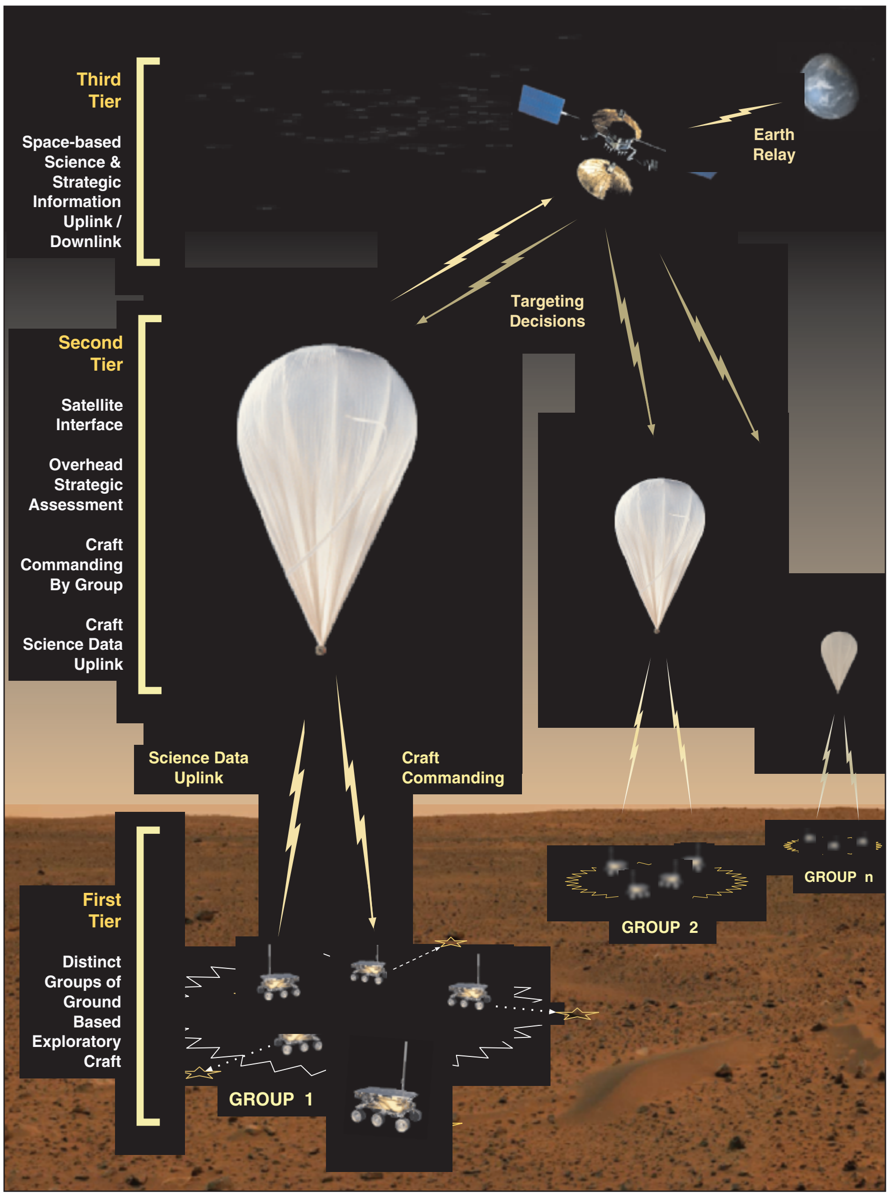
Multiple-Agent Air/Ground Autonomous Exploration Systems

These systems would cover large areas and would function robustly.

NASA's Jet Propulsion Laboratory, Pasadena, California

Autonomous systems of multiple-agent air/ground robotic units for exploration of the surfaces of remote planets are undergoing development. Modified versions of these systems could be used on Earth to perform tasks in environments dangerous or inaccessible to humans: examples of tasks could include scientific exploration of remote regions of Antarctica, removal of land mines, cleanup of hazardous chemicals, and military reconnaissance.

A basic system according to this concept (see figure) would include a unit, suspended by a balloon or a blimp, that would be in radio communication with multiple robotic ground vehicles (rovers) equipped with video cameras and possibly other sensors for scientific exploration. The airborne unit would be free-floating, controlled by thrusters, or tethered either to one of the rovers or to a stationary object in or on the ground. Each rover would contain a semiautonomous control system for maneuvering and would function under the supervision of a control system in the airborne unit. The rover maneuvering control system would utilize imagery from the onboard camera to navigate around obstacles. Avoidance of obstacles would also be aided by readout from an onboard (e.g., ultrasonic) sensor. Together, the rover and airborne control systems would constitute an overarching closed-loop control system to coordinate scientific exploration by the rovers.



A **Balloon-Borne Unit** would supervise the maneuvers of multiple rovers from an overhead perspective.

The rovers would be relatively inexpensive (and, hence, somewhat expendable) units equipped with task-specific sensors. The redundancy afforded by the use of many such rovers (in contradistinction to a single, more generally capable and thus more expensive rover) would help to ensure the success in the event of loss of one or a few rovers. The use of many rovers would also make it possible to cover a large terrain area in a short time. The airborne unit would have an overhead perspective that would enable it to provide guidance to the rovers. For example, the airborne unit could "see" a scientifically interesting terrain feature or a hazard or obstacle hidden from a rover camera by an intervening hill. One or more camera(s) in the airborne unit would acquire terrain images that would be digitized and processed by feature-extraction algorithms. The feature data would be used by planning algorithms to choose potential targets for close examination by the rovers and for planning the paths of the rovers across the terrain. The paths would be chosen to enable the rovers to avoid obstacles and hazards (e.g., hills and cliffs) on their way to their designated targets. Among the planning algorithms would be algorithms for prioritization and sequencing of targets. There would also be algorithms for replanning in response to information on local conditions observed by the rovers and in response to deviations of rovers from planned paths.

Once a rover reached a target, it would acquire close-up images and possibly other sensory information about the target. Features would be extracted from the image data and from any other sensory data to characterize the site. Then the rover would be commanded to move on to the next target. The exploratory process as described thus far would be repeated by each rover until all targets in the terrain area of interest had been examined. A partly functional model of such a system operates in a 4-by-5-ft (1.22-by-1.52-m) test bed that simulates terrain.

The test bed is strewn with variously colored and shaped blocks to simulate targets and obstacles. An overhead view is provided by a camera on a mast above the center of the test bed. Miniature rovers equipped with cameras maneuver on the simulated terrain. At the time of reporting the information for this article, efforts to develop a more fully functional model for testing advanced hardware and software designs were under way.

This work was done by Wolfgang Fink, Tien-Hsin Chao, Jay Hanan, and Mark Tarbell of Caltech, and James M. Dohm of the University of Arizona for **NASA's Jet Propulsion Laboratory**. *Further information is contained in a TSP (see page 1).*

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A 640 × 512-Pixel Portable Long-Wavelength Infrared Camera

This hand-held camera shows promise for imaging at high thermal resolution.

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A portable long-wavelength infrared electronic camera having a cutoff wavelength of 9 µm has been built around an image sensor in the form of a 640 × 512-pixel array of $Al_xGa_{1-x}As/GaAs$ quantum-well infrared photodetectors (QWIPs). This camera is an intermediate product of a continuing program to develop high-resolution, high-sensitivity infrared cameras.

This **Image Was Generated From One Frame** of video readout, at frame rate of 30 Hz, from the camera described in the text.

Major features of the design and fabrication of the camera are the following:

- The QWIPs are of the bound-to-quasi-bound type, for which the thermionic component of dark current is less than for other types. [This concept was discussed in more detail in "Bound-to-Quasi-Bound Quantum-Well Infrared Photodetectors" (NPO-19633), *NASA Tech Briefs*, Vol. 22, No. 9 (September 1998), page 54.]
- The basic multiple-quantum-well (MQW) structure of the QWIP array in the present camera is a stack of about 50 identical quantum-well bilayers. Each bilayer comprises (1) a 45-Å-thick well layer of GaAs n-doped at a density ≈5 × 10^{17} cm^3 and (2) a 500-Å-thick barrier layer of $Al_{0.3}Ga_{0.7}As$.
- The MQW structure is sandwiched between 0.5-µm-thick top and bottom contact layers of GaAs doped similarly to the well layers.
- All of the aforementioned layers were fabricated on a semi-insulating GaAs substrate by molecular-beam epitaxy. A 300-Å-thick $Al_{0.3}Ga_{0.7}As$ stop-etch layer was grown on top of the top contact layer. A 0.7-µm-thick GaAs cap layer was grown on top of the stop-etch layer. A cross-grating structure for coupling light into the QWIPs was fabricated in the cap layer by photolithography and dry chemical etching. [The cross-grating-coupler concept was described in "Cross-Grating Coupling for Focal-Plane Arrays of QWIPs" (NPO-19657), *NASA Tech Briefs*, Vol. 22, No. 1 (January 1998), page 6a.]
- The array of 640 × 512 photodetectors, with a pitch of 25 µm and a pixel size of 23 × 23 μm^2, was then formed by wet chemical etching through the MQW layers into the bottom contact layer. The cross gratings on the tops of the detectors thus formed were covered with Au/Ge and Au for ohmic contact and reflection.
- Indium bumps were evaporated onto the top (Au/Ge)/Au layers, then the bumps were used to bond (hybridize) the array to a silicon-based complementary metal oxide semiconductor (CMOS) integrated-circuit 640 × 512 readout multiplexer.

As described thus far, with the exception of the sizes and numbers of pixels,