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Introduction to the Special Issue on Biomorphic Robotics

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1. Introduction

This special issue of *Autonomous Robots* is based on presentations given at the NASA workshop on Biomorphic Robotics[1] hosted in August 2000 by the Jet Propulsion Laboratory at the California Institute of Technology. The purpose of the workshop was to bring together a representative sample of work in biomorphic robotics likely to have an impact in future NASA missions.

Biomorphic robotics can be broadly defined as the transfer of biological principles to robotics and the use of robots to evaluate and test computational models in biology. Robotics has historically been grounded in control theory, generally meant for the precise control of machines in well-defined, predictable environments. In contrast, biological systems are uniquely competent at interactions with unpredictable and dynamic environments. Thus, a primary goal of biomorphic robotics is to imbue robotic systems with the capabilities of biological organisms, to successfully maneuver within and explore unpredictable environments.

This body of work is of great interest to NASA and the Jet Propulsion Laboratory. In particular, the surfaces of other planets are not well characterized, are likely to be environmentally hostile, and will demand a high degree of autonomy. Robots for space exploration are thus faced with unique challenges, and a biomorphic approach may be particularly appropriate.

2. NASA Motivation

Two of NASA's prime areas of interest, the search for life beyond Earth and the human exploration of space, are linked by a common objective—the search for extraterrestrial water. Life as we know it depends upon the availability of water, and two planetary bodies within our solar system stand out as prime candidates in the search: Mars and Europa. These two targets were highlighted in opening-session talks by Dan McCleese, the chief scientist for the Mars Exploration Program, and Torrence Johnson, project scientist for the Europa Orbiter mission.

McCleese explained that a significant challenge for Mars exploration is to determine whether water exists in accessible forms near the surface. Recent images from the Mars Global Surveyor have suggested that water may be trapped in channels only a few hundred meters below the surface, as evidenced by geologically young gullies and debris fans emanating from the steep walls of craters near the southern pole (Fig. 1; Malin and Edgett, 2000). To deliver sensors to these sites to search for groundwater more closely will require rovers that can negotiate the martian cliffs. The crater walls are typically several hundred meters high, and have steep slopes of 30 to 90 degrees. Robots built with advanced mobility to function in extreme environments will be necessary for the exploration of such difficult terrain.

Johnson described the challenges in exploring Europa, a moon of Jupiter and the other leading candidate in the search for extraterrestrial water. The Galileo spacecraft in orbit around Jupiter has provided intriguing evidence to support the hypothesis that Europa has a liquid ocean (Fig. 2). The surface geology and fracture patterns suggest a frozen ice field churned by Jupiter's great tidal forces, and magnetic field fluctuations

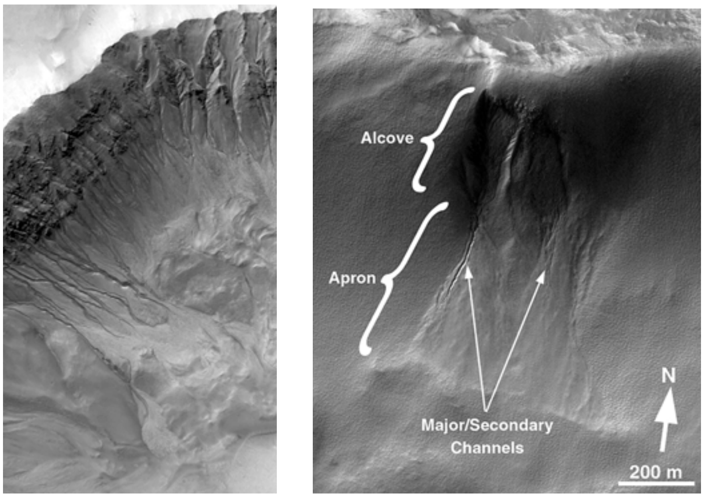

Figure 1. Gullies formed on the walls of martian craters (left) have features (right) that suggest that water flowed from the cliff face.

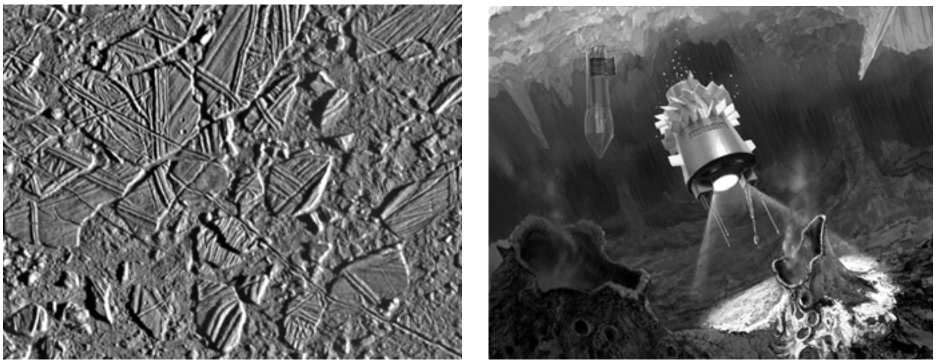

Figure 2. (Left) Fracture patterns on Europa's surface, showing crustal plates ranging up to 13 km across, suggest an icy surface with an underlying ocean. (Right) Artist's conception of an autonomous hydrobot exploring Europa's ocean. Such a submersible could be augmented with biomorphic solutions.

indicate the presence of a large liquid conductor, such as salt water, beneath Europa's surface (Kivelson et al., 2000). Goals of future missions will be to characterize the frozen crust of the ocean, to drill through that crust, and to characterize the global ocean. This forbidding terrain will require advanced robotic systems to explore the geophysical, geochemical and biological aspects of the ocean—its organic chemistry and potential biomarkers.

3. Technology Requirements and Biomorphic Solutions

Whether negotiating a steep precipice on Mars or dangerous ice fissures on Europa, future robotic rovers far from Earth must carry a range of autonomous capabilities and built-in intelligence, and NASA is now looking for biological inspirations. Leon Alkalai, head of the Center for Integrated Space Microsystems (CISM), spoke about the requirements for these new technologies for deep space missions: the autonomous and intelligent systems must also be long term, reliable, and low power. Deep space exploration will not only require revolutionary computing, but also tolerance for temperature and radiation extremes.

Closer to Earth, the human exploration of space also requires more capable robotics, and shares many of the technology challenges of the deep space exploration missions. For example, Neville Marzwell of the Advanced Concepts office at JPL presented a movie of Robonaut, a humanoid robot under development at Johnson Space Center to meet NASA's increasing requirements for extravehicular activities (e.g., spacewalks). Robonaut and other similar telerobotic or autonomous robotic assistants may benefit from biomorphically inspired advances in sensing, manipulation, and intelligent control.

The examples above illustrate that successful exploratory systems for future NASA missions must include the following attributes:

- *Functionality*—perform critical scientific measurements about life, climate, geology.
- *Performance*—incorporate capable methods for landing, deployment and navigation in extreme environments.
- *Reliability*—operate safely in hazardous terrain.

The challenge for biomorphic robotics research is to demonstrate that biologically-inspired solutions can incorporate these attributes and contribute significant new advantages for space exploration.

4. Overview of Workshop Presentations

This special issue features short papers by more than 20 speakers at the workshop. The sessions represented in this issue are: (1) Biomorphic Locomotion, (2) Neuromorphic Sensory Systems, (3) Biomorphic Actuation, (4) Bio-Inspired Sensory-Motor control, (5) Learning and Navigation. A sixth session, Learning and Control of Robot Behaviors, is not represented here because work in that session has been (or soon will be) published elsewhere. The reader is referred to work by Arkin (ICRA 2001 proceedings), and papers by Mataric and Stoica that will be presented in a special issue of *Autonomous Robots* on the topic of humanoid robotics. Below, we briefly describe the potential contributions of biomorphic robots for each session included here.

4.1. Locomotion in Biomorphic Robotic Systems

Given the success of the Mars Sojourner rover, future missions are likely to employ increasingly sophisticated rovers. Both wheeled and legged locomotion offer distinct advantages, but we would like to point out certain unique capabilities of limbed (biomorphic) systems.

For enhanced mobility, space applications will require a transition from wheeled based technology, useful in environments with full gravity, to brachiating robots, which may excel in microgravity for in-space operations. Limbed locomotion naturally suggests multiple use capability: most primates use their forelimbs not only for locomotion, but also for manipulation of small objects. Kennedy and colleagues describe such a multilimbed robot with legs that can convert into tool-using manipulators. In contrast, a manipulator on a wheeled system may be used only sporadically, and thus becomes a payload during locomotion. By capitalizing on the dual-use strategy of primate forelimbs, this inherent inefficiency is avoided in Kennedy's work.

The article by Altendorfer et al. demonstrates an autonomous 6-legged robot made to run with dynamics that resemble a pogo stick. Their work suggests that with the proper design, many seemingly complex articulate systems will exhibit such dynamics, and thus be simpler to control. The resulting robot can quickly move over terrain that would challenge most wheeled vehicles.

Quinn and colleagues expand the discussion of biologically-inspired legged robots. They present an overview of a series of robots inspired by the mechanical architecture and neural circuitry of one of the world's most successful insects: the cockroach. Each of the robots in the series represents a potential improvement in agility, strength, and/or autonomy.

For legged robots to locomote most effectively, they must anticipate interactions with the environment. Humans and many animals rely principally on vision as the most important distal sense, but a key problem is the quick acquisition of relevant information about the environment and the integration of visual input with locomotion to achieve smooth modulations of gait. Lewis and Simó describe perceptual components needed for fast visually-guided locomotion, including learning to anticipate and step over obstacles, as well as an innovative biologically inspired custom aVLSI locomotor controller chip.

4.2. Neuromorphic Sensory Systems

Because vision is such an important distal sense, visual processing dominates current missions. In addition to vision, however, animals rely heavily on complementary senses to establish an awareness of the environment. Presentations in the neuromorphic sensory systems session included work not only on vision, but also on audition, tactile sensing, and echolocation.

High-speed visual processing of images using conventional technology is computationally intensive and requires relatively large amounts of power. Two papers in this issue examine biologically-inspired approaches to the design of more efficient visual sensor systems. Etienne-Cummings et al. present several different 2D visual processing chips that perform flexibly-programmed image processing functions as an image is serially read from the chip. This can provide significant savings in pixel density and accumulated mismatch error in the processing while using very low power. Landolt and Mitros present a 2D vision sensor that can take advantage of measurable mechanical vibrations to estimate image intensity at a single pixel with multiple photoreceptors. This technique not only reduces component mismatch error, it can produce higher resolution images than the photoreceptor density normally supports.

In the auditory domain, Horiuchi and Hynna present a VLSI-based implementation of the neural circuitry supporting echolocation in bats. This work includes the development of high-frequency silicon cochleae chips and a generally applicable sound-localization architecture. In tactile sensing, Hartmann presents an investigation of the rat whisker system and its use for active sensing in environmental conditions where vision is limited. In particular, the paper discusses several types of information that rats can extract with their whiskers, and the scanning strategies that rats use with their different types of whiskers.

Related to both auditory and tactile sensing, the lateral line system in fish was presented in the context of fluid-flow measurement. Coombs presents an investigation of the neuromast system (hair-cell-like structures) to measure tiny fluid-flows produced by prey animals in the water. Open, fluid-filled canals in the skin were shown to measure pressure-gradient (or acceleration), while superficial neuromasts on the surface of the skin were shown to be sensitive to the velocity of the fluid. These two measurements are used to localize prey movements. In another talk at the workshop, Anderson et al. found evidence that fish actively control the boundary flow around the skin (see Anderson et al., 2001).

In dark murky waters, certain fish have developed active electroreception abilities. This enables localization of potential prey using electric fields. MacIver and Nelson describe a robotic implementation of this electrosense, and investigate the strategies that the black ghost knifefish uses to actively control the sensory information it receives about its prey.

The presentations in the sensory systems session all suggested that sensory strategies found in animals might provide excellent guidance in producing viable planetary explorers. Multiple sensory systems will clearly be needed to explore environments as disparate as the dry, rocky surface of Mars and the icy oceans of Europa.

4.3. *Biomorphic Actuation*

Biological muscle and associated tissue provides many of the wonderful properties associated with animal mechanics. These include a high strength to actuator weight ratio, compliance, high speed, and energy storage and recovery. Hannaford and colleagues describe progress in creating physical models of biological muscle and muscle spindle sensors. Their system includes a braided pneumatic (McKibben) actuator with mechanical dampening that mimics muscle tissue. In the next talk, Bar-Cohen described a competing technology for artificial muscle—electroactive polymers (see Bar-Cohen, 2001). Biologically inspired muscles will likely be one of the most important aspects of the robotics mechanical embodiment.

4.4. *Bio-Inspired Sensory-Motor Control*

The cerebellum plays a key role in the control of agile movements, and thus many of the talks in the sensory-motor control session concerned models of cerebellar function. Spoelstra and Arbib present a computational model of how the cerebellum may adaptively adjust movement commands generated elsewhere in the nervous system. The model results match experimental evidence, which implies that the cerebellum adjusts motor output rather than representations of movement goals.

Paulin and colleagues present a computational model of cerebellum as a dynamical state estimator by analyzing spike activity in vestibular neurons. The model is based on the observation that individual sensory spikes can be treated as measurements of sensory state, and that conventional statistical and dynamical methods can be adapted to construct computational neural models that have spikes as operands. The result illustrates the potential for using this approach to analyze and model computation by spiking neurons.

Models of cerebellar function and learning remain strongly influenced by the early theoretical work of Marr and Albus, and Ito's subsequent experimental program which focused on the nature of plasticity at parallel fiber—Purkinje cell synapses. Assad points out that because the ascending branches of granule cell axons make numerous synaptic contacts with Purkinje cells, the functional organization of cerebellar cortex is computationally richer and more dynamic than the basic circuit assumed in the Marr-Albus-Ito paradigm.

Marr originally suggested that cerebellar granule cells separate incoming sensory signals into more readily distinguishable patterns. Coenen and colleagues investigated the implications of synaptic plasticity in the granular layer. Their work shows how unsupervised learning in the granular layer could lead to sparse, statistically independent coding of input signals. This would enhance learning in subsequent cerebellar circuits by minimizing destructive interference between input signals.

The work presented in this area represents only a portion of the range of ideas and methods used to investigate and model cerebellar function. Cerebellar modeling is an active research area, and there is an exciting sense that realistic computational models are now possible with today's tools.

In other sensory-motor control research areas, Harty et al. describe a collective control strategy for pointing and reaching behavior in the presence of obstacles. Their work shows that simple rules that control only the local movements of individual arm segments can produce a coordinated group behavior. This type of computation may provide more flexible control for unpredictable and dynamic environments.

DeMarse and colleagues describe research that uses the activity from living neurons to directly control the behavior of a computer "animat," which interacts with a simulated environment. Sensory feedback from the environment is then used to directly stimulate the neurons, thus closing the loop between neurons and simulation. Understanding of how feedback changes the activity and connectivity within networks of neurons will almost certainly shed light on the codes within these control networks.

4.5. Learning for Navigation

Uncertainty is the only certainty about the environments of other planets. Successful navigation across uncertain terrain will require robots to adapt to the circumstances of the environment, and make choices consistent with changing goals, destinations, and surface conditions. The talks in the navigation session offered a wide variety of solutions for these problems.

Evolutionary robotics offers a way to fundamentally alter the computations a robot performs to achieve a specified goal, without explicit models of the environment or robot. Floreano and Urzelai present progress in evolutionary robotics that promises to speed the process of artificial evolution. The algorithm does not encode a particular strategy that suits a particular environment, but rather forces the generation of individuals capable of developing a strategy to cope with their local environments.

GPS is a well-known system for navigation on earth, but such systems require calculations involving absolute coordinates, and installing such systems on remote planets would be extremely expensive. Payton et al. demonstrate a multi-robot navigation system based on "virtual pheromones," which are symbolic messages tied to the collective of robots, rather than to fixed locations in the environment. This allows the robot collective to function as a distributed computing mesh, and may prove a cost-effective way to do navigation on distant planets.

Animals and humans navigate very effectively with the aid of cognitive maps. Kuipers compares cognitive map-making in ants and humans with his Spatial Semantic Hierarchy for representing knowledge of the environment. He presents a computationally efficient and robust bio-inspired spatial behavior using cognitive map learning that allows robots to move autonomously in unknown environments.

Active research at JPL is demonstrating bio-inspired navigational strategies on flight-ready wheeled rovers. Tunstel describes an ethologically-motivated control approach that uses fuzzy logic to establish behavioral hierarchies for successful navigation. He employs a blend of local path planning and hierarchical action selection to solve local navigation problems. Huntsberger also uses both fuzzy logic and a map-making memory similar to the Spatial Semantic Hierarchy in his implementation of the BISMARC system. BISMARC's additional action-selection mechanisms give it a broad system-wide scope that can be used to control multiple robots performing cooperative navigation tasks.

The papers presented in this session show that navigation mechanisms inspired from biology can definitively be used to build adaptive, cost effective and robust navigation systems for future robotic exploration of unknown planetary environments.

5. Summary and Conclusions

Biological systems have attributes that are desirable in uncertain, potentially hostile worlds and in space. The six workshop sessions covered major issues in constructing capable autonomous systems. Recent work in these fields indicates that strong and steady progress has been made over the last decade. Undoubtedly, biomorphic robotics will become part of NASA's repertoire of technology aimed at understanding the solar system, and ultimately more about our origins and ourselves.

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Note

1. http://cism.jpl.nasa.gov/biocomputing/workshop

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