55/63

22P

Biomorphic Systems and Biomorphic Missions

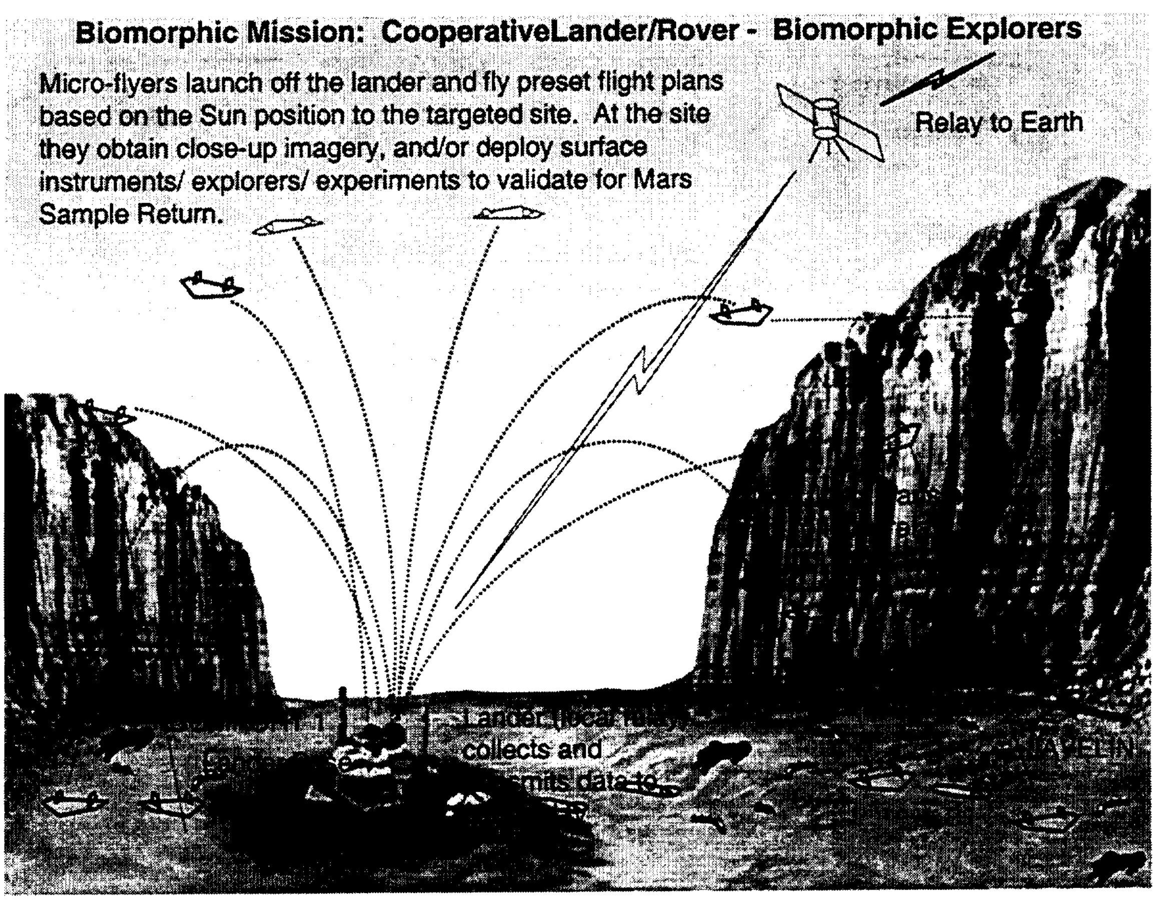
Sarita Thakoor
Jet Propulsion Laboratory
Pasadena, CA 91109

Biomorphic Systems and Biomorphic Missions

Sarita Thakoor

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, CA 91109-8099
(818) 354-3991
Email: sarita.thakoor@jpl.nasa.gov

Training Workshop on Nano-biotechnology
NASA Langley Research Center, Hampton, VA
June 14-15, 2000

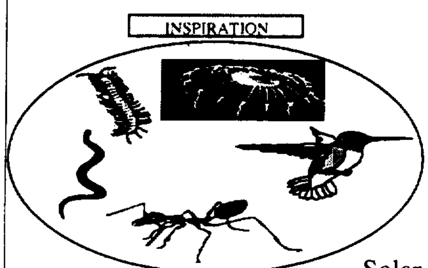


Biomorphic Explorers

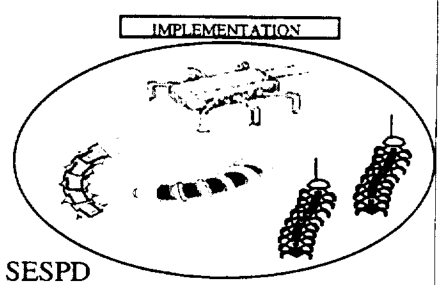
- A multidisciplinary system concept for small, dedicated, low-cost explorers that capture some of the key features of biological organisms
  - Small… 100-1000g (useful space/terrestrial exploration functions are implementable* using this mass).
- Conducted workshop, Aug 19-20, 1998
  - Sponsored by NASA/JPL
  - WEBSITE: http:/nmp.jpl.nasa.gov/bees/
  - An enthusiastic response: over 150 participants

* JPL document D-14879A, JPL document D-16300A
JPL document D-16500, Author: Sarita Thakoor

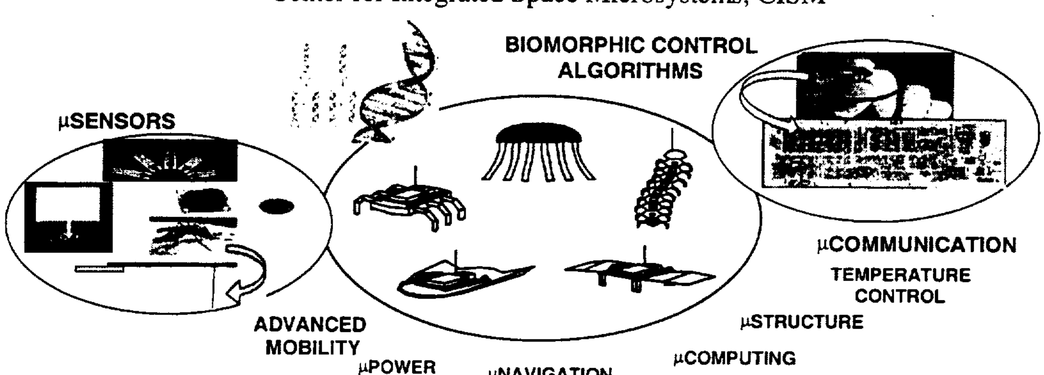
FIRST NASA/JPL WORKSHOP ON
BIOMORPHIC EXPLORERS FOR FUTURE MISSIONS (BEES 98)



August 19-20, 1998
Jet Propulsion Laboratory
Pasadena, CA
Auditorium 180 - 101



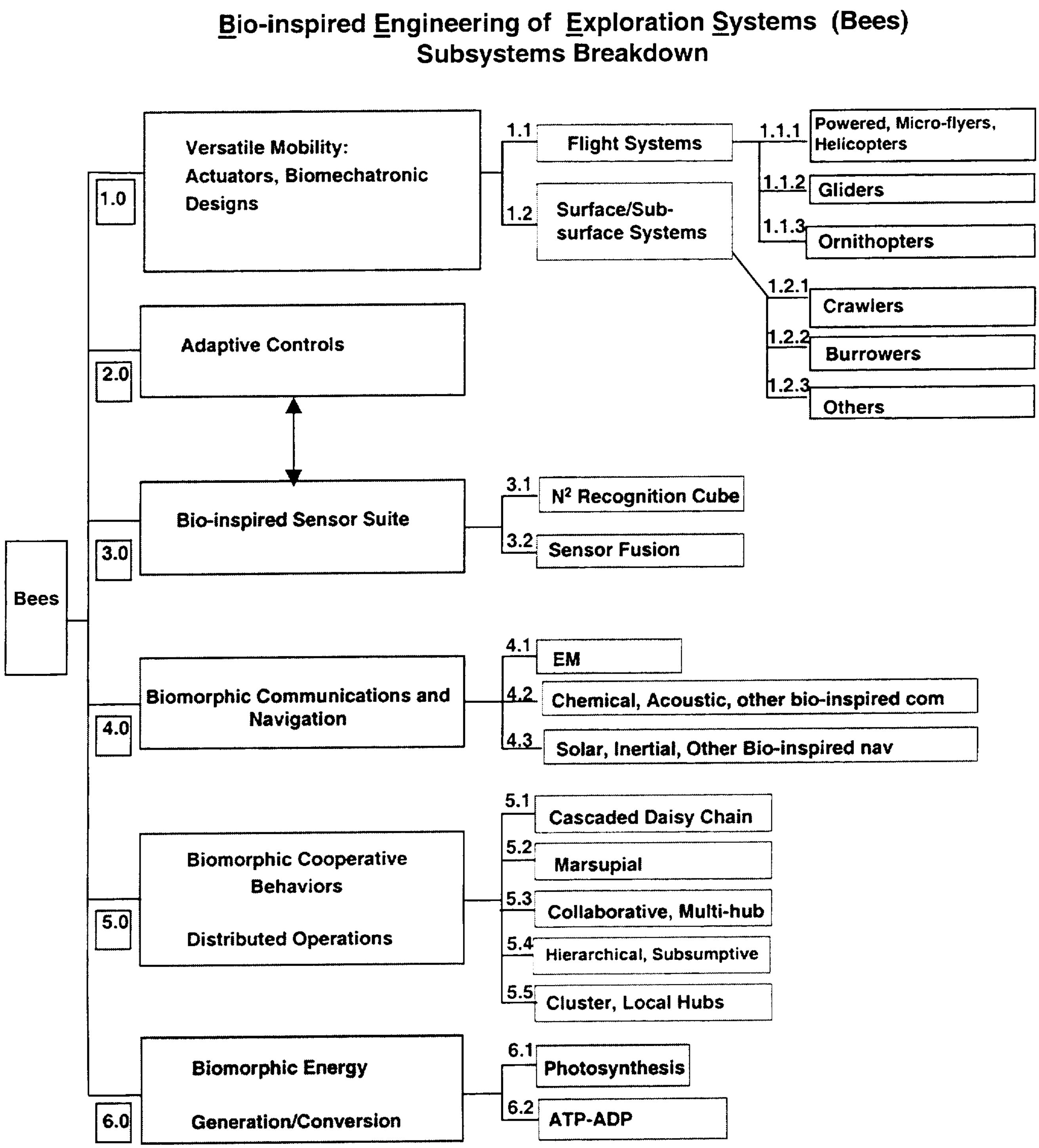
Sponsored by NASA/JPL
Solar System Exploration Program, SESPD
New Millennium Program, NMP
Space Mission Technology Development Program, TAP
Center for Integrated Space Microsystems, CISM



TECHNICAL POC: SARITA THAKOOR

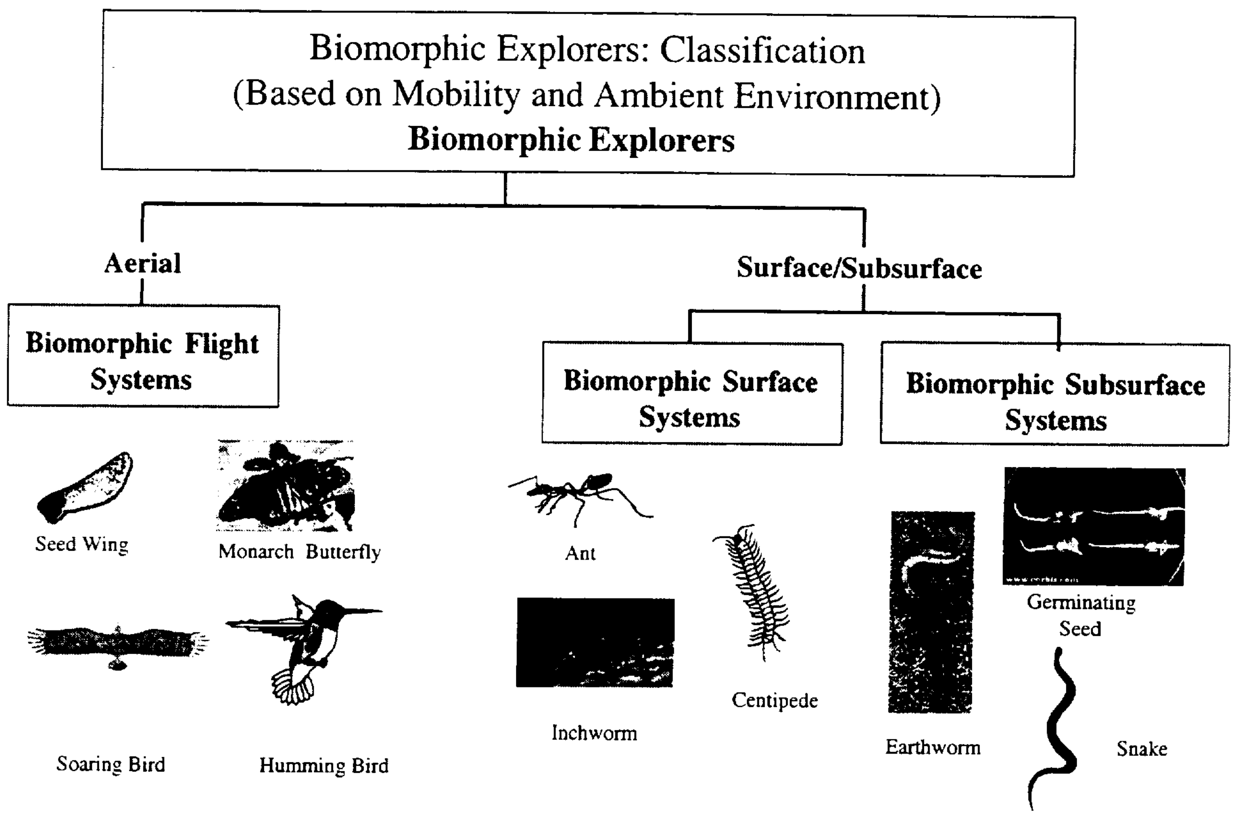
Bio-inspired Engineering of Exploration Systems (Bees) Subsystems Breakdown

The following slide shows the sub-categories within the subject of bio-inspired engineering of exploration systems. This talk will focus mainly on the versatile mobility area and will briefly mention the highlights on the other sub-categories.



Biomorphic Explorers: Classification

Examples of biological systems that serve as inspiration for designing the biomorphic explorers are illustrated. Choose a feature, say soaring. The intent is to make an explorer that combines the different attributes seen in nature in diverse species and capture them all in one artificial entity. In that sense the explorer goes beyond biology to provide us the adaptability that we need in encountering and exploring what is yet unknown.



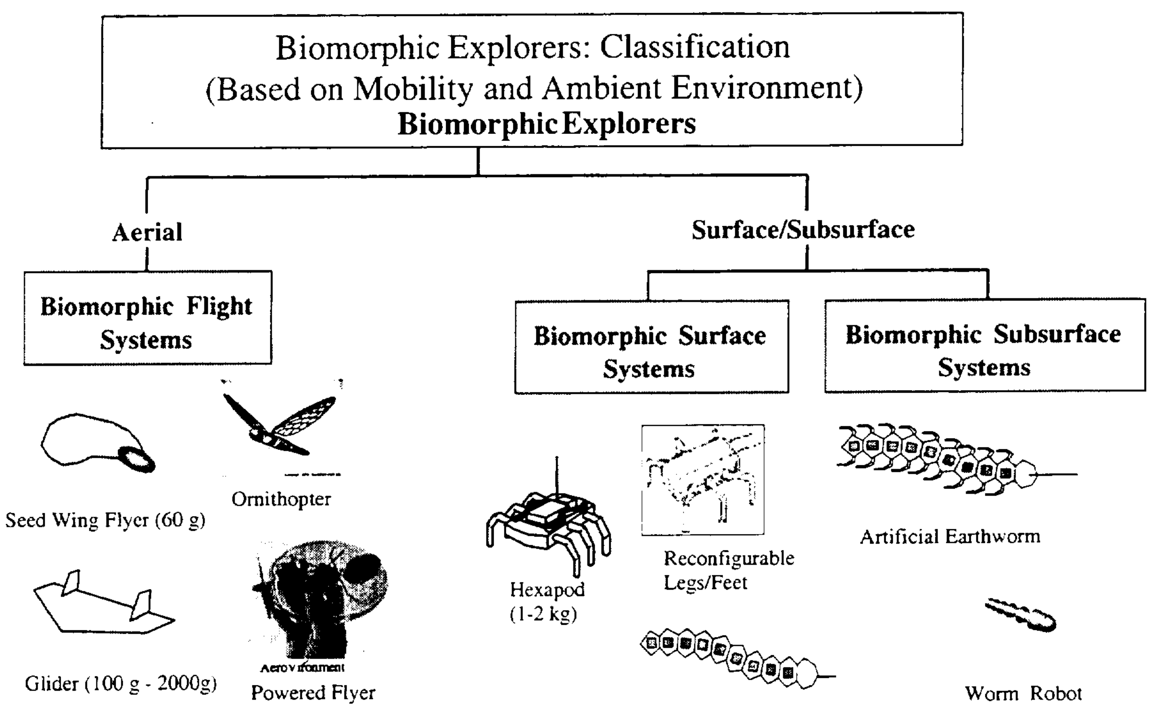
The Challenge to Obtain A Biomorphic Robot

Nature's Creations

- Primarily organics based.
- Evolution led surviving design and minimalist operational principles are inherent.
- Geological time scale has been used for evolution.

Bio-morphic Robot

- Primarily inorganics based, the ingredients/materials are available to us.
- Needs to be created by distilling the principles offered by natural mechanisms.
- Capturing the bio-mechatronic designs and minimalist operation principles from nature's success strategies.
- Do it within a lifetime.

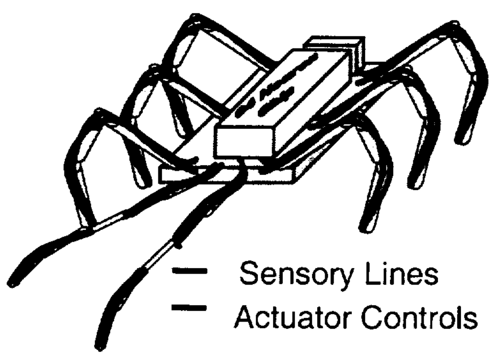


Candidate biomorphic explorers on the drawing board, with mass of design under study in parentheses

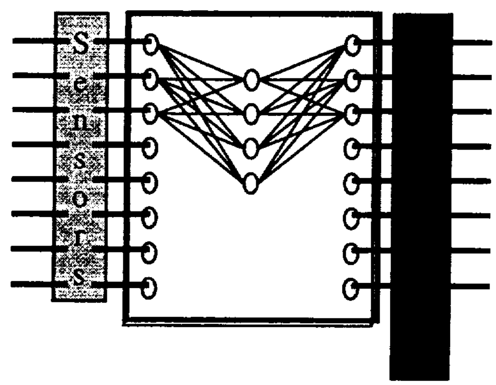
Multi-terrain Biomorphic Explorer

This development is geared toward the creation of an explorer that is capable of identifying its environmental condition/situation and adaptively change its mobility mode to suit the prevailing/impending situation. For example, if the terrain changes from hard and rocky to swampy slushy ground, then the explorer changes from a small footprint pogo stick type mode to a duck foot like wide footprint mode.

MULTITERRAIN Biomorphic Explorer



Neural connections mapped on 64 Neural Network (NN) Chip

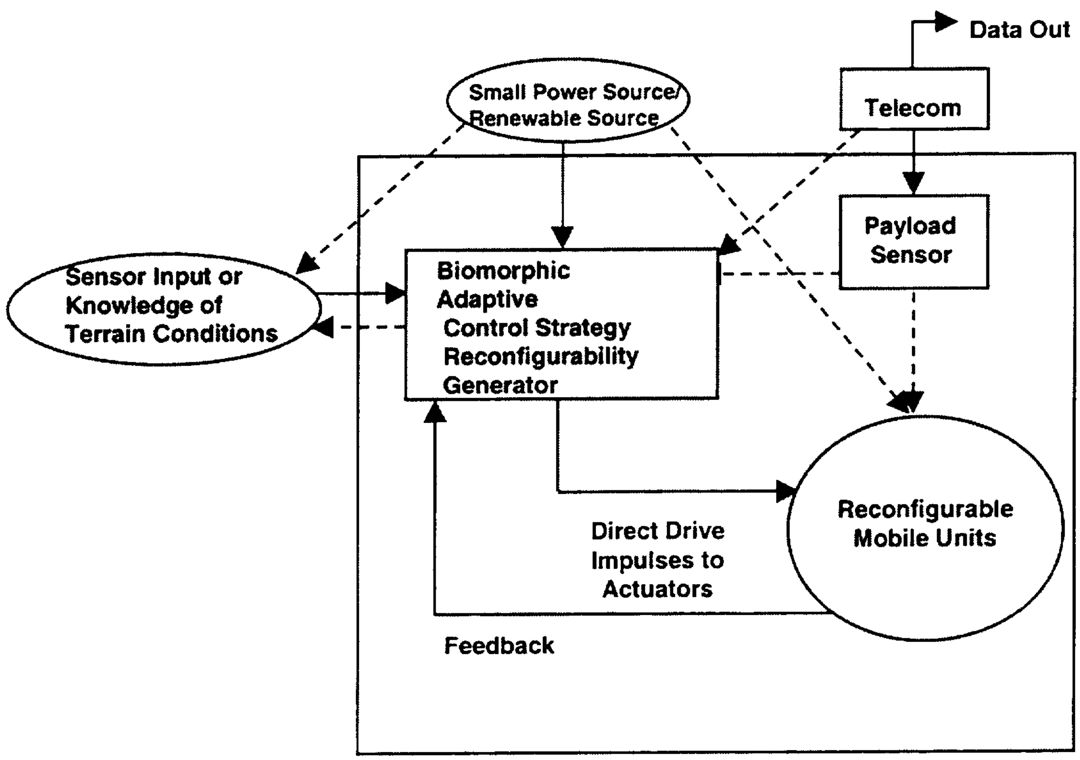


JPL's 64 NN chip characteristics:
- Low weight (5 g)
- Small size (1 cm x 1 cm)
- Low power (12 mW)
- High speed (~250 ns)
- Programmable neural network architecture

Distributed Control Operational Schematic

The following slide shows the operational schematic of the biomorphic strategy controller that utilizes multiple sensory inputs and generates the most suited output choice of mobility mode both in terms of the reconfigurable unit that is used and the mobility parameters that need to be used.

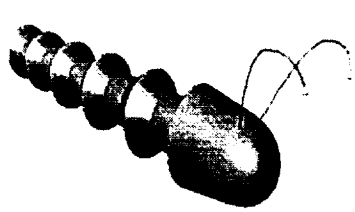
Distributed Control Operational Schematic



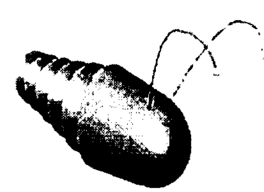
Worm Robot for In-situ Exploration

The worm robot conceptual design illustrated in the following slide, and shown in animation, is inspired by the technique used by earthworms and inchworms. The mobile entity is composed of a series of modules in which each module is capable of contracting or expanding and has anchors at each end. It anchors at one end and expands fully, then it de-anchors the back end and anchors the front end and contracts again and re-anchors the back end. This wave of contraction/expansion and anchoring/ de-anchoring proceeds continuously to achieve the forward motion. The animation shows how such a worm would be capable of burrowing in sandy soil and entering narrow cracks in rocks for obtaining pristine samples from such hard to reach places.

Worm Robot for In-Situ Exploration



Extended Configuration



Contracted Configuration

Z. Gorjian and S. Thakoor, "Biomorphic Explorers Animation Video," First NASA/JPL Workshop on Biomorphic Explorers for Future Missions, August 19-20, 1998, Jet Propulsion Laboratory, Pasadena, CA

Biomorphic Explorers: Versatile Mobility

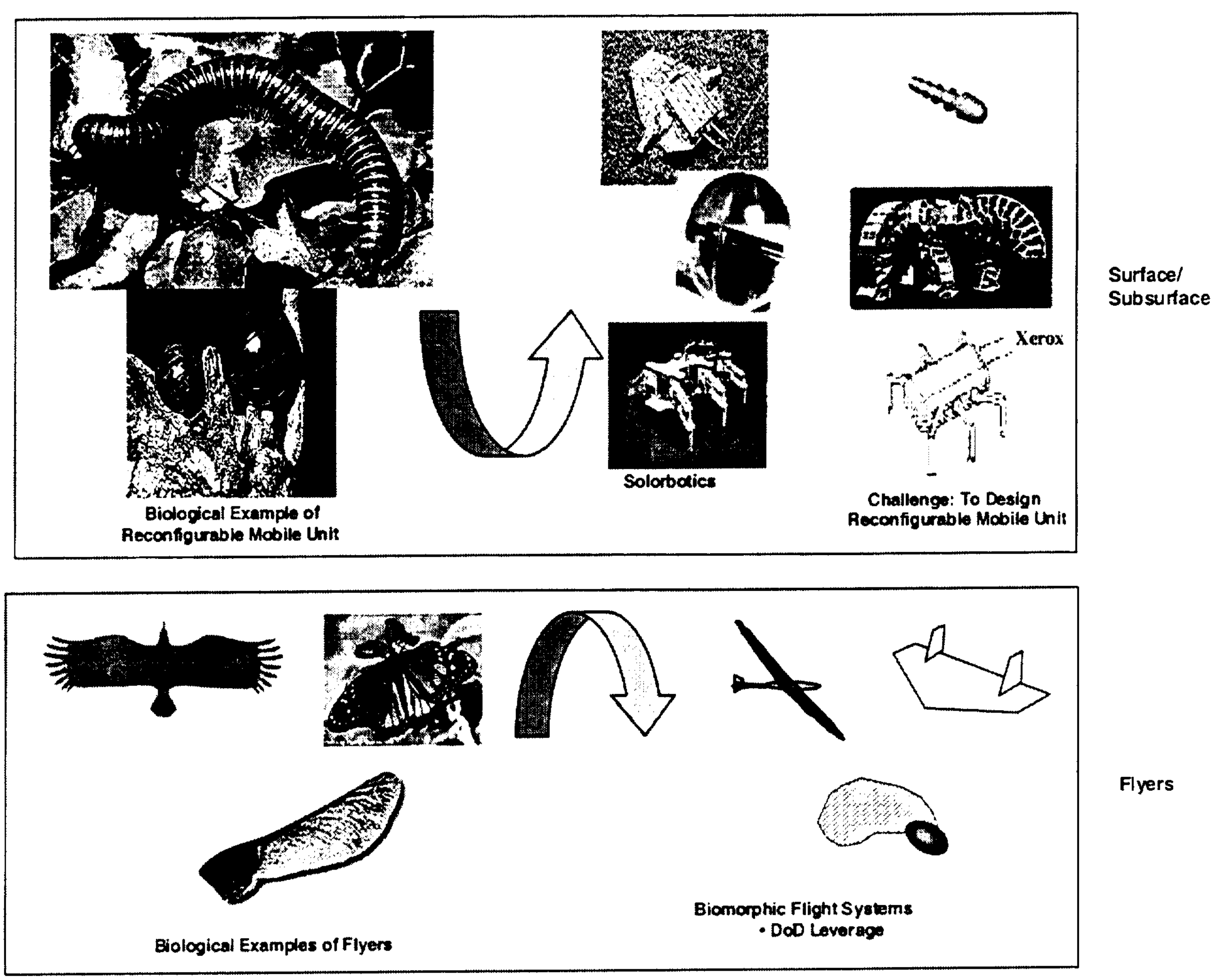
The surface/subsurface examples of versatile mobility discussed thus far are summarized in the top section of this slide. The bottom section of the slide shows examples of biomorphic flight systems and their respective inspirations.

Biomorphic flight systems are attractive because they provide:

- Extended reach over all kinds of terrain.
- Unique perspective for IMAGING, SPECTRAL SIGNATURE.
- Ability to perform distributed ATMOSPHERIC MEASUREMENTS.
- Ability to deploy/distribute payloads.

Many biomorphic explorers (seed wing flyers, crawlers, burrowers, gliders, etc.) can work in cooperation with large UXV's to enable new missions and achieve successfully (currently) UNATTAINABLE MISSIONS.

Biomorphic Explorers: Versatile Mobility

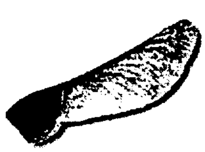


Biomorphic Controls in Seed Wing Flyers

Active control of seed wing descent is a significant concept for further development to impact the usefulness of seed wing flyers. This is an effort to influence the direction of descent, by periodic movement of a control surface on the wing portion. For example, a simple wing structural element made of advanced piezo-polymeric composite actuators could play a dual role as a structural member as well as an active control element when activated, altering the lift characteristics for a fraction of one rotation. The signal to drive the structural element would be generated by the measurement of sunlight on the upper payload surface. That signal would normally vary with rotation due to changing sun angle. Detection of a certain part of that periodic signal would be programmed to activate the change in wing shape. Thus, the seed wing would tend to move in a consistent pattern relative to the sun's direction. Individual seed wings in an ensemble could be programmed to have varying solar response patterns, ensuring that the group travels away from each other, for maximum dispersion in the landing location.

Plant World Inspired Payload Distribution Methods

- **Simpler and smaller than parachute on small scale for dispersion of sensors and small surveillance instruments.**
- **Controlled Descent Rate ~ 15 m/s (on surface of Mars)**



(a)

Maple Seed Samara

(b)

Dandelions

Design Goals:
- Small total mass, ~100 g.
- High payload mass fraction > 80%.
- Captures key features of controlled and stable descent as observed in Samaras, such as maple seeds.
- Reliable, minimal infrastructure.
- Unobstructed view overhead for atmospheric measurements.
- Simple construction, few constituent parts.

Biomorphic Explorers

- Bio-morphic explorers constitute a new paradigm in mobile systems that capture key features and mobility attributes of biological systems to enable new scientific endeavors.
- The general premise of biomorphic systems is to distill the principles offered by natural mechanisms to obtain the selected features/functional traits and capture the biomechatronic designs and minimalist operation principles from nature's success strategies.
- Bio-morphic explorers are a unique combination of versatile mobility controlled by adaptive, fault tolerant biomorphic algorithms to autonomously match with the changing ambient/terrain conditions.
- Significant scientific payoff at a low cost is realizable by using the potential of a large number of such cooperatively operating biomorphic systems.
- Biomorphic explorers can empower the human to obtain extended reach and sensory acquisition capability from locations otherwise hazardous/ inaccessible.

Biomorphic Missions

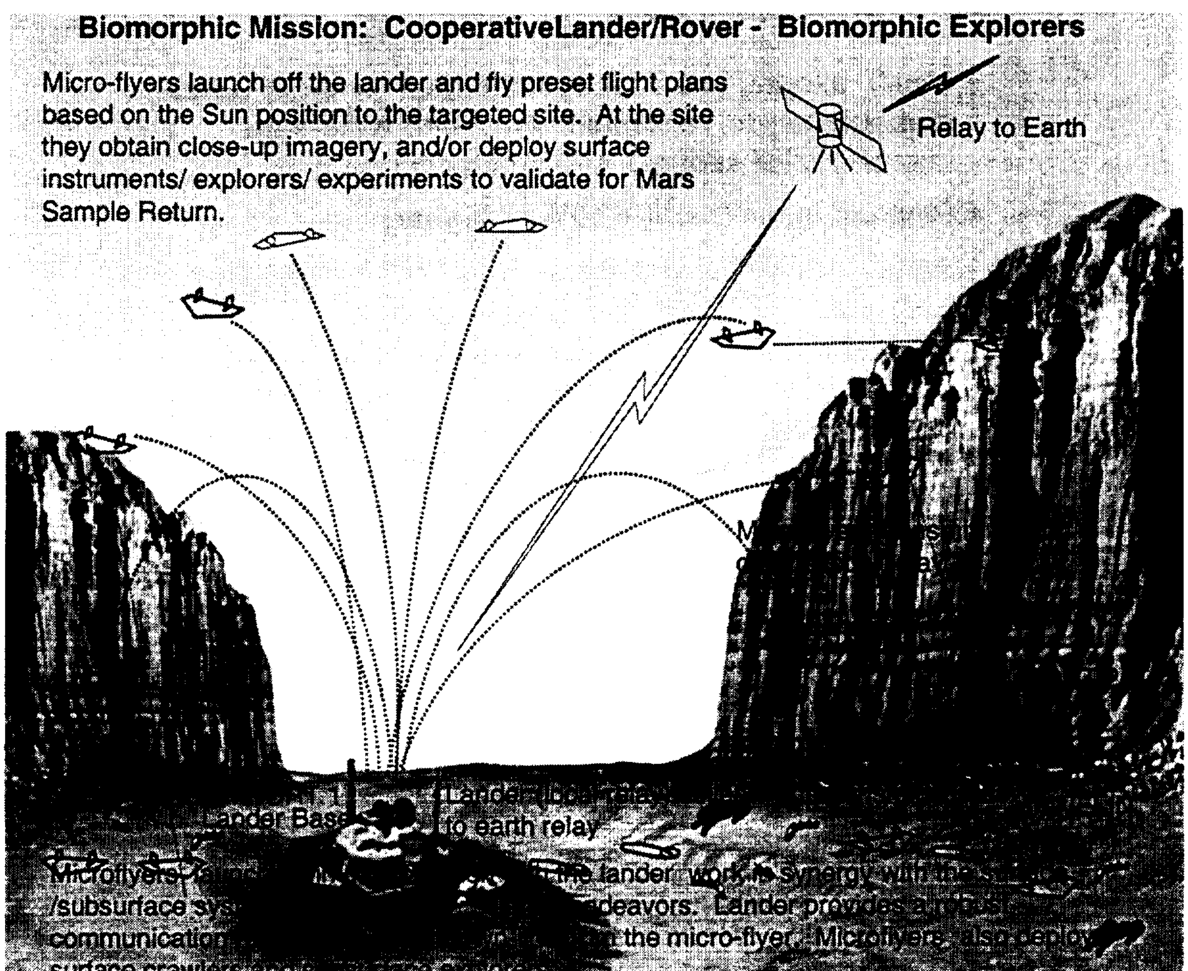
- Biomorphic missions are cooperative missions that make synergistic use of existing/conventional surface and aerial assets along with biomorphic robots.
- Just as in nature, biological systems offer a proof of concept of symbiotic co-existence. The intent is to capture/imbibe some of the key principles/success strategies utilized by nature and capture them in our biomorphic mission implementations.
- Specific science objectives targeted for these missions include:
  - Close-up imaging for identifying hazards and slopes;
  - Assessing sample return potential of target geological sites;
  - Atmospheric information gathering by distributed multiple site measurements; and
  - Deployment of surface payloads such as instruments/biomorphic surface systems or surface experiments.

Science Requirements

- Orbiter provides imaging perspective from ~ 400 Km height with resolution ~ 60cm to 1 m/pixel; lander mast imagery is viewed from ~ 1-2 m height. *The essential mid range 50m-1000m altitude perspective is as yet uncovered and is an essential science need. Imaging from this mid-range is required to obtain details of surface features/topography, particularly to identify hazards and slopes for a successful mission).*
  - Close-up imagery of sites of interest (~ 5 - 10 cm resolution).
  - 1-10 Km range, wide area coverage.
  - Distributed measurements across the entire range.
  - In-situ surface mineralogy.
- Candidate instruments include:
  - Camera (hazard and slope identification by close-up imagery).
  - Meteorological suite (in-flight atmospheric measurements).
  - Microphone to hear surface sounds, wind and particle impact noises.
  - Electrical measurement of surface conductivity.
  - Accelerometer measurement of surface hardness.
  - Seismic measurement (accelerometers).

Biomorphic Mission: Cooperative Lander/Rover - Biomorphic Explorers

- An auxiliary payload of a Mars Lander (2-10kg).
- Micro-gliders (4 - 20) launched/deployed from the Lander.
- Lander serves as a local relay for imagery/data downlink.
- Micro-glider provides:
  - Close-up imagery of sites of interest (~ 5-10 cm resolution).
  - Deploys surface payload/experiments (20g - 500 g).
  - In-flight atmospheric measurements.
  - Candidate instruments:
    - Camera (hazard and slope identification by close-up imagery).
    - Meteorological suite (in-flight atmospheric measurements).
    - Microphone to hear surface sounds, wind and particle impact noises.
    - Electrical measurement of surface conductivity.
    - Accelerometer measurement of surface hardness.
    - Seismic measurement (accelerometers).
- 50m-500m height, unique and essential perspective for imaging.
- 1-10 Km range, wide area coverage very quickly.
- Useful close-up imagery and surface payload deployment.
- 2005 Missions: Scout Missions, Sample Return Missions 2007 and beyond.

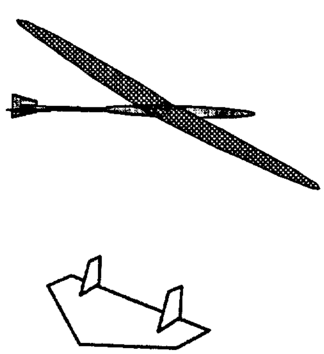


Surface Launched Microflyers: Options Comparison

- Contamination free launch options:
  - Spring launched (massive, KE leftover, complex possibly damaging recoil).
  - Electric launch options (power hungry):
    - Electrically driven propeller (Mars atmosphere is too thin).
    - Electromagnetic gun.
  - Inflate and release a balloon (complicated mechanism, thin atmosphere a challenge, susceptible to winds).
  - Pneumatic, compressed gas launch (simple mechanism, simple recoil, leading candidate).
- Rocket boosted launch (contaminants, HCl, nitrates, etc.) a good option for application such as scouting where contamination is not an issue.

Biomorphic Microflyers

- **Small, simple, low-cost system ideal for distributed measurements, reconnaissance and wide-area dispersion of sensors and small experiments.**
- **Payload mass fraction 50% or higher.**



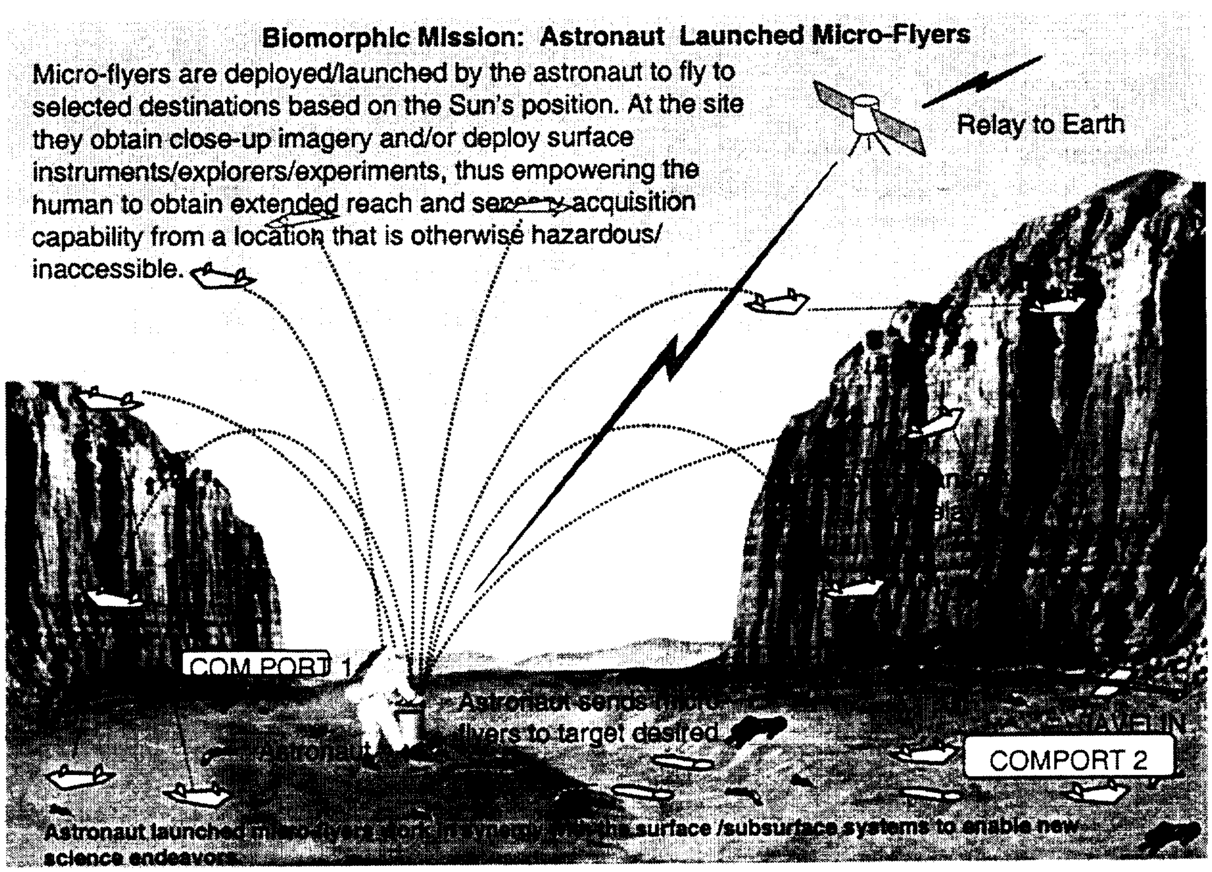
- **Small mass (100 g - 1000 g)**
- **Low radar cross section**
- **Larger numbers for given payload due to low mass**
- **Precision targeting to destination**
- **Amenable to cooperative behaviors**
- **Missions can use potential energy by deploying from existing craft at high altitude**
- **Captures features of soaring birds, utilizing rising currents in the environment**
- ***Adaptive behavior***
- ***Self repair features***

Science Objectives

- Near Term 2005
  - Image surface topography.
  - Characterize terrain around lander.
  - Identify rocks of interest for rover.
  - Distribution of instruments/experiments/surface explorers to targeted sites.

- 2007-2009
  - Enable sample return by allowing scouting and long range maps of areas of interest.

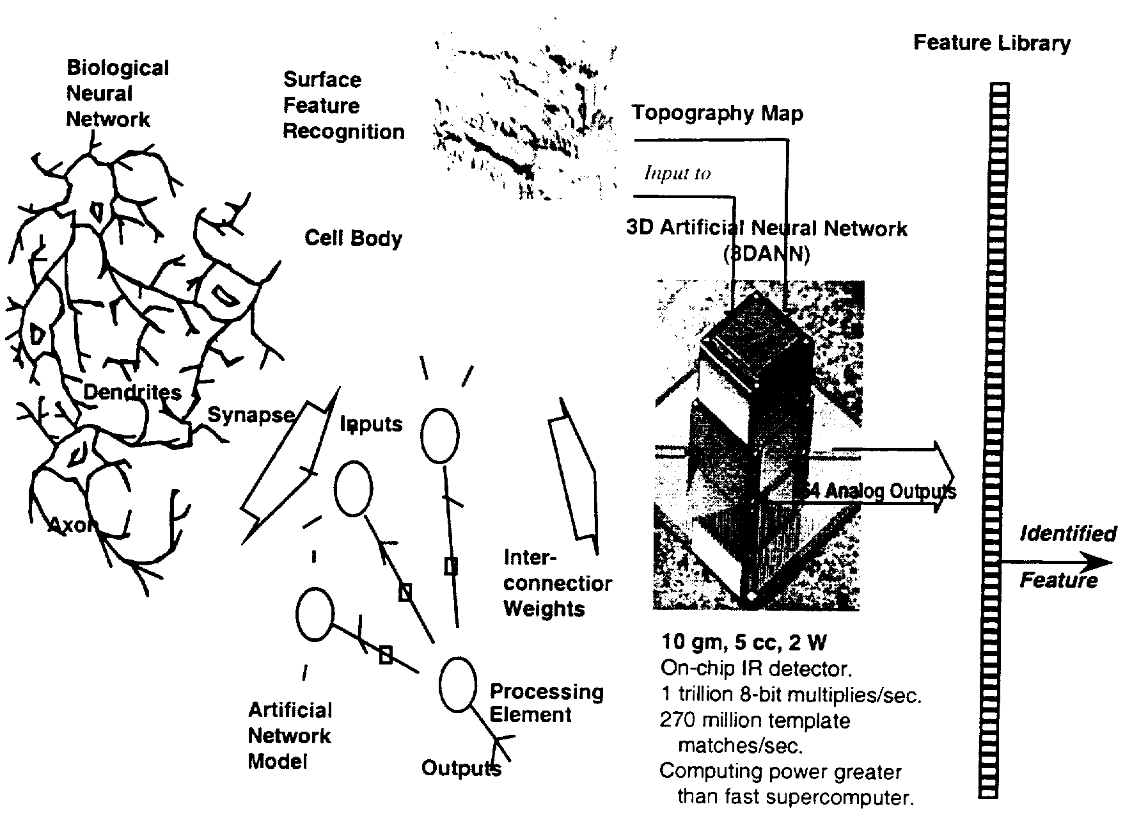
- Long Term 2011 and Beyond
  - Cooperative operation of a multitude of explorers together to obtain imagery and deploy surface payloads.
  - Astronaut launched micro-flyers: Empowering the human to obtain extended reach and sensory acquisition capability from locations that are otherwise hazardous/inaccessible.



Enabling Processor for Surface Feature Recognition

Modeled after the massively parallel neural networks in the human brain, 3DANN is a low-power, analog computing device capable of achieving human-like target recognition capability. The sugar-cube sized 3DANN processor has achieved an overall computing speed of ~ 1 trillion operations per second, consuming only ~ 8 watts of power. This is ~ 3 orders of magnitude higher than the state-of-the-art image-processing on conventional digital machines (e.g., Apple's recently introduced G4 computer which delivers ~ 1 billion operations per second, consuming ~ 200 watts of power). The N3 processor can be trained to recognize geological features of interest and used to obtain real time processing of camera input imagery to identify surface features of interest. As a compact, low-power, intelligent processor on-board a space system, it would enable for the first time, real-time functions such as in-situ landing site selection with hazard avoidance, visual navigation, precision rendezvous and docking, and visually intelligent planetary robots/rovers capable of autonomous selection of scientifically interesting spots for maximum science return.

Enabling Processor for Surface Feature Recognition



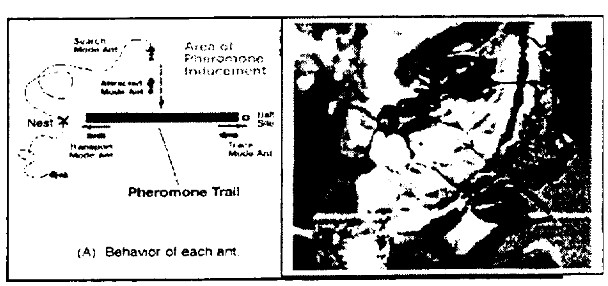
Biomorphic Cooperative Behaviors

The behavior of ant colonies, specifically, how the ants coordinate complex activities like foraging and nest building, has fascinated researchers in ethology and animal behavior for a long time. Several behavioral models have been proposed to explain these capabilities. Algorithms inspired by the behavior of ant colonies have already entered the mathematical field of multi-parameter optimization. Solar system exploration, particularly of Mars and certain planet/satellites, could be substantially enhanced through the use of a multitude of simple, small, somewhat autonomous explorers that as a group would be capable of "covering" large areas. A fleet of such explorers would have some form of limited communication with a mother ship (a larger lander/rover or an orbiter). In many cases, cooperation among all the "fleet-mates" could greatly enhance group effectiveness. Our program is geared to identify potential useful cooperative behaviors for such explorers by surveying emerging multi-robot multi-agent techniques and by assessing some of the uniquely powerful examples of cooperative behavior and self-organization observed in nature, specifically in the insect kingdom.

Biomorphic Communication and Navigation

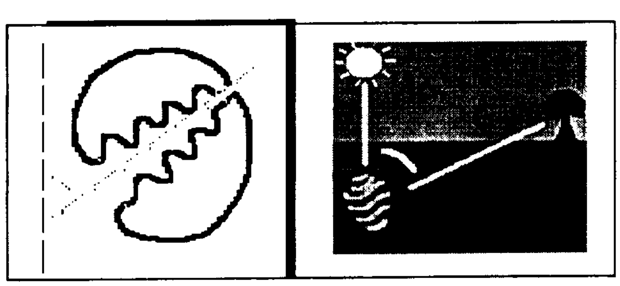
Honeybees are impressive in their ability to communicate precise navigational information. They use a recruitment dance and the sun as a celestial reference to communicate the location of a food source. Such principles related to planetary exploration could be utilized in a new class of small, dedicated, low cost biomorphic explorers.

Insects Operating Cooperatively:



Nakamura and Kurumatani, 1995
Kubo, 1996

Ants' elaborate communication method with pheromone trails.



Karl von Frisch, 1965,
Wehner and Rossel, 1985,
Barbara Shipman, 1997

Honeybee's recruitment dance with the sun as a celestial reference.

Science Applications

....which would be enabled/enhanced by such explorers.....

- Valles Marineris' Exploration
  - One single site rich in geologic units
  - Study strati-graphic column top to bottom along the canyon wall
  - Optimum science sample site

  ....imager, temperature sensor, pressure sensor, sniffer: e-nose, individual gases, elements, etc.

- Scouting for conditions compatible with life to lead us to the spots that may hold samples of extinct/extant life
  - Wide-area search with inexpensive explorers executing dedicated sensing functions: close-up imaging!!!!

  ....individual gases, sniffer: e-nose, chemical reactions, pyrotechnic test, elements, specific amino acids, signatures of prebiotic chemistry, etc.
- Geological data gathering:
  - Distributed temperature sensing
  - Seismic activity monitoring
  - Volcanic site

  ....multitude of explorers working in a cascade or daisy-chain fashion cooperatively to fulfill task.

Applications (Dual Use NASA and DoD)

- Close-up Imaging, Site Selection
- Meteorological Events: Storm Watch
- Reconnaissance
- Biological Chemical Warfare
- Search and Rescue, etc.
- Surveillance
- Jamming
- Distributed Aerial Measurements
  - Ephemeral Phenomena
  - Extended Duration Using Soaring
- Delivery and Lateral Distribution of Agents (Sensors, Surface/Subsurface Crawlers, Clean-up Agents)

Acknowledgements

JPL
Matt Golombek: Mars Geology
Brett Kennedy: Mechanical Design
Gerhard Klose: Structure
Ken Klassen: Camera
Terry Martin/Tim Schofield: Atmospheric Science
John Michael Morookian: Electrical Design and System Integration
Frank Palluconi: Science Imagery
Satish Krishnan/Robert Manning: Lander/Rover
Dara Sabahi: Entry and Landing
Anil Thakoor: Image Processing
Ken Nealson: Astrobiology

CALTECH:
Ali Hajimiri and Dave Rutledge: Telecom

RAYTHEON:
Jim Small: Aerodynamics and Navigation

ACKNOWLEDGMENTS

The research described in this document was carried out at the Jet Propulsion Laboratory (JPL), California Institute of Technology, under a contract with the National Aeronautics and Space Administration (NASA).

JET PROPULSION LABORATORY

INDUSTRY: RAYTHEON, AEROVIRONMENT, SONY, XEROX, PIONEER

NATIONAL LABS: LANL, SRI, ORNL, SANDIA

ACADEMIA: MINNESOTA, BERKELEY, CALTECH, PENN STATE, VANDERBILT, USC, UCLA, ARIZONA, ROCHESTER, MONTANA, CORNELL, NAGOYA, JAPAN, AUSTRALIA

OTHER NASA CENTERS: GSFC, AMES, LANGLEY, JSC