Biologically-Inspired Navigation and Flight Control for Mars Flyer Missions

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Abstract

Mars offers a substantial challenge to conventional flight due to its thin atmosphere (about a hundredth that on Earth); lack of a magnetic field for navigation, and limited telecommunications or navigational infrastructure. To meet and overcome these challenges, we are adapting principles proven successful in nature to achieve stable flight control and navigation for Mars exploration. When exploring a new planetary surface in situ, a challenge is to be able to quickly survey and select sites of scientific interest. Imaging done by orbiters allows broad coverage but at limited spatial resolution. Currently Mars Global Surveyor provides ~ 1m–1.5m /pixel resolution at best and the 2005 Mars Reconnaissance orbiter is expected to provide ~ 60 cm /pixel high resolution imaging from 400 km altitude. Descent imaging may provide a context for landed vehicles, however, it is not broad enough to plan exploration paths for an explorer or to characterize potential sample return sites. Images taken from surface-sited landers or rovers with masts ~1-2 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, 50–1000m altitude perspective is as yet uncovered and is an essential science need. Imaging from this mid-range is required to obtain details of surface features/topography, particularly to identify hazards and slopes for a successful rover mission. Low altitude airborne exploration of Mars offers a means for covering large areas, perhaps up to several hundred kilometers, quickly and efficiently, providing a close-up birds-eye view of the planetary terrain. A novel approach to low-mass yet highly capable Mars flyers lies in adapting principles proven successful in nature to achieve stable flight control and navigation. We will describe the results of successful flight tests of small flyers that incorporate bioinspired sensors including: a dragonfly ocellus-based horizon sensor for attitude reference, a honey-bee based optic flow sensor for altitude control and hazard avoidance, and insect inspired sun/polarization compassing. These autonomous flight capabilities are crucial for enabling nap-of-the-Mars flight and imaging of vertical stratigraphy for geologically-rich sites on Mars. This approach: Bioinspired Engineering of Exploration Systems (BEES), is enabling new bioinspired sensors for autonomous exploration of Mars. The steps towards autonomy in development of these BEES flyers are described. A future set of Mars missions that are uniquely enabled by such flyers are finally described.

1. Introduction

Aerodynamic and reactive flight is possible on Mars. Earlier publications and reports[1-9] have considered the possibilities, and practicalities of aerial exploration of Mars. Historically in these earlier concepts, the suggested missions have primarily involved a single large aircraft being unfolded and released after reentry, while descending. 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 [10-17] and are developing further for demonstration is that a smaller vehicle, a small unmanned aerial vehicle (UAV) can be launched from the surface, that is still capable of performing many of the imaging tasks of a larger craft, with much lower cost and risk. The key to such near-surface exploration lies in low cost, lightweight autopilots that are capable of obstacle

avoidance, navigation and terrain following, while imaging the surface and sampling the atmosphere. This paper describes the highlights of the steps to autonomy in our development of small UAV's that incorporate bioinspired sensors to enable autonomous navigation and flight control. Defined as "BEES flyers" or "biomorphic flyers" we have described these in detail in earlier publications. We also describe a few viable mission architecture options using the BEES flyers that allow reliable data return options using the limited telecom infrastructure on Mars that can be made available with a lander base/orbiter combination.

Aerial imaging from orbiters and high altitude aircraft has proved invaluable for collecting detailed imagery of wide areas for more than a century in NASA, DoD and a wide variety of commercial domains. Such high altitude surveillance, however requires sophisticated optics and quality camera gimbals to capture high resolution imagery of the surface. Low altitude surveillance provides high spatial resolution over a smaller region without sophisticated mechano-optical assemblies. On the other hand, high altitude craft can remain within line of site of their command and control station for significant distances, potentially hundreds of kilometers. The same does not hold for low altitude surveillance as range of line of sight drops sharply with altitude. As a solution to this predicament, we describe in this paper Mission scenarios that instead use aerial telecom relays (shepherding flyers) or high altitude placed relays in a dual role (metamorphic flyers) linked to the local lander/rover base station to enable robust return of the low altitude imagery data.

2. Development of BEES Flyer

Delta wing flyers with distinct functional roles as described below have been flight tested during the last two years within our development effort. The results of development towards embedding a range of sensor suites as accomplished already have been as reported earlier[13-17]. The bioinspired sensor suite consists of dragonfly inspired ocelli for flight stabilization/attitude referencing, optic flow sensor for terrain following and lateral drift containment by altitude hold, sun/polarization compassing for maintaining a heading along with a panoramic camera rapid for target and threat detection, as well as reducing the computational demands of navigation.

Aircraft Type 1, the Imaging Flyer

The imaging flyer is being developed as an assisted ground launched mini-UAV weighing less than 650g, range of 15km, endurance 10 minutes, cruise speed of 70km/h and wingspan of ca. 700mm. The vehicle will demonstrate behaviors required of a craft that could provide a Mars lander with the means to project its perception beyond the immediate surroundings. This view would allow operators on Earth (during a future Mars mission as envisioned in Section 4 and 5) to obtain a powerful blackbox for crucial descent and landing data from a Mission and develop improved science missions for planetary rovers by providing valuable pre-mapping of the sites of interest to help path planning of the rover

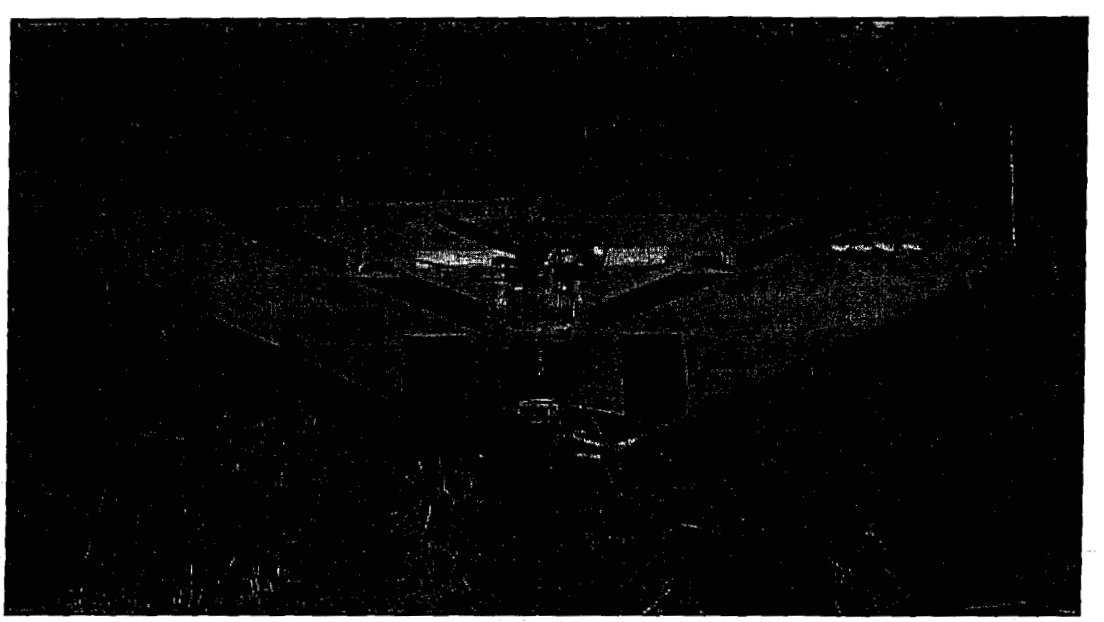

Figure 1. A typical BEES Flyer Prototype with the ocellus mounted on the nose

traverse. The vehicle will fly straight radial courses away from the launch site. Navigation behavior will focus on level flight and sun compassing, with altitude hold behavior and holding the radial ground track regardless of crosswinds and aircraft trim problems.

Aircraft Type 2, The Shepherding Flyer

The shepherding flyer is about four-five times larger UAV, weighing 4- 5kg, wingspan ~ 1.2 –1.5 m, endurance of over 30 minutes and range well in excess of 60km. It will be either assisted launched or conventionally launched using a potential energy drop from a larger craft. This vehicle will contain navigation functions for course control and terrain following to allow long range exploration of geological and geographical features. A vehicle with these behaviors on the surface of Mars would perform detailed, long-range exploration of regions of interest. The vehicle control systems will be designed such that navigation "outer loops" such as embedded geological feature detectors will be able to steer the craft and set new courses while low level control is taken care of by the bioinspired sensor suite.

Common Features

While the vehicles have fundamentally different roles, much of the underlying technology within the autopilots will be the same. Both will contain bio-inspired attitude and heading sensors to allow navigation without magnetometer, gyrocompass, gravity, or GPS. Both vehicles will be entirely autonomous after launch, requiring no external systems, sensors or control inputs to fulfill their missions. Such autonomy will require light, high performance sensors to meet the size and weight constraints. The Type 2 craft will be heavily dependent on optic flow for terrain following/terrain avoidance, with the Type 1 craft also having altitude hold based on optic flow. Both vehicles will contain conventional and panoramic cameras to demonstrate the utility of such sensors during exploration, and as attitude/landmark sensors. The current designs[17] for the aircraft are extremely strong, easily capable of surviving being dropped from a full size aircraft at high speed, or being launched from the ground by a rocket or spring at 40g. They have been flown successfully in wind gusts of over 60 Km/hour. The successful performance of the biomorphic ocellus has already been tested and reported earlier[13-16]

3. Pathway to Autonomous Flight

Aircraft are typically simpler and faster to build and simulate than rover type mobile robots and they can provide a leap in terms of range of area that can be covered for exploration. The focus of our development has therefore been on a development pathway that leads to autonomous flight. Development of avionics, communications and control systems are significantly more difficult due to stringent constraints on mass and size. Since the platform must be in constant motion in order to fly, the process of testing and debugging the real system are technically demanding. We are doing this in the following systematic steps as outlined in the following:

Phase 1

In our BEES for Mars project the path to autonomy is gradual. Initial testing of the bioinspired sensors described earlier[13-16], were performed in simulations that were ground-truthed against real data. For example in the case of the ocelli and polarization sensing the simulation contained multispectral imagery captured using a panoramic scanning device. The panoramic nature of the data allowed the vehicle to rotate in all three degrees of freedom to test the response of the sensors. The addition of sensor and platform dynamics to the simulator allowed closed loop control to be tested inside the simulator.

Phase 2

The second phase of testing, which is currently ongoing, was to implement all of the control systems on a ground computer, with sensor data downlinked, and command data uplinked. Commercial remote control equipment is well suited to this approach. Standard remote control transmitters contain an input connector to accept a "pulse position modulated" (PPM) signal that can be selected to be the output of unit by deflecting a spring loaded switch. A Philips 80C552 microcontroller board with standard parallel port communications to the control PC was programmed to produce PPM signals corresponding to the deflection of control surfaces commanded by the PC. The pilot could fly the plane as normal, and occasionally allow the control PC to take command.

The inputs to the control system were the video data from the aircraft, and a stream of avionics sensor data. The latter was composed of air temperature, static pressure, dynamic pressure, engine RPM, exhaust manifold temperature, roll rate, pitch rate, and battery voltages. The avionics sensors were sampled by an onboard Philips 80C552 microcontroller board containing a precision 16 bit analog to digital converter. The counter/timer array on the microcontroller could decode the incoming servo stream and was capable of producing an output servo stream. The outgoing and incoming streams can be included in the telemetry stream. We have studied and reported[13-16] the performance of the

biomorphic ocelli earlier using this interim stage of autonomy.

Phase 3

Further, to proceed to true autonomy, independent of the ground station, requires significant technical development. In order to control homing behavior for terrestrial demonstrations and testing, the system must have some form of on-board attitude control. In order to test the sensors it is necessary to fly the aircraft out under the control of the sensor suite, which includes optic flow, ocelli and polarization compassing sensors. At 30-50m/s the tyical test speeds used, the aircraft is rapidly beyond the range at which a remote human pilot can fly the craft. Remote control transmitters provide a reliable command link at over 2km, however this is less than 1 minute of flying at maximum throttle. Clearly to retrieve the aircraft intact, the aircraft must have an independent navigation system, which can actually return to the operator. GPS is now a simple and convenient commodity for all autonomous systems, however unlike some aircraft, the BEES flyer requires a full artificial horizon system (AHRS) based on inertial and magnetic sensors if the aircraft is to return intact.

Continuous interaction between the aircraft and the command/control station is required for failsafe operation. This means that the hardware must run constantly and can't be powered on when a fault in the experimental systems is detected or an abort command is received. Ideally the failsafe system would run on a single tasking, highly integrated system such as a microcontroller, preferably a very simple one, with a minimal interrupt load and no operating system. Fortunately a number of developments are moving us towards a nearly ideal failsafe system. The primary barrier being the heavy arithmetic burden associated with computing attitude in real time. Currently we have embedded all air-data control systems, throttle management, and rate damping on an 8 bit microcontroller. A pure quaternion, integer arithmetic AHRS using MEMs gyros, accelerometers, and magneto-resistive magnetometers shows early promise and is expected to be accommodated on the 8 bit flight computer. Should the performance of the flight computer prove inadequate to simultaneuosly perform navigation, control and sensor processing, we will upgrade the flight computer to a 16 bit Philips XA class microcontroller, which will definitely be capable of the task.

Through this process we expect to transition from supervised autonomy, to full autonomy with miniaturized avionics in the space of a year and a half rather than multiple years.

4. BEES Flyer Descent and Landing Observation Mission

This Mission provides a technique for the first time to observe the crucial descent and landing of the main payload (such as the lander) by utilizing the imaging of the event that is possible using BEES flyers that have been deployed few-several minutes earlier from the backshell and are in flight following the descent of the lander, imaging it, storing that critical data to provide a first on-lookers view of Descent and Landing of the main payload. The station keeping and pointing capabilities that are enabled by the bio-inspired sensors that we have recently demonstrated allow the successful imaging of the descent event with the BEES flyers successfully following the descending payload. The study and observation of other ephemeral events such as dust storms or boundary layer phenomena is also uniquely enabled by this new technology development. The key features of the BEES flyers utilized here are station keeping to follow the descending main payload, steady attitude referencing and resulting pointing capability, maintaining steady altitude while imaging and the design optimization of accommodation of flyers in the backshell

In this Mission the BEES flyers are accommodated in the backshell of the Aeroshell. One example of how the flyers may be accommodated is shown in figure 1. On entry into Mars atmosphere, right after the backshell is jettisioned and supersonic chute is deployed, the BEES flyers are released from the dropping backshell.

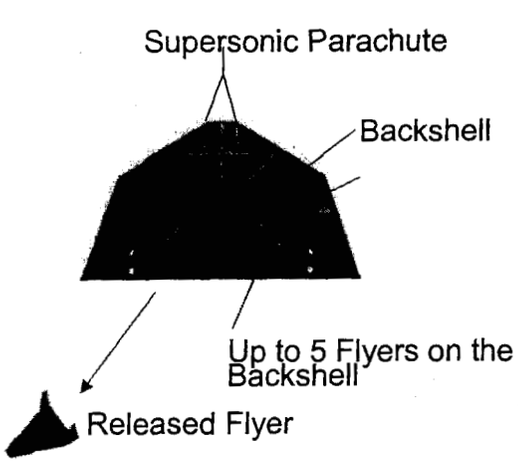

Figure 2. BEES Flyer accommodation in the backshell

One example of the envisioned Mission is illustrated in Figure 3. In this Mars Entry Descent Landing (EDL) scenario, the backshell containing the flyers is jettisioned away at an altitude of ~ 5 km. The main payload (lander) shute deploys thereafter and it starts descending. The flyers are now released from the backshell and are at a safe distance away from the main payload. They perform their function of following and observing by imagery and sensing the main payload maintaining the safe distance from it continuously. The imaging and shepherding flyers perform their respective functions.

Two types of functions can be performed utilizing the imaging and shepherding type of BEES Flyers respectively. The imaging flyers are short lived ~ 10min, have a smaller range, and are much smaller in size so a larger number can be accommodated. They are released successively one after the other as the back-shell is dropping to pursue a trajectory following the descending main payload (in this case being described, it is the descending lander). These flyers constantly image the various events of descent and then landing. The shepherding flyer is released and stays overhead to take imagery using a panoramic camera and additionally it serves as a local telecom port to receive imagery from the imaging flyers. The shepherding flyer circles above at a safe distance from the descending lander to observe the whole view. It has a longer lifetime of about 30 minutes and can accomplish ranges ~ 60 Km. It can glide race-track or do figure 8 loops overhead slowly spiraling down if the safety check is all go such that it always maintains well its dual functions of obtaining panoramic imagery of the event and providing a telecom port for the imaging flyers.

Similarly other significant events such as dust storms and a variety of atmospheric phenomena can be studied using such BEES flyers soon after entry.

All the flyers are designed to store the imagery they collect and then after end of flight life await at their landing site to send data back to earth via the orbiter down link whenever the next link cycle with the orbiter occurs. The telecom payload is placed so as to withstand landing impact and survive the crash. The shepherding flyers are fabricated particularly more robustly to be risk averse and survive the landing because they are the master repertoire of all imaging data including their own panoramic data and the data that they collect in interim breaks from the imaging flyers. The telecom can be placed on the aeroshell as well. By multiple relay options robustness in data downlink is accomplished.

The other scenario can be of the type of EDL used by Mars pathfinder or as is planned for MER. In this case the backshell remains connected to the main payload almost down to 100m into descent through the bridle. The flyers therefore obtain descent imagery much more easily riding together with the main payload connected on top through the bridle. The pointing is easier, although they share risk of loss due to any accident in the 5Km down to 100 m range. At about 100m, the flyers can be released away and they work in the same way as the previous case detached away from the main payload to be an observer of its events by close-up imaging and sensing.

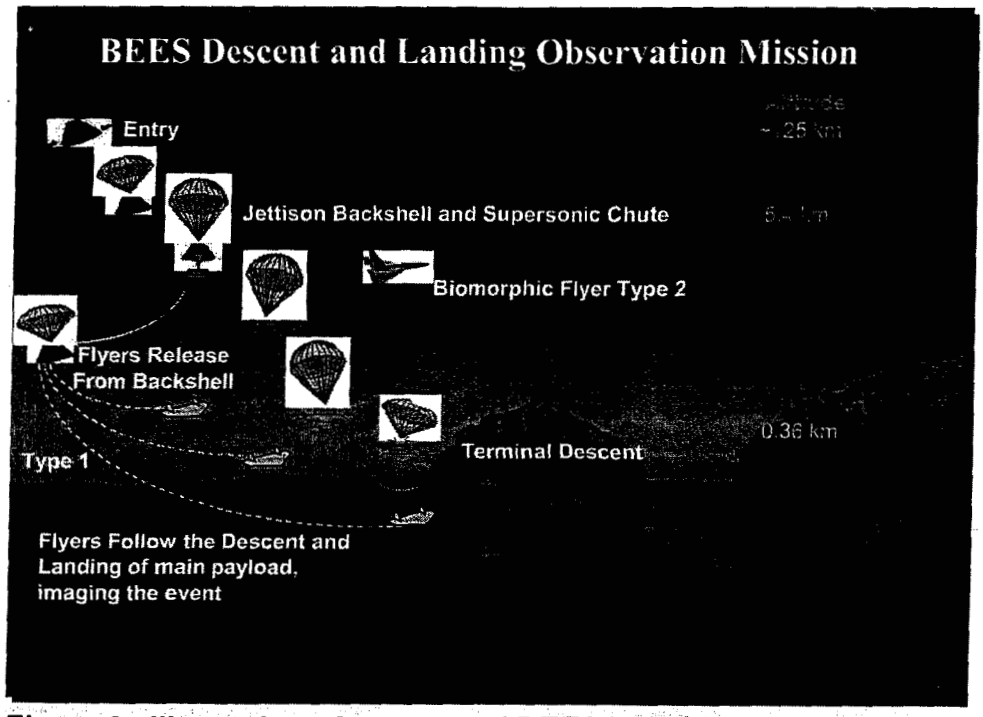

Figure 3. Illustration of envisioned BEES Descent and Landing Observation Mission

5. Mars Mission Architecture and Exploration Applications

When exploring a new planetary surface *in situ*, a challenge is to be able to quickly survey and select sites of scientific interest. Imaging done by orbiters allows broad coverage but at limited spatial resolution. Currently Mars Global Surveyor provides ~1m –1.5m/pixel resolution at best and the 2005 Mars Reconnaissance orbiter is expected to provide ~60 cm/pixel high resolution imaging from 400 km altitude. Descent imaging may provide a context for landed vehicles, however, it is not broad enough to plan exploration paths for an explorer or to characterize potential sample return sites. Images taken from surface-sited landers or rovers with masts ~1-2 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, 50–1000m altitude perspective is as yet uncovered and is an essential science need. Imaging from this mid-range is required to obtain details of surface features/topography, particularly to identify hazards and slopes for a successful rover mission. Low altitude air-borne exploration of Mars offers a means for covering large areas, perhaps up to several hundred kilometers, quickly and efficiently, providing a close-up birds-eye view of the planetary terrain. As described earlier a novel approach to low-mass yet highly capable Mars flyers lies in adapting principles proven successful in nature to achieve stable flight control and navigation.

The mission architecture to be utilized, deals with the challenge of rare atmosphere on MARS by using surface launched BEES flyers essentially like payload carrying darts with an extended powered glide/cruise. Launch energy could be provided by single or multiple solid rocket boosts, pneumatic thrust, a spring launch, electrically powered launch or a mechanism combining two or more of the stated techniques. Either a lander or rover could be used as the surface launch base for such flyers.

Two kinds of BEES flyers are in development. First, small (< 1 Kg) imaging explorers with less than ~ 10. minute flight duration during which the camera will acquire and transmit motion imagery data in real time.

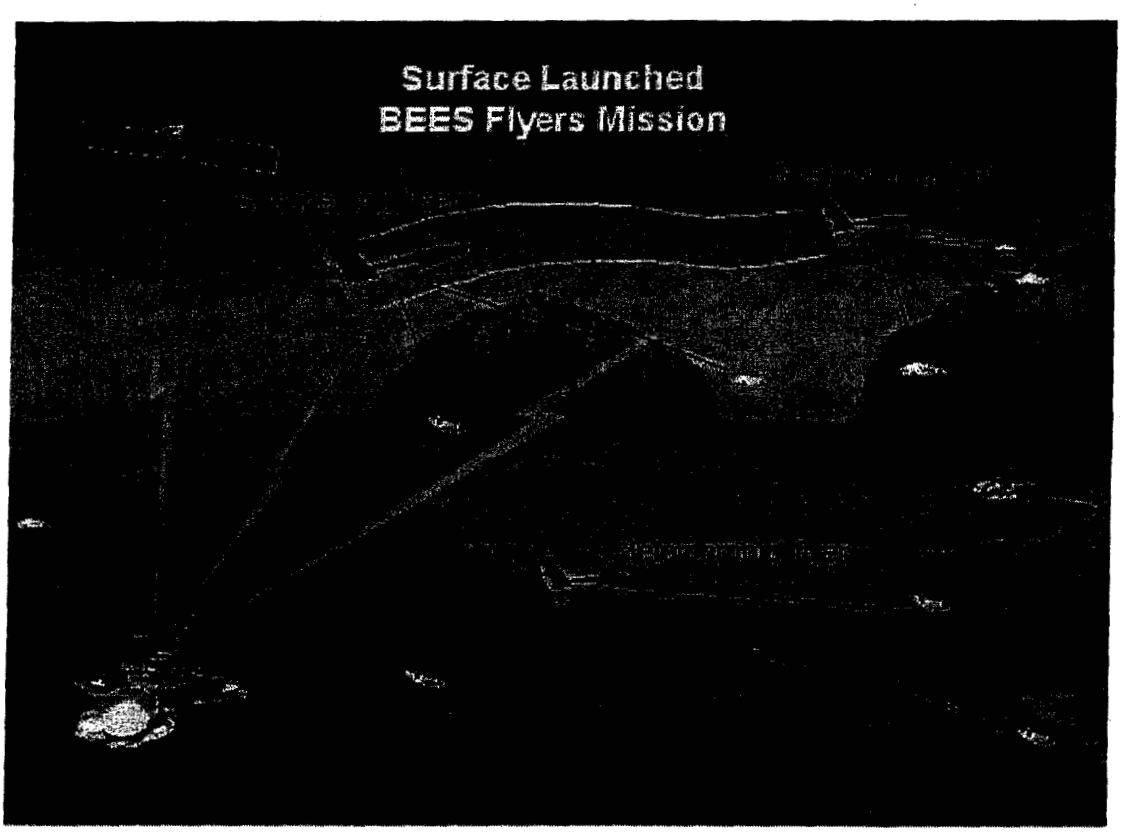

Figure 4a. Illustration of envisioned Mars Mission of the BEES surface launched flyers as a small Mission sent in quick succession of the 2009 Mission to enable long range exploration of Mars by imaging terrain that is otherwise hard to reach to-date.

The second kind of flyers will serve the dual role of imaging explorers and a telecom relay (mass ~ 5 Kg, flight duration ~ 30 min). The lander/rover lands in the site of interest roughly 10-500 Km from an area of potential scientific significance. A launching mechanism is used to launch the BEES flyer from the lander/rover towards the target site specifying a flight heading. The communication range depending on the science goal could be line of sight to the lander/rover base to a few hundred kilometers by using additional telecom bases. The larger flyer is sent out first as a shepherding flyer telecom local relay to provide an intermediate relay node when the smaller imaging flyers go survey sites beyond the line of sight of the lander. Surface imagery is obtained using miniature camera systems on the flyers. The flyer 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. The lander receives the images and beacon signals transmitted by the flyers and relays them to the science team and mission planners on Earth via the orbiter. Another way of using the dual role flyers is to land them at a relatively high spot (~ 500m 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 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.

This envisioned mission illustrated as an artist's conception in Fig 3a – 3c offers the most robust telecom architecture[11, 18] and the longest range for exploration with two landers being available as main local relays in addition to an ephemeral aerial probe local relay and the shepherding or metamorphic planes in their dual role as local relays and storage nodes. The placement of the landing site for the Core MARS Lander (2009 Lander for example) with respect to the BEES Flyer Lander/Rover Base can

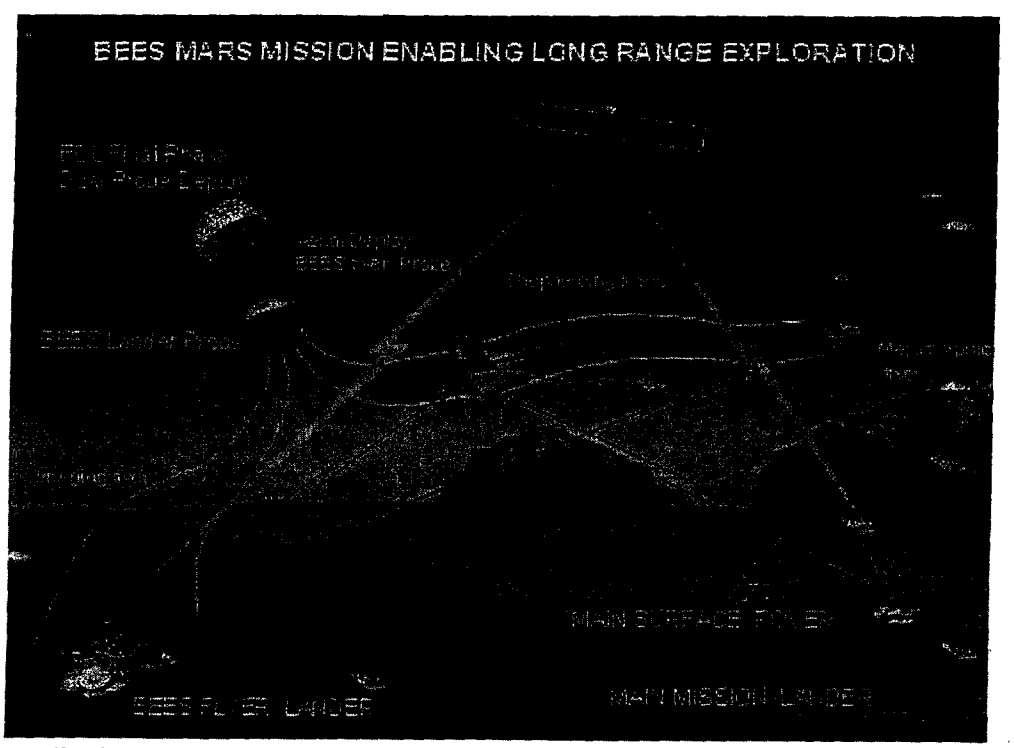

Figure 4b. Illustration of envisioned Mars Mission that uses a dual probe delivery of the BEES surface launched flyers in the BEES lander probe and the shepherding flyers in a dual aerial probe to enable long range exploration of Mars and accomplish new science functions that are hard to achieve otherwise like imaging stratigraphy or canyon sidewalls in hard terrain such as Valles Marineris.

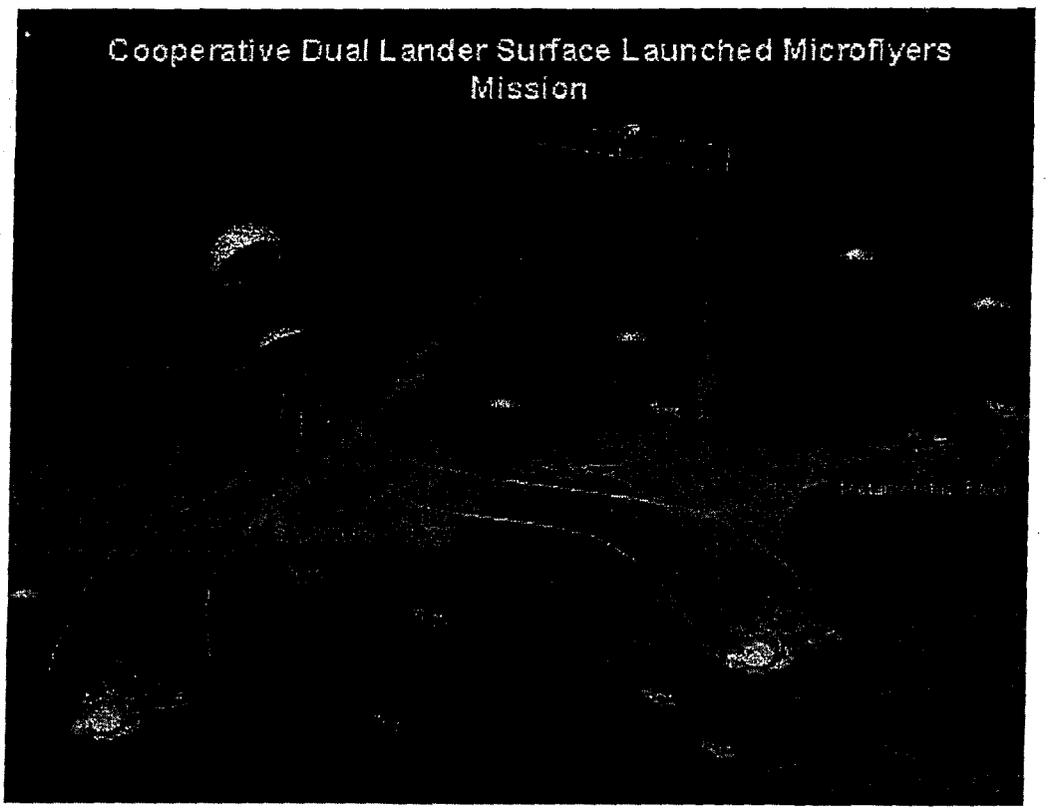

Figure 4c. Illustration of envisioned Mars Mission that uses a dual probe delivery of two BEES lander probes to provide long range exploration of Mars.

allow coverage of extremely large ranges and/or exhaustive survey of the area of interest. This Mission can be implemented in three different alternate configurations shown respectively in figures 3a, 3b and 3c. One possibility shown in figure 3a is to send the BEES Lander as a small separate Mission to follow the main lander . Another possibility is to send following the main 2009 Mission Lander a larger BEES Mission consists of a dual probe entry into the Mars atmosphere with one probe containing the BEES Lander and another probe containing an aerially deployable shepherding flyer. A third independent possibility is to send a main Mission containing two BEES Landers as dual probes to obtain such a long range exploration Mission.

Hard terrains such as Valles Marineris on Mars, ten times the size of Grand Canyon on Earth are as yet impossible to explore because they are beyond the capability of existing means such as landers or rovers. BEES flyers, either surface launched from landers or rovers, or aerially launched from a space craft directly, will enable navigation into and within Valles Marineris to explore this unique geology rich site including stratigraphy features, shear faces, outcrops, layering, depositional history etc by sideways imaging of the canyon walls in close detail and deploying instruments for localized in-situ measurements of regions otherwise unapproachable.

Conclusions

We are implementing a combination of unique and distinct biologically inspired capabilities in a scaleable microflyer robotic platform. 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 pathway to autonomous flight is identified and flight results accomplished to date look promising. We have described a viable set of Missions both for Mars and Terrestrial applications that are possible illustrating feasible architectures with a robust data downlink architecture to obtain high (~ 5-10 cm) resolution imagery of Mars at low altitudes.

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References

[1] Pyle, J. S., "Lift and Drag Characteristics of the HL-10 Lifting Body During Subsonic Gliding Flight," NASA TN D-6263, 1971.

[2] Stivers, L. S. and Malick, A. W., "Wind-Tunnel Investigation at Mach Numbers from 0.50 to 1.29 of an All-Movable Triangular Wing of Aspect Ratio 4 Alone and with a Body," NACA RM A9L01, 1950.

[3] V.C. Clarke, A. Kerem, and R. Lewis, "A Mars Airplane", *J. of Astronautics and Aeronautics*, vol 17, jan 1979, p 42-54.

[4] V.C. Clarke. A. Kerem, and R. Lewis, , "A Mars Airplane .... Oh Really", 17th Aerospace Sciences Meeting, New Orleans, Jan 1979AIAA, Paper # A79 –19516.

[5] P. Bouras and T. Fox, An autonomous flying vehicle for Mars Exploration, AIAA/AHS/ASEE Aircraft Design, Systems, and Operations Conference, Sep 1990, Dayton, Ohio, AIAA – 90-3235.

[6] B.W. Augenstein, "The Mars Airplane Revived –Global Mars Surface Surveys". AAS 87-270.

[7] A. J. Colozza. "Preliminary Design of a Long endurance Mars Aircraft", NASA Contractor Report 185243, April, 1990, AIAA –90-2000, N90 –21763.

[8] D. Reed, High Flying Mini-Sniffer RPV –Mars Bound, *J. of Astronautics and Aeronautics*, vol 16, june 1978, p 26-39.

[9] Hall, C. F., "Lift, Drag and Pitching Moment of Low-Aspect Ratio Wings at Subsonic and Supersonic Speeds," NACA RM A53A30, 1953.

[10] Thakoor, S. and Martin, T. Surface Launched Explorers for Reconnaissance/Scouting, (2002), *Nasa Tech Briefs,* Vol 26, No 4, p. 69.

[11] Thakoor S., Lay, N., Hine, B., Zornetzer, S. (2001, May 11) "Cooperative Lander-Surface/Aerial Microflyers Scout Mission", JPL New Technology Report NPO # 30286.

[12] Thakoor, S. (2000) "Bio-Inspired Engineering of Exploration Systems", *Journal of Space Mission Architecture,* Issue 2, p 49-7.

[13] Chahl, J., Thakoor, S., Bouffant, N. L., Stange G., Srinivasan, M.V., Hine, B., Zornetzer, S. (2003), "Bioinspired Engineering of Exploration Systems: A Horizon Sensor/Attitude Reference System Based on the Dragonfly Ocelli for Mars Exploration Applications", *Journal of Robotic Systems, Vol 20 Issue 1, pp35-42.*

[14] S. Thakoor, J. Chahl, M.V. Srinivasan, F. Werblin, L.Young, B. Hine, S. Zornetzer "Bioinspired Engineering of Exploration Systems for NASA and DoD", ", Artificial Life Journal, 2002, Vol 8, Issue 4, pages 357-369.

[15] Thakoor, S, Chahl, J., Srinivasan, M.V, Cabrol, N, Young, L., Hine, B., Zornetzer, S. (2002, Oct 10-Oct 19), "Mars Exploration Using Biomorphic Flyers", Poster Presentation at the COSPAR 2002 held at Houston, Texas, Oct 10-Oct 19, 2002, Poster # F 058, Sponsored by the AIAA, World Space Congress 2002.

[16] D.D. Soccol, J.S. Chahl, N. Le Bouffant, M.A. Garratt, A. Mizutani, S.A. Thurrowgood, G. Ewyk, S. Thakoor, A Utilitarian UAV Design For NASA Bioinspired Flight Control Research, Proceedings of the 41st Aerospace Sciences Meeting and Exhibit, AIAA 2003-461, Jan 6-9, 03, Reno, Nevada.

[17] Thakoor S., Hine, B., Zornetzer, S "Mars Missions Enabled by Biomorphic Flyers" New Technology Report, December 23, 2002, NPO # 40118.

[18] Lay, N., C. Cheetham, H. Mojaradi, and J. Neal, "Developing Low-Power Transceiver Technologies for In Situ Communication Applications," InterPlanetary Network Progress Report 42-147, July-September 2001, pp. 1-22, November 15, 2001. url for the progress report: http://ipnpr.jpl.nasa.gov/tmo/progress_report/42-147/title.htm