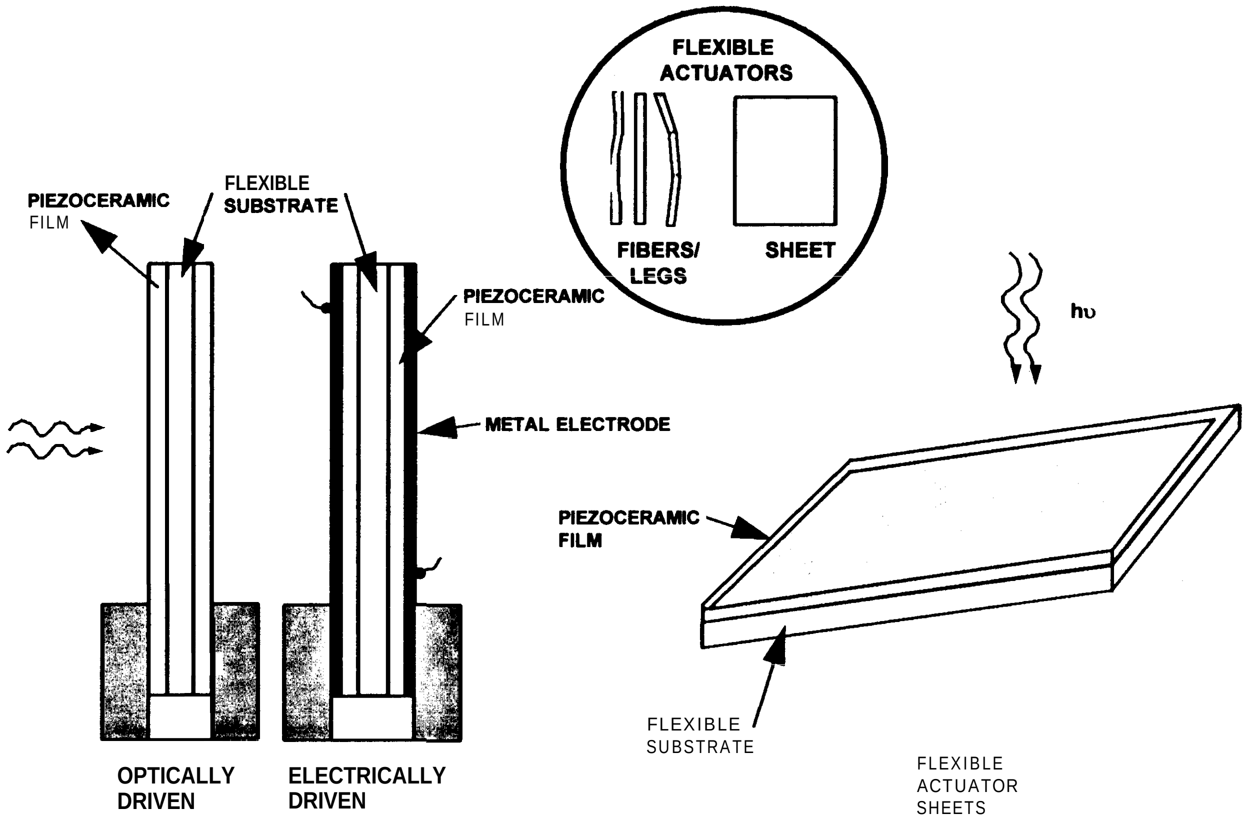
SUMMARY
RECONFIGURABLE, ADAPTABLE, MOBILE SYSTEMS
"BIO-MORPHIC EXPLORERS"

- BIO-MORPHIC EXPLORERS ARE AN EXCITING, REVOLUTIONARY APPROACH ADVANCED MOBILITY
    - FLEXIBLE ACTUATORS
    - BIO-MORPHIC CONTROL

- REQUIRES AN INTER-DISCIPLINARY TEAM
    - NUCLEUS EXISTS

- IS JPL's "BIO-MORPHIC EXPLORER" APPROACH RELEVANT TO DARPA's ADVANCED MOBILITY NEEDS?

Flexible Actuators For Advanced Mobility



Flexible actuators are envisioned by depositing tailored thick (~ 2-10 micron) films of active materials on judiciously chosen, strong flexible substrates.

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FLEXIBLE ACTUATORS

Flexible actuators are envisioned by depositing tailored thick (~ 2-10 micron) films of active materials on judiciously chosen, strong flexible (polymeric) substrates. Flexible actuators would provide a combination of high force and displacement and be operable over a wide temperature range as is required for a variety of advanced mobility applications. Potential advantages of flexible actuators are:

- low power (low voltage operation, < 5 V), low mass, low volume
- low cost, batch production of the components compatible with VLSI processing
- high force/volume even with low voltage operation
- higher deflection
- flexible, miniaturizable: scaleable for MEMS/MOMS
- excellent cyclability -more than million cycles
- amenable to both electrical or optical activation

FLEXIBLE ACTUATORS

- **Enable a new generation of electro- mechanical and opto- mechanical systems**
- **Actuators not restricted by the clamping effect due to the rigid substrate**
- **Actuation force not limited by the thickness - thicker films can be deposited at high rate**
- **Results in mobile elements with**
  - **higher force to input power ratio**
  - **contact-less optical activation as an option.**

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FLEXIBLE ACTUATORS
APPROACH

- **Optimization of the Piezoceramic films:**

  Optimization of the optical penetration effect

  Optical quality enhancement

  Polarization direction & intensity optimization

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COMPARISON OF PIEZOCERAMIC BULK AND THIN FILM ACTUATOR

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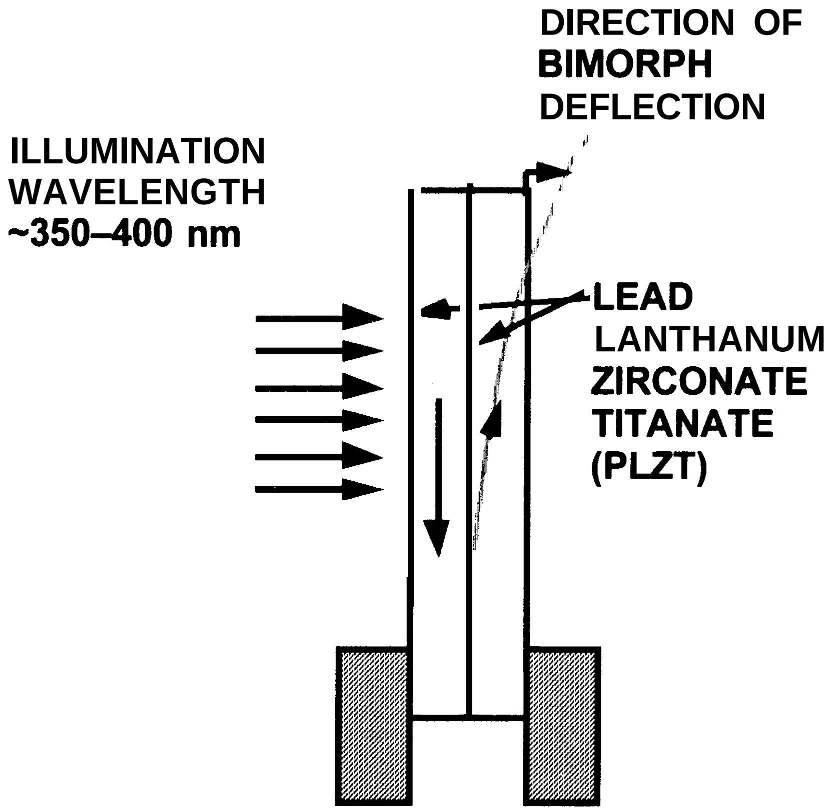
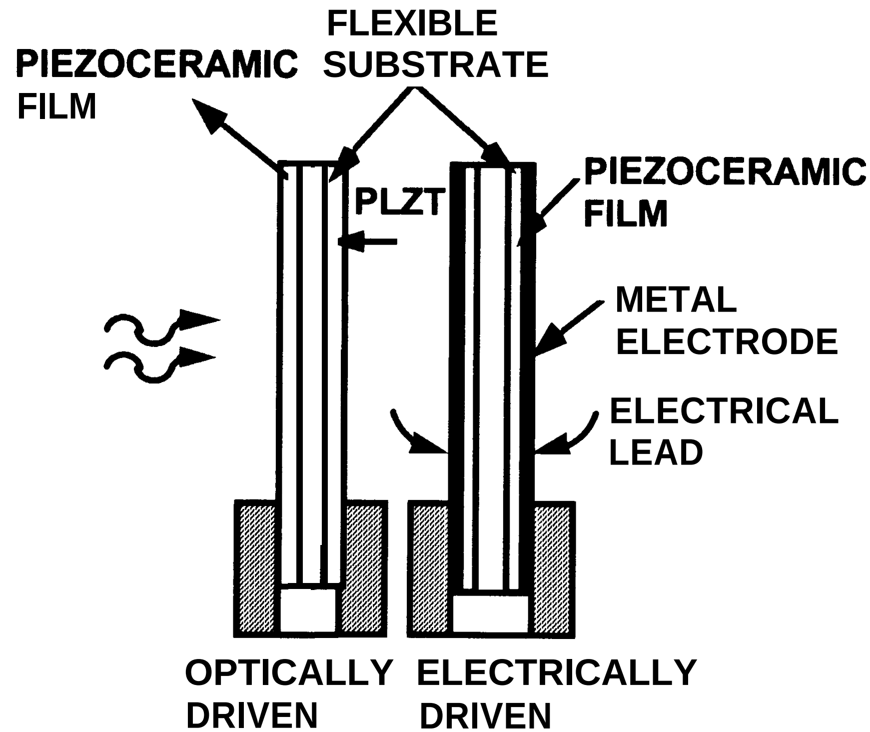


PIEZOCERAMIC BIMORPH

ceramic thickness: 200 micron

(a)

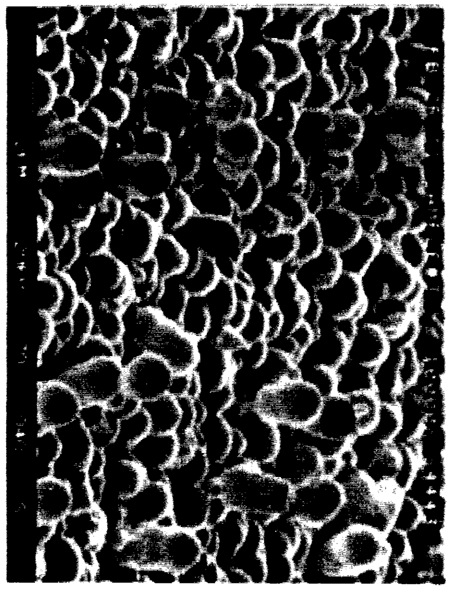


FLEXIBLE FILM ACTUATOR

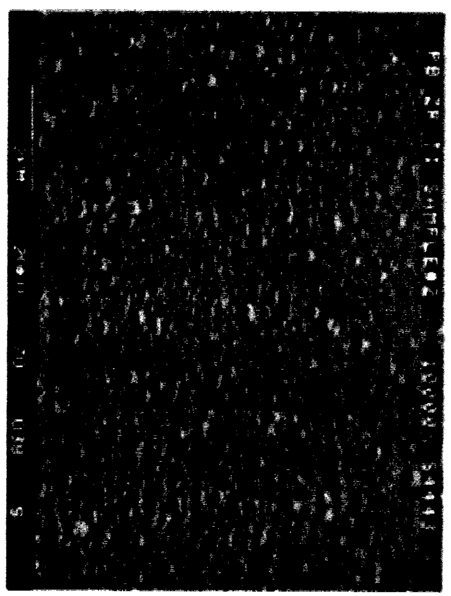
film thickness: 2 micron

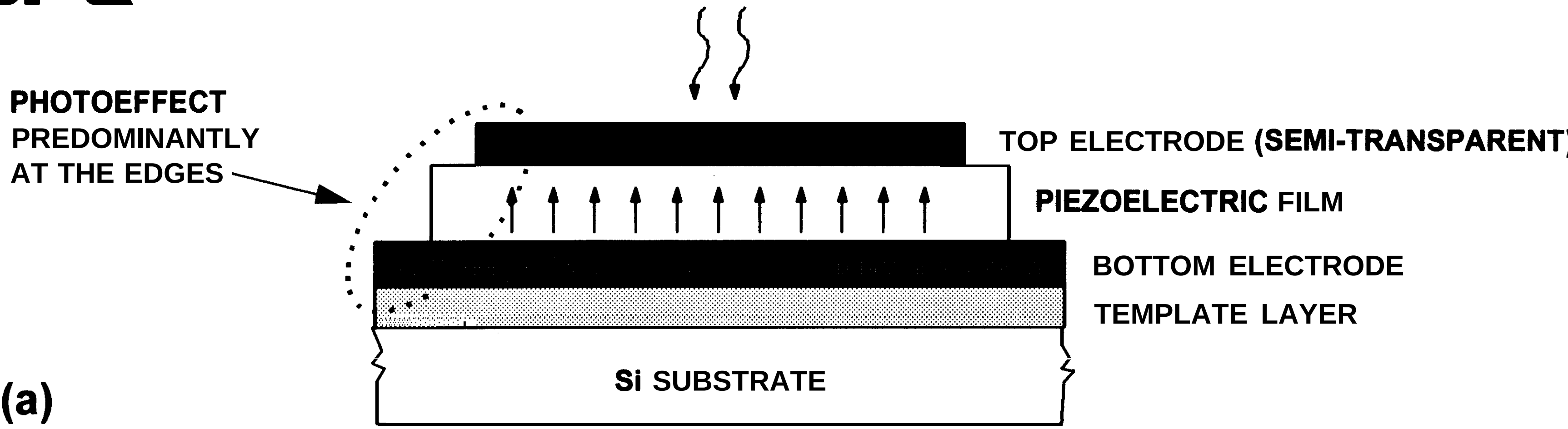
(b)

a



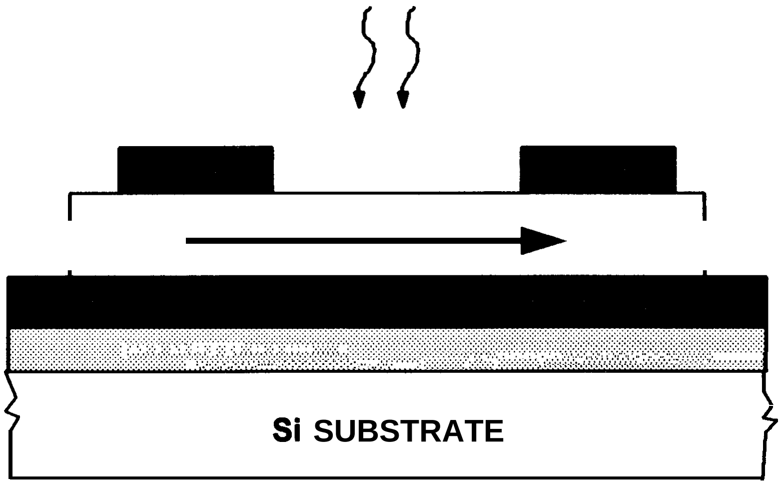
b





(a)

➪ **HYPOTHESIS:** EFFECT **WOULD BE MAXIMUM FOR NORMAL INCIDENCE OF PHOTONS WHEN C-AXIS IS PARALLEL TO SUBSTRATE**



(b)

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TABLE 4: COMPARISON OF BULK PIEZOCERAMIC ACTUATOR WITH PROJECTED PERFORMANCE OF FLEXIBLE FILM ACTUATOR

		Current Status Ceramic Actuator	Projected Improvement Film Actuator
ELECTRICAL ACTUATION PARAMETERS	Thickness	200 microns	2 microns: Thickness reduced, material tailored
	Operating Voltage	100 V	5 V : Operational voltage reduced
	Energy Density	1 x	25 X: Inherent advantage of reduced thickness
	Force/Volume	1 x	5X enhancement for film actuator
OPTICAL ACTUATION PARAMETERS	Optical Power	80 mW/cm^2	8 mW/cm^2 : Illumination Intensity
	Power Ratio	10 x	1 x
	Photonic to Mechanical Conversion Efficiency	0.1%	1% - 10%: significant enhancement in overall efficiency
	Force/Energy	1 x	2X to 20X: Multifold enhancement in the film actuator
	Force/Power	1 x	20X to 200X

COMPARISON ACTUATOR ATTRIBUTES

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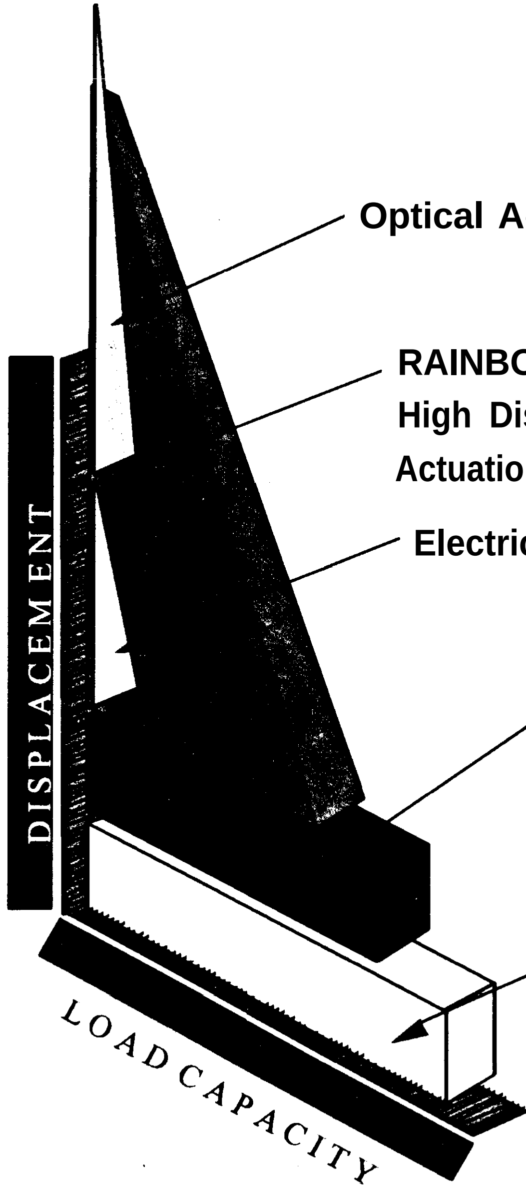

27b

SARITA THAKOOR
PIEZO 02

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BIO-MORPHIC ROBOTICS

- Some of the most influential recent approaches to mobile robotics are discussed in the following. In the behavior-based approach introduced by Brooks[2], the robot behaviors are developed gradually, from simple to more complex. The approach puts an important accent on embodiment and situatedness (real robots performing in their target environments). A primary purpose in robot life is its survival in the environment. The neuromorphic approach illustrates the power of neural models using artificial neural networks for sensory-motor control. A good example of an application oriented system using neural networks is the vision guided vehicle NAVLAB, which drives autonomously at 55m/h under neural control[3]. The evolutionary approach ("evolve by a natural selection mechanism") makes use of evolutionary techniques (such as genetic algorithms or genetic programming) to shape robot controls and sensory-motor maps. A variety of insect-like robots have been evolved[4] to exhibit different gait patterns, adapted to the particular environments in which they behave. Bio-hybrid robots combine natural and artificial parts. One such hybrid from Shimoyama's[5] lab is the roboroach, hybrid cockroach-robot which has no motor or gears but two real cockroach legs actuated by electrostimulation. Biorobotics[6-13] is the area of robotics in which robots can either utilize, mimic, or are inspired from, the biological functions, morphology, or behaviors of plants and animals.

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BIO-MORPHIC ROBOTICS

- 2. R. A. Brooks, New approaches to robotic science. Science Vol. 253,1227-1232; R. A. Brooks, A. M. Flynn, Journal of the British Interplanetary Society, Vol. 42, Ott 1989, 478-485; R. A. Brooks, A. M. Flynn, Aerospace America, Vol 27,22-26, Ott 1989
- 3. D. A. Pomerleau, Neural network perception for mobile robot guidance. Kluwer Academic Publishers, 1993.
- 4. J. C. Gallagher, R. D. Beer, K. S. Espenschield, R. D. Quinn, Application of evolved locomotion controllers to a hexapod robot, Robotics and Autonomous Systems, Vol. 19,95-103, 1996.
- 5. I. Shimoyama, G. Bekey, S. Asaad. Control/Communications group report, Robotics and Autonomous Systems, Vol. 18,7-1 1, (1996).
- 6. M. Ejiri, Towards meaningful robotics for the future: Are we headed in the right direction?, Robotics and Autonomous Systems, Vol 18 pp1-5 , 1996.
- 7. J. Engelberger, Service robots arise, International Federation of Robotics Newsletter, No. 18, pp. 1,1995.
- 8. G.A. Bekey, Biologically inspired control of autonomous robots, Robotics and Autonomous Systems, Vol 18, pp21-31, (1996
- 9. K. Suzumori, Elastic materials producing compliant robots, Robotics and Autonomous Systems 18(1996), 135-140; R. M. Voyles, Jr., G. Fedder, P. K. Khosla, Int. Conf. Robotics and Automation, Vol 1, pp13-17, (1996)
- 10. L. Steels (Ed.), Special Issue: The Biology and Technology of Intelligent Autonomous Agents, Robotics and Autonomous Systems Vol. 15, Nos. 1-2, July 1995.
- 11. P. Gaussier and S. Zrehen (Eds.), Special Issue: Moving the Frontiers between Robotics and Biology, Robotics and Autonomous Systems, Vol. 16, Nos. 2-4, December 1995.
- 12. H. Fukuda (Ed.), Special Issue on Evolutional Robots, Robotics and Autonomous Systems, Vol. 16, Nos. 2-4, December 1995; N. Mitsumoto, T. Fukuda, F. Arai, H. Tadashi, T. Idogaki; ICRA Minneapolis, Minnesota, pp16 14-1619, (1996).
- 13. M. W. Tilden; "Biomorphic robots as a persistent means for removing explosive mines", Autonomous Vehicles in Mine Countermeasures Symposium, Monterey (April 5 1995) (LAUR 95-841); Frigo Jan R, Tilden M. W., Mobile Robots X, Proc SPIE 2591, pages 65-74.

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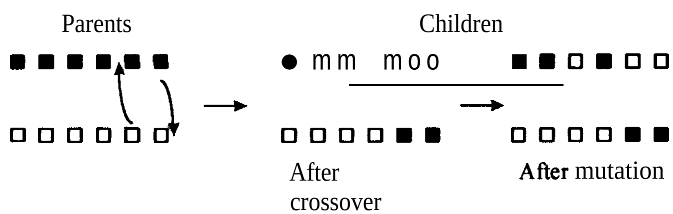
BIO-MORPHIC CONTROLS
GENETIC ALGORITHM

Simple Genetic Algorithm
{**create** an initial population of solutions (**generation 1**)
evaluate individuals in current generation
for a number of generations
{**select** most fitted/promising individuals as **"parents"**
combine the genetic code of **"parents"** to obtain the new generation of offspring
mutate the genetic code of some individual offspring
evaluate/rank individuals in current **generation}**
}



The straightforward combination is by simple one-point **crossover,** in which the genetic code of **2** parents gets cut **at one point,** and one of the two **"chunks"** gets swapped between the **parents,** resulting in **2** offspring with a hybrid genetic **information**. This is illustrated in Figure **3,** where a binary code of **1s (black)** and **0s (white)** is **used.** Mutation is the **"flip"** of one of more bits in the **offspring.**

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BIO-MORPHIC CONTROLS APPROACH

Biology tells us that the control of periodic limb motion sequences are generally delegated to a lower level controller (e.g. spinal cord in humans) than the powerful CPU (e.g. the brain). Obviously, this relieves the brain resources to attend to the higher level cognitive functions including sensory information processing (e.g. vision, hearing, etc.). This arrangement does not of course rule out a higher level command from the brain to the spinal cord to modulate/change the ongoing periodic motion whenever necessary, based on sensory input received and processed. For example, decision to turn or run in a specific direction rather than walk on the sight of a prey/predator.

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BIO-MORPHIC CONTROLS APPROACH

Biological mobility systems have two important characteristics which could be used in the development of increased performance engineering systems: they are controlled by neurons, and they have evolved by natural selection to highly adapted solutions. The most popular "evolutionary engineering" mechanism are genetic algorithms (GA). GAs are a search/optimization method using principles of natural selection to obtain systems adapted to their environment. GAs perform a parallel search, operating on a population of individuals, each individual having a unique genotype (information coded in "chromosomes") and fitness, which is a measure of phenotype's (external behavior determined by genotype) success in meeting some objectives. GAs aim to improve the general fitness of the population by selective breeding, merging the genetic material of most fitted individuals, (and also some random mutations) to obtain the genotypes of offspring in a new generation. The fittest member of the final generation is taken to be the optimum. In evolving robots, our approach would be behavior-based1 in the sense that the robot behaviors would be developed gradually, from simplest to more complex.

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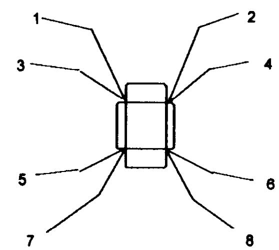
BIO-MORPHIC CONTROLS APPROACH

In a first stage, simple mobility mechanisms, such as gait would be evolved. As an example the control of the leg motion can be evolved into several types of gait pattern. Consider the schematic of an artificial insect, modeled after a spider, with 8 legs. A neural network controller is associated with each leg, the controllers being interconnected. The neural weights are randomly initiated and accordingly a sequence of leg movements is produced. Scoring the walk of the robot in several trials with different parameters (for example giving higher score to those who move further), and applying a genetic algorithm reproducing the genetic code with a selectionist bias on most fittest individuals lead to a insect-like gait pattern.

An example of a gait pattern evolved in simulation is:



At time= t1, simultaneously trigger legs 1,2,5, and 6;
At time= t2, simultaneously trigger legs 3,4,7, and 8.

A variety of insect-like robots have been evolved to exhibit different gait patterns, adapted to the particular environments in which they behave. Examples of evolved locomotion controller for insect-like robots are given earlier4, 8. The evolutionary approach is scale-invariant. The same evolution mechanisms apply for both big and small robots. Miniature robots can be ideally paired with small sensors and built at lower cost. *In a second stage,* simple behaviors would be coordinated into more complex ones (such as moving in some direction, while actively looking for the home-target and balancing a load). *A third stage* would address the development of collective behaviors of several individual robots tasked with the same mission.

BIO-MORPHIC CONTROLS APPROACH

For developing mobility mechanisms, evolutionary algorithms would shape the type and position of actuators, and the neuro-motor control signals to the actuators and sensory-motor maps. Previous evolutionary robotics approaches consisted of determining control commands to electric motors that powered legs or wheels. Based on advanced actuators, our approach eliminates motors from the system, the controlled electric signals to the active limbs, directly produce forces used for locomotion. Tolerances in the characteristics of the actuator materials are accepted by the method, evolution through trial and error compensates for them.

A successful conclusion of the first year's activity therefore would lay an excellent foundation for undertaking actual development of a biomorphic explorer using flexible actuators by providing a full quantitative 3D visual/mechanical design and kinematic model of the explorer mobility and its controls. Demonstration of the Bio-morphic explorer concept feasibility in simulation will be the key milestone of Year 1.

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WHY THE WHEELS WON'T GO?

- Michael LaBarbera, The American Naturalist, Vol. 121, # 3, (1983) p395-408

" I believe an all-terrain roller skate is a physical impossibility; certainly an antlike organism with wheels 2 mm in diameter would be unable to leave its nest without stalling on sand grains, pebbles, and fallen grass blades. On natural substrates, there are thus scaling limitations to the utility of wheels, with smaller wheels being at an increasing disadvantage in mobility. These problems may be reduced by decreasing vehicle weight to make it easier to surmount obstacles, since the total weight which must be raised in elevating the center of mass will be lower."

- Stephen Jay Gould, Natural History, Vol 90, #3, (1981) p42-48

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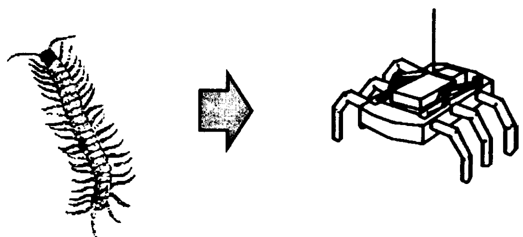
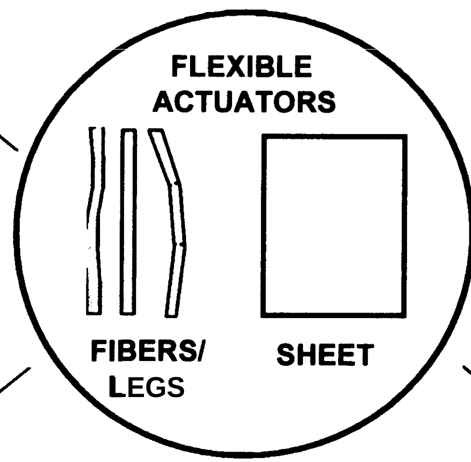
ADVANCED MOBILITY FOR BIO-MORPHIC EXPLORERS

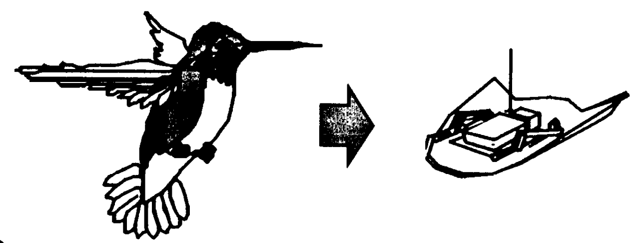
CILIARY/FLAGELLAR MECHANISMS FOR FLUID NAVIGATION

MULTIPOD CRAWLING MECHANISMS (INSECT ROVERS/CRAWLERS)





HOVERING MECHANISMS (AERIAL EXPLORATION)



HOPPING MECHANISMS (OPTICAL/ELECTRICAL BURST TECHNIQUE INNOVATIONS)