NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
CONTRACT NO. NAS 7-918

TECHNICAL SUPPORT PACKAGE

On

BIO-INSPIRED ENGINEERING OF EXPLORATION SYSTEMS

for 05/01/2003

NASA TECH BRIEF Vol. 27, No. 5

From

JPL NEW TECHNOLOGY REPORT NPO- 21142

Inventor(s):
SARITA THAKOOR

TSP assembled by:
JPL Intellectual Assets office
pp. i-ii, 1-29

JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY
PASADENA, CALIFORNIA

Bio-Inspired Engineering of Exploration Systems

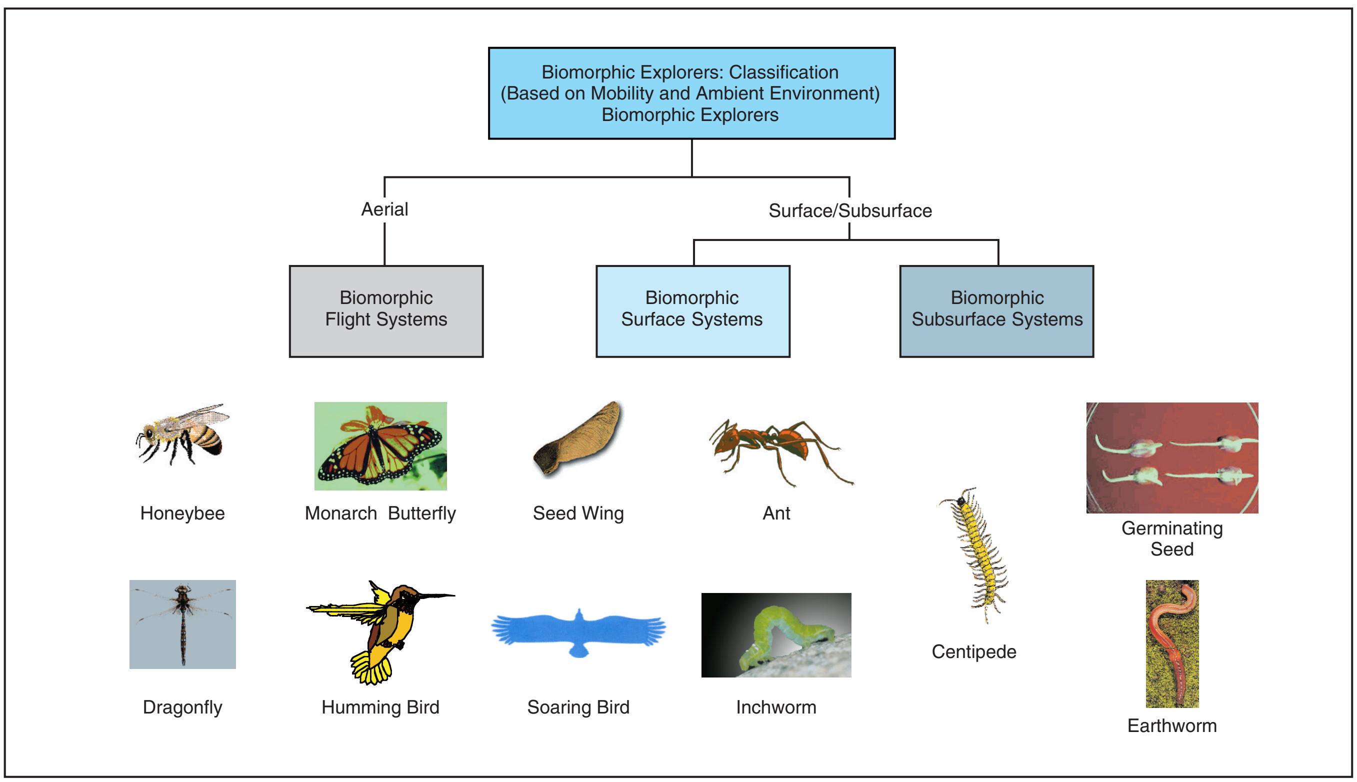
Exploration systems with capabilities imbibed from nature enable new operations that were otherwise very difficult or impossible to accomplish.

NASA's Jet Propulsion Laboratory, Pasadena, California

The multidisciplinary concept of "bioinspired engineering of exploration systems" (BEES) is described, which is a guiding principle of the continuing effort to develop biomorphic explorers as reported in a number of articles in the past issues of *NASA Tech Briefs*. The intent of BEES is to distill from the principles found in successful nature-tested mechanisms of specific "crucial functions" that are hard to accomplish by conventional methods but that are accomplished rather deftly in nature by biological organisms. The intent is not just to mimic operational mechanisms found in a specific biological organism but to imbibe the salient principles from a variety of diverse bio-organisms for the desired "crucial function." Thereby, we can build explorer systems that have specific capabilities endowed beyond nature, as they will possess a combination of the best nature-tested mechanisms for that particular function. The approach consists of selecting a crucial function, for example, flight or some selected aspects of flight, and develop an explorer that combines the principles of those specific attributes as seen in diverse flying species into one artificial entity. This will allow going beyond biology and achieving unprecedented capability and adaptability needed in encountering and exploring what is as yet unknown. A classification of biomorphic flyers into two main classes of surface and aerial explorers is illustrated in the figure, with examples of a variety of biological organisms that provide the inspiration in each respective subclass.

Such biomorphic explorers may possess varied mobility modes: surface-roving, burrowing, hopping, hovering, or flying, to accomplish surface, subsurface, and aerial exploration. Preprogrammed for a specific function, they could serve as one-way communicating beacons, spread over the exploration site, autonomously looking for/at the targets of interest. In a hierarchical organization, these biomorphic explorers would report to the next level of exploration mode (say, a large conventional lander/rover) in the vicinity. A widespread and affordable exploration of new/hazardous sites at lower cost and risk would thus become possible by utilizing a faster aerial flyer to cover long ranges and deploying a variety of function-specific, smaller biomorphic explorers for distributed sensing and local sample acquisition. Several conceptual biomorphic missions for planetary and terrestrial exploration applications have been illustrated in "Surface-Launched Explorers for Reconnaissance/Scouting" (NPO-20871), *NASA Tech Briefs*, Vol. 26, No. 4 (April, 2002), page 69 and "Bio-Inspired Engineering of Exploration Systems," *Journal of Space Mission Architecture*, Issue 2, Fall 2000, pages 49-79.

Insects (for example, honey bees and dragonflies) cope remarkably well with their world, despite possessing a brain that carries less than 0.01 percent as many neurons as that of the human. Although most insects have immobile eyes, fixed-focus optics, and lack stereo vision, they use a number of ingenious strategies for perceiving their world in three dimensions and navigating suc-



These **Examples of Biological Inspirations** show different mobility categories.

cessfully in it. We are distilling some of these insect-inspired strategies to obtain unique solutions to navigation, hazard avoidance, terrain following, and smooth deployment of payload. Such functionality can enable one to reach previously unreachable exploration sites.

In-situ, autonomous exploration and science return from planetary surfaces and subsurfaces would be substantially enhanced if a large number of small, inexpensive, and therefore dispensable, biomorphic explorers equipped with dedicated microsensors could be spread over the surface. Their low-cost and small size would make them ideal for hazardous or difficult site exploration, inspection, and testing. Their dedicated sensing functions and autonomous maneuverability would be valuable in scouting missions and sample acquisition from hard-to-reach places. As was mentioned earlier, when preprogrammed for a specific function and spread over the exploration site, these explorers could serve as intelligent, downlink-only beacons that autonomously look for objects of interest. Alternatively, these biomorphic explorers can operate in a hierarchical organization and report their findings to the next higher level of exploration (say, a large conventional lander/rover) in the vicinity. Specifically, our recent results demonstrate the novelty of our approach in adapting principles proven successful in nature to achieve stable flight control, navigation, and visual search/recognition. This approach has enabled overall a robust architecture for reliable image data return in application scenarios both for terrestrial and planetary needs where only a limited telecommunications or navigational infrastructure is available and is therefore otherwise by traditional methods hard or impossible to explore.

This work was done by Sarita Thakoor of Caltech for **NASA's Jet Propulsion Laboratory**. *For further information, access the Technical Support Package (TSP)* ***free on-line at www.nasatech.com/tsp*** *under the Machinery/Automation category.*
NPO-21142

New Technology Report

BIO-INSPIRED ENGINEERING OF EXPLORATION SYSTEMS

RECEIVED
SEP 18 2000
JPL TU OFFICE
21142
07436

Sarita Thakoor
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, CA 91109-8099

ABSTRACT

This paper describes the multidisciplinary concept of "Bio-inspired Engineering of Exploration Systems" (BEES). The new terminology associated with this concept is defined. BEES utilizes small, dedicated, low power, and low-cost "biomorphic explorers" that capture selected functional traits of biological systems to obtain leap-frog advances over existing mobile robotic systems to enable cooperative "biomorphic missions". Biomorphic explorers can empower the human to obtain extended reach and sensory acquisition capability from locations otherwise hazardous/inaccessible. Biomorphic missions are co-operative missions that make synergistic use of existing and conventional surface and aerial assets such as lander, rover and orbiter along with biomorphic explorers. Just as in nature, biological systems offer a proof of concept of symbiotic co-existence. The intent here is to distill some of the key principles and success strategies demonstrated 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 or surface experiments. A few candidate biomorphic mission scenarios are also described.

1. Introduction:

Space exploration presents the daunting and expensive challenge of reaching to the unknown uncharted planets. Be it for exploring new planets as is for NASA or to deal with the needs of DoD surveillance of unfriendly/hazardous territories, the challenge is to deal with unpredictable situations/environmental conditions and to have the versatility of adapting to unknown and unanticipated situations. Advanced robotics, in spite of all the recent engineering advances, remains short on capabilities with respect to agility, adaptability, intelligent sensing, fault-tolerance, stealth, and utilization of in-situ resources for power compared to some of the simplest of biological organisms. The multidisciplinary system concept of "Bio-inspired Engineering of Exploration Systems" (BEES) described in this paper utilizes small, dedicated, low power, and low-cost biomorphic explorers that capture selected functional traits of biological systems to obtain leap-frog advances over existing mobile robotic systems. The bio-morphic systems so enabled can range from insectoids to humanoids.

43991

p. 15

The general premise of bio-inspired engineering is to distill the principles incorporated in successful, nature-tested mechanisms of selected features /functional traits that can be enabling to new endeavors; capturing biomechatronic designs and minimalist operation principles from nature's success strategies. The intent is not just to mimic operational mechanisms found in biological organisms but to imbibe from a variety of diverse bio-organisms that employ differing manifestations of a salient principles common through apparently diverse species, to obtain key functional traits of interest. Such features include adaptive controls, agile and stealthy response, versatile mobility (e.g. burrowing, soaring), bio-inspired sensor mechanisms, sensor fusion, biomorphic communications, biomorphic cooperative and distributed operations. The major subsystems breakdown of BEES and major categories there-in are highlighted in figure 1.

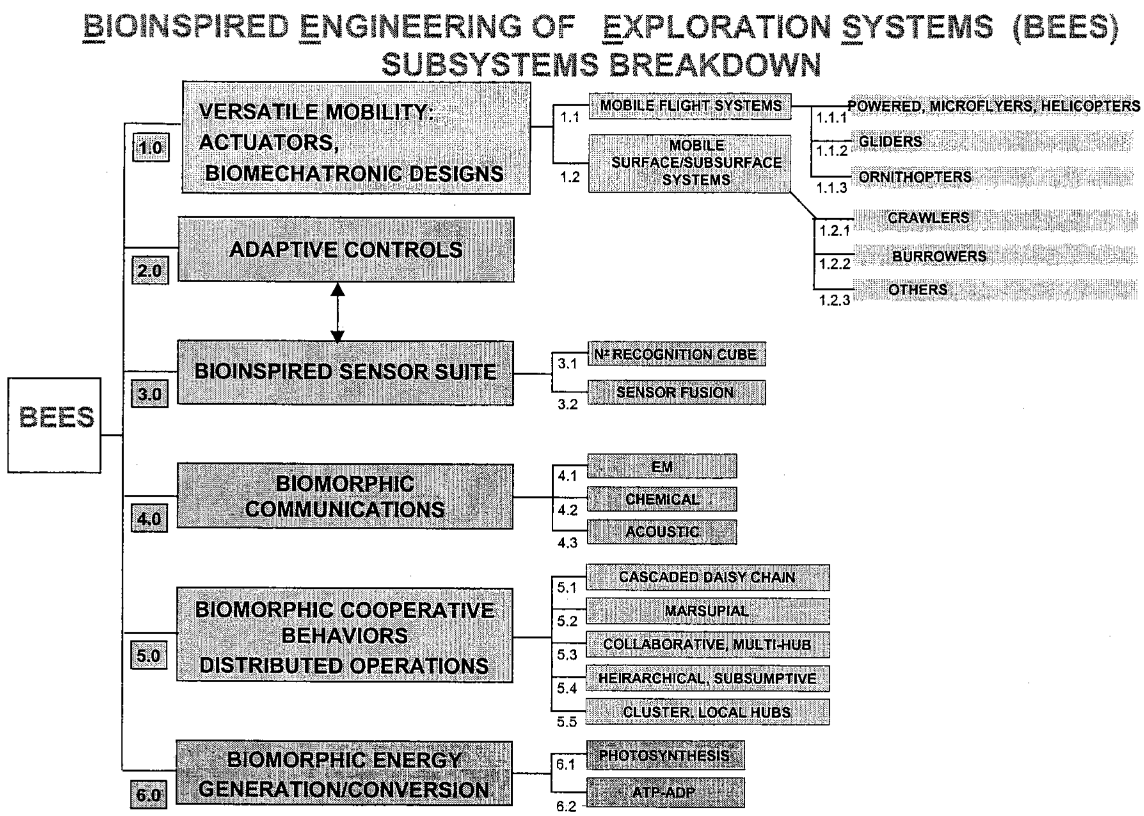


Figure 1: Subsystem breakdown for BEES

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 would be realized 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. A classification of such explorers with example candidates in each category is illustrated in this paper. The biomorphic flight systems are extremely attractive for solar system exploration because of their potential large range, unique imaging perspective, and the access to here-to fore inaccessible sites that they would provide. **Biomorphic Missions** are co-operative missions that make synergistic use of existing/conventional surface and aerial assets such as lander, rover and orbiter along with biomorphic explorers. Just as in nature, biological systems offer a proof of concept of symbiotic co-existence. The intent here is to distill some of the key principles/success strategies demonstrated 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 or surface experiments. A few candidate biomorphic mission scenarios are also described.

2. Classification Of Biomorphic Explorers

Figure 2 illustrates examples of natural biological systems that serve as inspiration for designing the biomorphic explorers. Pick a feature, such as soaring. The intent is to make an explorer that combines different attributes seen in diverse soaring species and capture many of them in one artificial entity, to go beyond biology and achieve unprecedented adaptability needed in encountering and exploring what is as yet unknown. As another example, consider the trait of "sub-surface burrowing". This is observed in as diverse species as, a germinating seed, an earthworm, and *Amphisbaenia,* a generally leg-less order of reptiles that creates tunnels by forcing themselves through the soil. A burrowing platform that would imbibe the characteristics of burrowing in a multifaceted way (like a swiss army knife) as seen in the diverse bio-species is needed for a range of NASA/DoD applications. For example, very little is known about the soil conditions and their variability on Mars. To realize the goal of looking for water, a biomorphic explorer is needed that can adapt to multi-terrain particularly sub-terranian conditions.

These inspiration examples are classified based on their mobility type and ambient environment into subdivisions of aerial systems and surface/subsurface systems.

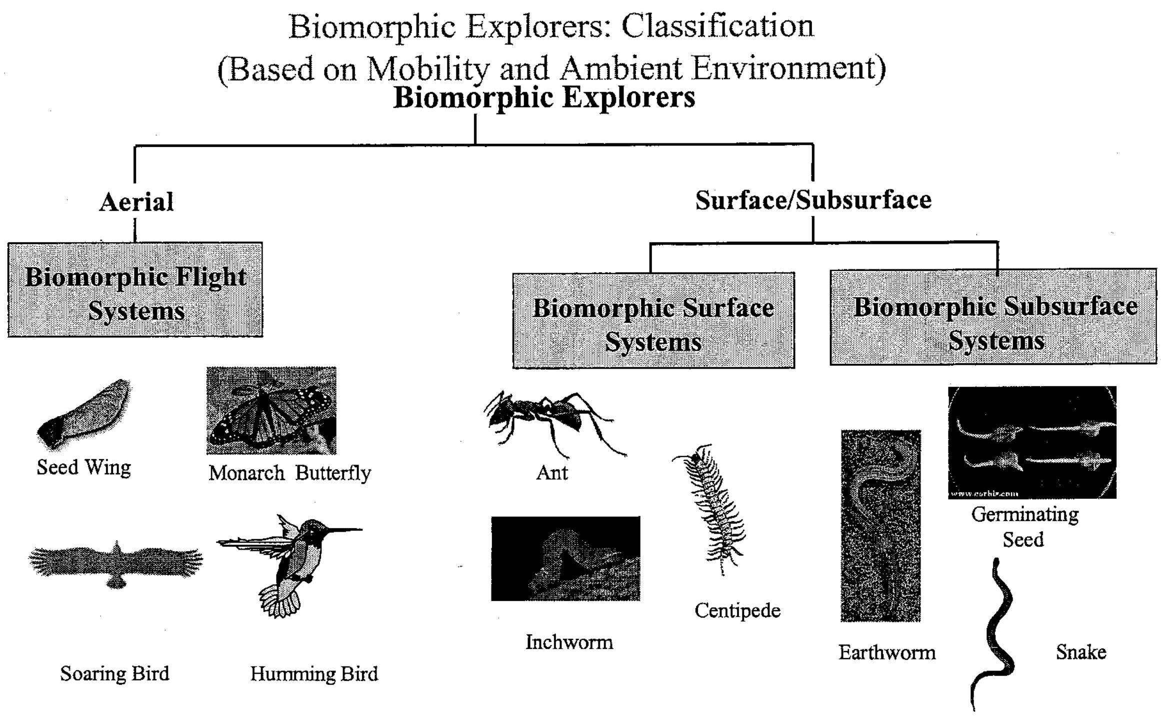


Figure 2: Examples of biological inspirations in different mobility categories

Such bio-morphic explorers may possess varied mobility modes: surface-roving, burrowing, hopping, hovering, or flying, to accomplish surface, subsurface, and aerial 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 one-way communicating beacons, spread over the exploration site, autonomously *looking for/at the targets of interest*. In a hierarchical organization, these bio-morphic explorers would report to the next level of exploration mode (say, a large conventional rover) in the vicinity. This would allow a wide-spread and affordable exploration with a substantial amount of scouting for information about a new/hazardous area at lower cost and risk, combining a fast running rover to cover long distances and deploying numerous bio-morphic explorers for distributed sensing and local sample acquisition.

3. Biomorphic Explorers- A New Paradigm In Mobility:

Figure 3 illustrates the key points of the new paradigm taking an example from the surface systems.

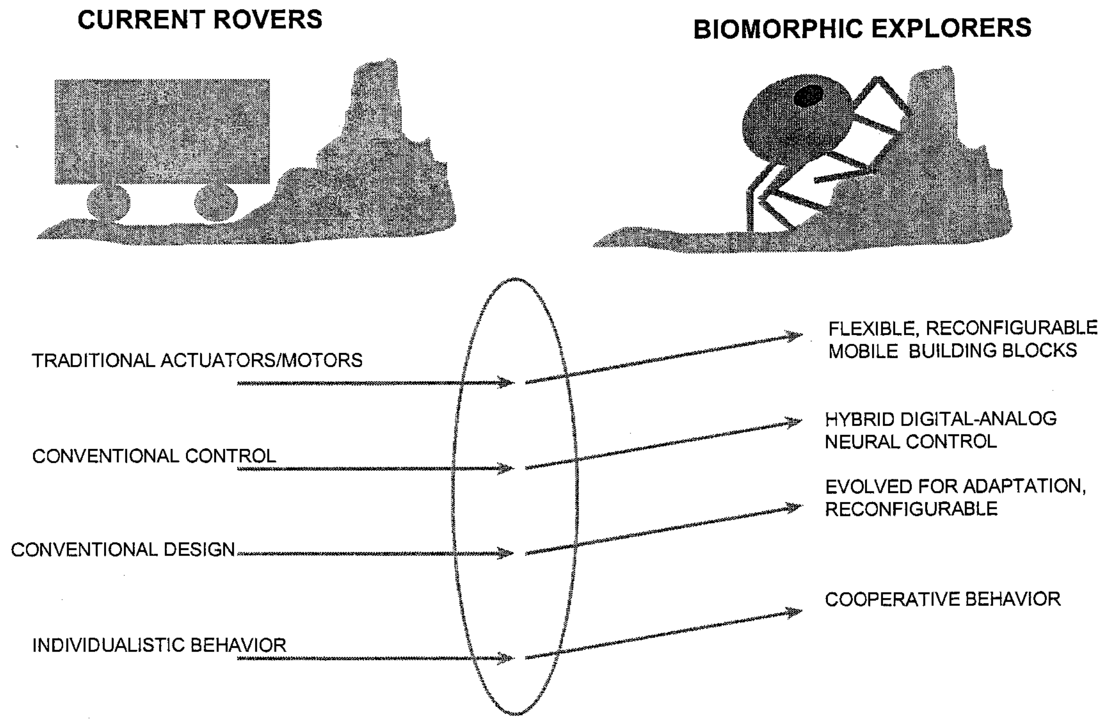


Figure 3: Mobility: New Paradigm

A quick response to even an unanticipated sensory stimulation and adaptation of the prevalent mobility style to suit changing environment/ambient conditions occur naturally in biological organisms - in striking contrast with respect to existing artificial mobile systems. This is primarily due to the basic differences between the naturally evolved "controls" in bio-organisms that smoothly "transform" the sensory inputs (say n) into the actuator outputs (m) and the human-engineered, mathematically rigorous controls, captured in discrete functions, typically optimized for a given system architecture, with limited adaptability. These are summarized in a table below.

Table 1. Comparison of Biological Systems with Existing Artificial Mobile Systems

<u>Biological Systems</u>	<u>Existing Artificial Mobile Systems</u>
"Live off the Land"	Usefulness limited by Battery life and size
Complex correlation embedded in transformation	Simple Rule based look up tables
Continuous, n is large	Typically n < 10
Adaptable, learning capable	Rule based, fixed
Response agile, smooth	Response jerky, discrete
Muscle Actuators, Organic	Motors, Inorganic Actuators

Earlier work on biologically inspired robots has been done by workers all over the world[1-16]. Biomorphic Explorers, the new paradigm[2,17] in mobility that we describe here, combines bio-inspired versatile mobile units and adaptive control, to capture key features and mobility attributes of biological systems that are of interest for specific applications. Bio-morphic explorers[18] are a unique combination of versatile mobility controlled by adaptive, fault tolerant biomorphic algorithms to autonomously match with the changing ambient/terrain conditions. This takes one from the rigid, mobility-limited traditional robotics to adaptive, bio-morphic explorers. Important features of the paradigm shift, illustrated in Figure 4, are discussed in the following.

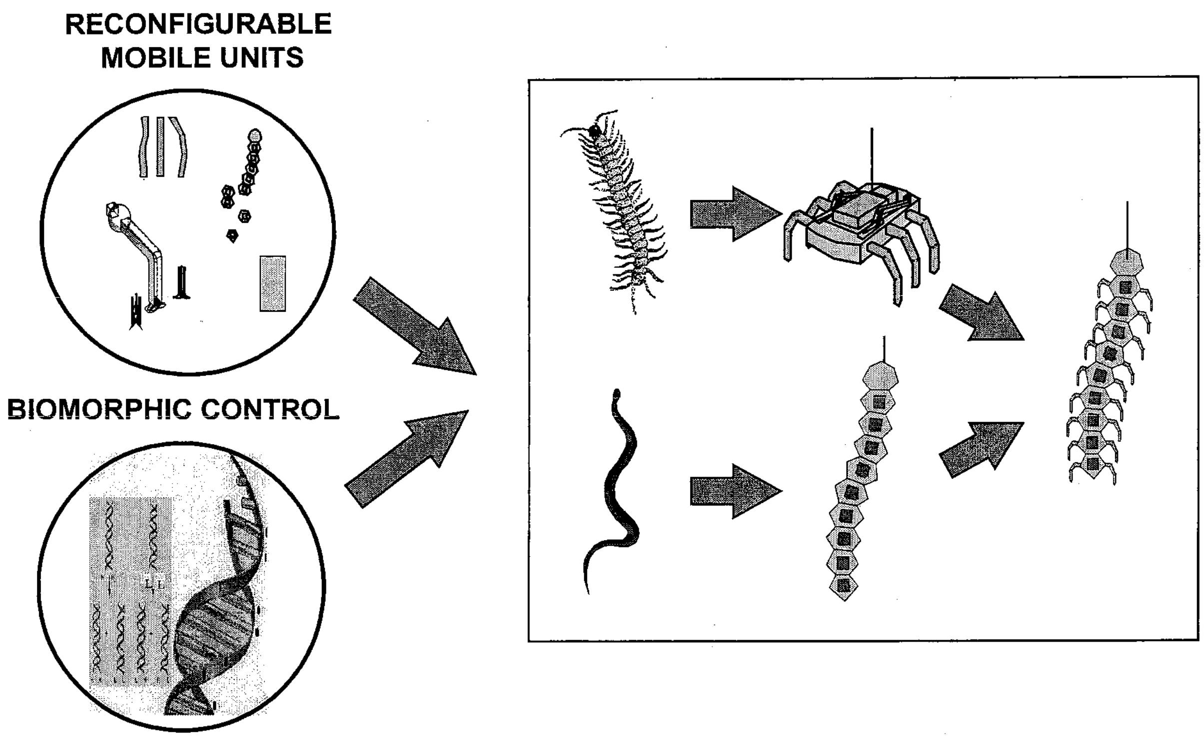


Figure 4: Schematic illustration of the concept of Biomorphic Explorers

Features :

A. Advanced reconfigurable mobile units will allow design of direct-driven limbs bypassing the need for complex chassis (drive systems). The limbs will possess the versatility of configurations within a certain domain of mobile systems.
B. Inspired from biology, bio-morphic controls (based on artificial neural network implemented in low-power VLSI hardware) would be especially suited for controlling the inherently non-linear mobility attributes.
C. Revolutionary mechanisms for adaptation would replace traditional fixed designs. For example, sensor-triggered control sequence to the legs may be determined for optimal ways to move in various different environmental conditions.
D. In addition, inspired from the ability of insects to home on targets using thermal and chemical sensors, and their unique communication abilities, cooperative behavior among many such explorers would enable new types of missions.

Using groups of bio-morphic explorers in conjunction with larger, traditional mobile robots will enable tasks, too complex for a single robot.
Table 2 compares the new approach with the conventional robots / conventional controls and conventional robots / bio-morphic controls.

Table 2: Comparison of Conventional Approaches and Biomorphic Approach

	Conventional Robot With Conventional Controls	Conventional Robot With Bio-Morphic Controls	Proposed Bio-Morphic Explorers With Bio-Morphic Control
Actuator Shape	Wheels (Legs – Experimental)	Wheels (Legs – Experimental)	Any Shape: (Legs, Limbs) Modifiable
Actuator Type	Conventional Actuator Materials, Mostly Rigid	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 (Bio-Morphic) Controls	Learning, Adaptive, Neural (Bio-Morphic) Controls Reconfigurable
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, Miniaturization	No	No	Yes
Spatial Access Narrow Crevices	No	No	Yes
Ratio: Complexity Or Cost/Capability	High	High	Low

Biomorphic explorers offer the potential to obtain significant scientific payoff at a low cost by utilizing the power of a large number of co-operatively functioning units. This is analogous to the approach seen in insect societies.

Recent NASA studies [19,20] suggested that biomorphic explorers could be feasible and cost-effective. An important application would be to use them as scouts in future planetary exploration where they would look for samples/sites of interest. Inspired by the world of insects and animals, the well-proven natural 'explorers' on this planet, biomorphic explorers represent an exciting alternative to traditional labor-intensive telerobotic operations. The studies concluded that combining flexible reconfigurable mobile units and biomorphic controls would offer, for the first time, a possibility of autonomous exploration with adaptation to varying terrain conditions. Figure 5 shows examples of reconfigurable mobile systems found in nature in the surface mobilty and aerial mobility domains that are specifically suited to their specific environment

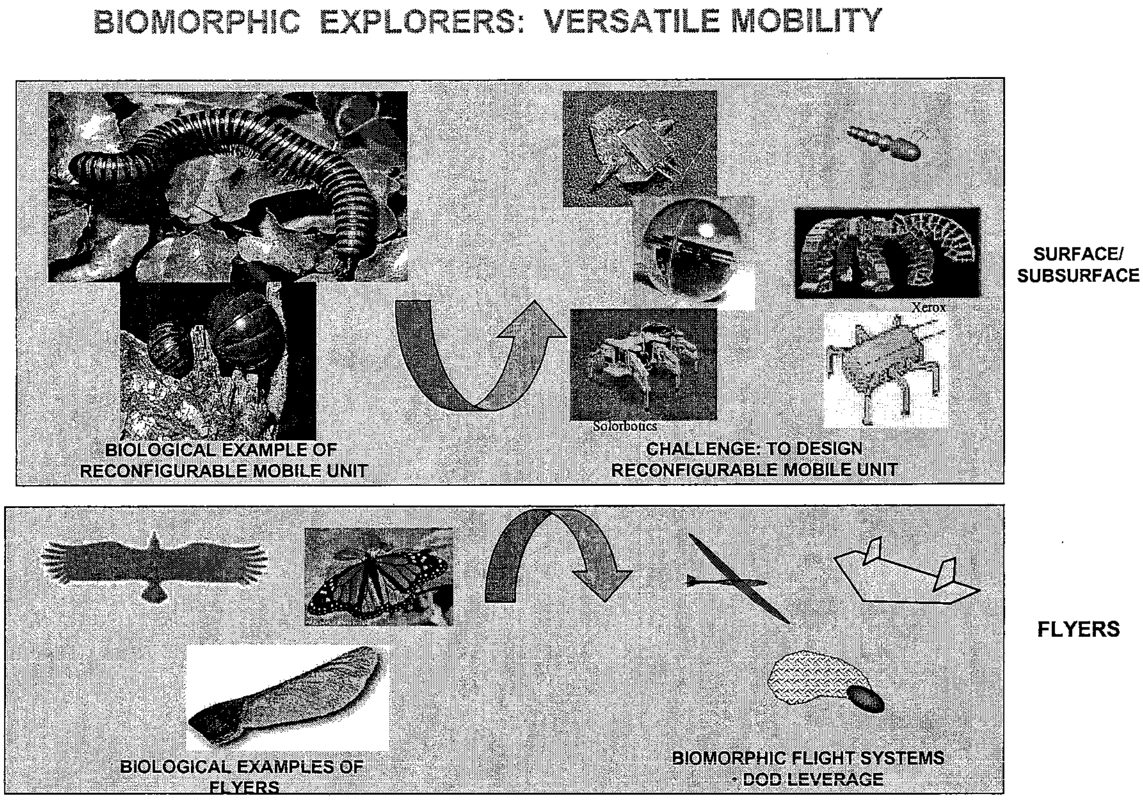


Figure 5: Reconfigurable mobile units

and function with corresponding examples of artificial biomorphic systems that are in the design process currently. Biomorphic explorers[21] could provide enhanced spatial access and ease of production with low recurring cost, due to their simple design. This level of autonomous exploration would be beneficial to several planetary science goals. These goals include: scouting for conditions compatible with life to lead us to the right spots that may hold samples of extinct/extant life; in situ sensing to obtain physical, meteorological, and chemical data on unexplored planetary surfaces; and investigation of previously inaccessible locations. On Earth, biomorphic explorers would offer new capabilities for exploration, surveillance, advanced warning systems, and access to difficult environments.

In-situ, autonomous exploration and science return from planetary surfaces and subsurfaces would be substantially enhanced if a large number of small, inexpensive, and therefore dispensable, biomorphic explorers equipped with dedicated microsensors could be spread over the surface by a lander or a larger rover. Capturing nature tested capabilities from biology, such biomorphic explorers may possess animal-like mobility and adaptability. Their low-cost and small size would make them ideal for hazardous or difficult site exploration, inspection, and testing. Their dedicated sensing functions and maneuverability would be valuable in scouting missions and sample acquisition from hard to reach places. Such biomorphic explorers would complement the capabilities of the larger and relatively expensive exploration platforms/modes (e.g., orbiters, landers, rovers etc). Biomorphic explorers can possess varied mobility modes such as surface-roving, burrowing, hopping, climbing, hovering, or flying to accomplish surface, subsurface, and aerial exploration. Preprogrammed for a specific function and spread over the exploration site, they could serve as intelligent, downlink-only beacons that autonomously look for objects of interest. It was conceptualized[19-21] that, in a hierarchical organization, these biomorphic explorers would report their findings to a next higher level of exploration (say, a large conventional rover) in the vicinity. For example this would allow more wide-spread and affordable exploration at lower cost and risk by combining a fast rover to cover long distances and deployment along its route of numerous biomorphic explorers for in-situ sensing and local sample analysis/acquisition. Section 5 to Section 8 detail a few cooperative exploration scenarios enabled by the use of Biomorphic explorers.

4. Biomorphic Flight Systems:

The biomorphic flight systems are a sub class of biomorphic explorers. Nature provides the ultimate example of alternative configurations to solve the problems of flight. Every insect or bird is uniquely different and each is optimally adapted to its specific niche–to literally its mission in life. Similarly with man's aerial creations from gossamer light human-powered aircraft to the tons of metal of a supersonic jet or the complexity of a helicopter, each is also refined for its specific, intended purpose. Biomorphic flight systems could follow the same trend. A number of different modes of flight and configurations could be developed, each of which would be optimized for achieving a particular combination of design parameters in accordance with the varied, yet specific interests of the customer community to provide solutions to exploration needs.

A new idea which holds promise for a more robust and compact alternative to the parachute for small payloads is inspired by the plant world, particularly the techniques plants use to disperse seeds. Soaring birds (e.g., frigate bird, albatross, and hawks) use wind currents to stay aloft for hours or even days using little power to search for food or travel great distances. Monarch butterflies exhibit soaring inspite of their small size. It is well observed and documented that the Monarch migrates all the way from Canada to Mexico. Biomorphic flyer concepts can be envisioned to take advantage of the same kinds of rising air currents on certain planets/planet satellites to stay aloft for periods of time to conduct meteorological and geological surveys. Gliders using this type of natural flight mechanism have greater mobility and far superior directional control than balloons, are much lower in mass (and higher in payload fraction than balloons or powered air vehicles), and in suitable atmospheric conditions can stay aloft longer than powered craft. Deployed in large numbers these flight systems could substantially enhance science return. Unlike other exploration platforms, the flight systems can cover distances of several kilometers in a very short time, nearly independent of terrain. Compared to surface crawlers, biomorphic flight systems have the potential for substantially higher mobility (in speed, range, and terrain independence). Biomorphic flight systems can even be made to deliver other biomorphic explorers to target sites, greatly extending the utility of those explorers. These flight systems with their ability to land relatively softly, have the advantage of being a good means for distribution of payload.

Three general overlapping volume based categories have been defined earlier within the Microexplorers study[22], ('a' = 1 to 20 cc, 'b' = 10 to 200 cc, 'c' = 100 to 2000 cc). In addition to the size and volume classification, these flight systems may be categorized further by vehicle class, flight regime, deployment, propulsion, and method of control. A few examples within these classifications are given below:

Class:	glider, powered, boost glider, balloon, helicopter, blimp, or autorotating seed wing
Flight regime:	subsonic, transonic, or supersonic
Deployment:	launch from surface, entry probe, orbiter, or from larger atmospheric platform
Propulsion:	propeller, flapping, rocket, or unpowered
Control:	autonomous, telerobotic, biomorphic controls, or uncontrolled

5. COOPERATIVE MISSION SCENARIOS FOR EXPLORATION: BIOMORPHIC MISSIONS

Cooperative mission scenarios utilizing a combination of biomorphic explorers with versatile mobility modes are conceptualized in this section. Cooperative exploration with a lander, a rover, and a multitude of inexpensive biomorphic explorers would allow comprehensive exploration at a low cost and with broad spatial coverage. For orbiters, landers, rovers, and manned missions, flight systems in particular provide a means for exploring beyond the visual range of on-board cameras. They aid in identifying targets of scientific interest and to determine optimal pathways to those targets. In the case of an orbiter or entry probe, a large number of gliders or seed wing pod flyers, for example, spread over a general region of interest could return in situ measurements to augment science from images taken from space.

Payloads can range from small cameras to specialized science experiments designed to measure geophysical, chemical, or atmospheric properties. The biomorphic flight system itself can be designed to seek out features of interest, crash at the target site, and then act as a homing beacon for a lander or rovers that would later conduct further experiments. For data return, multiple communication options such as daisy chain, beacon, global broadcast and/or heirarchical organization would be practical.

Biomorphic Missions are therefore co-operative missions that make synergistic use of existing/ conventional surface and aerial assets along with biomorphic robotic systems. 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. Two Biomorphic missions pertinent to NASA exploration goals are described and illustrated in figure 6 and figure 7.

5.1 COOPERATIVE LANDER-ROVER –BIOMORPHIC EXPLORERS MISSION

When exploring a new terrestrial/planetary surface *in situ*, the challenge is to be able to quickly survey and select the sites of interest. Imaging done from orbiters allows broad coverage but at limited spatial resolution; ~1- 2 m. Descent imaging may provide a context for landed vehicles; however, it is not broad enough to plan exploration paths/areas for a rover or to characterize potential sample return sites. Images taken from surface-sited landers/rovers with masts ~1- 2 m high do not cover the surroundings adequately far from their location. Coverage of a large area is warranted, and close up imaging (~5 – 10 cm resolution) is desired. This essential mid-range, 50 – 1000-m 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 rover mission. For a planet with an atmosphere, such as Mars, flyers carrying cameras can provide the larger-scale visibility at the required spatial resolution within the context of orbiter and/or descent imaging. A cooperative lander-rover-biomorphic explorers mission is therefore suggested and illustrated in figure 6.

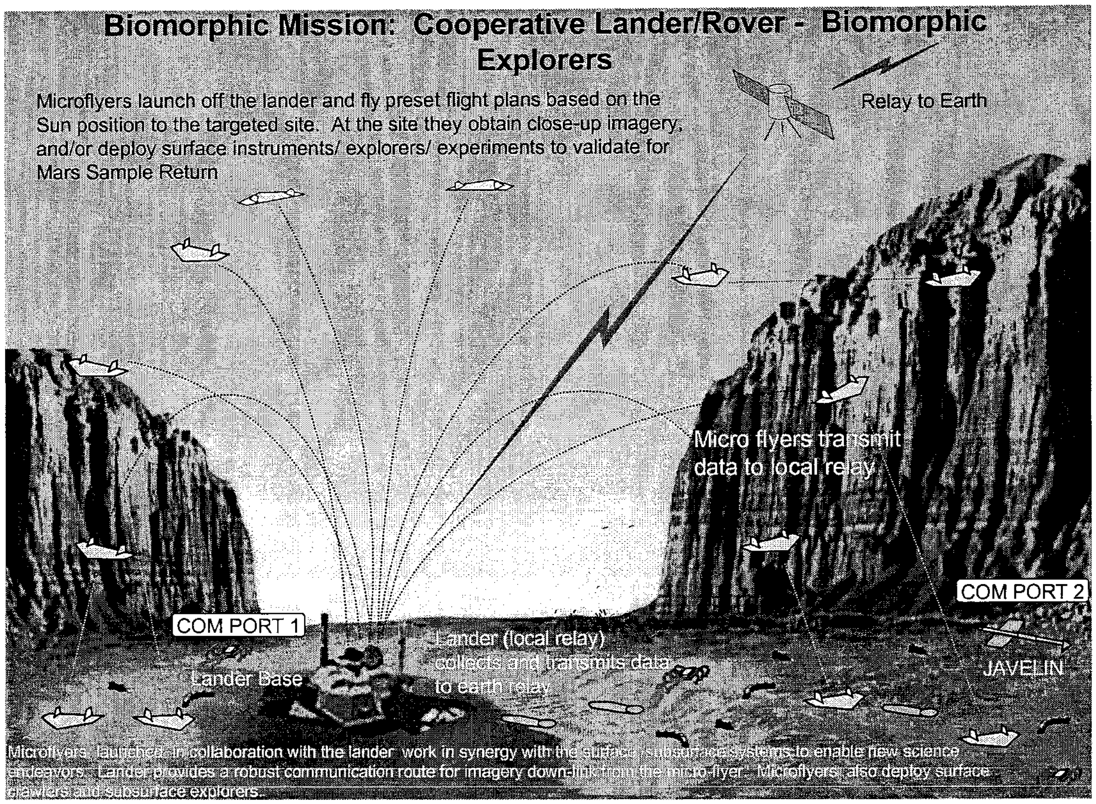


Figure 6: Biomorphic Mission: Cooperative Lander/Rover - Biomorphic Explorers

The mission objective is to image over the horizon terrain and perform surface measurements for site selection and sample return reconnaissance. A. Specific objective is to obtain samples from potential exobiology sites and areas of geological interest on Mars. Valles Marineris on Mars is a potentially favored landing site because, by comparison with our Grand Canyon here on Earth, it is expected to be potentially rich in geological data in one single site. Additionally, if accessible, it will be possible to sample the whole section from top to bottom from one single landing site. Bridger[23] has proposed a study of the entire stratigraphic column exposed along the canyon wall. Lucchita[24] has described Valles Marineris as an optimum science sample site. A lander equipped with a large rover (and ascent vehicle) lands in the Valles Marineris roughly 10-100 km from an area of potential exobiological significance, fault zones with exposed geological features, and eroded canyon walls with exposed sedimentary layers. The lander is targeted in a relatively flat area (devoid of interesting samples) to minimize risk in landing. The rover is designed for traversing rugged terrain and is equipped with an arsenal of scientific experiments including the ability to obtain and store samples. The rover is heavily nstrumented and therefore quite expensive and by no-means expendible. However, there is always a risk of damage or loss in negotiating the rugged terrain. Therefore, some knowledge of the terrain and locations of scientific targets can significantly reduce mission risk and improve sample collection efficiency. After shedding the protective gear and making necessary deployments, a javelin is launched from the lander, and lands ~ 500m –1Km away. The javelin and lander begin emitting low-power RF signals, which will be used for radio navigation by the microflyers and other explorers. The canyons in the foothills of the Valles Marineris are varied, some with steep walls and rubble at the base; others are filled with wind-blown sands. Many canyons end abruptly after a short distance or become impassable due to rockslides. From its vantage point in the valley, the lander cannot determine the location of ideal science targets or the best paths to reach them. The rover could waste a tremendous amount of time searching for a suitable path and going down dead ends.

The lander is equipped with several microflyers. A launching mechanism is used to launch the microflyer specifying a flight heading. Launch energy could be provided by a small solid rocket, pneumatic thrust, compressed *in-situ* resource gas launch, a spring, electrically powered launch or a mechanism combining two or more of the stated techniques. The communication range is kept small (<10 km), and the relay base is always available. Different flight paths over different terrains of interest are followed by the different flyers. Surface imagery is obtained using miniature camera systems on the flyers. The microflyer relays imagery/meteorological data to the lander and after landing conducts/deploys a surface experiment and acts as a radio beacon to indicate the selected site.
This particular flyer also can be equipped with the logic to identify specific features that may signify an area of scientific interest. The flyer then makes a decision to terminate the flight when its sensor identifies a potential exobiological site. Its small size, low mass and rugged design enable it to survive the impact with the ground. It then deploys a small science experiment with a chemical or pyrotechnic device and a "sniffer" to determine the presence of some trace element. Perhaps this experiment might even burrow several centimeters below the surface. The flyer then uses its remaining power and the power from a small photovoltaic cell to periodically transmit the results of its tests. This transmission also acts as a beacon.

The lander receives the images and beacon signals transmitted by the flyers and relays them to the science team and mission planners on Earth. Several other flyers are launched in succession, each on its own radial, and the images and data are collected and sent to the project team. Based on this data, the project team identifies target sites with the greatest science potential, and suitable pathways are mapped.

The rover then begins its mission with numerous radio beacons aiding in its navigation. Along the way, the rover finds itself unable to negotiate a way around some fallen rock and debris. The rover itself carries several flyers, designed for slow flight, and deploys one to survey the area. Also, the rover could carry several microflyers to allow functional subdivision. Using the rover as a beacon, the flyer takes images of the rover and surrounding area while sending the images back to the lander. Mission planners are able to use the information to plan an effective route not to mention getting an image of the rover in a rugged remote location for the media. Little time is wasted and the risk is minimized. The rover executes its mission plan and obtains samples from several sites before returning to the lander and depositing the samples into the ascent vehicle. Microflyers launched from the rover could also disperse other biomorphic multiterrain surface/subsurface explorers. These tiny multiterrain explorers could be the climbing type or rapelling type, scaling the columns of Valles Marineris obtaining close-up stratigraphic data. Microflyers could also be used to send the samples back to the lander for collection. In this reconnaissance role the microflyers maximize the effectiveness of the larger rover.

If the feasibility of this approach can be verified, use of surface-launched imaging micro-flyers would be a powerful option for enhancing the public interest and science return from a Mars '05 and/or '07 rover or sample return mission. Use of flyers at Mars would have great public appeal. The unique perspective of the images acquired from such flyers will excite the public as well as provide valuable mission support. The chances of selecting the most interesting sites for visitation by a rover within the limited time and resources of the mission could be increased dramatically. Identification of the most interesting specimens to be collected as returned samples could be enabled over a much wider area than could be done from the rover directly. In these ways, the scientific return from a rover mission would be increased. Further development of a planetary flyer capability will also have potential application to future missions to other planets and satellites with atmospheres such as Venus, Jupiter, Saturn, and Titan.

5.2 BIOMORPHIC MISSIONS FOR HUMAN EXPLORATION AND DEVELOPMENT OF SPACE:

Biomorphic Explorers can be deployed/launched by the astronaut to selected destination. Solar navigation is utilized by the launched biomorphic explorer. At the targeted site the explorers obtain close-up imagery and can further deploy surface instruments or biomorphic surface explorers. Thus the human (astronaut) is empowered to obtain extended reach and extended sensory acquisition capability from a location that otherwise would be inaccessible or hazardous to access. Such a mission is illustrated in figure 7 for human exploration and development of space.

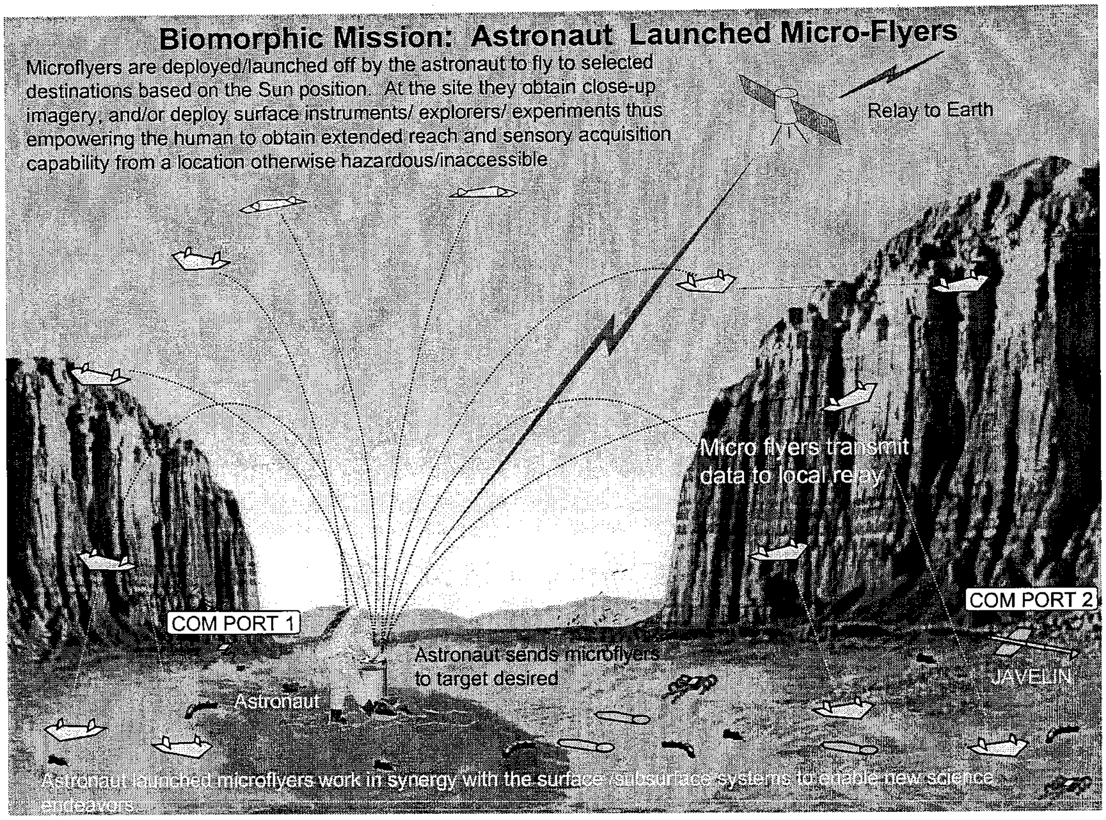


Figure 7: Biomorphic Mission: Astronaut Launched Biomorphic Explorers

Biomorphic Explorers could also assist with the building, repair and periodic maintenance inspection of human habitats on Moon or Mars.

6. Plant Inspired Biomorphic Techniques for Dispersal of Payloads:

In this section are presented a few envisioned biomorphic missions for distribution of instruments/biomorphic surface systems (payload) by using ideas inspired from the plant-world such as dandelions and seed wing pods. These are illustrated in figure s 8,9 and 10

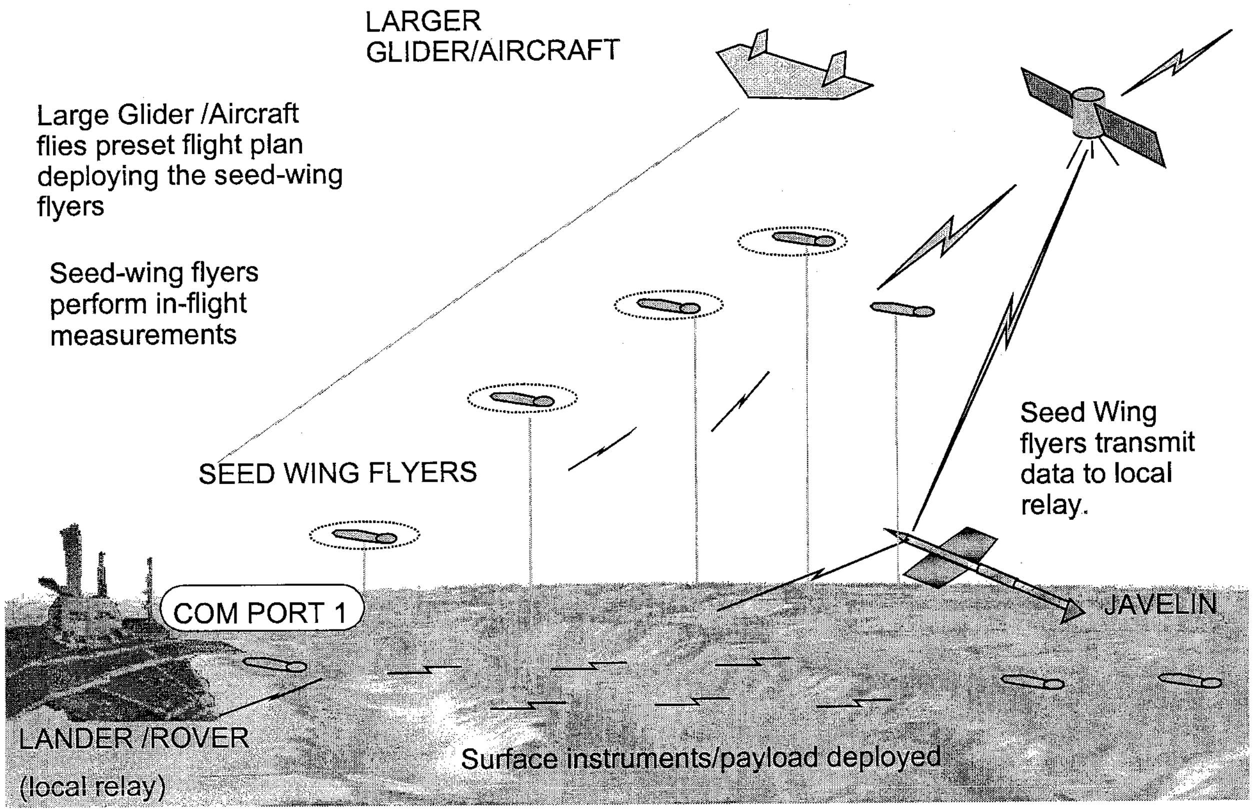


Figure 8. Deployment Scenario where the seed wings are aerially deployed by a glider/ aircraft

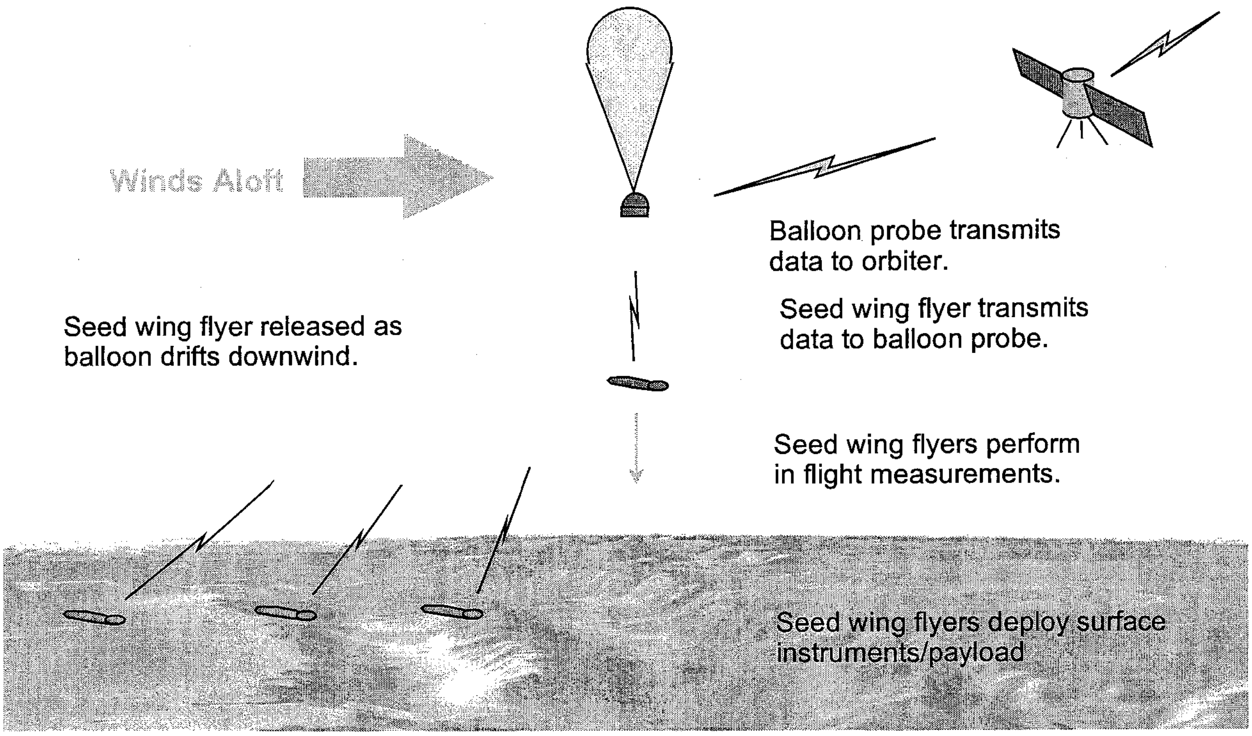


Figure 9. Deployment Scenario where the seed wings are aerially deployed by a balloon

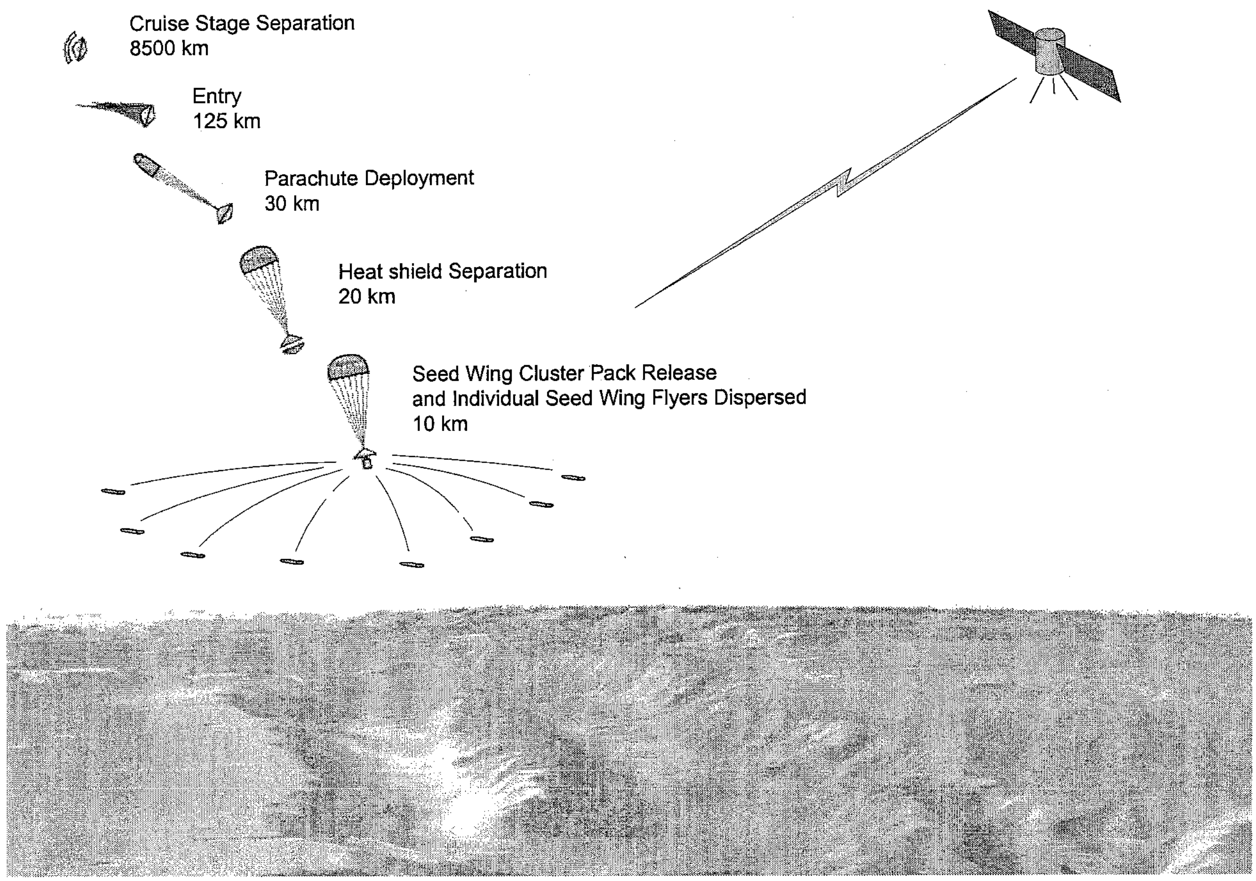


Figure 10. Deployment Scenario where the seed wing cluster is aerially deployed directly after initial slow down

7 BIOMORPHIC MISSIONS UTILIZING LANDER LOCAL RELAY:

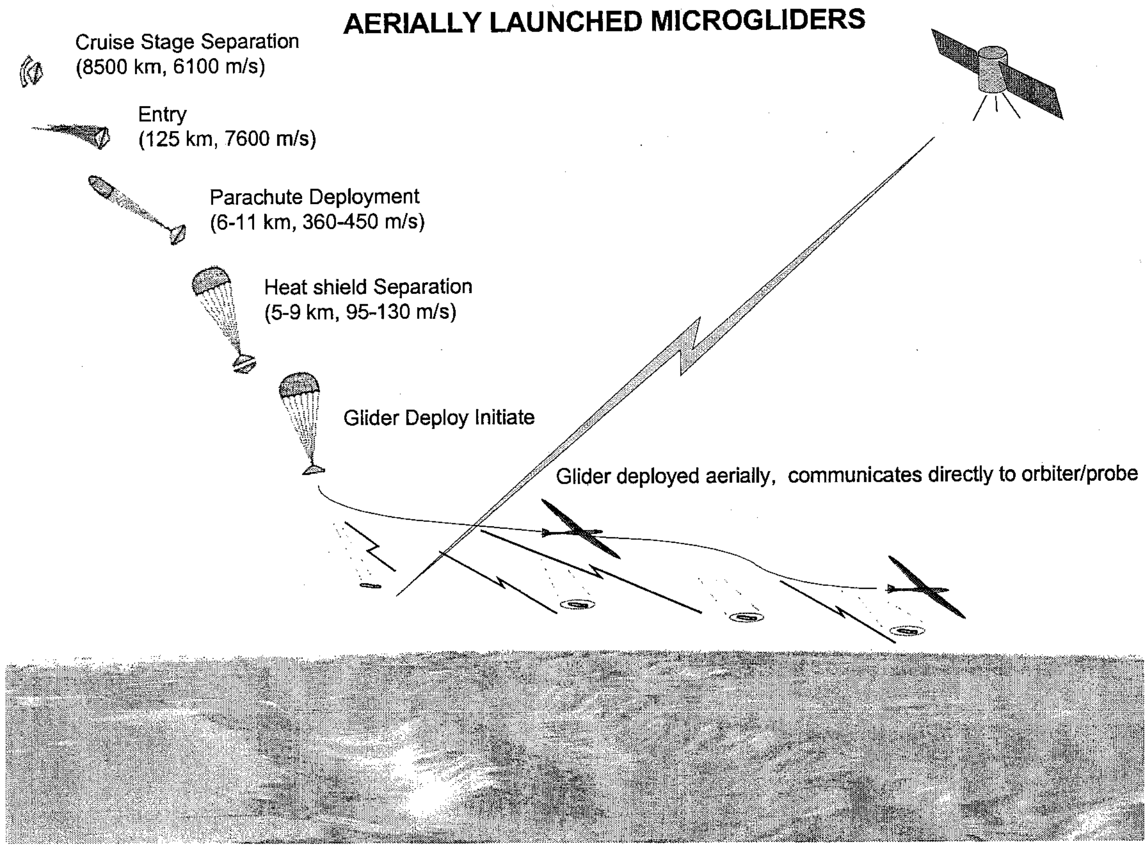


Figure11: Aerially deployed Micro-gliders need telecom infrastructure for viable operation

A high altitude Near Synchronous Orbit providing Long-Dwell service to any point on Mars is necessary or preferable for success on the type of mission shown in figure 11. While our telecom infrastructure is still in its infancy, a cooperative mission using a Lander/Rover as a robust local relay can enable even with existing low altitude orbiter a mission of imagery by biomorphic flyers as shown in figure 12.

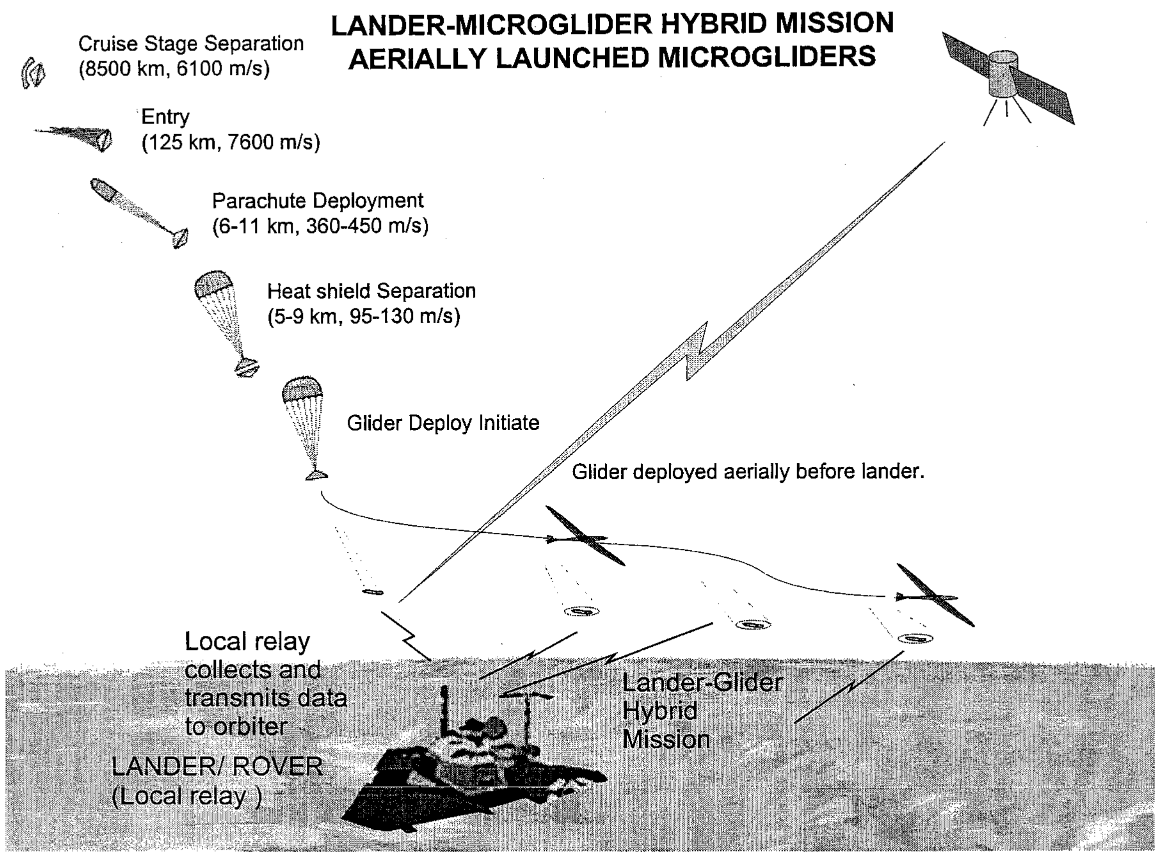


Figure 12: Cooperative use of a Lander/ Probe provides a robust local telecom relay for data downlink from the biomorphic flyer

8. BIOMORPHIC MISSIONS: A FEW FUNCTIONAL SAMPLES:

The following mission concepts represent a small sample of the many potential mission scenarios possible with biomorphic exploration systems. Each scenario is written in a stand alone fashion and some of the same pertinent issues are addressed for each case independently.

8.1 Orbiter Based Seed Wing Pod Flyers for In Situ Measurement

Motivation:

The mission objective is to augment orbiter image data with in situ surface measurements. The information will also assist in identifying suitable lander sites for future missions. Orbiters have been used very successfully to obtain large scale geological and meteorological data. Although the information is extremely useful, image resolution is limited to several meters in scale due to practical constraints. Furthermore, in situ compositional measurements at specific sites of interest can significantly add to the science return and aid in future mission planning.

Mission Description:

After orbiting a planet or satellite (e.g., Mars, Titan) and sending images to Earth for several weeks, the science team identifies several regions of geological interest. One of three entry vehicles is launched from the orbiter so that the payload is released over a target area. The entry vehicle contains 10-20 small seed wing flyers, each equipped with a small surface probe, chemical experiment, camera or another specialized biomorphic/microexplorer. Seed wing pods are a very compact way of dispersing experiments / microexplorers over a broad area.

At an altitude of about 15 km, the entry vehicle begins a controlled release of the seed wing flyers, which autorotate to the surface. The entry vehicle will traverse 50 to 100 km during the course of releasing the seed wings. A straight, circular, or intelligent flight plan may be used. Meteorological information on weather patterns will be utilized to select the timing of release of the seed wings in this mission to maximize the science return.

After the seed wings have landed, each conducts a surface experiment that may consist of a surface probe and/or a chemical test, which analyzes for the presence of key trace elements. Next, the orbiter emits a signal initiating communications. The identified seed wing then transmits the results of its experiment. No return indicates a failure of that specific seed wing, or the signal is obscured by terrain so another attempt to communicate should be made from a different aspect angle. The orbiter receives the transmissions and locates each seed wing using a phased array antenna.

Two other regions of interest may be explored in the same manner with the remaining two entry vehicles and seed wing pods.

Impact on Orbiter Mission:

Mass - The total mass of the three entry vehicles and a total of about 50 seed wing pod flyers is on the order of 9 kg (60 g per seed wing, plus 2 kg per entry vehicle @ 50% payload mass fraction). In addition, the orbiter will have a phased array antenna ~1 kg mass.

Development status - The seed wing is a passive entry device much like a parachute (only simpler). Biomorphic 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 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. The small scale, simplicity, and economies of scale with volume production suggest that this concept would be very low in cost and could be ready for deployment in a minimum of time. The entry vehicle development cost and schedule will most likely be dependent on the complexity of its flight profile. The simplest and cheapest will be a passively stable entry vehicle capable of gliding without controls or active stabilization and will most likely fly in a large circular flight path.

Risk - It is unlikely that incorporating this concept will in any way jeopardize the primary orbiter mission. Any entry vehicle related failure could be partly mitigated by triggering dispersal of all the seed wings before the entry vehicle impacts the surface. Some seed wings are expected to fail with little impact on the overall results. Improper placement of the seed wings will result in acquiring data for a site other than the preferred site but still some data would be acquired from an alternate site.

Benefit - The benefits include in situ measurement of the mineralogical or chemical composition of soil at or near the surface to correlate with orbiter images. Key findings or validation of image data for use in selection of future lander sites would be valuable.

8.2 Orbiter Based Biomorphic Gliders for In Situ Measurement

Motivation:

The mission objective is to augment orbiter image data with in situ surface measurements and assist in identifying suitable lander sites for future missions. Orbiters have been used very successfully to obtain large scale geological and meteorological data. Although the information is extremely useful, image resolution is limited to several meters in scale due to practical constraints. Furthermore, in situ compositional measurements and higher resolution close-ups of specific sites of interest can significantly add to the science return and aid in future mission planning.

Mission Description:

After orbiting a planet or satellite (e.g., Mars or Titan) and sending images to Earth for several weeks, the science team identifies several regions of geological interest. One of three entry vehicle is launched from the orbiter so that the payload is released over the target area. The entry vehicle contains 25 or so small biomorphic gliders; each equipped with a small IR camera, surface probe, and a chemical experiment. At an altitude of about 12 km, the entry vehicle releases the gliders.

The gliders transition to flight and initially head out in a more or less random directions. Each glider is equipped to identify several geological features of interest based on a hierarchical list and using the IR sensor image. A high priority target feature is selected within its field of view and glide performance. The flight path is adjusted to intercept the target feature. (This is the search, identify, and target mode.)

En route, each glider in turn emits a weak signal identifying the type of feature targeted and the number of other feature classes identified within its glide range. Each glider also receives the signals from the gliders near it. Based on this information, gliders with a large number of neighbors targeting the same feature type have the option of selecting a different feature or adjusting course to seek new features thus insuring maximum dispersal and variation of science return.

After the gliders have landed, the orbiter emits a signal initiating communications with each of the gliders. The identified glider then transmits the last camera images for a close-up view of the surface. No return indicates a failure of that specific glider or that the signal is obscured by terrain. Another attempt to communicate should be made from a different aspect angle. While on the surface, the glider also conducts a surface experiment that may consist of a surface probe and a chemical test, which is analyzed for presence of key trace elements. This data is then included in the transmission. The orbiter receives the glider transmissions and locates each using a phased array antenna.

Two other regions of interest may be explored in the same manner with the remaining entry vehicles.

Impact on Orbiter Mission:

Mass - The total mass of the 75 gliders and three entry vehicles is 12 kg (assuming 100 g per glider plus 1.5 kg per entry vehicle). In addition, the orbiter will have a phased array antenna with ~1 kg mass.

Development status - The glider is relatively simple due to the lack of a propulsion system. Also, flight performance and range is directly related to lift/drag and release altitude. As compared to powered flyers, the glider is relatively insensitive to mass and other design complexities which make the glider a fairly low risk development effort. Most technologies for flight related systems exist or are being proven through micro air vehicle (MAV) development. MEMS technologies are now being developed for chemical sensing and navigational aids which may be adapted for this application. The very small IR camera and biomorphic/multi-agent controls are likely the most difficult developments.

Risk - It is unlikely that incorporating this concept will in any way jeopardize the primary orbiter mission.

Benefit - In situ measurement of the mineralogical or chemical composition of soil at or near the surface can be used to correlate with orbiter images. Key findings and near surface image data will be extremely valuable in selection of future lander sites.

8.3 Cooperative Lander-Rover-Biomorphic Flyers Mission

This Mission has been described in detail in Section 5.1

Impact on Lander Mission:

Mass – Assuming the lander is carrying 12 microflyers. The total mass of the 12 flyers can range from 1.2 -6 kg (assuming 100 -500 g per flyer). Correspondingly an additional 1 –6 kg would be needed for the launcher and communications.

Development status - This microflyer envisioned here to be launched from the lander could be a boosted glider. For Mars with its thin atmosphere (~ 1/100 th of that on Earth), a single stage or multiple stage rocket boosted payload package, almost like a dart is envisioned[25]. The number of rocket stages and therefore the mass of the microflyers) will be determined by the range required for the Mission. An electrically powered microflyer is another possibility[26]. DoD/ Industry sponsored developments in each of these areas are emerging including boosted microgliders[27] and electrically powered microflyers[26.28,29]. Modifying the design for such a lander launchable microflyer for Mars ambient is the major challenging step yet requiring development. Most technologies for flight related systems exist or are being proven through on-going MAV development. MEMS technologies are now being developed for chemical sensing and navigational aids that may be adapted for this application. The very small IR camera and communications equipment providing high data rates with minimal power are other outstanding developments required. The lander/rover in this mission scenario provides a robust telecom locay relay to downlink the data to Earth via the the existing Mars orbiter. This mission could therefore be achieved relatively easily without need for additional telecom infrastructure. Therefore a scouting mission of this type is quite possible in the 2005 timeframe, assuming a concerted start of development at the time of writing of this paper. Furtheron, by

2007-2009 dispersal of surface instruments and other multiterrain biomorphic surface/subsurface systems by the microflyers could enable a thorough investigation of the stratigraphy of columns in Valles Marineris by locally deployed biomorphic explorers of the climbing or rapelling kind. A fetch and return of samples capability could be obtained by 2011. Beyond 2011, aclosely related scenario described in 5.2 could be realized as an enabling aid to the human exploration and development of space.

Risk - Incorporating this concept will not in any way jeopardize the primary lander mission. In fact, the flyers in this case are used to minimize mission risk and enable new science endeavors.

Benefit - A scouting mission to map out the regions of interest and pathways of interest can be enabled by such a cooperative biomorphic mission implementation. In situ measurements can be made of the mineralogical or chemical composition of soil at or near the surface over a broader area than the lander/rover will be able to cover. Key findings and near surface image data will be extremely valuable in lander/rover pathway selection and planning for maximum science return from the Mission. Dispersal of payload and a fetch and return of samples capability are other longer term benefits of such mission developments

8.4 Biomorphic Gliders for Sample Return Mission Reconnaissance

Motivation:

The mission objective is to obtain samples from potential exobiology sites and areas of geological interest.

Mission Description:

A lander equipped with a large rover and an ascent vehicle lands in the Valles Marineris roughly 10 km from an area of potential exobiological significance, fault zones with exposed geological features, and eroded canyon walls with exposed sedimentary layers. The lander is targeted in a relatively flat area (devoid of interesting samples) to minimize risk in landing. The rover is designed for traversing rugged terrain and is equipped with an arsenal of scientific experiments including the ability to collect samples for return. Unfortunately, the rover is expected to have a limited life and there is always a risk of damage or loss. Therefore, some knowledge of the terrain and locations of scientific targets can significantly reduce mission risk.

Gliders, equipped with a miniature camera and, possibly, a small IR detector and a simple surface experiment may be deployed to obtain intelligence for targeting specific sites of scientific interest and for planning rover pathways. The lander would most likely have to be in place within the Valles Marineris before glider deployment to minimize the transmit power required.

Perhaps as many as 50 small gliders are stored inside a simple passively stable entry vehicle. The entry vehicle would begin releasing the gliders near the top of the canyon walls at an altitude of about 14 km so they can glide down toward the bottom of the canyon at nearly a constant altitude above the surface. Each glider will use a small camera to take images of the terrain below and transmit the images to the lander, which will relay them to Earth via the orbiter. After landing, each glider may conduct a simple experiment or deploy another biomorphic explorer. It transmits the results to the lander while acting as a radio beacon. Each glider would be programmed for a specific flight trajectory based on navigation using the sun. Thus, the images may be geologically referenced using the beacon signal location. The project team uses the information to identify target sites with the greatest science potential and to map suitable pathways for the rover. The rover is then deployed having a mission plan and numerous radio beacons to aid in navigation.

Impact on Lander Mission:

Mass - The total mass of the 50 gliders and entry vehicle is about 10 kg (assuming 100 g per glider plus 5 kg for the entry vehicle).

Development cost and schedule - The glider is relatively simple because a propulsion system is not required. Flight performance and range is directly related to lift/drag and release altitude. The glider would be a low cost and fairly low risk development effort. Most technologies for flight related systems exist or are being proven through DoD/Industry sponsored MAV development. MEMS technologies are now being developed for chemical sensing and navigational aids which may be adapted for this application. The very small IR camera and communications equipment with multiple data streams, high data and high power efficiency are other developments needed.

Risk - It is unlikely that incorporating this concept will in any way jeopardize the primary lander mission. In fact, the flyers in this case are used to minimize mission risk.

Benefit - The benefits include in situ measurements of the mineralogical or chemical composition of soil at or near the surface over a broader area than the rover will be able to cover. Key findings and near surface image data will be extremely valuable in rover pathway selection and planning for maximum return.

8.5 Biomorphic Gliders for Payload Deployment to the Polar Ice Cap

Motivation:

The mission objective here is to obtain historical climatology data on Mars through in situ compositional measurements, analogous to core samples, of the ice cap taken at various depths below the surface. The experiments are to be conducted at ten sites over a broad area (without specific targeting) to gain information on ice uniformity. The project is to be carried out as a piggyback micro-mission and the hardware is to be contained within one entry vehicle.

Mission Description:

During approach to Mars, the entry vehicle is released toward the polar ice cap. Gliders may be used to obtain images of the ice layers at the edges of the ice sheet. Contained inside the entry vehicle are 10 biomorphic gliders carrying one experiment each. At 15 km above the surface, the entry vehicle releases/disperses these gliders. The gliders are simple, passively stable, free flight (uncontrolled), platforms that glide in random directions traveling roughly 6 km forward for every 1 km lost in altitude. The total dispersal pattern for the 10 gliders will be roughly 100 km in diameter. Once on the surface, the glider shape is designed to minimize the chance of becoming airborne once on the surface, perhaps aided by use of an anchor.

Each glider carries a biomorphic explorer designed to burrow through ice, snow, and soil using a combination of scraping and heat while pulling debris around itself and applying downward pressure with its limbs. Upon landing, the burrowers begin digging into the surface. Power and communications with the spacecraft can be provided the burrower if needed by the glider via an umbilical cord, which is unwound as the burrower makes its progress. The glider is equipped with batteries, photovoltaic cells, and transmitter.

The limited light available for solar power implies that progress will be slow, but a simple spring-loaded panel with solar cells is released into a vertical orientation to maximize sun exposure and capture reflected light from the surrounding ice. Burrowing will periodically need to be stopped to enable the solar cells to recharge the battery. Once deployment is complete, there are no moving parts on the surface that must endure the harsh polar environment. The batteries would utilize self-heating and good insulation to maintain reasonable performance.

The burrowers would carry narrow-band LEDs or other instrumentation to detect different ice layers and possibly to determine composition (H_2O or CO_2). Measurements and reports on progress (depth) would regularly be transmitted to the orbiter.

Impact on Orbiter Mission:

Mass - The total mass of the 10 gliders, 10 burrowers, and the entry vehicle is about
3.5 kg (assuming 100 g per glider, 100 g per burrower, 1.5 kg for the entry vehicle).

Development cost and schedule - The glider is relatively simple due to the lack of a propulsion system. Flight performance and range are directly related to lift/drag and release altitude. The glider would be a low cost and fairly low risk development effort. Most technologies for flight and burrower support related systems exist or are being proven through MAV development. The burrower is likely to be the most expensive and risky development effort.

Risk - Use of multiple instruments and delivery vehicles helps to reduce mission risk significantly.

Benefit - In situ measurements of the ice cap can be made over a broader area than a single lander will be able to cover.

9. OTHER POTENTIAL APPLICATIONS OF BIOMORPHIC MISSIONS:

The earlier sections of this paper detailed cooperative scenarios relevant to planetary exploration. More generally, utilizing cooperative behaviors may be indicated in aspects of missions that are inherently distributed in space, time, or functionality. The advantages of distributed, cooperative exploration can include increased reliability and robustness (through redundancy), decreased task completion time (through parallelism), and decreased cost (through simpler individual explorer design). Also, a multitude of other applications exist in both the human exploration and development of space and in the terrestrial domain. A partial list of tasks that can be supported includes cleanup of hazardous waste, nuclear power plant decommissioning, search and rescue missions, construction, mining, automated manufacturing, industrial/household maintenance, security, surveillance, and reconnaissance.

10. ACKNOWLEDGEMENTS:

The research described in this document was carried out by the Jet Propulsion Laboratory (JPL), California Institute of Technology, under a contract with the National Aeronautics and Space Administration (NASA). I would like to acknowledge useful discussions and inputs on flight systems and related technology from C. Miralles, M. Keenon, J. Grasmeyer, and P. MacCready at Aerovironment. I would like to acknowledge useful discussions and inputs on solid rocket boosted flyers from J. G. Small at Raytheon Systems Company, Tucson AZ. I would like to acknowledge useful discussions with Matt Golombek, Ken Nealson, F. Palluconi, T. Martin, T. Scofield at JPL and useful discussions

with Barbara Lucchitta at USGS related to science applications of biomorphic explorers.

-
BIO:

Sarita Thakoor, MS, MPhil in Physics from Univ. of Delhi India (1977, 1979) is Senior Member of the Technical Staff at Jet Propulsion Laboratory (JPL). She has been with JPL/CALTECH for the last fifteen years. She is a recipient of over thirty five certificates of recognition/awards from NASA for new technology innovations and received 7 patents on the new innovations developed. She has taken a lead role in conceptualizing and promoting "Biomorphic Explorers". In August 1998, she organized the 1st NASA/JPL WORKSHOP ON BIOMORPHIC EXPLORERS FOR FUTURE MISSIONS which was extremely successful and timely in bringing together the scientific community working on the fast emerging multidisciplinary subject area of biomorphic explorers. Her current research interests include future missions particularly cooperative surface/aerial biomorphic missions, telecom architecture to enable such missions, system design of biomorphic explorers and their related application scenarios, cooperative behaviors in small exploration systems, innovative concepts of mobility, adaptive control, reconfigurable robotic systems, biomorphic controls, flexible advanced actuators, sensors, and bio-inspired computing/ processing. She has published ~ 25 refereed articles and made over 50 conference presentations including invited presentations.

"The work described here was carried out at the Jet Propulsion Laboratory, California Institute of Technology under contract with the National Aeronautics and Space Administration."