Invited Paper

Bioinspired Engineering of Exploration Systems for NASA and DoD
From bees to BEES

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The intent of "Bio-inspired Engineering of Exploration Systems"(BEES) is to distill the principles found in successful, nature-tested mechanisms of specific "crucial functions" that are hard to accomplish by conventional methods, but accomplished rather deftly in nature by biological organisms. It is not just to mimic operational mechanisms found in a specific biological organism but to imbibe the salient principles from a variety of diverse bio-organisms for the desired "crucial function". There by, we can build explorer systems that have specific capabilities endowed beyond nature, as they will possess a mix of the best nature tested mechanisms for that particular function. Insects (for example honey bees and dragonflies) cope remarkably well with their world, despite possessing a brain that carries less than 0.01% as many neurons as ours does. Although most insects have immobile eyes, fixed focus optics and lack stereo vision, they use a number of ingenious strategies for perceiving their world in three dimensions and navigating successfully in it. We are distilling some of these insect inspired strategies to obtain unique solutions to navigation, hazard avoidance, altitude hold, stable flight, terrain following and smooth deployment of payload. Such functionality can enable a reach to otherwise unreachable exploration sites for much sought for endeavors. A BEES approach to developing autonomous flight systems, particularly at small sizes, can thus have a tremendous impact on flight control of such "biomorphic flyers" for both planetary exploration missions as well as public service and military UAV applications. Recent biological studies primarily from mammalian vision systems have further confirmed that representations of each different characteristic of the visual world is formed in parallel, and embodied in a stack of "strata" in the retina. Each of these representations can be efficiently modeled in semiconductor Cellular Nonlinear Network (CNN) chips. Many of the biological image processing operations when translated into CNN image processing operations, constitute algorithmic cornerstones, useful in practical image processing missions/applications. Recent breakthroughs on exploring the feasibility of incorporating these success strategies of bioinspired navigation and visual search/pattern recognition/image understanding into biomorphic flyers for future planetary and terrestrial applications will be described. Specifically we have obtained lightweight (~ 6g), low power (< 40 mW), and robust autonomous horizon sensing for flight stabilization based on distilling the principles of a dragonfly ocellus. Such level of miniaturization is essential to enable biomorphic microflyers (< 1 Kg) that can be deployed in large numbers for distributed measurements

These results demonstrate the advantage of our approach in adapting principles proven successful in nature to achieve stable flight control, navigation, visual search/recognition to enable overall a robust architecture for reliable image data return in application scenarios where only a limited telecommunications or navigational infrastructure is available . We will describe a few future Mission Scenarios for Mars exploration, uniquely enabled by these newly developed biomorphic flyers. 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).

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Concept: The intent of "Bio-inspired Engineering of Exploration Systems"(BEES) is to distill the principles found in successful, nature-tested mechanisms of specific "crucial functions" that are hard to accomplish by conventional methods, but accomplished rather deftly in nature by biological organisms. It is not just to mimic operational mechanisms found in a specific biological organism but to imbibe the salient principles from a variety of diverse bio-organisms for the desired "crucial function". There by, we can build explorer systems that have specific capabilities endowed beyond nature, as they will possess a mix of the best nature tested mechanisms for that particular function. Towards proving this concept, we have picked up three relatively mature areas where substantial amount of work has already been done in distilling the principles from the biological world. Figure 1 shows these three as cornerstones. First the principles of navigation based on visual cues as deciphered from the honey bee is being implemented electronically by translation of the optic flow algorithms. Second, the principles that a dragonfly uses in the functioning of its flight stabilization as understood by study of its "Ocellus" are incorporated in a very compact 6gm "biomorphic ocellus". Together the optic flow chip and "biomorphic ocellus" hold the potential of providing unique solutions to navigation, hazard avoidance, altitude hold, stable flight, terrain following and smooth deployment of payload.

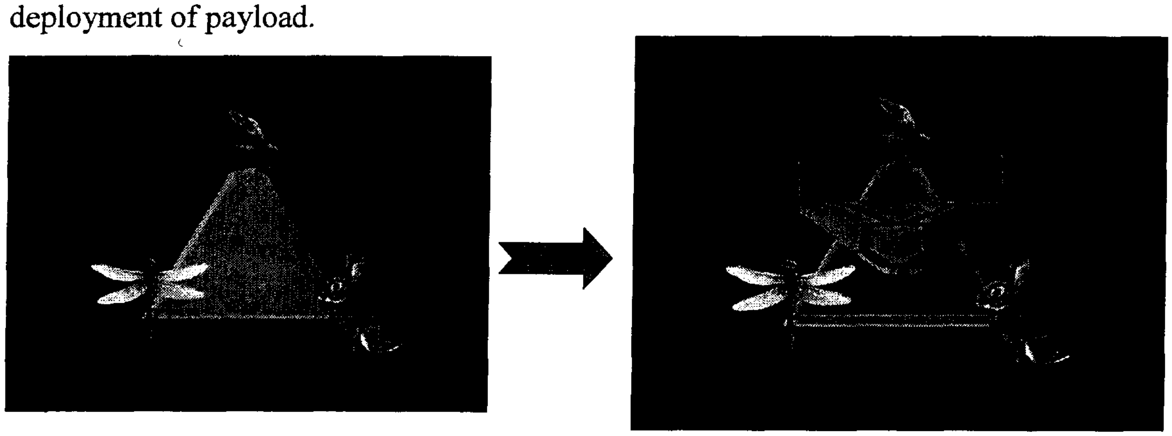


Fig 1: Visual Illustration of the concept of "Bioinspired Engineering of Exploration Systems" (BEES)

The third cornerstone is obtained from studies of the rabbit retina. These studies are representative of the functions excelled by the visual ocular system of the mammals. Feature extraction and pattern recognition are adroitly learned and performed by mammals. Recent breakthroughs on exploring the feasibility of incorporating these success strategies of bioinspired navigation and visual search/pattern recognition/image understanding into biomorphic flyers for future planetary and terrestrial applications are described in this paper

Honey Bee based Optic Flow Algorithms

Srinivasan et al have earlier utilized some of the vision cue based strategies utilized by honey bee to obtain autonomous control of mobile robots and unmanned aerial vehicles.

Insects (for example honey bees and dragonflies) cope remarkably well with their world, despite possessing a brain that carries less than 0.01% as many neurons as ours does. Although most insects have immobile eyes, fixed focus optics and lack of stereo vision, they use a number of ingenious strategies for perceiving their world in three dimensions and navigating successfully in it. We are distilling some of these insect inspired strategies of utilizing optical cues to obtain unique solutions to navigation, hazard avoidance, altitude hold, stable flight, terrain following and smooth deployment of payload. Such functionality can enable access to otherwise unreachable exploration sites for much sought for endeavors. A BEES approach to developing autonomous flight systems, particularly at small sizes, can thus have a tremendous impact on autonomous navigation of such "biomorphic flyers" particularly for planetary exploration missions

Dragon Fly Inspired Ocellus: "Biomorphic Ocellus"

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. In many insects behavioral responses to ocelli stimuli are hard to observe. The notable exception is dragonflies, whose flight control is notably degraded by any interference with the ocellar system. Our group has discovered recently that the ocelli are a dedicated horizon sensor, with substantial optical processing and multiple spectral sensitivity. A hardware device substantially mimicking the function of the dragonfly ocelli was constructed and is shown in figure 1. We believe that this is the World's first demonstrated use of a "biomorphic ocellus" as a flight stabilization system.

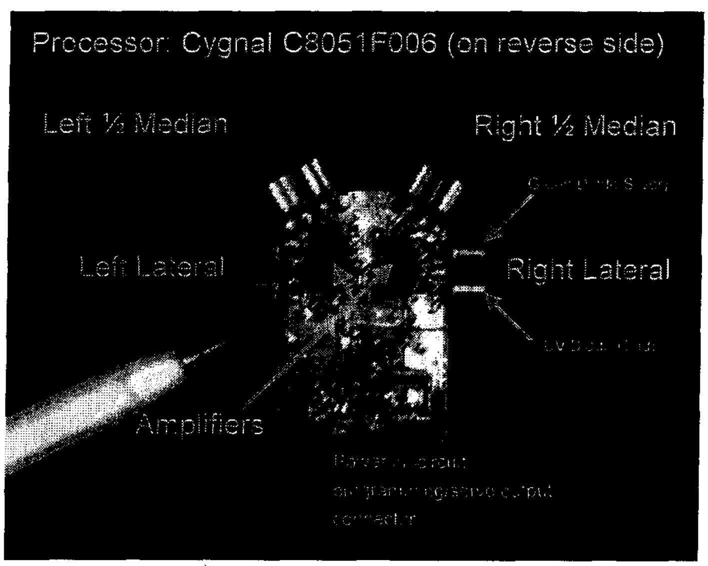


Fig 1: An embedded implementation of the biomorphic dragonfly ocelli. Power consumption is less than 40mW, dimensions 25mmx35mm. Processing and control is performed by a Cygnal C8051F006 8 bit microcontroller. Conversions of analog data are performed with 12bit resolution.

Using color opponent processing of UV and green eliminates false attitude signals caused by the sun when it is near the horizon.

- UV channel sees a dark ground, bright sky, and very bright sun
- Green channel sees a uniform intensity across the field, and a very bright sun

Appropriate processing of the two signals removes the common feature (the sun) from the output signal, and eliminates many effects caused by varying sky color.

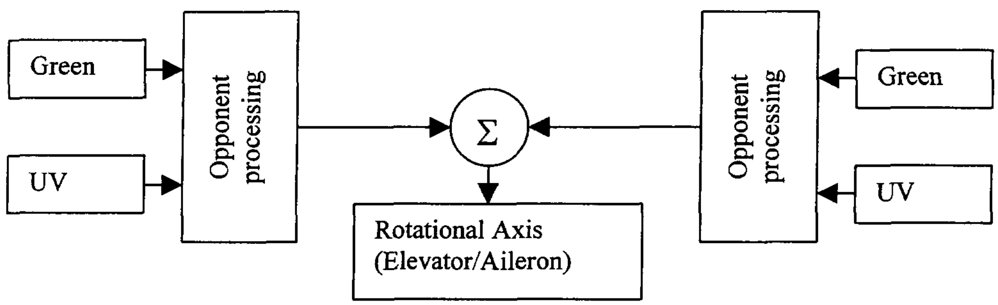


Fig 2 Description of ocellus function. Spectral opponent processing is used to eliminate the potentially biasing effect of the sun, and clouds.

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

Mammalian Retina Function Inspired Autonomous recognition System:

Recent biological studies primarily from mammalian vision systems have further confirmed that representations of each different characteristic of the visual world is formed in parallel, and embodied in a stack of "strata" in the retina. Each of these representations can be efficiently modeled in semiconductor Cellular Nonlinear Network (CNN) chips. Many of the biological image processing operations when translated into CNN image processing operations, constitute algorithmic cornerstones, useful in practical image processing missions/applications. The CNN architecture is based on local connectivity among neighboring pixels. Each pixel's intensity can be modulated by the pixels in the neighboring region. This architecture appears to be particularly well suited for identifying morphologies and temporal tracking of optical flow.
To accomplish the complex problem of terrain recognition, a number of image processing operations are be combined into a complete algorithm that is readily amenable to compact hardware implementation. The functions that are performed well by CNN implementation include image filtering, noise suppression, feature extraction,

segmentation, and locating connected regions. Higher-lever processing includes fine-course structure analysis and finding regions of predefined morphology.

Recent studies in retinal research have revealed that the retina is capable of extracting about a dozen different features from the visual environment and that this visual coding is being used to represent and transmit information to higher visual centers. These retinal feature detectors have been implemented in CNN as shown in the example in Figure 1 below, where seven of these retinal feature detectors have been applied to an image of a human face.

The CNN can be incorporated into a relatively small package now. Figure 2 below shows a card containing a CNN processor on top of a standard PC-104+ card stack used for CNN hardware development. A more compact, fly-able version of this device is expected for Q4 2002.

CNN can perform a variety of conventional image processing operations at unparalleled speed including image arithmetic, diffusion, gradient and Sobel edge detection, morphology, etc., as well as bio-morphic operations which utilize its retina-like architecture.

We are applying CNN to two UAV tasks of interest, terrain analysis and calculation of aerodynamic parameters. These applications are discussed in grater detail below.

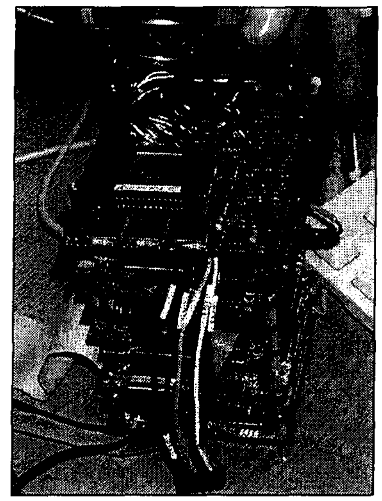


Figure 2. The CNN development system with the CNN processor module on top. The system is used for

Terrain Analysis

For terrain analysis a number of image processing operations are be combined into a complete algorithm. These include image filtering, noise suppression, feature extraction, segmentation, and locating connected regions. Higher-lever processing includes fine-course structure analysis and finding regions of predefined morphology. Classification is performed using strategies including statistical and adaptive resonance methods. A flow diagram describing terrain analysis is sown in Figure 3 below.

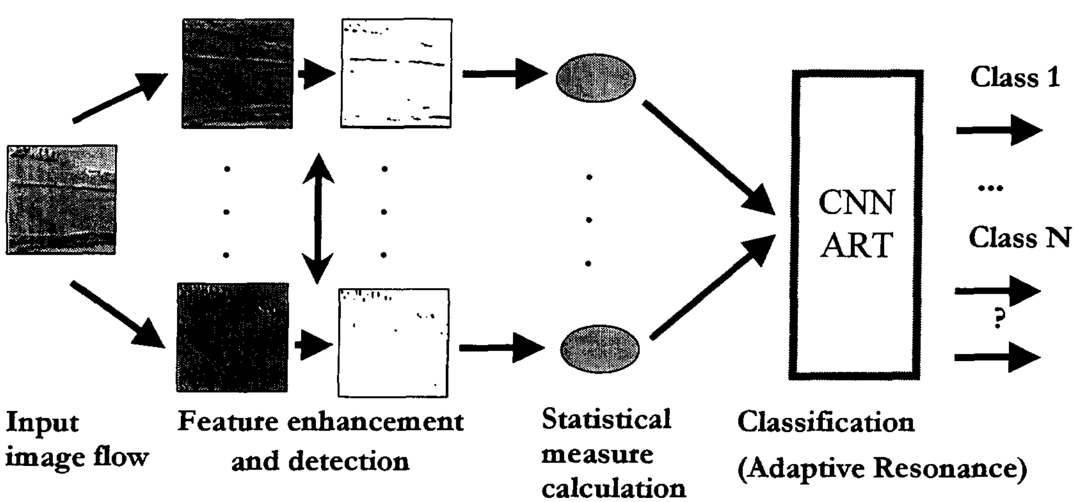


Figure 3. Flow diagram of the terrain analysis task. Topographic maps derived from the input imagery by a variety of feature detectors are analyzed using robust statistical measures and a CNN-based adaptive resonance classifier.

The adaptive resonance classifier is also implemented on the CNN processor eliminating the need to transfer information off-chip. The implementation of the CNN ART classifier is outlined in Figure 4.

Yaw, Pitch, and Roll Estimation

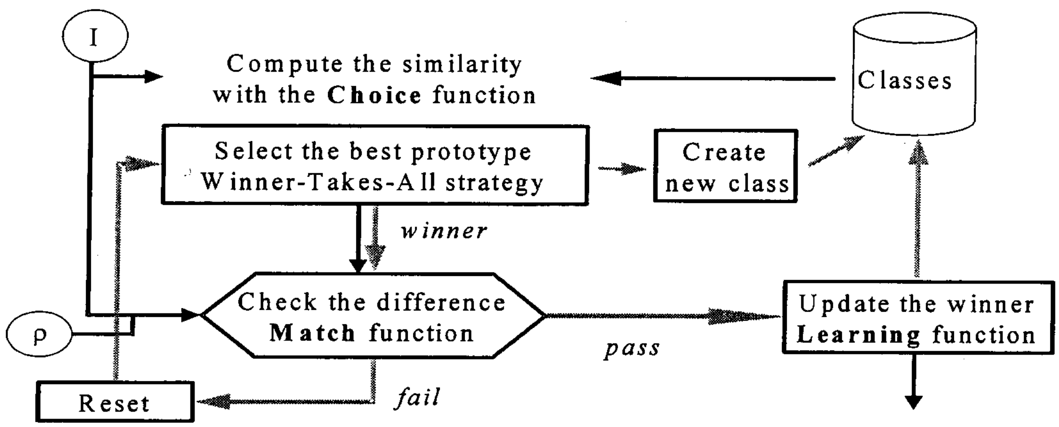


Figure 4. Flow diagram of the CNN adaptive resonance classifier.

The estimates of yaw, pitch and roll can be calculated from optical flow data. There are various approaches to making these calculations using CNN technology. We are considering two of these based on implementation tradeoffs:

1. **Optical Flow** in which translation is calculated with high accuracy based on a dense flow field but calculating rotation is relatively difficult using CNN.

2. **Multitarget Tracking** involves the computation of apparent motion of automatically selected features. Motion can be reliably computed from the mean displacement of object and through the characteristics of group motion. Yaw and pitch are computed from translation in the image plane, yaw is derived from rotation. A flow diagram showing the general structure of this technique is shown in Figure 5 below.

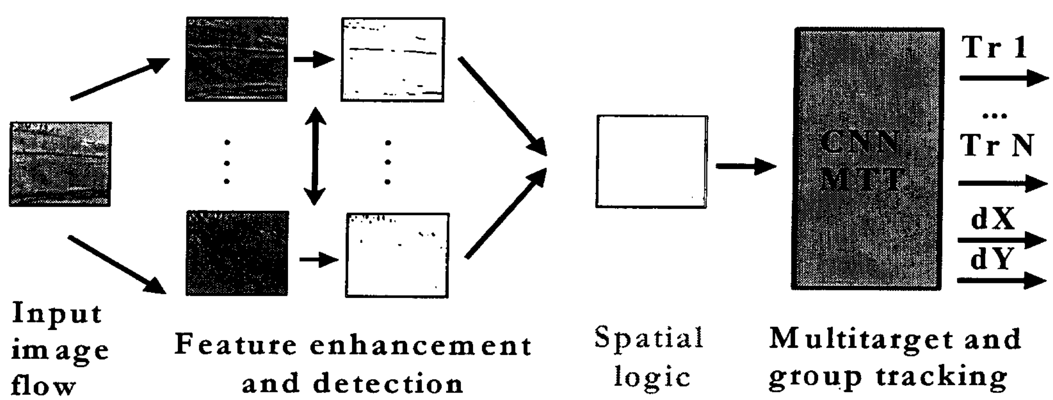


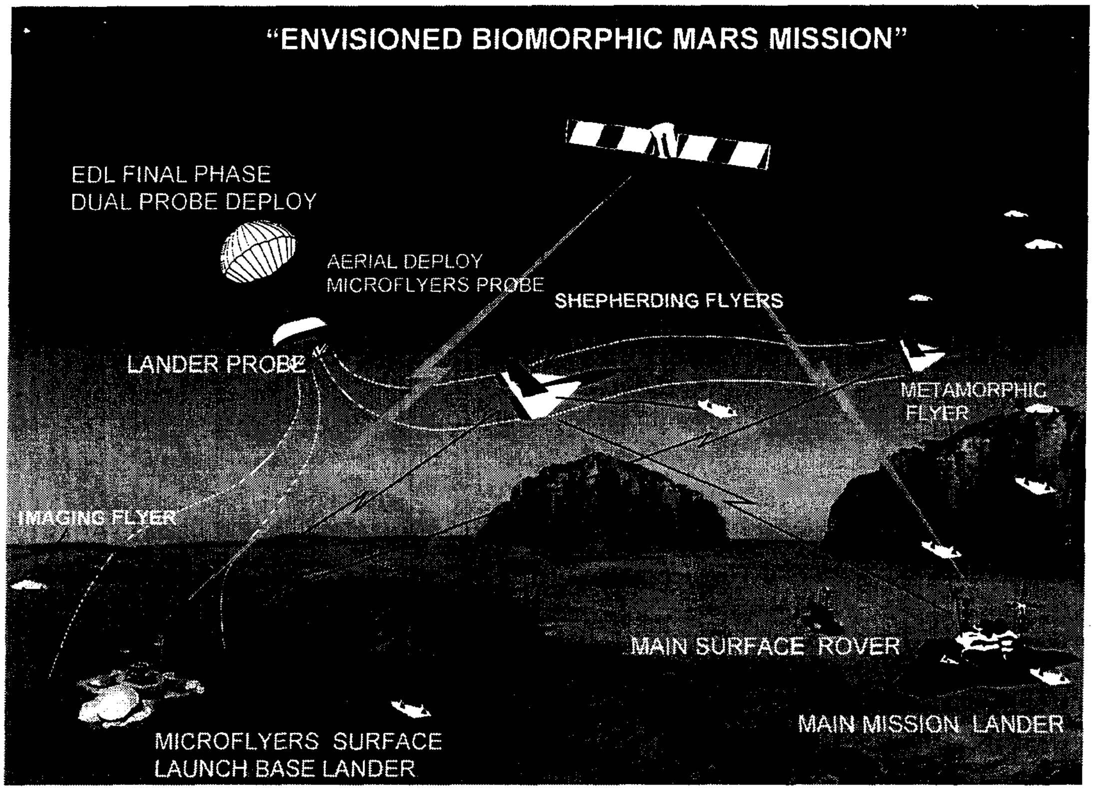
Figure 5. Flow diagram of the yaw, pitch, and roll estimation algorithm using CNN-based multi-target tracking.

Mars Application:

We plan to do a demo of "Bio-inspired Engineering of Exploration Systems for MARS" (BEES for MARS) at a MARS analog site on Earth. A variety of biologically-inspired flyers (biomorphic flyers) are released or launched each containing biologically inspired technologies capable of, for example, autonomous navigation, visual search, selective feature detection, intelligent flight control, image enhancement by sensory data fusion, etc.

The mission architecture to be utilized, deals with the challenge of rare atmosphere on MARS by using surface launched biomorphic flyers essentially like payload carrying darts with an extended powered glide. Launch energy could be provided by single or multiple solid rocket boosts, pneumatic thrust, compressed *in-situ* resource gas launch, 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 biomorphic flyers.

Two kinds of biomorphic flyers are in development. First, small (< 1 Kg) imaging explorers with less than ~ 15 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, flight duration ~ 45 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 biomorphic 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 mission illustrated in Fig 1 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.

Acknowledgements

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