Review: The Benefits and Applications of Bioinspired Flight Capabilities

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100 years ago, details the scientific need for such flyers, highlights the bioinspired engineering of exploration systems (BEES) flyer development and finally describes a few viable mission architecture options that allow reliable data return from the BEES flyers using the limited telecom infrastructure that can be made available with a lander base to orbiter combination on Mars. Our recent developments using inspiration from biology that are enabling the pathway to demonstrate flight capability for Mars exploration are described. These developments hold substantial spin-offs for a variety of applications both for NASA and DoD. Unmanned exploration to date suggests that Mars once had abundant liquid water (considered essential for life as we know it). It is not clear what transpired on the Martian climate to have turned the planet into the desert that it is today. Developing a comprehensive understanding of the past and present climatic events for Mars may provide important information relevant to the future of our own planet. Such exploration missions are enabled using the BEES technology.

1. INTRODUCTION

In 1903, the Wright brothers made history[1,2] by demonstrating the first powered flight over the dunes of Kitty Hawk, NC. Just about 100 years after that event, and by using the guiding principles of bioinspired engineering of exploration systems (BEES),[3–6] we are getting ready to do a demonstration of "BEES for Mars" in the true spirit of innovation signified by the centennial of Kitty Hawk. This new approach of BEES technology development has wide ranging impact on pressing needs of surveillance and reconnaissance for the Department of Defense and robotic exploration of planetary surfaces for NASA. Autonomous robotic systems are essential for the exploration of Mars and other planetary systems. Humanity over the ages has been intrigued by the flight maneuvers of birds and insects. Borrowing from nature to implement biologically inspired capabilities in robotic systems is one approach to achieving autonomy. This project is combining biological features and capabilities derived from three separate species: the dragonfly, the honeybee and the rabbit.[7] By reverse engineering and blending nature's solutions to orienting and navigating in the physical world, we are demonstrating the power of this approach for future robotic explorers. Figure 1 illustrates pictorially this theme of developing a capable hybrid, the BEES flyer, that incorporates biological principles distilled from three distinct biological organisms. We have described this principle in detail elsewhere.[3,4,7]

Unmanned exploration to date suggests that Mars once had abundant liquid water (considered essential for life as we know it). It is not clear what transpired on the Martian climate to have turned the planet into the desert that it is today. Developing a comprehensive understanding of the past and present climatic events for Mars may provide important information relevant to the future of our own planet. Such investigation of Mars is crucial in order to learn lessons for preserving and nurturing life on Earth. Further, it satisfies our scientific curiosity, and could provide answers to the fundamental questions regarding the origin of life and its preservation in our solar system by learning about the history of water on Mars. Low altitude air-borne exploration of Mars offers a means for covering large areas, perhaps up to several hundred kilometers, quickly and efficiently. Aerial exploration can provide a close-up bird's eye view of the planetary terrain. Exploration that can only be imagined today could become a reality if we develop methods to fly on Mars and navigate through its difficult terrain to image/study sites of interest. Mars offers a substantial challenge to conventional flight due to its thin atmosphere (about a hundredth that on Earth), lack of magnetic compassing for navigation, and the limited telecommunications or navigational infrastructure. To meet and overcome these challenges, we are adapting for Mars exploration principles proven successful in nature to achieve stable flight control and navigation. By incorporating engineering solutions modeled on successful biological solutions we will provide novel and highly effective bioinspired flight capabilities suitable for aerial surveillance of Mars. We describe in this paper a few example sites on Mars whose exploration and understanding absolutely require the ability to cover several hundred kilometers. Such exploration scenarios are enabled by a mission that combines the use of conventional assets such as landers and rovers along with the BEES flyers. We also describe future mission scenarios for Mars exploration, uniquely enabled by these newly developed flyers. Autonomous BEES flyers will enable imagery and environmental measurements to be captured from low altitudes and even inside terrain features such as craters, gullies, and canyons that are impossible to explore on a large scale

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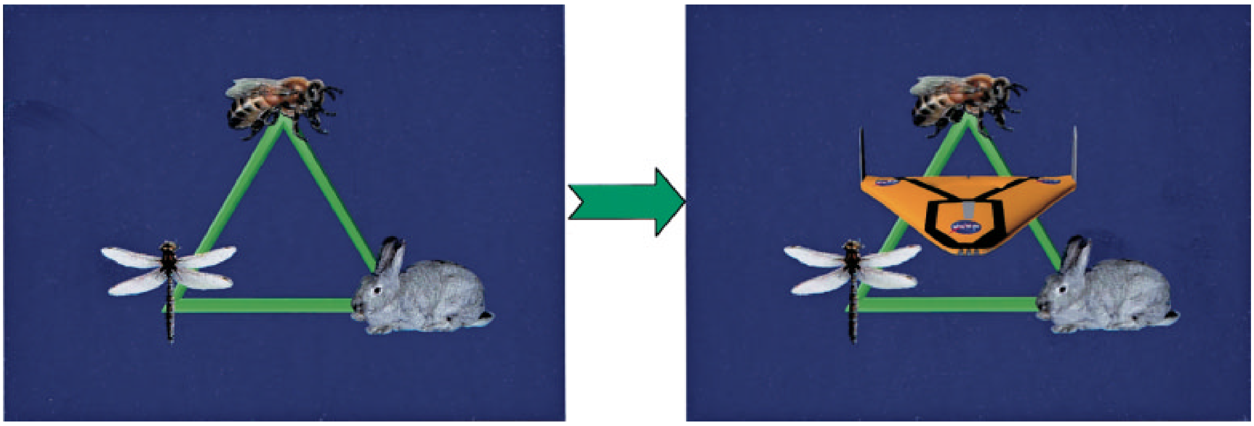

Figure 1. Best of class capabilities are incorporated to develop a very capable hybrid flyer that excels in navigating autonomously with inspiration from insects (honey bees and dragonflies) to sites of interest recognized and tracked using a system inspired by studies of mammalian retina from the rabbit.

by surface rovers alone today. At a terrestrial analog Martian site, we plan to demonstrate a proof of concept simulation experiment, emulating selected conditions of Mars. The demonstration will consist of launching/deploying a variety of BEES flyers each containing biologically inspired technologies capable of, for example, autonomous real time navigation, visual search, selective feature detection, intelligent flight control and image enhancement by sensory data fusion. Terrestrial applications of such BEES flyers include reconnaissance and surveillance of strategic sites, distributed aerial/surface measurements of meteorological events, i.e., storm watch, seismic monitoring, biological chemical sensing, search and rescue, surveillance, autonomous security/protection agents and/or delivery and lateral distribution of agents (sensors, surface/subsurface crawlers, clean-up agents).

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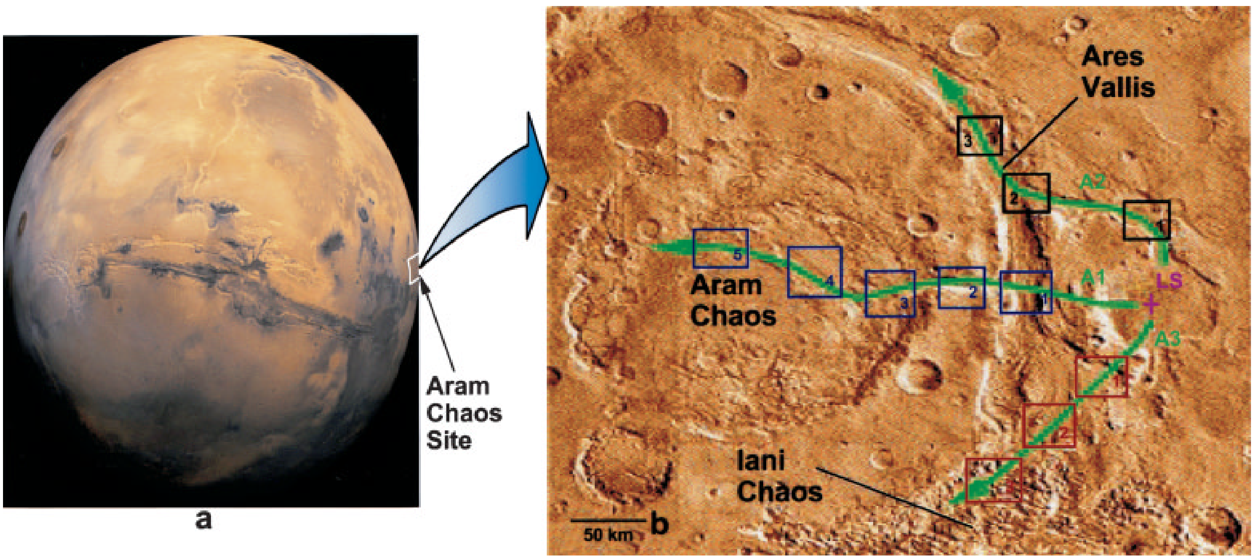

Figure 2. (a) This mosaic of Mars is a compilation of images captured by the Viking Orbiter 1(NASA/USGS). The center of the scene shows the entire Valles Marineris canyon system, over 3000 km long and up to 8 km deep. To the extreme right lies the Aram Chaos site which is shown in exploded view in (b). (b) Detailed topography of the Aram Chaos area showing a potential landing site in violet color, LS, three possible flight traverses marked A1, A2, A3 emerging from there and further a number of different specific target sites for exploration on each of those traverses.

elty as flight on Earth itself was a novelty in the Kitty Hawk era almost 100 years ago, details the scientific need for such flyers, summarizes the highlights of the BEES flyer development and finally describes a few viable mission architecture options that allow reliable data return from these BEES flyers using the limited telecom infrastructure that can be made available with a lander base/orbiter combination.

2. CHALLENGES OF FLIGHT ON MARS

Mars poses[1–7] some unique challenges for the navigation of unmanned aerial vehicles due to its thin atmosphere ($\sim$1% that of Earth at best), low gravity ($\sim$37% of that on Earth), and a weak, nonuniform magnetic field across the planet surface that is hard to use for navigation. The low gravity causes increased attitude uncertainty, with errors in computing a static vertical reference exceeding 1° under static conditions when using state of the art MEMS accelerometers that are effective for terrestrial usage in all applications where miniaturization is of importance. Passive approaches to aircraft stabilization are of decreased effectiveness, as the driving force behind upright attitude is gravity. The combination of low lift and low gravity will lead to slow, large amplitude, oscillatory modes in the aircraft dynamic response. Active stabilization and accurate attitude information would be desirable under these circumstances. To enable missions using robotic aircraft it is therefore necessary to develop the bioinspired technologies described in Section 4, and prove that the technologies function on Earth and can be extended for performance on Mars. We have described the issues of Mars flight and how bioinspired sensors offer a good alternate solution to enable navigation on Mars in greater detail in an earlier paper.[4] Aerodynamic and reactive flight is possible on Mars. Earlier publications and reports[8–16] have considered the possibilities and practicalities of aerial exploration of Mars. In many cases the suggested missions have involved a single large aircraft being unfolded and released after entry into the Mars atmosphere. This technology is unproven, and clearly contains many points where a single failure would end the mission. Also, it is challenging and risky in terms of data return to Earth because it would rely on the limited telecom infrastructure of orbiting telecom satellites that exist at this time. It has been demonstrated by the Mars Pathfinder mission in 1997 that it is possible to safely deploy landers and instrumented Rovers on the surface of Mars. What we have conceptualized earlier[5,7,17–19] and are developing further to demonstrate is that a smaller vehicle, a flyer, can be launched from the surface that is capable of performing some unique imaging tasks of significant geological features at close-up by low-altitude flights, with much lower cost and lower risk.

3. WHY MARS EXPLORATION NEEDS BEES FLYERS

Exploration of many sites on Mars requires the ability to cover hundreds of kilometers to acquire a proper understanding of their history. Such sites include, for example, the ambient lacustrine sedimentary deposits whose history would be incomplete if we limit our investigation to the basin. Little will be understood about the mineralogy if we do not explore the channels and the watershed of the fluvial systems that emerge in the basin. Other examples where long range mobility may be critical will include the exploration of the shorelines of the putative Mars ocean. A significant part of the shorelines lies at the boundary of the highlands and lowlands characterized by chaotic terrain where surface mobility will be hazardous.

A few examples of science explorations requiring long range exploration are illustrated in the following subsections.

3.1. Aram Chaos Site

The approximate directional location of the Aram Chaos site on a Mars globe is indicated in Figure 2(a) and the exploded view of the site is shown in Figure 2(b).

3.2. Description of Aram Basin Exploration Scientific Need/Requirement

The scientific goal of this exploration is to characterize one of the hematite sites of Mars that is not currently accessible by a rover and that shows evidence of fluvio-lacustrine activity. Furthermore, this site offers the unique opportunity of providing data from the upstream source region of Ares Vallis that earlier has provided parent-rocks for the sites visited by Viking I in 1976 and Pathfinder in 1997. In one mission, we could acquire data on a new Martian site and provide critical background information to three previous missions (Viking 1, 2 and the Mars Pathfinder mission) including the most recent Mars global surveyor mission.

3.2.1. Envisioned Scenario

As illustrated in Figure 2(b), the mission lands at the site "LS" in an impact crater floor located on the path of one branch of Ares Vallis. The crater has experienced fluvial activity (through outflow) and possibly some ponding. The lander could be equipped with a rover that can investigate the crater. The lander may instead of a rover or in addition to the rover be equipped with a science instrument capable of detecting minerals bearing biosignatures (for example, XRD/XRF spectrometer, Raman). The main goal of the mission is to investigate Aram Basin (noted as Aram Chaos) in the figure. The site is covered with rough terrain and is chaotic, which prevents a landing directly in the basin itself. The proposed site LS, marked in violet color, is a smoother crater east of Aram that will provide a safer place to land. The BEES flyers will be enabling to the exploration of hardier terrain of the Aram Chaos Basin that is located within few hundred kilometers of the LS. Further, the mission can accomplish significant science using three other distinct aerial traverse paths for the flyers to provide complementary data to characterize the upstream part of one of the major outflows of Mars. Descriptions of potential flyer exploration traverses are provided in the following.

3.2.2. Detail of Traverse A1: Aram Investigation

The BEES flyer A1 is released from the landing site, LS. During the first 50 km, the aircraft acquires data from the landing region and potential aqueous morphologies associated with the landing site. This data is relayed to the lander (launching base station). If a rover is included in the mission, the rover is sent to sites of science interest discovered by the flyer. The first target in this traverse marked as [1] is the traverse of an upstream section of Ares Vallis that A1 will detail by close-up imagery. Previous missions (Viking 1 and Pathfinder) have landed in the flood plain of this outflow 2000 km downstream. This is a unique opportunity to have more information about the dynamics of these channels only 200 km from the source and to know more about potential parent-rocks of these two previously visited sites. This could provide some "ground-truth" to data acquired during the previous missions. The second target [2] on A1's path is the lateral branch of Ares Vallis that communicates with Aram Basin. The 50 km long fly-over in the connecting channel will provide important information about the relationship between this branch and the main Ares Vallis channel: stratigraphic relationship between the two, numbers of flow episodes through connecting terraces, and potential for discovering and characterizing layered deposits belonging to geological events that happened early in the Martian history. Target [3] corresponds to the debouchment area of the channel into the Aram Basin. This region is characterized by a gigantic delta structure which is co-located with one of the hematite deposits discovered by thermal emission spectroscopy within the Mars global surveyor mission. There the flyer could test the hypothesis of a lake scenario in the region. In future missions it is conceivable that the flyer could drop a science payload in this region to study *in situ* the mineralogical and possibly biological signatures of the site in addition to the structure of the deltaic platform that will tell us about the dynamics of the flow and its history (episodes, volumes of water, etc.). Target [4] surveys the finer fraction of the aqueous deposits and the margins of the basin to unravel potential shoreline morphologies and continue the survey of the hematite signature. This region, as that of target [5], is also characterized by layered deposits alternating high and low albedo signatures that need to be deciphered.

3.2.3. Traverse A2: Ares Fly-Over

This traverse following targets from [1] to [3] will document the morphological, dynamical, geological, and mineralogical characteristics of the Ares Vallis as far as the flyer range allows. The goal of this traverse is to acquire complementary data to that obtained during the Viking 1 and Pathfinder missions and understand the nature of the terrain eroded by Ares Vallis.

3.2.4. Traverse A3: Ares Sources

Little is known about the origin of outflows, except that they are starting in collapsed terrains that cover millions of square kilometers. The flow trigger hypothesis suggests a collapse due to outburst of water from confined aquifers in tectonic environment. The potential role of CO2, clathrates, etc. is an interesting study as well. These sites are out of reach of current exploration means such as landers and rovers for safety reasons (owing to blocked and chaotic terrain). The third BEES flyer A3's task will be to return data from this heretofore unreachable Ares source region. Leaving the landing site area, the flyer will capture data from the channel floor morphology and residual reliefs mineralogy near its source at targets [1] and

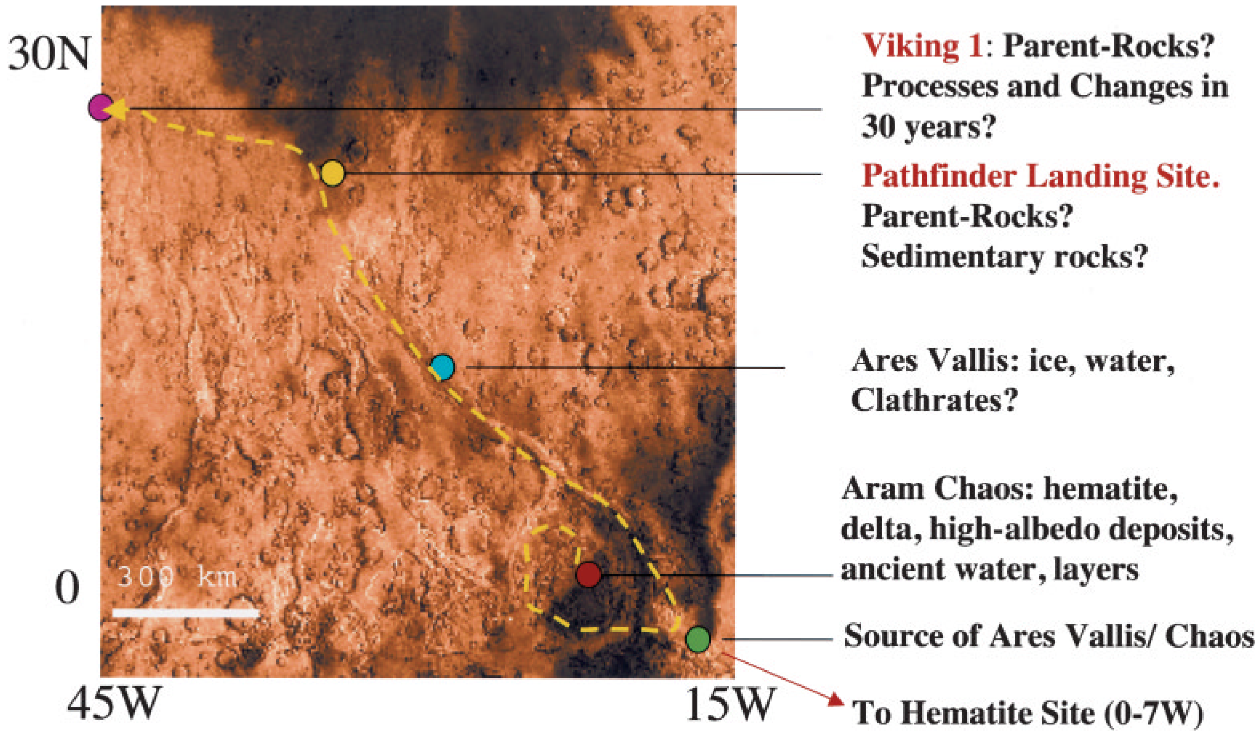

Figure 3. Summary illustration of the value of Ares Vallis/Aram Chaos site.

[2]. Flying over Iani Chaos, A3 can drop a series of science payloads as instruments or probes to characterize the mineralogy, volatile nature and contents of the site.

The overall mission highlights summarized in Figure 3 will provide important information currently not accessible due to the safety limitations of landers and rovers and the limited range that they

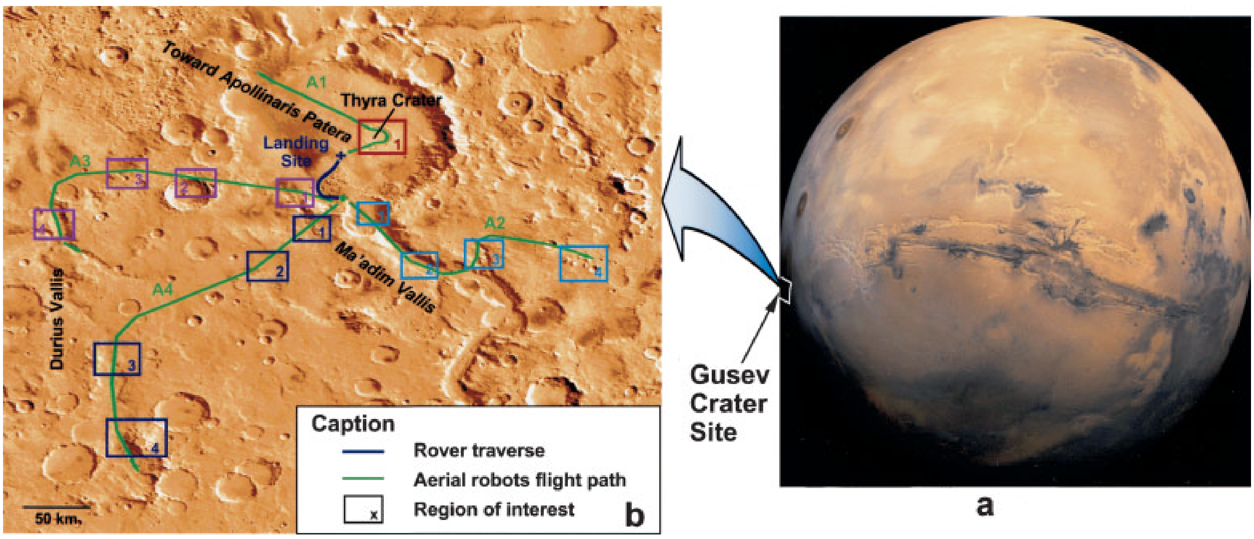

Figure 4. (a) The complete mosaic of Mars taken by Viking I (NASA/USGS) showing Gusev crater site to the extreme left which is exploded in (b). (b) Detailed topography of the Gusev Crater area showing a potential landing site marked by a cross in blue, four possible flight traverses marked A1, A2, A3, A4 emerging from there are shown and further a number of different specific target sites for exploration on each of those traverse paths are marked in boxes as regions of interest.

can cover. Plus, it will document the upstream part of Ares Vallis and complement past Viking and Pathfinder missions.[20] Moreover, it will characterize one of the hematite sites, complementing also the survey by one of the 2003 MER sites of the Meridiani Planum hematite site. Aram is also the only hematite site for which a fluvio-lacustrine setting is clearly visible in the morphological record and supports the hypothesis that the hematite may be related to water activity. There are seven ways in which hematite can be formed, five of those originate from water activity and the others are volcanic in origin. A flyer can make possible such investigations to distinguish the mode of origin. Furthermore, the results from this site can be compared to those of the hematite site that is to be explored by the MER rovers in the 2003 Mars mission.

3.3. Gusev Crater Site

See Figure 4.

3.4. Description of Gusev Crater/Ma'adim Vallis Exploration Scientific Need/Requirement

Figure 4(a) shows directionally the approximate location of the Gusev Crater site and the exploded view of the site is shown in Figure 4(b). The scientific goal in this case is to document the fluvio-lacustrine system of the Ma'adim Vallis/Gusev crater system and Durius Valles, test hydrological, limnological hypotheses, and survey the possible role of hydrothermal activity, sapping, and tectonics in the formation of the channels.

3.4.1. Envisioned Scenario

As shown in Figure 4(b), the Lander lands in the Gusev Basin near structures labeled as the "deltaic mesas"(deep blue cross). The rover is deployed from the landing platform. A variety of aerial traverses could be utilized as illustrated to cover the areas of interest.

3.4.2. Detail of Traverse A1

The BEES flyer flies 50 km over the boundary between the putative shoreline and terraces located southeast of Gusev Crater to reach the 21 km diameter Thyra crater. Thyra is of the utmost interest as the site displays terraces that seem to be sedimentary in origin and the site of the latest lake in Gusev Crater.[21–26] Leaving Thyra, the aircraft flies over a series of mounds originally interpreted as potential frost mounds—pingo-types[27]—but whose origin is still unclear. Depending upon aircraft range, it would be of the highest scientific interest to reach Apollinaris Patera, a large, 5000 m high volcano located 300 km north of Gusev. That would complete the transect.

While A1 is complete, the rover undertakes its traverses toward the deltaic mesas for complete investigation of the delta structure. En route, it samples soil and rocks on the lakebed. In the landing region, the lander/rover are likely to be located on the delta bottom set and will find fines, silt and mud, plus aeolian veeneer. Looking for thin beddings in residual buttes would also be pertinent. The deltaic mesas are the locus of intense investigation by the rover that will cover about 100 km in this sedimentary domain. Reaching the region of connection between Ma'adim Vallis outlet and the basin, trafficability is expected to become more difficult and hazardous for the rover. In this region, the rover will release A2, A3, and A4 that will fly different paths to continue the documentation of the fluvio-lacustrine system and complete the profile. These traverses are possible examples and can be modified upon changes in flight range and number of flyers.

3.4.3. Detail of Traverse A2: Ma'adim Vallis Fly-Over

The goal of this traverse is to document the downstream part of the valley spreading over 150 km and to survey the terrace setting targets [1] and [2], including the floor deposits and landforms possibly associated with aqueous activity. A short tributary system, the target [3] will also be investigated. The combination of its general morphology and its sources located in a depression seems to support the hypothesis that this system was fed through sapping processes associated with release of groundwater rather than surface runoff. The flyer will allow a good opportunity by its traverse to assess this hypothesis further. Finally, mounds target region [4], interpreted as possible volcanoes, will be reached by the flyer to verify the volcanic hypothesis and the potential role of hydrothermal activity in the supply of Ma'adim Vallis.

3.4.4. Detail of Traverse A3: Durius Vallis Downstream Fly-Over

The overall Aeolis region (where Ma'adim and Gusev Crater are located) is populated with large fluvial valley networks, one of them being the Durius Vallis system. The goal of this traverse is to assess the fluvial activity of Durius by studying its sedimentary basin and verifying the existence of possible shorelines at

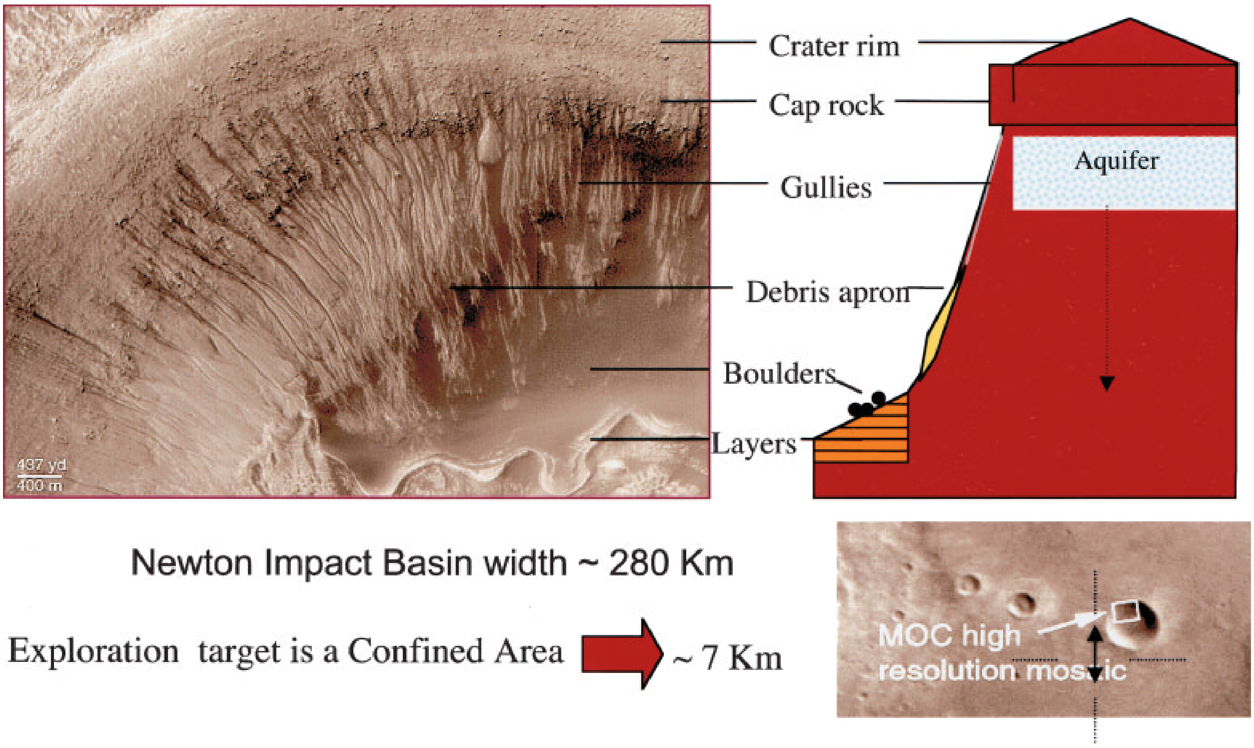

Figure 5. An example of fresh craters and gullies recently imaged using the Mars orbital camera (MOC) on the MGS mission. Other sites are potential debris, covered glaciers, rock glaciers, flows, etc., and sites[28] where Mars global surveyor (MGS) and Mars Odyssey (MO) have found signatures of recent ice and water activity.

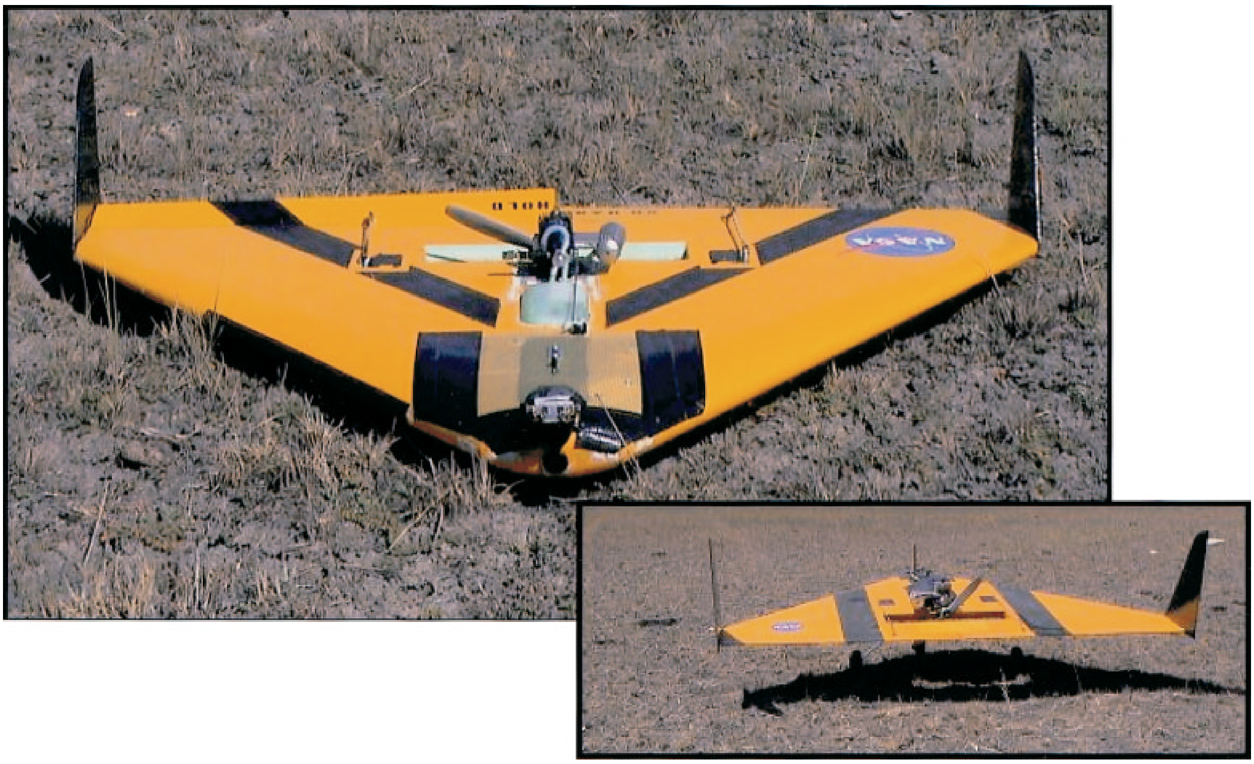

Figure 6. Two views of a typical BEES flyer prototype with the ocelli set mounted on the nose.

the boundary of the plateau and the plain [1], the presence of sedimentary deposits, alluvial fans or delta relics [2], acquire images and reconstruct the altimetric profile of its downstream section and terraces to compare with Ma'adim and document the hypothesis that the two channels have been active at the same time [3]. More targets can be planned if range permits.

3.4.5. Detail of Traverse A4: Upstream Durius and Zephyra Patera

This traverse offers a short-cut through the plateau to document the transition between the watershed of Ma'adim Vallis and that of Durius. We would like to document the separation of watersheds. The first site of interest, [1], is near Gusev where a small valley enters the crater. Images and altimetry will provide elements to reconstruct the water activity and its timing compared to the main channel of Ma'adim and Durius to the west. About 100 km farther, [2], the flyer reaches the transition between the two watersheds. The abrupt dichotomy there can be studied to understand better the question of the role of tectonics in the formation of the valley. Site [3] will be a fly-over of the upstream part of Durius, characterized with lacustrine basins and outflows. The final site of interest in the traverse [4] is the fly-by over Zephyra Patera. Of utmost interest is documenting the morphology of recent lava flows and gullies that could be of hydrothermal origin.

3.5. Exploring Sites of Evidence for Recent Water and Ice Activity

Flyers can help reach targets that present small and confined morphology, while holding critical clues about the present history of water on Mars. A clear example of such sites would be impact craters and valley walls showing fresh gullies; these sites are not accessible currently to rovers or landers,[28] but flyers can make their up-close exploration possible (Figure 5).

4. INSECT INSPIRED NAVIGATION AND BEES FLYER IMPLEMENTATION

Flight-control and navigation systems inspired by the structure and function of the visual system and brain of insects is utilized to form "BEES flyers" for they incorporate technologies developed using the BEES approach. Earlier we have also called them biomorphic flyers. Such flyers are a viable enabling technology for long range exploration needs and requirements as described in Section 3 and could help realize missions as described in Section 5 for accomplishing these exploration goals and requirements. BEES flyers could be used on Earth or remote planets to explore otherwise difficult or impossible to reach sites.

The control functions to be implemented by the systems in development include holding altitude, avoiding hazards, following terrain, navigation by reference to recognizable terrain features, stabilization of flight, and smooth landing. Flying insects perform these and other functions remarkably well, even though insect brains contain fewer than 10^{-4} as many neurons as does the human brain. Although most insects have immobile, fixed-focus eyes and lack stereoscopy (and hence cannot perceive depth directly), they utilize a number of ingenious strategies for perceiving, and navigating in, three dimensions.

Insects infer[29] distances to potential obstacles and objects of interest from image motion cues that result from their own motion in the environment. The angular motion of texture in images is denoted generally as optic or optical flow. Computationally, a strategy based on optical flow is simpler than is stereoscopy for avoiding hazards and following terrain. Hence, this strategy offers the potential to design vision-based sensing and control subsystems that would be more compact, higher performance, lighter weight, and would demand less power than would subsystems of equivalent capability based on a conventional stereoscopic approach. These principles of navigation based on visual cues as deciphered from the honeybee are being implemented electronically by translation of the optic flow algorithms onto embedded hardware.

The ocelli are small eyes on the dorsal and forward regions of the heads of many insects. The ocelli are distinct from the compound eyes that are most commonly associated with insect vision. In many insects, the ocelli are little more than single-point detectors of short-wavelength light and behavioral responses to ocelli stimuli are hard to observe. The notable exception is found in dragonflies, where flight control is notably degraded by any interference with the ocellar system. Our team has discovered recently that the ocelli are a dedicated horizon sensor,[4,30] with substantial optical processing and multiple spectral sensitivity. Figure 6 shows a "BEES flyer" incorporating such a set of ocelli on it that we have successfully flight tested.

On Earth, bees,[31] crickets[32] and ants[33] use sky polarization patterns in the ultraviolet/blue part of the spectrum as a direction reference relative to the position of the Sun. A robotic direction-finding technique based on this concept is more robust in comparison to a simple Sun compass because the polarization pattern is distributed across the entire sky on Earth and is redundant. Heading direction can be extrapolated from a small region of clear sky in an otherwise cloudy sky that hides the Sun.

Bees tend to adjust their flight speed to maintain a constant optical flow (that is, a constant angular velocity of the image of the environment) over the compound eye. Consistent with this strategy, bees utilize[34] the following simple control laws when approaching a landing site on a flat surface:

1. The optical flow of the surface is held constant throughout the descent.
2. Forward speed is held proportional to vertical speed throughout the descent.

This simple combination of control laws enables a smooth landing with minimal computation. The forward speed and rate of descent are reduced together, and are both close to zero at touchdown. No knowledge or measurement of instantaneous speed or height above the ground is necessary. This combination of control laws can readily be modified for a BEES flyer, which has a nonzero stalling speed.

Sensors developed thus far include a robust, lightweight (~6 g), and low power (~40 mW) horizon sensor for flight stabilization. It integrates successfully the principles of the dragonfly ocelli. To our knowledge, this is the world's first demonstrated use of a "biomorphic ocellus" as a flight-stabilization system. Also developed are a simple low resolution imaging polarization compass and related software that allows solar compassing without directly imaging the sun. Optical flow algorithms have been developed and partially tested in the demanding role of the landing algorithm described above. To implement an optic flow sensor on-board the flyer, innovative use[35] of a COTS optical mouse chip has been made to successfully obtain low altitude terrain following and hazard avoidance.

4.1. Advantages of the Biomorphic Ocelli Implementation over Inertial Systems

The advantage of the ocelli over a similarly sized system of rate gyroscopes is that both attitude control and rate damping can be realized in one device. A full inertial unit and significant processing would otherwise be required to achieve the same effect. As a prelude to full autonomy, substantial stability augmentation is provided to the pilot at very low cost in terms of space, power, and mass. The sensor is about 40 times lighter than a comparable inertial attitude reference system.

Table I illustrates comparison of inertial vertical reference systems made by our team using conventional COTS part, custom parts and the bioinspired ocellus implementation using COTS parts. The ocellus has a clear mass advantage, which obviously is more significant in the total payload for small craft. Even for a custom inertial unit the difference in mass is equivalent to a CMOS imaging device and lens. Inertial units are subject to a number of couplings. Rotational motion induces accelerations if the inertial unit is slightly displaced from the axis of rotation; vibration passes through the gyro mechanics and electronics to be registered as rotation. Sustained banked turns or climbs degrade the attitude reference provided by inertial units, due to the sensed acceleration deviating from the direction of gravity. More complex inertial processing can mitigate these problems at the cost of computational power and mass. The ocellus suffers from none of these problems.

Some of the characteristics of the complementary schemes for attitude control developed by us over the last 3 years representing the evolution of this work are presented in Table I.

The challenges faced by the ocelli are based primarily on biases in the distribution of features on the horizon. Usually these biases are small (1–5°) and any sustained bank errors can be corrected by a sun or polarization compass overriding the ocellus bank command in an effort to hold course. The ocelli measurements are differential and relative to each other, thus common mode signals such as thermal biases are not detected and do not cause significant errors. Inertial units are intrinsically mechanical, leading to both electrical and thermal problems from the conditioning circuitry, and also mechanical properties changing with temperature. Power for the ocelli that we are implementing is dominated by the microcontroller, as in miniature inertial units; the actual sensors use very little power. Total power consumption is on the order of 15 mW. The difference in power consumption of the ocelli as opposed to an inertial unit is enough to power a CMOS camera or a narrow bandwidth telemetry system. This would impact power system design with attendant repercussions on aircraft mass.

Table I. Evolution of the development of the dragonfly inspired ocelli.

Feature	COTS inertial vertical reference (surface mount)[1]	Custom inertial vertical reference (die level)[2]	COTS ocellus (hybrid digital/analog)[3]
Mass	100 g	25 g	6 g
Voltage	5 V	3.3 V	2.9 V
Current	100 mA	40 mA	5 mA
90° phase shift frequency	90 Hz	90 Hz	2 kHz
Min light level	Immune	Immune	0.01 lux
Autopilot requirement	DSP	Fast μcontroller	Slow μcontroller
Thermal stability	Poor	Poor	Excellent
Thermal range	−20 to +70 °C	−20 to +70 °C	−50 to +90 °C
Rotation/acceleration/ cross axis coupling	Some	Substantial	None

[1]Note the size of the COTS inertial unit and the performance parameters are based on a system built to the minimum possible size using surface mount technology by our team in mid 2001.
[2]Note the size of the custom inertial unit is based on the mass of state of the art motion sensing components.
[3]The COTS ocellus is based on the performance parameters of the current ocellus, with all non-control-related circuitry and wiring subtracted.

4.2. BEES Flyer Implementation

Two types of flyers are being built, corresponding to the imaging and shepherding flyers for BEES missions described in Section 5. The common features of these two types of flyers are that both are delta-wing airplanes incorporating bio-inspired capabilities of control, navigation, and visual search for exploration. The delta wing design is robust to ~40 G axial load and offers ease of stowing and packaging. Other significant features of the BEES flyer shown in Figure 6 include its ability to fly at high angles of attack (~30°) and a deep wing chord which allows scaling to small size and low Reynolds number situations. Furthermore, the placement of the propulsion system near the center of gravity allows continued control authority at low speeds. These attributes make such flyers uniquely suited to planetary and terrestrial exploration where small size and autonomous airborne operation are required. The prototype that we have built recently has been described in detail elsewhere.[4,5,7,36]

The level of miniaturization we have accomplished for the bioinspired sensors for autonomous navigation is essential to enable such flyers (~1 kg) that can be deployed in large numbers for distributed measurements and exploration of difficult terrain while avoiding hazards. The following table (Table II) gives the details of the BEES flyers that we demonstrated[4,7] in 2001 and the two types meant to obtain shepherding and imaging functions that we are developing for demonstration at a Mars analog site. These flyers are readily scaleable in design and are shown in three-view in Figure 7. The basic delta wing platform that we are testing is robust, compact, and offers ease of packaging for use on a Mars Mission. The version that we are using currently, mainly to test out the bioinspired suite of instruments is propeller driven using two-stroke ethanol engines, which can be readily used for Earth testing. For the Mars implementation we will replace the propulsion system, for example, by a solid rocket boost followed by glide or, depending on application, an extended cruise using a hydrazine propulsion system for steady level flight thrust will be utilized.

4.3. BEES Flyer Design Targets

For these test flyers, the focus has been on speedy implementation to enable testing of the bioinspired sensors. No attempt has been made to specialize the hardware yet to reduce power consumption and mass significantly. The focus in these test flyers is on reduction in programming time and hardware construction time. Total payload mass available in the imaging and shepherding flyer from Table III is 427 g and 1.9 kg, respectively. In the case of both types of flyers, we see that the autonomy and sensor payload is taking less than 20% of the total payload mass available. The rest can therefore be used for other instruments and/or extra fuel to provide more exploration range.

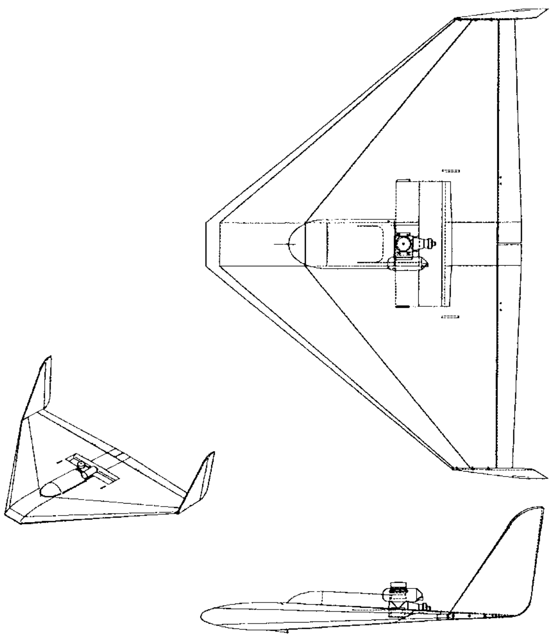

Figure 7. Three view drawing of the BEES flyer, each version (1 kg, 1.5 kg, 5 kg) is a direct scale of this generic planform as detailed in Table II.

5. COOPERATIVE LANDER/ROVER—BEES FLYER MISSIONS FOR MARS EXPLORATION

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 by orbiters allows broad coverage but at limited spatial resolution; the orbiter mission currently operational, Mars global surveyor, provides ~1.5 m/pixel resolution at best, and the 2005 Mars reconnaissance orbiter is expected to provide ~20–30 cm/pixel resolution imaging from its 400 km altitude. Descent imaging may provide a context for landed vehicles; however, it is not broad enough to plan exploration paths/areas for an explorer or to characterize potential sample return sites. Images taken from surface-sited landers/rovers with masts ~2 m high do not cover the surroundings to adequate ranges. Coverage of a large area is warranted, and close up imaging at ~5–10 cm resolution and *in situ* imaging of rocks and features of interest at even greater resolutions is desired. The 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-surface-aerial BEES mission is therefore suggested and illustrated in Figure 8.

The lander is equipped with two kinds of flyers. First, the small ~1 kg imaging flyers have ~10 min endurance during which the camera will acquire and

Table II. Complete data including design parameters and performance numbers for the first BEES flyer built in 2001 are in column 1 and the two classes of flyers now being developed as representative of shepherding and imaging flyers are in columns 2 and 3, respectively.

Item	2001 BEES Flyer platform 1.5 kg	5 kg, BEES shepherding flyer	1 kg, BEES imaging flyer
Dry mass	900 g	2670 g	600 g
Fuel	100 g	340 g	225 g
Payload	427 g	1990 g	174 g
Takeoff weight	1427 g	5000 g	1000 g
Engine	178 g	698 g	145 g
Propeller	9 g	58 g	8 g
Engine type	OS 15LA	OS 61FX	OS 10LA
Propeller size	20.3×15.2 cm^2	28.0×20 cm^2	17.8×10.1 cm^2
Top speed	≈135 km/h	≈165 km/h	≈110 km/h
Landing speed	≈45 km/h	≈55 km/h	≈37 km/h
Range	25 000 m	55 000 m	37 000 m
Endurance	>12 min	>20 min	>20 min
Wing span	0.81 m	1.240 m	0.708 m
MAC	0.396 m	0.606 m	0.346 m
Leading edge sweep back	50.8°	50.8°	50.8°
Aspect ratio	2.206	2.206	2.206
Taper ratio	0.19	0.19	0.19
Wing area	0.297 m^2	0.701 m^2	0.227 m^2
Glide ratio (L/D)	8.5	8.5	8.5

Table III. Autonomy and sensor payload design targets for the BEES flyers.

	Imaging flyer type (1.5 kg)			Shepherding flyer (5 kg)		
System	Note	mW	gm	Note	mW	gm
Forward looking camera	CMOS	100	6	CMOS	100	10
Panoramic camera	...	...	...	CMOS+optics	100	60
Polarization imaging	Photodiodes	20	4	Photodiodes	120	10
Ocellus imaging	and filters			Filters/Imager		
Polarization/ocellus microcontroller	8 bit	40	5	8 bit	40	5
Air data system	8 bit, speed	100	20	8 bit, all	150	40
Telemetry transmitter	2.4 Ghz, half wave simplex	1000	25	RF modem	750	35
Video transmitter				2.4 Ghz	1000	35
Inertial measurement unit	...	...	...	6 axis MEMS	150	25
Optic flow computer	COTS solution	200	5	ETX PC	5000	150
Instruments (voltage, rpm,...)	Sensors	20	5	Sensors	40	40
Payload total		**1480**	**70**		**7450**	**410**

transmit motion imagery data in real time. The envisioned BEES flyer is essentially a payload (imager) carrying dart that is launched off the lander with the right amount of momentum to launch it into its ballistic trajectory. The Delta wing design offers a reasonable amount of glide as the launch/boost phase concludes. To obtain extended cruise several options exist including repeated rocket boosts, or an extended cruise using a hydrazine propulsion system for steady level flight thrust can be utilized. The second kind of flyers, "the shepherding flyers," will serve the dual role of imaging explorers and a telecom relay (mass $\sim$5 kg, endurance $\sim$30 min). The lander lands in the site of interest roughly 10–100 km from an area of potential scientific significance. A launching mechanism is used to launch the BEES flyer from the lander towards the target site specifying a flight heading. Launch energy could be provided by several techniques including a small solid rocket (single or multiple stage), pneumatic thrust, mechanical energy storage, i.e., springs, electrically powered launch, pyrotechnic gas generator, or a mechanism combining two or more of the techniques suggested. The communication range depending on the science goal could be few hundred meters to $\sim$100 km, and the lander as the main local relay base would always be available. Different flight paths over different terrains of interest are followed by the different flyers that are sent out one at a time in succession of each other. The larger shepherding flyer is sent out first as a high altitude telecom relay node when the smaller imaging flyer goes to survey sites beyond the line of sight of the lander. Surface imagery (5–10 cm resolution) is obtained using miniature camera systems on the flyers. The BEES flyer sends imagery/meteorological data through the relays to the lander, and after landing conducts/deploys a surface experiment and acts as a radio beacon to indicate the selected site to the orbiter/lander. The orbiter/lander receives the images and beacon signals transmitted by the flyers and relays them to the science team and mission planners on Earth. Several other flyers or pairs of shepherding imaging flyers as needed are launched in succession over the duration of the mission, each on its own radial, and the images and data are collected and sent to the project team. Based on this data, the project team identifies target sites with the greatest science potential, and suitable pathways are mapped for further investigation by heavily instrumented long distance surface traverse rovers. Another way of using the dual role flyers is to land them at a relatively high spot ($\sim$500 m or higher) and remain stationed there as a "metamorphic" flyer which is now in its telecom role permanently for the duration of the mission. The metamorphic flyer could also as needed deliver a crawler that has the required mobility to station the relay autonomously at a favorable location to accomplish optimum communication coverage. The imagery data will be broadcast both to the primary lander and to the nearby dual role flyer (shepherding and/or metamorphic) intermediate relays for guaranteed science data storage and eventual return to an orbiting telecommunications relay. By providing redundant receiving stations, communications link uncertainties related to signal blockage and multipath interference are mitigated.[37] Shepherding flyers, "the aerial telecom nodes," are the primary ones that can serve well for all cases. The use of the metamorphic flyers may be very much dependent on the specific locale of exploration, nevertheless the possibility of

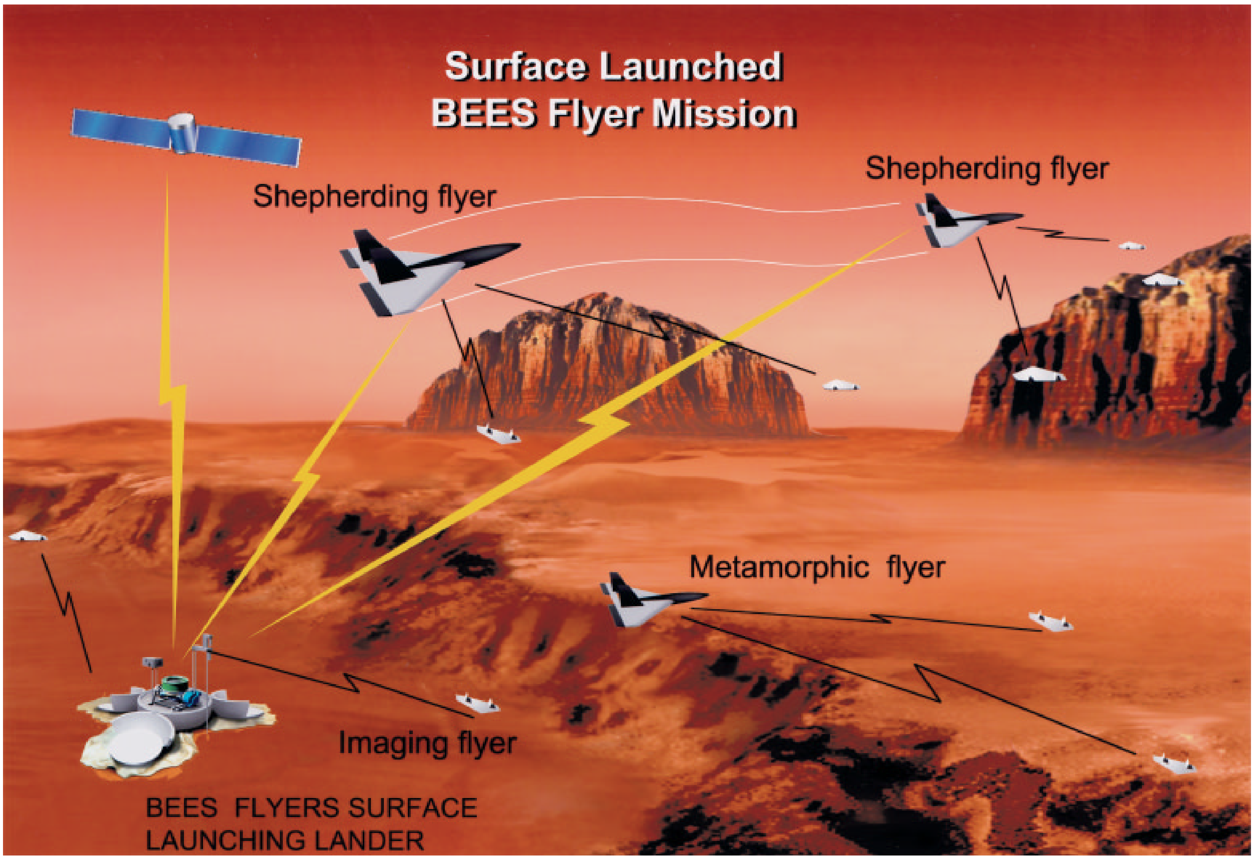

Figure 8. Artist's conception of the cooperative lander surface launched BEES flyer mission.

such additional nodes can be envisioned for specific geographies that may entail them useful. BEES flyers launched from the lander could also disperse other multiterrain surface or subsurface explorers. These tiny multiterrain explorers could be the climbing type or burrowing type, to locate and image as many Martian geological units as possible in these otherwise hard to reach locales.

If the feasibility of this approach can be verified, use of surface-launched imaging flyers would be a powerful option for enhancing the public interest and science return from a future Mars mission in the 2009 timeframe or beyond. 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 surface explorer within the limited time and resources of the mission could be increased dramatically. 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.

To summarize, some of the clear benefits of a surface launched cooperative rover–BEES flyer and/or lander–BEES flyer approach include

- surface launched flyer allows selection of launch time and weather,
- on call use of launched flyers allows multiple trials for same or different targeted locations,
- directed travel for close-up imaging,
- targeted deployment of in-situ experiments, instrument or other surface or subsurface explorers,
- provide valuable path planning information to other surface explorers including the rover. This variation of the mission is illustrated in Figure 9.

Another set of BEES mission scenarios described earlier[5,7] offers the most robust telecom architecture and the longest range for exploration. Two landers would be available as main local relays in addition to an aerial probe acting as an ephemeral local relay and

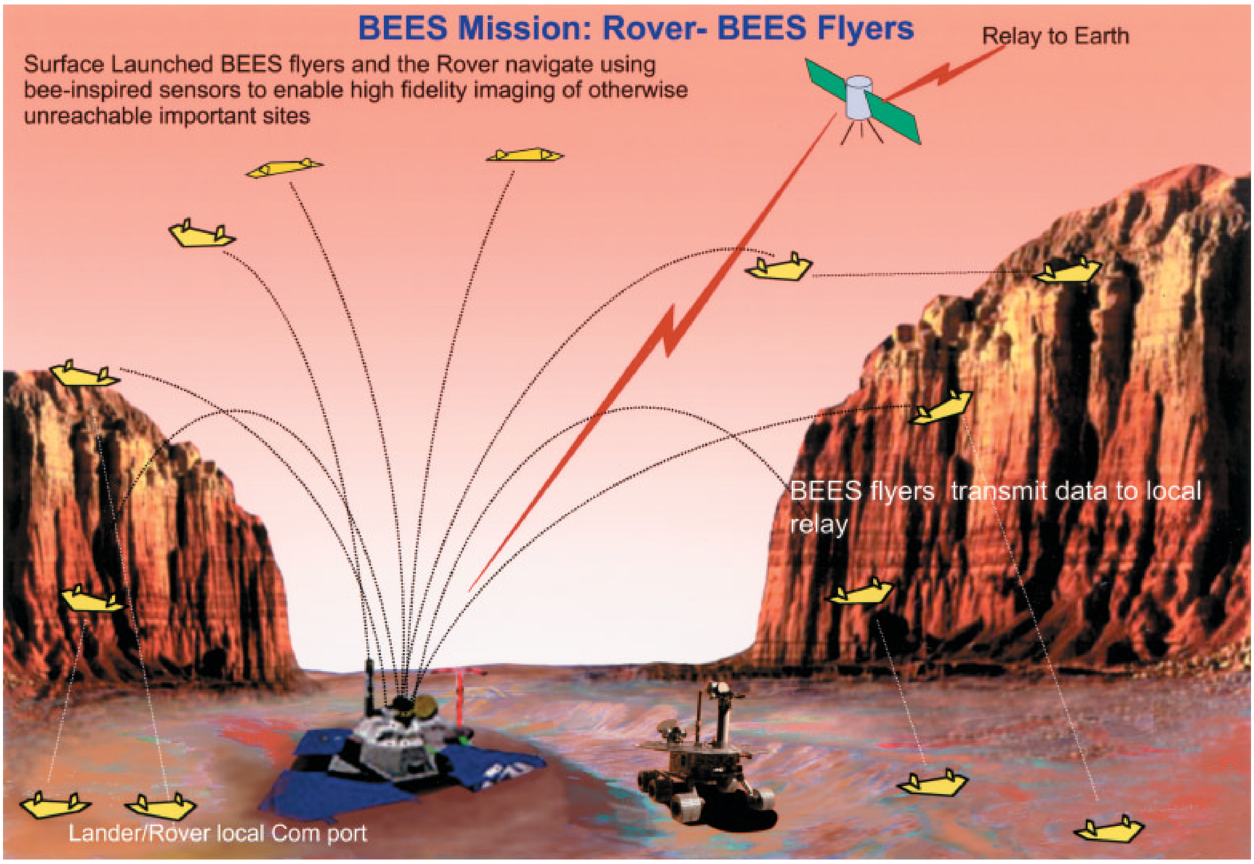

Figure 9. Artist's conception of a surface launched cooperative BEES flyer and rover mission.

the shepherding or metamorphic planes would be in their dual role as local relays nodes and imagers. The placement of the landing site for the Core MARS Lander with respect to the surface launching lander/rover base can allow coverage of extremely large ranges and/or exhaustive survey of the areas of interest, examples of which have been described in Section 3.

6. TELECOM ARCHITECTURE

The telecom architecture for such missions described earlier[6] is highlighted in the following:

6.1. Phases of Telecom Required for the Cooperative Lander-BEES Flyer Mars Mission Architecture

- Launch and cruise: During this phase the standard deep space Consultative Committee on Space Data Systems (CCSDS) protocol using X band to communicate from spacecraft to Earth will be utilized
- Entry, descent and landing: UHF to orbiter using standard CCSDS proximity telecom
- Surface operations:
  - Lander/metamorphic flyer to orbiter use UHF standard CCSDS proximity telecom
  - Imaging flyer to lander/shepherding/metamorphic flyers will use custom UHF telecom using multiple local relay redundant architecture to ensure successful imagery data return.

Multi-node telecommunications system architecture is designed to assure data return for such a short duration mission. Communications link requirements are driven by the flyer's principal instrument, an imaging system. For the baseline mission profile

Table IV. Required telecom functions for the variety of BEES flyer types.

BEES flyer type	High rate data transmission	On-board mass data storage	High rate data reception	Low rate command link reception	Simultaneous transmit and receive
Imager	X	X		X	
Shepherd relay	X	X optional	X	X	X
Metamorphic relay	X	X	X	X	

described above, we define various levels of telecom subsystem functionality for the three different types of BEES flyers—imaging, shepherding and metamorphic. By categorizing functional subelements required for mission communications, we are able to identify common reusable subsystems for a cost-effective approach to realizing telecom payloads, as shown in Table IV.

Definitions for each subsystem's functionality are given by the following:

- *High rate data transmission*: Capable of formatting (including error correction coding) and generating a UHF (400 MHz) modulated carrier at various data rates consistent with short range surface links (including airborne) and longer range orbital return links. Maximum data rates: 2.5 Mbps.
- *On-board mass data storage*: Sufficient solid state storage to accommodate a full mission data set (e.g., 93.8 MB for a continuous 5 min mission at 2.5 Mbps).
- *High rate data reception*: Capable of demodulating and decoding the encoded high rate data transmission.
- *Low rate command link reception*: Capable of demodulating command/hailing links from an orbiting telecom relay so that the metamorphic or storage nodes will be able to identify return link transmission opportunities.
- *Simultaneous transmit/receive*: By providing this capability, the shepherd flyer will not require any on-board storage and will simply act either as a demod-remod relay or as a bent pipe transponder. Antenna placement and self-interference are challenges to this complexity-reducing configuration.

The main local relay node is the lander. Imaging flyers within line of sight of the lander can complete the data down link readily. Additional flyers acting as shepherding/metamorphic flyers can be pre-deployed as secondary local relays for imagery tasks that require approach to locations beyond the line of sight of the lander so as to obtain good aggregate signal reception over the planned mission flight path. These relays can provide sufficient digital storage capabilities to enable full recording of a complete mission data set. Having acquired and stored the science data, each of these relays would then await uplink opportunities to an overhead orbiter to individually return their data payloads.

6.2. Data Characteristics

Based upon the objective of returning full motion imagery, both low frame rate (3 Hz), uncompressed (512×512), color images (24 bits/pixel), and full rate (30 frames per second) compressed digital video (MPEG2 operating at 2.5 Mbps) were compared in terms of required data volume for a mission allowing at least 5 min of imaging time. The uncompressed option of 24 bit color images at 3 Hz yields a volume requirement of 675 MBytes and real-time rate requirement of 18.9 Mbps. In comparison, the 2.5 Mbps compressed signal requires a total mission data volume of 93.8 MBytes.

6.3. Functional Requirements

The proposed telecom architecture therefore requires two types of communications payloads for a Mars mission:

- transmitter and antenna subsystems for the imaging flyer with sufficient energy and power resources to close a line of sight link for a 60 km range at a real-time data rate of 2.5 Mbps and
- receiver, storage, transmitter and antenna subsystems for the lander and relay flyer with sufficient capability and capacity to demodulate a 2.5 Mbps transmission, store up to 93.8 MB,

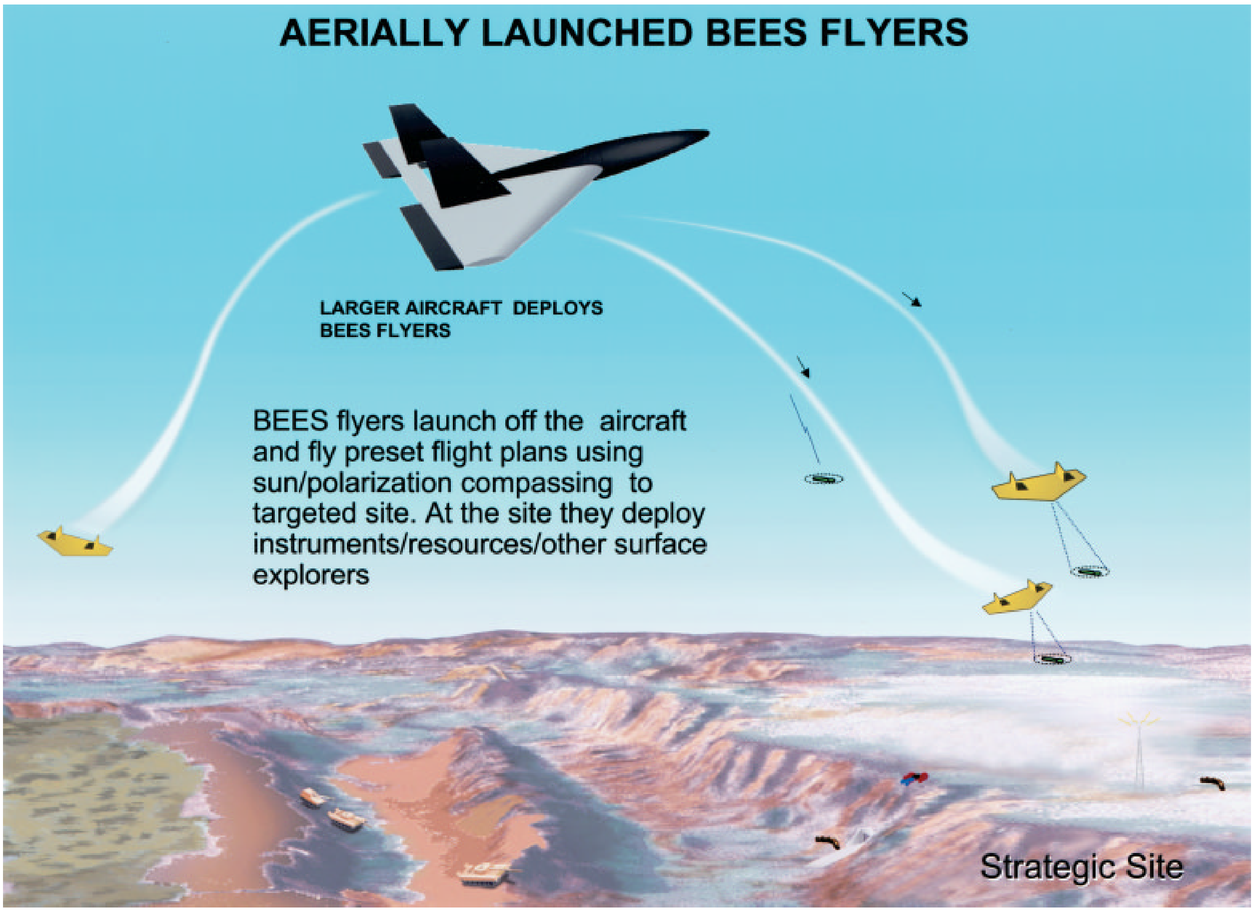

Figure 10. A defense scenario of aerially deployed BEES flyers from other larger aircraft is illustrated for surveillance and reconnaissance of imagery and data from strategic sites. Further-on the BEES flyers can deploy additional small surface explorers.

detect an orbiter overhead hailing command and uplink the total data collection—possibly at a non-real time data rate.

Use of the 400 MHz UHF band is appropriate under assumptions of low gain antennas on both transmit and receive terminals. Furthermore, use of this frequency provides antenna commonality in communicating with overhead resources. Preliminary calculations of the required rf transmit power and associated margins for the imager downlinks suggest that such an architecture is viable.

6.4. Mission Geometries

The communications link geometries associated with the cooperative mission scenarios being considered here correspond to two types. For imager-to-relay, imager-to-shepherd or shepherd-to-lander, the link is characterized by line-of-sight communications with shallow grazing angles between the two terminals (e.g., 50–100 km horizontal separation, 0.5–2.0 km vertical separation). Several impairments to the links arise from these geometries. One effect corresponds to blockage by wings or other structures occluding antenna fields-of-view during flyer movement and operation. Another effect occurring in links to the lander is the change in propagation model from a *distance squared* loss function to a *distance to the power four* ground wave propagation model at extreme distances. This crossover point is a monotonic function of the relative antenna heights for transmitter and receiver. Consequently, high altitude deployments of the shepherding/metamorphic flyers are preferred to allow enhanced communications ranges. Under cases of shallow elevation angles to the lander, flat and frequency selective multipath will also occur. Study[18,37] of parametric contour plots incorporating the transition between square law and fourth power propagation models provides preliminary confirmation of the viability of this architecture.

The second general type of communications link corresponds to the transmission to an orbiter from the lander or metamorphic flyer or shepherding flyer storage node. This link is fairly well characterized as a line-of-sight communications channel with multipath and blockage issues arising only at small surface-to-orbiter elevation angles.

7. TERRESTRIAL MISSIONS UTILIZING BEES DEVELOPMENTS

Terrestrial applications of these BEES flyers in cooperative surface/aerial exploration scenarios include aerial/surface distributed measurements of meteorological events, storm watch, seismic monitoring, reconnaissance, biological chemical sensing, search and rescue, surveillance, autonomous security/protection agents and/or delivery and lateral distribution of agents (sensors, surface/subsurface crawlers, clean-up agents).

There is a broad requirement for telemetry relays in infantry operations. Rugged terrain (and cities) makes line of sight conditions between units rare. Simple, light, disposable airborne relays with minimal mass devoted to autopilot would be a highly desirable asset. Developments in BEES can provide serious navigating autopilots that weigh less than 15% of the total mass of the flyer, leaving the remainder of the payload for the actual task and its power supply.

Time on station is a concern with communications infrastructure, and in the case where a relay needs to be in place for more than a few hours it is desirable to have the relay placed on high ground. Often the "high ground" might be very high, and completely inaccessible, so the ability of an autonomous system to fly, and then land near the crest of the hill, before crawling to the very apex would be even more valuable than an ephemeral relay.

Sampling of atmosphere and radiation close to the ground is clearly also an important capability in a world with loose biological agents and fissile material. A terrain following small UAV that does not require extensive programming based on GPS to stay close to the ground would provide a new and very valuable capability for defense needs.

Figure 10 illustrates an example scenario of interest to defense needs of surveillance and reconnaissance from strategic targets.

8. CONCLUSIONS

We are implementing a combination of unique and distinct biologically inspired capabilities in a scaleable unmanned small flyer robotic platform, "the BEES flyer." Specific strides in insect inspired navigation sensors and bioinspired recognition systems are leading to capable BEES flyers that can enable such exploration needs. This new BEES approach is demonstrating the power of incorporating selected and highly evolved biological capabilities into engineered systems. The resulting uniquely engineered "hybrid" system emulates in many ways the various characteristics of its biological progenitors, enabling functions and operations otherwise hard to perform by conventional methods. We believe this approach will prove to be very powerful for future autonomous robotic explorers for both NASA and terrestrial applications. Design and performance results of BEES flyers based on these bioinspired sensors are summarized as the enabling units being developed for the future Mars missions described. We have described a viable set of missions both for Mars and terrestrial applications that are possible illustrating feasible architectures with a robust telecom architecture to obtain high ($\sim$5–10 cm) resolution imagery of Mars at low altitudes. Scientific needs and requirements of long range exploration on Mars absolutely necessitating BEES flyer missions are described.

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