

Bioinspired Engineering of Exploration Systems for NASA and DoD

Abstract A new approach called *bioinspired engineering of exploration systems* (BEES) and its value for solving pressing NASA and DoD needs are described. Insects (for example honeybees and dragonflies) cope remarkably well with their world, despite possessing a brain containing less than 0.01% as many neurons as the human brain. Although most insects have immobile eyes with fixed focus optics and lack stereo vision, they use a number of ingenious, computationally simple strategies for perceiving their world in three dimensions and navigating successfully within it. We are distilling selected insect-inspired strategies to obtain novel solutions for navigation, hazard avoidance, altitude hold, stable flight, terrain following, and gentle deployment of payload. Such functionality provides potential solutions for future autonomous robotic space and planetary explorers. A BEES approach to developing lightweight low-power autonomous flight systems should be useful for flight control of such biomorphic flyers for both NASA and DoD needs. Recent biological studies of mammalian retinas confirm that representations of multiple features of the visual world are systematically parsed and processed in parallel. Features are mapped to a stack of cellular strata within the retina. Each of these representations can be efficiently modeled in semiconductor cellular nonlinear network (CNN) chips. We describe recent breakthroughs in exploring the feasibility of the unique blending of insect strategies of navigation with mammalian visual search, pattern recognition, and image understanding into hybrid biomorphic flyers for future planetary and terrestrial applications. We describe a few future mission scenarios for Mars exploration, uniquely enabled by these newly developed biomorphic flyers.

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I Introduction and Concept Description

A key element of NASA's business is planetary and space exploration. Space exploration involves a multi-pronged strategy that includes the design and deployment of unmanned robotic systems for exploring other planets in our solar system. Such exploration systems require coordinated autonomous accomplishment of a variety of crucial functions. These functions include autonomous navigation, hazard avoidance, altitude hold, visual search, and identification of features of interest for further imaging and study. Conventional methods like landers and rovers have their limits in accessing difficult sites and leave a vast domain of exploration sites unreachable. On the

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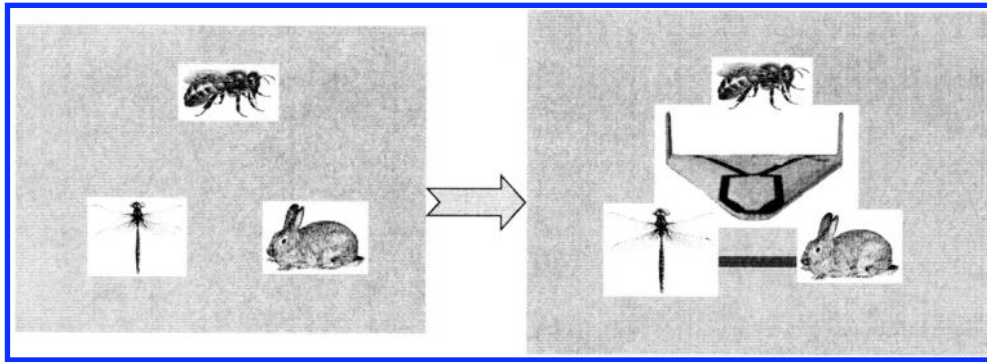


Figure 1. Visual illustration of the concept of BEES, showing how the approach allows one to distill principles from diverse species to enable crucial related functions in a biomorphic flyer.

other hand, we observe that nature's biological world abounds in marvelous examples of autonomous explorers and successful implementation of crucial functions to reach the most difficult and tightest spots by such explorers. The intent of *bioinspired engineering of exploration systems* (BEES) [9–15] is to distill the principles by which natural systems deftly accomplish several such crucial functions. Our aim is not just to mimic the operational mechanisms found in a specific biological organism, but to incorporate the salient principles from a variety of diverse bio-organisms for the desired crucial functions. Thereby, we can build explorer systems whose performance can, in principle, surpass that of any particular organism, as they will possess a mix of the best nature-tested mechanisms for that particular function. Focus on BEES, in order to incorporate biology validated strategies and capabilities for autonomous biomorphic microflyers for future missions, is imperative, to obtain leapfrog advances over existing exploration systems.

Toward proving the value of this concept, we have picked three relatively mature areas where a substantial amount of work has already been done in distilling the principles from the biological world. Figure 1 shows these three areas as cornerstones. First, the principles of navigation based on visual cues as deciphered from the honeybee are being implemented electronically by translation of the optic flow algorithms into an on-chip implementation. Second, the principles that a dragonfly uses in the functioning of its flight stabilization as understood by study of its ocelli are incorporated in very compact (6 g) *biomorphic ocelli*. Together, the optic flow chip and biomorphic ocellus hold the potential of providing unique solutions for navigation, hazard avoidance, altitude hold, stable flight, terrain following and smooth deployment of payload. The third cornerstone is obtained from studies of the rabbit retina. These studies are representative of the functions excelled in by the visual ocular systems of mammals. Feature extraction and pattern recognition are adroitly learned and performed by mammals. Recent breakthroughs in exploring the feasibility of incorporating these success strategies of bioinspired navigation and visual search, pattern recognition, and image understanding into biomorphic flyers for future planetary and terrestrial applications are described in this article.

2 Honeybee-Based Optic Flow Algorithms

Srinivasan et al. [4] have utilized some of the vision-cue-based strategies utilized by honeybees to obtain autonomous control of mobile robots and unmanned aerial vehicles. Insects (for example honeybees and dragonflies) cope remarkably well with their

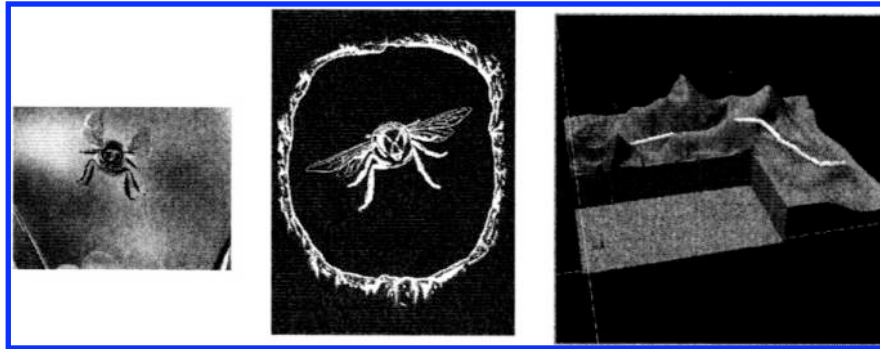


Figure 2. Illustration of bee-inspired techniques for gentle landing, hazard avoidance, gorge following, and terrain following, using optic flow derived from panoramic images.

world, despite possessing a brain that carries less than 0.01% as many neurons as ours does. Although most insects have immobile eyes with 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 of utilizing optical cues to obtain unique solutions for navigation, hazard avoidance, altitude hold, stable flight, terrain following, and gentle deployment of payload. Such functionality can enable access to important and otherwise unreachable exploration sites. A BEES approach to developing autonomous flight systems, particularly at small sizes, can thus be useful for implementing autonomous navigation into such *biomorphic flyers* for planetary exploration missions.

2.1 Insect-Inspired Hazard Avoidance Strategies

Flight poses particular problems for artificial vision systems. Typically, obstacle avoidance by visually guided robots is achieved using stereo vision. Stereo vision is limited in range by the stereo baseline—the separation between the cameras. Wide baselines allow large ranges to be measured, but then nearby objects may not even appear in both images. Small baselines, on the other hand, allow acute depth imaging of nearby objects at the expense of distance vision. Furthermore, stereo vision is not well suited to robotic aircraft, particularly when size and weight are at a premium.

Flying insects (Figure 2) overcome the limitations of stereo by depending on *motion vision*, an analysis of the rates and patterns of image motion on the retina, for many of their in-flight behaviors. Under linear translation, apparent image motion is inversely proportional to range. In the simplest terms, flying insects achieve terrain following and obstacle avoidance by avoiding directions in which the image motion appears high. In using this technique, image motion need not be computed at the full bandwidth of the system: for example, at low altitudes—when the image of the ground moves rapidly—it may be necessary to compute motion between successive frames of a video camera, whereas at high altitudes it may be sufficient to compute motion between every tenth frame. Hence, unlike the case in stereo vision, scale and variations in scale are not significant issues. The frame interval for motion computation can be varied to suit a given range, and the interval itself tracked and modified in flight to suit changing situations.

2.2 Specific Advantages of Optic Flow over Existing Techniques

The competitors to optic-flow-based techniques for hazard avoidance in navigating to a desired destination are time-of-flight systems based on microwave radar, ultrasound, lasers, and millimeter wave radar.

Radar altimeters are an established sensor for this purpose, but they do not scale down well, due to the size and bulk of the required antenna. They also only respond to the first return signal from the terrain; hence they have no spatial resolution. An autonomous aircraft using a radar altimeter is restricted to vertical control, since no information is available about the structure of the environment.

Ultrasound can be used to form a crude range image, but it is ruled out in a thin atmosphere, at high flight speeds, and over long ranges.

Laser rangefinders require a scanning technique to be effective, as would millimeter wave radar, as both produce narrow beams. All of these systems occasionally fail due to specular surfaces in the environment. All of them are active, and thus will work in the dark, but they require substantially more power, space, and payload than a vision-based technique using a CMOS camera.

A technique based on lidar (light detection and ranging) measures the range to a surface using the time of flight of laser light by pointing at the surface. A scanning lidar emits a continuous stream of laser pulses and uses rotating-mirror optics to sweep the laser beam across a scene. The resulting system is large and heavy and produces very low frame rates (2–4 Hz), making it unsuitable for a small fast craft close to the ground. The power of the laser, the aperture of the optics, and mechanical considerations limit the maximum frame rate of lidar.

By comparison, small, low-power, lightweight video cameras can provide frame rates in excess of 500 Hz even under dim Mars twilight conditions. Processing optic flow from these images allows terrain following and terrain avoidance at very low altitudes, despite cluttered terrain. Physical limits on active sensing make optic flow the sensor of choice for terrain-following biomorphic flyers in Mars exploration.

2.3 Current Status of Optic Flow Approach

Image motion can be computed using many techniques, some of which are extremely computation-intensive. The *image interpolation algorithm* (I^2A) developed by Srinivasan [5] is a highly robust, yet computationally inexpensive, technique for computing image motion. The I^2A computes image motion to within 5% (1σ) of the true angular motion. A high-precision variant called the *iterative I^2A* (I^3A) is accurate to within 1% (1σ), but requires greater computational time. These figures assume that the scene texture and movement between frames are well above the noise floor of the imaging device. The accuracy of range computations is a function of optic-flow accuracy, camera noise, scene information content, and errors in the velocity state estimate for the craft.

2.4 Panoramic Vision for Navigation

Insects accomplish their visual navigation tasks very adroitly by making use of their compound eyes, which endow them with panoramic vision that covers nearly the entire viewsphere (almost 4π steradians). We have developed and patented panoramic imaging systems [2, 3] that provide this functionality to a single, off-the-shelf video camera. This system is now being tested on flying aircraft.

2.5 Gorge-Following Strategies

Bees negotiate narrow gaps by balancing the optic flow that is experienced [6] by the two eyes. This strategy ensures collision-free flight through the middle of the gap. This technique can be applied to navigate through a gorge. A variant of the technique can be used to fly at a constant distance from one of the walls of a canyon. In this case, the distance to the wall is regulated by holding the motion of the wall's image at a constant, predetermined value.

2.6 Landing Strategies

Video analysis of bees landing on a horizontal surface has revealed [7] a simple yet effective visuomotor control stratagem. The control law operates as follows: Consider a bee 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 stratagem allows a smooth landing with minimal computation. Forward speed and rate of descent are reduced together, and are both close to zero at touch-down. No knowledge or measurement of instantaneous speed or height above the ground is necessary. Variations of the algorithm allow for vehicles, such as fixed wing aircraft, that have a nonzero stall speed. A useful byproduct of the algorithm is that, throughout the descent, the projected time to contact is constant. This algorithm has been successfully tested using the robotic gantry described in the next subsection. Terrain following can be accomplished by a simple variant of the landing technique, in which flight is directed forward (rather than downward) and height is adjusted to keep the velocity of the image of the ground at a constant, pre-determined value.

The unique advantages of the bee-derived algorithm for landing are as follows: The technique requires no knowledge of instantaneous height or flight speed. The computational load is low enough to be borne on current digital signal processors (DSPs) at video rates or better. Alternative techniques that use sonar or radar are likely to be slower and heavier, requiring payloads of hundreds of grams rather than tens of grams. The use of a camera to compute 2D optic flow has the added advantage of also providing a 2D range map, which is impossible to obtain using sonar, and time-consuming to obtain using radar.

Optical flow can be used for two different tasks in the approach to the target. The simplest use is to track the motion of the image of the target and use the measurements to give a high-bandwidth attitude correction during approach. This technique, however, would tend to drift in the long term, as it depends on integration of angular derivatives, and it would leave centering of the target to some other pattern-based technique. One might use such a technique, though, to reduce the computational load by decreasing the update rate for higher-level pattern recognition techniques.

2.7 Realization of Bee-Inspired Navigational Principles in a Robotic Gantry

We have implemented and successfully tested [3] the navigational strategies described above by using a robotic gantry, equipped with an arm with three degrees of translational freedom, to move a panoramic vision system over an artificial, Mars-like indoor terrain. The gantry, operating in closed loop with the vision system, simulates an autonomous, visually guided aircraft. This system executes point-to-point navigation, gorge following, and terrain following. Optic flow information obtained from the panoramic image is combined with information on the speed and direction of motion of the simulated aircraft (assumed to be known) to derive a panoramic range map that specifies the range in the direction of each pixel. This range map is used to compute a collision-free path through the terrain that meets the desired objectives of moving toward the goal and maintaining a prescribed height above the ground. Generally, range errors are in the order of 10% of the true range. The panoramic range algorithm requires about 1 second to operate on a 200-MHz AMD-K6-based PC, with a video image of 288×288 pixels. This video rate is achievable using current DSPs.

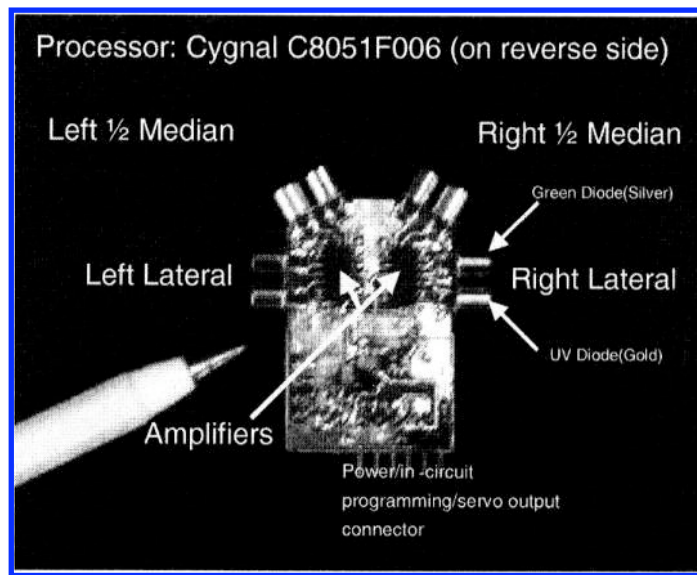


Figure 3. An embedded implementation of the biomorphic dragonfly ocelli. Power consumption is less than 40 mW, dimensions 25 mm $\times$ 35 mm. Processing and control are performed by a Cygnal C8051F006 8-bit microcontroller. Conversions of analog data are performed with 12-bit resolution.

3 Dragonfly-Inspired Biomorphic Ocellus

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. Behavioral responses to ocellus stimuli are often hard to observe. The notable exception is dragonflies, whose flight control is significantly degraded by any interference with the ocellar system. Our team has discovered recently that the ocelli are a dedicated horizon sensor [8], 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 3. We believe that this is the world's first demonstrated use of a *biomorphic ocellus* as a flight stabilization system. The two key principles from dragonflies that are distilled and implemented here are (a) use of an elementary motion detector that responds selectively to correlated inputs and (b) use of spectral color opponent processing. We find that for terrestrial applications, color opponent processing of UV and green eliminates false attitude signals caused by the sun when it is near the horizon:

The UV channel sees a dark ground, bright sky, and very bright sun.

The 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.

There are two major advantages of an ocellus-based system over a similar-size conventional system of rate gyroscopes. First, the ocellus system provides an absolute attitude reference, whereas the rate gyro system accumulates noise-induced drift be-

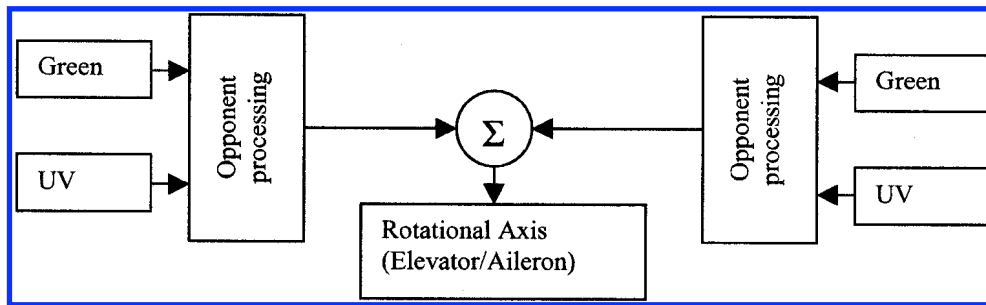


Figure 4. Description of ocellus function. Spectral opponent processing is used to eliminate the potentially biasing effect of the sun and clouds.

cause it integrates angular rate to determine attitude. Second, with an ocellus system 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 standalone unit, the ocellus system would provide stability augmentation to a pilot at low cost in space, power, and mass. The sensor is about 40 times lighter than a comparable inertial attitude reference system. Results on performance of the biomorphic ocellus and its application as a horizon sensor are described in detail elsewhere [13–15].

4 Autonomous Recognition System Inspired by Mammalian Retina Function

Recent biological studies, primarily on mammalian (rabbit) vision systems, have further confirmed that representations of each different characteristic of the visual world are 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 and 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 solve the complex problem of terrain recognition, a number of image processing operations must be combined into a complete algorithm that is readily amenable to compact hardware implementation. The functions that are performed well by CNNs include image filtering, noise suppression, feature extraction, segmentation, and locating connected regions. Higher-level 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 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 5, 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 6 shows a card containing a CNN processor on top of a standard PC-104+ card stack used for CNN hardware development. CNN can perform a variety of conventional image processing operations at unparalleled speed, including image arithmetic, diffusion, gradient and Sobel edge detection, and morphology, as well as biomorphic operations that utilize its

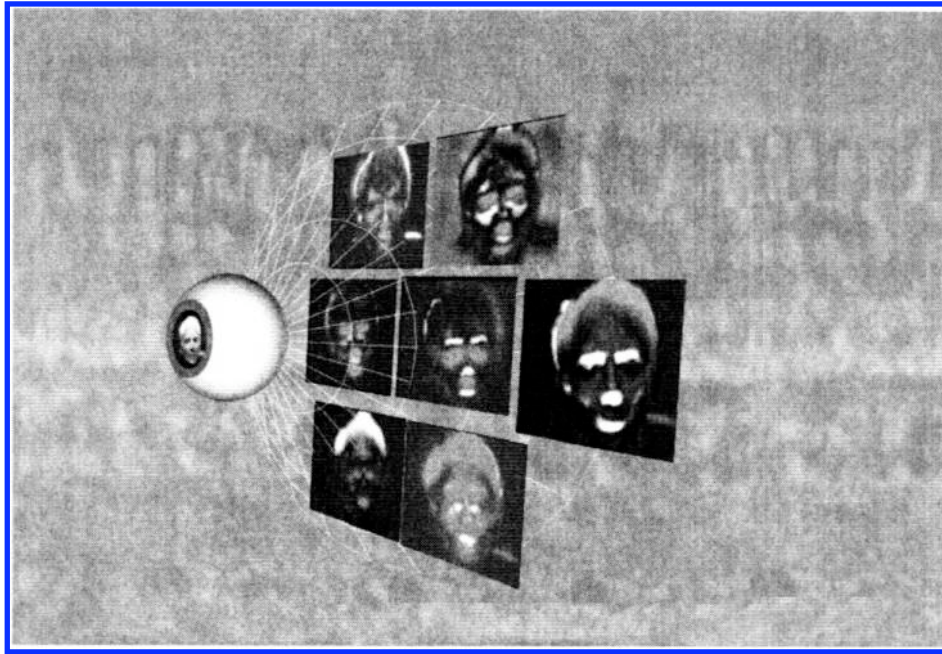


Figure 5. Seven of the dozen or so representations of the visual world formed by sophisticated image processing operations in the vertebrate retina. Each representation extracts a different feature from the visual world.

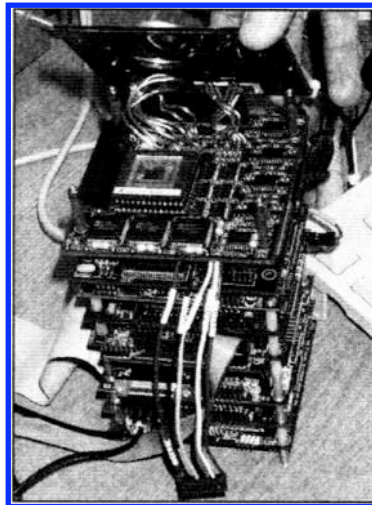


Figure 6. The CNN development system with the CNN processor module on top. The system is used for algorithm development and also as a starting point for the design of compact, embedded CNN systems.

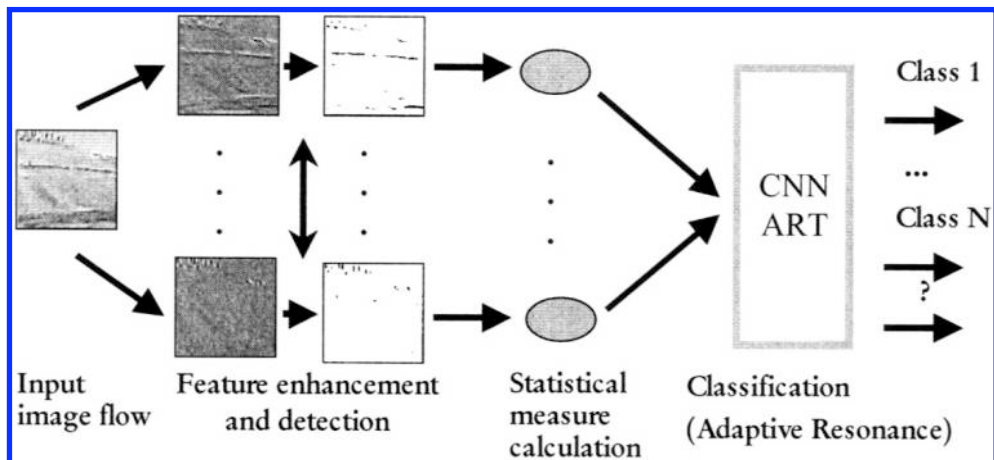


Figure 7. Flow diagram of the terrain analysis architecture. Topographic maps derived from the input imagery by a variety of feature detectors are analyzed using robust statistical measures and a CNN-based adaptive resonance classifier.

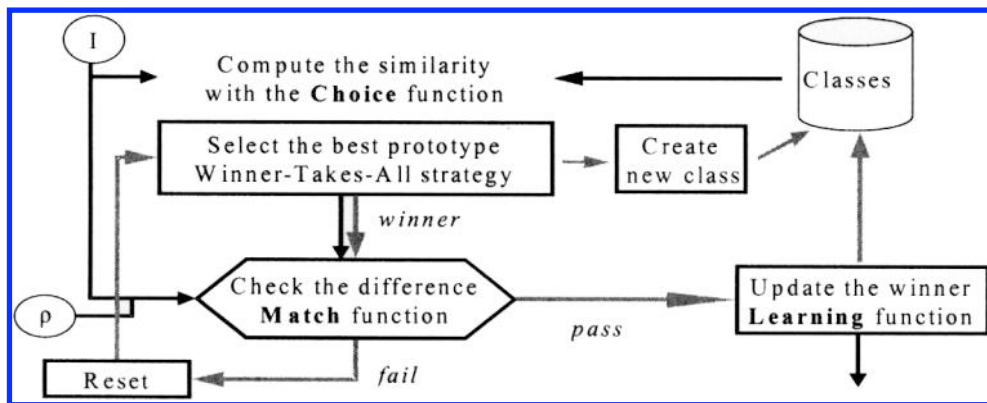


Figure 8. Flow diagram of the CNN adaptive resonance classifier.

retina-like architecture. We are exploring the feasibility of using CNN for recognizing features in a natural scene.

For *terrain analysis* also a number of image processing operations are combined into a complete algorithm. Classification is performed using strategies including statistical and adaptive resonance methods. A flow diagram describing terrain analysis is shown in Figure 7.

The adaptive resonance classifier is also implemented on the CNN processor, eliminating the need to transfer information off-chip. The implementation of the classifier is outlined in Figure 8.

Because of the corresponding architecture of the two systems, the transformations performed by the retina are easily mapped into CNN algorithms. Figure 9 shows how patterns of activity, measured in the retina, can be generated by CNN. The three columns represent space-time plots of the representation of a simple flashed square, for five of the retinal feature detectors. Column 1 shows the spiking activity, column 2 shows the

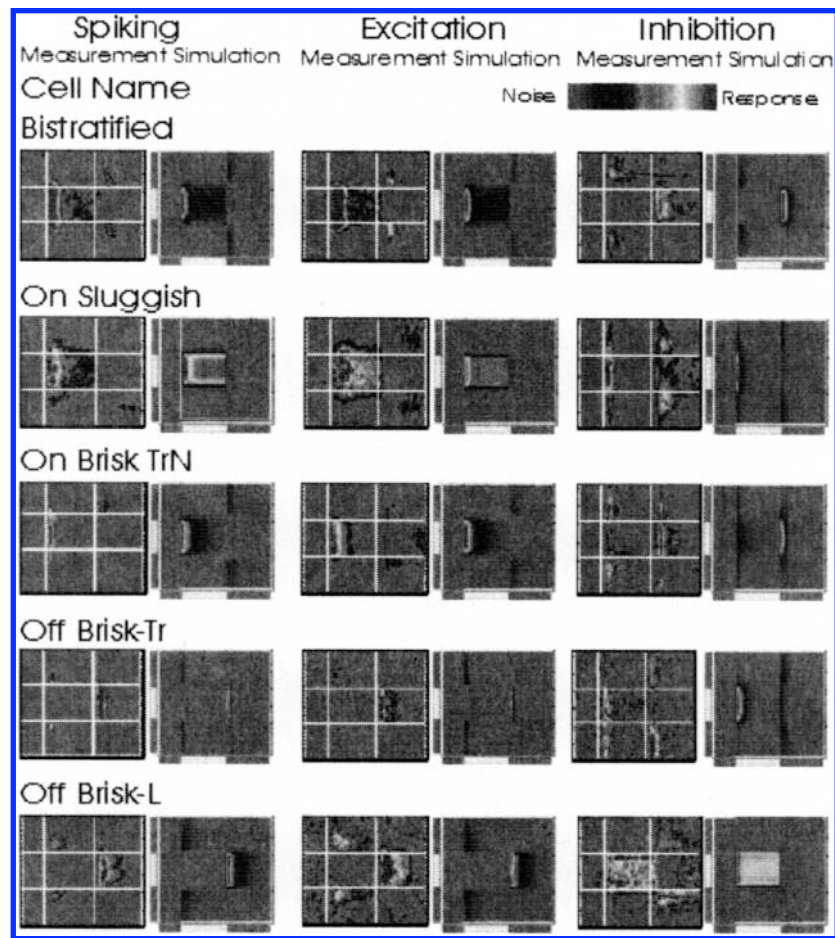


Figure 9. Illustration of performance of CNN with respect to retinal response for five examples of feature detectors for spiking, excitatory, and inhibitory conditions.

excitatory current profiles, and column 3 shows the inhibitory current profiles. The vertical axis for each plot is space, and the stimulus spans the height of the central box. The horizontal axis is time, and the square is presented for the duration of the central box. If the feature detector faithfully represented the stimulus, it would show a bright red square filling the vertical and horizontal dimensions of the central box corresponding to a square of full dimension that was on for the duration of the square. But each representation fills less than the central box, and some representations fall outside the box completely, corresponding to a response that occurs after the stimulus is terminated or in retina regions outside the space occupied by the flashed square. The right half of each column shows the responses obtained using CNN, and these responses fit nicely with those generated by the living retina as shown on the left. The details of the CNN algorithms are given in the article by Balya et al. [1].

5 Mars Mission Architecture and Applications

We plan to do a demonstration of BEES for Mars at a Mars analog site on Earth. A variety of biologically inspired flyers (biomorphic flyers) will be released or launched,

each containing biologically inspired technologies capable of, for example, autonomous navigation, visual search, selective feature detection, intelligent flight control, or image enhancement by sensory data fusion. In previous sections we have described the development of three of these bioinspired technologies that we plan to demonstrate.

The mission architectures [9–12] to be utilized deal with the challenge of the rare atmosphere on Mars by using surface-launched biomorphic 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, compressed in situ resource gas, a spring, electrical power, or a combination of two or more of those sources. Either a lander or a rover could be used as the surface launch base for such biomorphic flyers.

Two kinds of biomorphic flyers are in development. First, there will be small (<1 kg) imaging explorers with less than 15-minute flight duration during which the camera will acquire and transmit video imagery data in real time. The second kind of flyers will serve the dual role of imaging explorers and serving as 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 toward the target site, specifying a flight heading. The communication range, depending on the science goal, could be line of sight to the base, or up to a few hundred kilometers away 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; the smaller imaging flyers then 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 and/or meteorological data to the lander and, after landing, conducts and/or deploys a surface experiment and acts as a radio beacon to indicate the landing 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 high spot (≈ 500 m or higher) and retain them there as *metamorphic flyers*, which play a telecom role 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), acting as 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 Figure 10, offers the most robust telecom architecture and the longest range for exploration. Two landers will be 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. Appropriate choice of the landing site for the core Mars lander in relation to the biomorphic lander-rover (the lander that surface-launches the biomorphic flyers) 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. Biomorphic flyers, either surface-launched from landers or rovers, or aerially launched directly from a spacecraft, will enable navigation [13–15] into and within Valles Marineris to explore this unique geology-rich site in hitherto unparalleled detail.

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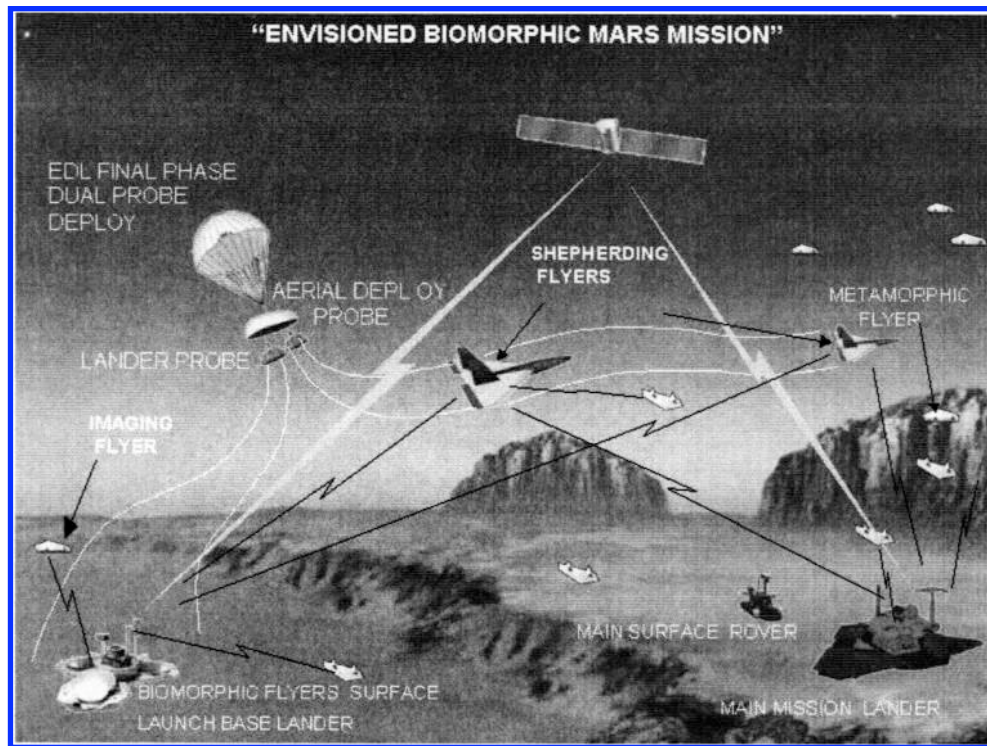


Figure 10. Illustration of envisioned Mars mission that uses traditional assets like landers and rovers in conjunction with biomorphic flyers to enable new science functions that are hard to achieve otherwise, such as imaging stratigraphy or canyon sidewalls in hard terrain such as Valles Marineris.

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