

Draft

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Benefits to Society of Bioinspired Flight Capabilities

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Humanity over the ages has been intrigued by the flight maneuvers of birds and insects. This paper highlights how in just about 100 years since the first successful flight took place at Kitty Hawk, our recent developments using inspiration from biology *is* enabling us to demonstrate flight capability for Mars exploration. This apart, these developments hold a substantial spin-off to the society at large. Unmanned exploration to date suggests that Mars once had abundant liquid water (considered essential for life as we know it) but it is not clear what went wrong with the Martian climate to have turned it to the desert that it is today. Getting to know and understand our sister planet is crucial in order to learn lessons for preserving and nurturing Life on Earth. Further it satisfies our fundamental scientific curiosity, and could provide answers to the fundamental questions surrounding the question of the origins of life in our solar system. "Bio-inspired engineering of exploration systems", is a guiding principle of this effort to develop biomorphic flyers. Specifically, the novelty of our approach is in adapting principles proven successful in nature to achieve stable flight control and navigation and the use of a robust architecture for reliable data return in applications where a limited telecommunications or navigational infrastructure is available. We will describe a future Mission Scenario for Mars exploration, uniquely enabled by these newly developed biomorphic flyers. Terrestrial applications of such biomorphic 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).

Introduction

In 1903, the Wright Brother's made history by demonstrating the first powered flight over the dunes of Kitty Hawk, North Carolina. Just about 100 years from that event, by using the guiding principles of bioinspired engineering of exploration systems (BEES), 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 has wide ranging impact on pressing needs of surveillance and reconnaissance from the Department of Defense and niche applications of NASA. Autonomous robotic systems will be essential for the exploration of Mars and other planetary systems. 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. 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.

Aerodynamic and reactive flight is possible on Mars. Earlier publications() and reports() 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 reentry, while descending. This technology is unproven, and clearly contains many points where a single failure ends the mission. Also it is challenging and risky in terms of data return back to Earth because it relies on the limited telecom infrastructure of orbiting telecom satellites that exist at this time.

Mars Pathfinder

It has been demonstrated by the ~~Sojourner~~ mission in 1997 that it is possible to safely deploy landers and instrumented Rovers on the surface of Mars. What we propose to demonstrate is that a smaller vehicle, a microflyer, 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, light weight autopilots, that are capable of obstacle avoidance, navigation and terrain following, while imaging and sampling the atmosphere. Another key to success of such a mission is to develop a craft that is capable of sustaining a high g assisted launch (to get above high stall speeds on Mars). This paper describes a few viable mission architecture options that allow sound data return options using the limited telecom infrastructure that can be made available with a lander base/orbiter combination.

Challenges of Flight on Mars:

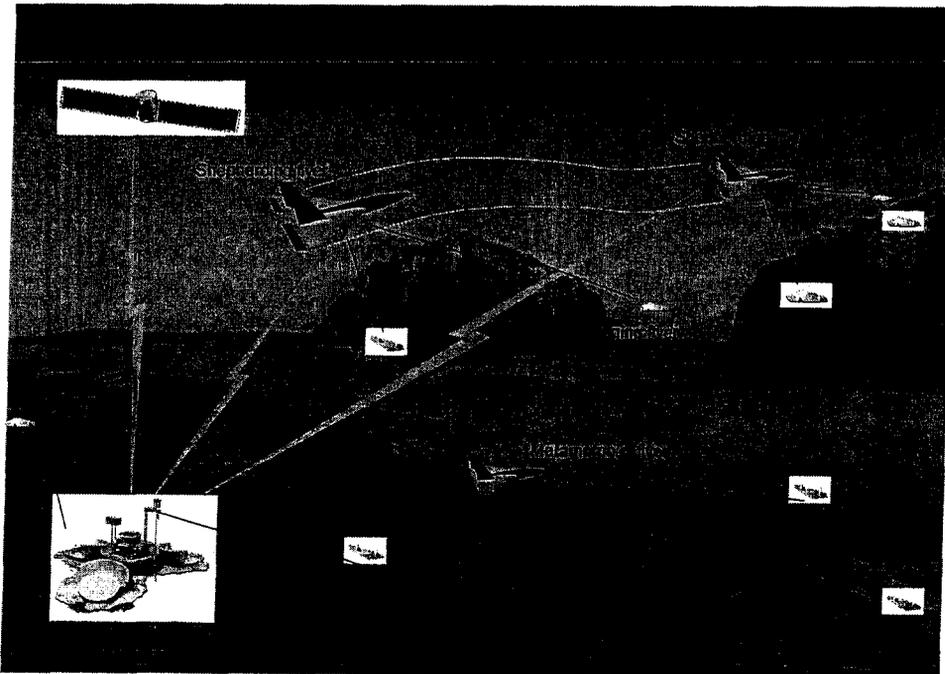
Mars poses some unique challenges for the navigation of unmanned aerial vehicles due to its thin atmosphere (~ 1% that of Earth at best), low gravity (~37% of that on Earth), and a weak, non-uniform magnetic field across the planet surface that is hard to use for navigation. The low gravity causes increased 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 stable 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.

In order to develop these technologies it is necessary to prove that the technology functions on Earth. The additional difficulties of lower maneuverability and higher flight speed on Mars can largely be overcome using more sophisticated processing of the same data (for example optic flow) as is required for an Earth demonstration.. We have described these issues of Mars flight in greater detail in an earlier paper ()

Surface Launched Cooperative Lander-Biomorphic 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; currently Mars Global Surveyor provides ~ 1m – 1.5m/pixel resolution at best and the 2005 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/areas for an explorer 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) and in-situ imaging of rocks and features of interest at even greater resolutions is desired. The 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-surface-aerial BEES mission is therefore suggested and illustrated in figure 1

Figure 1: Artist's Conception of the Cooperative Lander Surface launched Microflyers



Mission

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The lander is equipped with two kinds of microflyers. First, small ~ 1 kg imaging explorers have ~ 10 minute flight duration during which the camera will acquire and transmit motion imagery data in real time. The second kind of flyers will serve the **dual role of imaging explorers and a telecom relay** (mass ~ 5 Kg, endurance ~ 30min). 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 microflyer from the lander towards the target site 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 depending on the science goal could be few ~~km~~ to few 100 ~~km~~, and the lander as the main local relay base is always available. Different flight paths over different terrains of interest are followed by the different flyers. For the first such BEES mission on Mars, we expect to use two flyers for each experiment, conducting up to 5 experiments in one mission. 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 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. 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 in 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 long distance surface traverse explorers. 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 metamorphic flyer will also as needed deliver a crawler which essentially has required limited mobility to station the relay autonomously at a favorable location to accomplish optimum communication and data downlink. 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.¹

Microflyers launched from the lander could also disperse other biomorphic 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 microflyers 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

km
what resolution?

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 lander-biomorphic flyer approach include:

- surface launched explorer allows selection of timing of task
- on call use of launched explorers allows multiple trials for same or different targeted locations¹
- directed travel for close-up imaging
- targeted deployment of in-situ experiment, instrument or other surface or subsurface explorers
- provide valuable path planning information to other surface explorers

Another related mission scenario described earlier () offers the most robust telecom architecture 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 (wrt the Surface Launching Lander/Rover Base) can allow coverage of extremely large ranges and/or exhaustive survey of the area of interest.

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. Biomorphoc flyers either surface launched from landers or rovers, or aeriaily launched from a space craft directly, will enable navigation into and within Valles Marineris to explore this unique geology rich site including stratigraphy features, outcrops etc by sideways imaging of the canyon walls in close detail and deploying instruments for localized in-situ measurements of regions otherwise unapproachable.

3e. Telecom Architecture:

Phases of Telecom required for the Cooperative Lander-Biomorphoc Flyer Mars Mission Architecture:

- Launch and cruise: During this phase the standard deep space CCSDS (Consultative Committee on Space Data Systems) 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 to orbiter use UHF standard CCSDS proximity telecom
 - Imaging Flyer to lander will use custom UHF telecom using multiple local relay redundant architecture to ensure successful imagery data return.

spell out

A 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 described above, we define various levels of telecom subsystem functionality for the three different types of microflyers – imaging, shepherding and metamorphic. By categorizing functional sub-elements required for mission communications, we are able to identify common re-usable subsystems for a cost-effective approach to realizing telecom payloads, as shown in Table 2.

<i>Microflyer Type</i>	<i>High rate data transmission</i>	<i>On-board mass data storage</i>	<i>High rate data reception</i>	<i>Low rate command link reception</i>	<i>Simultaneous transmit and receive</i>
Imager	X	X		X	
Shepherd Relay	X	X	X	X	
Metamorphic Relay	X	X	X	X	

Table 2. Required Telecom Functions by Flyer Type

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 as shepherding 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.

Data Characteristics: Based upon the objective of returning full motion imagery, both low frame rate (3 Hz), uncompressed (512 x 512), color images (24 bits/pixel), and full rate (30 fps) compressed digital video (MPEG2 operating at 2.5 Mbps) were compared in terms of required data volume for a mission allowing at least five minutes of imaging time. The uncompressed option yields a volume requirement of 707.8 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.

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.
- 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

2 words

up to 93.8 MB, 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.

Mission Geometries:

The communications link geometries associated with the cooperative mission scenarios being considered 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 to 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*²” loss function to a “*distance*⁴” 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 metamorphic flyers is preferred to allow enhanced communications ranges. Under cases of shallow elevation angles to the lander, flat and frequency selective multipath will also occur. Study () of parametric contour plots incorporating the transition between square law and fourth power propagation models has confirmed the viability of this architecture.

The second general type of communications link corresponds to the metamorphic flyer/storage node transmission to an orbiter. 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.

Link Analyses:

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. Point designs delineating the required RF transmit power and associated margins for imager data return links are shown in table 3 for systems with and without error correction coding. By sizing the imager’s transmitter power to the imager-to-shepherd link, the larger link margins shown in the final column will result for the nearby relays aiding in overall system robustness. An imager-to-shepherd range of 60 km is used in this design as an intermediate distance to span a communications range goal of 100 km between the imager and lander. The separation between shepherd and lander is kept shorter as this link will suffer an earlier crossover to ground wave propagation due to the relatively low lander antenna height. The 15 km range between the imager and the landed metamorphic relay assumes a midpoint location for the relay relative to a 30 km linear flight path (100 m/s velocity, 5 minute mission duration) for the imaging flyer.

System assumptions entering in to the link calculations include the following:

- Transmit and Receive antenna gains of 0 dB
- Receiver noise figure of 3 dB
- Sky temperature 240° K
- Implementation loss of 1.5 dB
- Transmit frequency of 400 MHz

<i>Downlink Type</i>	<i>Maximum Range to closest Receiver</i>	<i>Required RF Transmit Power (with Coding¹) 10⁶ BER</i>	<i>Required RF Transmit Power (w/out Coding²) 10⁶ BER</i>	<i>Link Margin at Maximum Power (60 km range)</i>
Imager-to-Shepherd	60 km	590 mW	4687 mW	6 dB
Imager-to-Metamorphic Relay (one node)	15 km	37 mW	294 mW	12 dB

Table 3. Imager Return Link RF Power Requirements and Margins: 2.5 Mbps

In table 4, point designs for the required uplink transmit powers are shown for low elevation angle, maximum slant range communications paths to low altitude relays positioned in circular orbits of 400 and 800 km. A 1:100 non-real time data rate of 25 kbps is assumed for determining these link parameters. Consequently, the overall required uplink duration is expanded over the original mission duration by a factor of 100 for each uplink node.

<i>Orbiter Altitude</i>	<i>Maximum Slant Range (20° Elevation Angle)</i>	<i>Required RF Transmit Power (with Coding) 10⁶ BER</i>	<i>Link Margin</i>
400 km	894 km	520 mW	3 dB
800 km	1563 km	1590 mW	3 dB

Table 4. Relay Uplink RF Power Requirements and Margins: 25 kbps

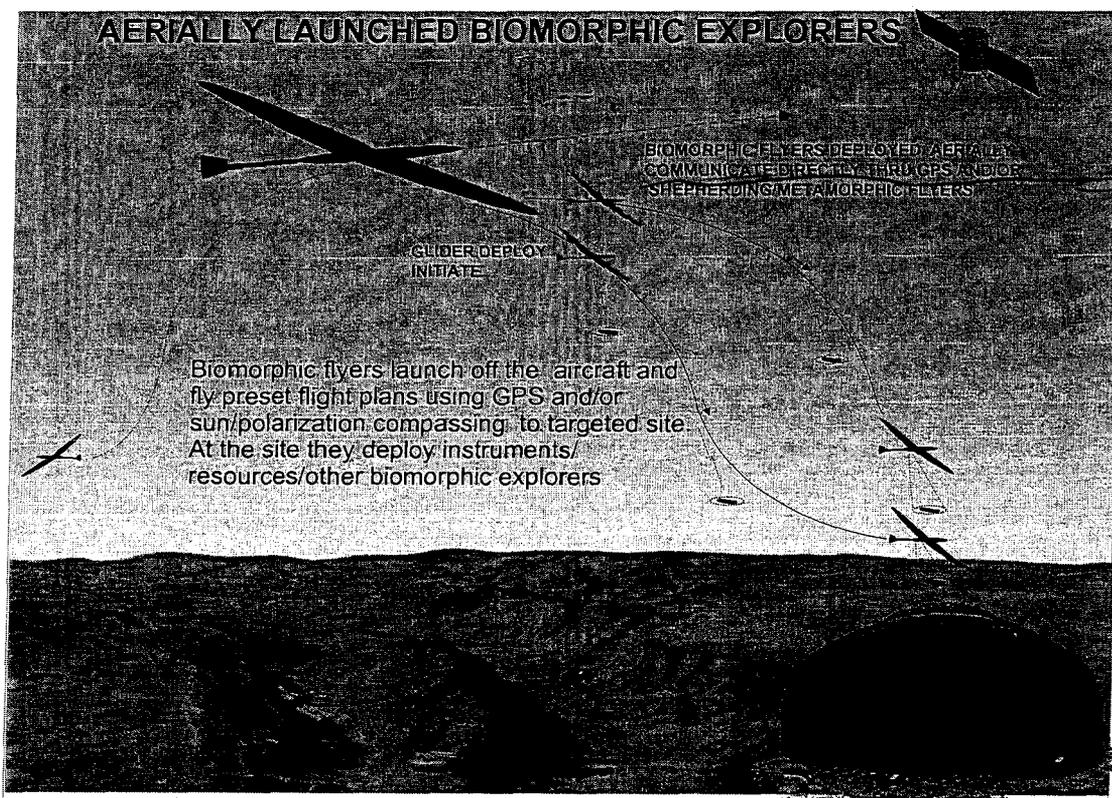
¹ Coherent BPSK or QPSK with (7,1/2) convolutional FEC, 5 dB Eb/No required.

² Differentially coherent uncoded QPSK (DQPSK), 14 dB Eb/No required.

Terrestrial Missions utilizing BEES developments:

Terrestrial applications of these biomorphic flyers in co-operative 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).

The figure 2 illustrates an example scenario of interest to defence needs of surveillance and reconnaissance from strategic targets.



Insect inspired Navigation and Biomorphic Flyer Implementation:

Flight-control and navigation systems inspired by the structure and function of the visual system and brain of insects have been proposed for a class of developmental miniature robotic aircraft called "biomorphic flyers" described earlier (). Biomorphic flyers could be used on Earth or remote planets to explore otherwise difficult or impossible to reach sites. An example of an exploratory task of search/surveillance functions to be tested in the BEES for Mars demonstration is to obtain high-resolution aerial imagery, using a variety of miniaturized electronic cameras.

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. Despite their lack of stereoscopy, insects infer distances to potential obstacles and other objects from image motion cues that result from their own motions in the environment. The concept of motion of texture in images as a source of motion cues is denoted generally as the concept of 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 control computing subsystems that would be more compact, would weigh less, 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 an on-chip implementation.

These control loops for stabilizing attitude and/or holding altitude would include optoelectronic ocelli and would be based partly on dragonfly ocelli - simple eyes that exist in addition to the better known compound eyes of insects. In many insects the ocelli only detect changes in light intensity and have minimal observable effect on flight. In dragonflies, the ocelli play an important role in stabilizing attitude with respect to dorsal light levels. The control loops to be implemented would incorporate elements of both dragonfly ocellar functions and optical flow computation as derived from principles observed in honey bee flight.

On Earth, bees use sky polarization patterns in the ultraviolet 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 with a simple Sun compass because the ultraviolet polarization pattern is distributed across the entire sky on Earth and is redundant, and hence can be extrapolated from a small region of clear sky in an elsewhere cloudy sky that hides the Sun.

A bee tends to adjust its flight speed to maintain a constant optical flow (that is, a constant angular velocity of the image of the environment) over its compound eye (see figure). Consistent with this strategy, a bee utilizes 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 biomorphic flyer, which has a nonzero stalling speed.

These sensors 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. 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, with substantial optical processing and multiple spectral sensitivity. To our knowledge, this is the world's first demonstrated use of a "biomorphic ocellus" as a flight-stabilization system.

Advantages of the Biomorphing Ocellus Implementation:

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. Other significant features of the biomorphic flyer shown in the figure include its ability to fly at high angles of attack $\sim 30^\circ$ and a deep wing chord which allows scaling to small size and low Reynold's number situations. Furthermore, the placement of the propulsion system near center of gravity allows continued control authority at low speeds. These attributes make such biomorphic flyers uniquely suited to planetary and terrestrial exploration where small size and autonomous airborne operation are required.

The table 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 two CMOS imaging devices. 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.

Comparison of inertial navigation system implementations and the “Biomorphic ocelli” for airborne imaging applications, illustrating its advantages

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	5V	3.3V	2.9V
Current	100mA	40mA	15mA
90 degree phase shift frequency	90Hz	?	2kHz
Min light level	Immune	Immune	0.01 lux
Autopilot requirement	DSP	DSP	µcontroller
Thermal stability	Poor	Poor	Excellent
Thermal range	-20 to +70	?	-50 to +90

Rotation/Acceleration/Cross Axis coupling	Some	Some	None
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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 group in mid 2001.
2. Note the size of the custom inertial unit is based on the die level products from companies such as Analog Devices.
3. The COTS ocellus is based on the performance parameters of the current ocellus, with all non-control related circuitry and wiring subtracted, and a higher integration microcontroller.

The challenges faced by the ocellus are based primarily on biases in the distribution of features on the horizon. Usually these biases are small (1-5 degrees) and any sustained bank errors can be corrected by a sun or polarization compass (which we are currently developing) over-riding 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 in the order of 40mW. The difference in power consumption of the ocelli as opposed to an inertial unit is enough to power a CMOS camera. This would impact power system design with attendant repercussions in aircraft mass.

Biomorphic Flyer Implementation

Two types of flyers are being built, corresponding to the imaging and shepherding flyers for a biomorphic mission described earlier. 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.

The prototype that we have built recently has been described in detail elsewhere(). The level of miniaturization we have accomplished for the bioinspired sensors for autonomous navigation is essential to enable such biomorphic microflyers (~1 kg) that can be deployed in large numbers for distributed measurements and exploration of difficult terrain while avoiding hazards. The following table gives the details of the Biomorphic Flyer that we already demonstrated in 2001 and the two types meant to obtain shepherding and imaging function that we are developing for demonstration in 2003 and 2004 at a Mars Analog Site. These flyers to test the bioinspired suite of instruments are currently propeller driven using two-stroke glow-fuel powered engines. For the Mars implementation we will replace the propulsion system for example by a solid rocket boosted flyer followed by glide and cruise using a hydrazine propulsion system for steady level flight thrust.

Item	2001 Biomorphic Flyer Platform 1.5 Kg	5 kg, 2002 Biomorphic Flyer (Shepherding flyer)	1 kg, 2002 Biomorphic Flyer (Imaging flyer)
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Dry Mass	900g	2670g	600g
Fuel	100g	340g	225g
Payload	427g	1990g	174g
Takeoff weight	1427g	5000g	1000g
Engine	178g	698g	145g
Propellor	9g	58g	8g
Engine Type	OS 15LA	OS 61FX	OS 10LA
Propellor Size	20.3cmx15.2cm	28.0cmx20cm	17.8cmx10.1cm
Top Speed	≈135km/h	≈165km/h	≈110km/h
Landing Speed	≈45km/h	≈55km/h	≈37km/h
Range	25000m	55000m	37000m
Endurance	>12min	>20min	>20min
Wing Span	0.81m	1.240m	0.708m
MAC	0.396m	0.606m	0.346m
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	0.701m ²	0.227m ²
Glide Ratio (L/D)	5.25	5.25	5.25

Conclusions:

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 resolution imagery of Mars at low altitudes. Specific strides in insect inspired navigation sensors are illustrated by highlighting those development results. Finally implementation results of Biomorphic Flyers based on these bioinspired sensors are summarized as the enabling units being developed for the future Mars Missions described. We are implementing a combination of unique and distinct biologically inspired capabilities in a scaleable microflyer robotic platform. This approach is demonstrating the power of incorporating selected and highly evolved biological capabilities into engineered systems. The resulting unique 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.

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