JET PROPULSION LABORATORY

ROVER AND TELEROBOTICS

TECHNOLOGY PROGRAM

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Accomplishments

and Technology Transfer

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The Jet Propulsion Laboratory's (JPL's) Rover and Telerobotics Technology Program, sponsored by the National Aeronautics and Space Administration (NASA), responds to opportunities presented by NASA space missions and systems, and seeds commercial applications of the emerging robotics technology. The primary goals of the JPL program, listed below, are derived from the overall NASA Telerobotics Program goals.

- *Develop, integrate, and demonstrate the science and technology of remote telerobotics leading to increases in operational capability, safety, cost effectiveness, and probability of success of NASA missions.*
- *Develop and demonstrate the required technology so that a significant number of operations on planetary surfaces and in Earth orbit may be conducted telerobotically.*

The scope of the JPL Rover and Telerobotics Technology program ranges from basic research, through synthesis of complete systems, to evaluation in realistic ground and flight experiments. Emerging technologies have important dual uses in support of NASA thrusts in space and in such commercial areas as medical robotics.

The Rover and Telerobotics Technology Program comprises three major segments of activity: NASA robotic systems for planetary exploration, robotic technology and terrestrial spin-offs, and technology for non-NASA sponsors. Significant technical achievements have been reached in each of these areas, including complete telerobotic system prototypes that have been built and tested in realistic scenarios relevant to prospective users. In addition, the program has conducted complementary basic research and created innovative technology and terrestrial applications, as well as enabled a variety of commercial spin-offs.

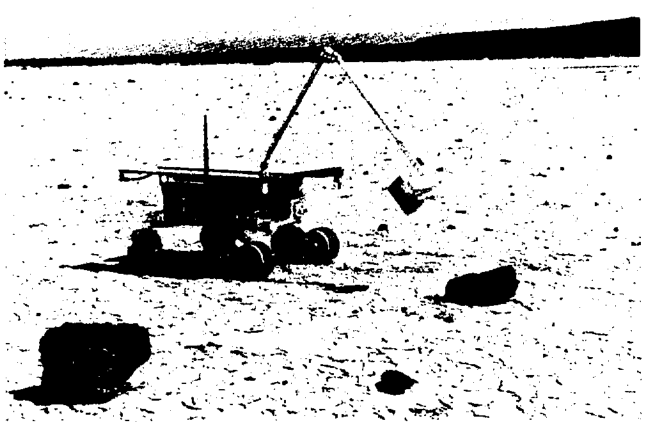
The Rover and Telerobotics Technology Program is an element of NASA's ongoing research program under the Office of Space Science. Universities and industrial partners are major participants in the JPL program. An operating division of the California Institute of Technology, JPL performs research, development, and related activities for NASA and plays a key role as NASA's lead center for the robotic exploration of space.

This segment of the Rover and Telerobotics Technology Program develops robots to satisfy planned requirements and to enable new capabilities for exploring planetary surfaces: exploring potential landing sites and areas of scientific interest, placing science instruments, and gathering samples for analysis and possible return to Earth. The robots for such operations will require high levels of local autonomy, including the ability to perform local navigation, identify areas of potential scientific interest, regulate onboard resources, and schedule activities — all with limited ground-command intervention. These robots must be low-cost and miniaturized to satisfy stringent mass and volume constraints. Technology developed for planetary rovers will also enable technological options for other efforts such as inner-planet and small-body exploration. Specific applications include the Mars Pathfinder Project and the Mars Surveyor Program.

Long-Range Science Rover

Long-range science rovers are those that would enable 10- to 50-kilometer traverses in 1–2 years in support of Mars rover sample-selection and sample-return missions on a timeline consistent with Mars Exploration mission plans (e.g., 2001 and 2003 missions). Enabling technologies include

- Long-distance, non-line-of-sight navigation.
- Survivability of systems operating in severe diurnal cycles and harsh terrain.
- Efficiently stowed vehicles (e.g., collapsible wheels) that can expand in volume upon arrival at their destination.
- Autonomous confirmation of goals and concatenation of commands.
- Communication via orbiter.
- Catalog and cache samples for later collection and return.
- Deployment and in situ analysis of data from multiple instruments.



Rocky 7 during field tests at Lavic Lake.

A prototype of NASA's next generation of Martian rovers, designated Rocky 7, has navigated successfully over a corner of Lavic Lake, an ancient lakebed about 280 kilometers east of Los Angeles, California, and has taken panoramic photographs and close-ups of the cratered terrain in two field tests. In the most recent test, a ~1-kilometer desert traverse was completed, including several site surveys, each consisting of performing experiments on several rocks. During this testing, simulated descent images taken by a helicopter were used by the science team and the rover operator to determine where to send the rover and to interpret the rover's position. Two new science instruments (a Mössbauer spectrometer and a nuclear resonance magnetometer spectrometer) were used to conduct science experiments on rocks in addition to the infrared spectrometer carried by the rover.

The first test was a three-day experiment that was designed to demonstrate the rover's ability to drive a much greater distance than current microrovers over rugged terrain with key features similar to those of Mars. The tests also demonstrated new mechanical innovations for 21st-century rovers, such as

- A robotic arm that would be used to dig into soil.
- An agile mast that could be used to image the surrounding terrain and position miniature science instruments in difficult locations.

The rover was successful in making a long journey on its own, driving more than 200 meters to its target and relying only on specified location points along the way and information about the location of the target. The 1.4-meter-tall mast, which would be deployed once the robot was out and about on Mars, was used successfully to take panoramic images of the surrounding area. The mast has 3 degrees of freedom and carries two cameras and a science instrument: a pair of CCD stereo cameras for panoramic imaging of the landscape, and an interchangeable science instrument. A close-up imager was used in the first experiment to take 50-micron/pixel-resolution images of rocks. This mast was also used to self-inspect the rover by commanding it to image the rover wheels.

During this first field testing, Rocky 7 carried all three cameras on its mast, in addition to a spectrometer on its digging arm and a pair of stereo imagers — which acted as "eyes" — on the front and back of the vehicle. The rover was furnished with simulated descent imaging to re-create the areas about the landing site, and was then asked to deploy its mast and take a panoramic photograph of the landscape. Part of the field testing also involved a demonstration of how well the rover could be controlled remotely from JPL using a World Wide Web operator interface called the Web Interface for Telescience (WITS).

A new rover (Rocky 8) is under construction that integrates the control capability of Rocky 7 with the technologies emerging from the Lightweight Survivable Rover. These technologies include lightweight structures and collapsible wheels, phase-change material accommodation, and low-temperature lithium batteries. The technologies increase the ability of the vehicle to survive the harsh Martian temperature cycles, while simultaneously reducing mass and stowed volume. The new vehicle will accommodate a 5-kilogram instrument payload.

The Rocky 7 experiment team, led by Samad Hayati of JPL, included scientists and engineers from NASA Ames Research Center, Washington University, Cornell University, and scientific institutions abroad.

Larry H. Matthies is leading a subtask in a related area — visual localization for rovers for Mars sample-return missions. These missions will require rover localization on scales ranging from under 1 meter near landers and sample caches, to tens of meters for local exploration and mapping, and hundreds of meters for long-range (100 kilometers) exploration. Issues are being explored involving localization using lander imagery, mast-mounted rover imagery, descent imagery, and orbital imagery.

The task is studying two methods of localization using lander imagery (when the rover is within view from a lander):

- Recognizing the rover in lander imagery.
- Mapping the area within view from the lander, using stereo cameras on the lander, then recognizing landmarks in the map in rover imagery.

To recognize the rover in lander imagery, it is assumed that the lander has a stereo pair of aimable cameras and has approximate knowledge of the rover's position. These cameras take images before and after the rover moves, then detect the moving patch in a difference image. This method has been implemented for the Rocky 7 Mars rover research vehicle.

The Rocky 7 rover testbed has a 1.5-meter-high mast with stereo cameras that can be panned to map the area around the rover.

Images are taken with one camera before and after the rover turns in place through a small angle, followed by difference and cross-correlation analysis and stereo triangulation. In tests, the rover, turning in place by 0.3 radians, was imaged at distances of 2–10 meters from a mock-up lander. The results show that the method is successful for near-lander locations.

Mapping the area within view from the lander, using stereo cameras on the lander, then recognizing landmarks in the map in rover imagery, is applicable for near-lander operations and for distant operations — providing the rover has mast-mounted stereo cameras that function as surrogates for lander cameras. The imagery would be used to map an approximately 10-meter radius around the rover; scientists would designate places to take measurements, and the rover would use the map to keep track of its position. Using elevation grids created from stereo imagery acquired as the rover drives around, and correlating the local grids with a reference grid, techniques were tested using images taken in the JPL Mars Yard with a stereo pair of cameras mounted on a tripod at approximately the Rocky 7 mast height. The reference grid may correspond to a previous rover position, an image panorama from the lander or rover, or descent imagery from the lander. Ongoing work is testing the approach with imagery from the Rocky 7 mast and obstacle-detection cameras.

Using descent imagery for rover localization could be accomplished using elevation maps computed from the descent sequence. Predictions of elevation resolution indicate that elevations will be known with a standard deviation of 1 meter or better within a kilometer of the lander; further work will involve determining how well the positions and orientations of the camera can be estimated for each descent image and by evaluating the precision with which features can be matched in consecutive imagery.

Rover missions will ultimately extend beyond the practical radius of descent imaging, necessitating visual rover position estimation using imagery acquired from orbit. Comparisons of available orbital imagery revealed that

- Viking covered 100 percent of Mars at approximately 260 meters per pixel. Viking digital terrain maps have a resolution of about 1 kilometer per pixel.
- Mars Global Surveyor (MGS) will have selective coverage at 280 meters per pixel and spot coverage at 1.4 meters per pixel. No stereo imagery is possible at spot resolution. MGS will produce a global topographic map with resolution about 12 kilometers per pixel, with 30-meter global accuracy in elevation.
- The Mars Surveyor '98 mission will provide selective coverage at 40 meters per pixel.

How well a rover could be localized with such digital terrain maps is an open question; certainly it will depend on the topography of the region being traversed. Much work remains to be done to determine how well rovers could be localized with orbital imagery.

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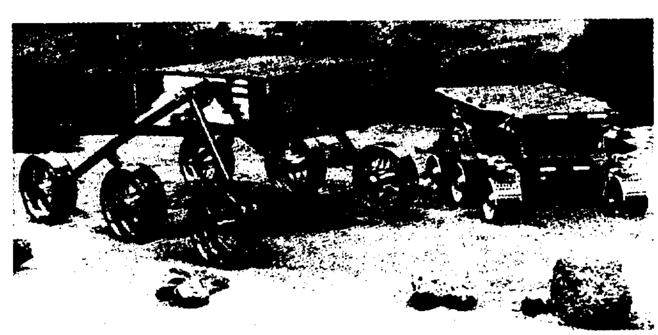
Lightweight Survivable Rover

The Lightweight Survivable Rover (LSR) task develops and demonstrates new rover technologies to enable low-mass, low-volume, low-power mobile Mars surface operations over diverse terrain and latitudes — increasing NASA capabilities for in situ planetary science. Target applications include mobile science and sample-return functions of the Mars Surveyor Program (MSP), and missions beyond. A first rover prototype for a Mars sample-return (MSP '05) is in development. The function of this Sample Retrieval Rover (SRR) is to quickly retrieve previously cached material in the near proximity of an Earth-return ascent vehicle (see the separate description of the SRR). We demonstrate and benchmark such system developments in ground-simulated operations, and by performing component-level tests in Mars-relevant environmental conditions.

The LSR-1 is an R&D prototype, 7-kilogram rover with 20-centimeter-diameter wheels, 97 centimeters long, 70 centimeters wide, and with 29 centimeters ground clearance. In comparison, Sojourner is an 11+-kilogram microrover with 13-centimeter-diameter wheels, 63 centimeters long, 45 centimeters wide, and with 15 centimeters ground clearance.

Compared with Sojourner, LSR-1 — which incorporates significant advances in composite and thermal materials, as well as a new exoskeletal thermal-structural chassis — is conceived to operate over larger obstacles (~0.4 meter), broader thermal latitudes (equatorial to near polar regions), longer distances (multiple kilometers), and extended duration (multiple months).

LSR-1 introduces a novel spot-pushbroom sensor, enabling rapid detection and avoidance of hazards in variably featured terrain, while using less power and computation. A central ele-



The LSR-1 integrated technology prototype (left) and the recently flown Mars Pathfinder Sojourner microrover. The LSR-1 rover is shown prior to bonding of composite helical growsers to its collapsible wheel rims.

ment of LSR design is volume-efficient mobility, wherein wheels and mobility running gear collapse for transport, allowing rover stowage during flight to as little as 25 percent of operational field volume. The LSR mobility platform concept scales to larger, heavier vehicles, and is being developed for use in a new 40+-kilogram-class mobile science platform.

Major lines of technology development within the LSR task include

- Increased mobility and science at fixed stowage volume.
- Higher strength-to-mass rover structures and materials.
- Higher power-to-mass actuation with reduced gearing.
- Improved thermal isolation and vehicular survivability.
- Reduced computation mass, volume, and power in sensing and control.

Previous task accomplishments include the development and demonstration of

- A novel rover mobility platform having a collapsible 20-centimeter-diameter rover wheel (260-gram, composite–aluminum structure) stowable to 30 percent of its operational volume, and all-composite running gear (2-D tubes, and new 3-D process joints and pivots). The design provides a basis for next-generation, low-mass, high-payload sample retrieval and long-range science vehicle LSR designs.
- A mass-saving approach to rover integrated thermal–structural design wherein the warm electronics enclosure (WEE) serves dual functions of thermal control and main chassis load-bearing member. The improved thermal isolation (using a new opacified aerogel) and stabilization (utilizing novel phase-change materials) reduce through-wall thermal losses up to 30 percent, and internal WEE temperature variations by 50 percent.
- A fast, robust rover obstacle-avoidance scheme based on diffracted, highly collimated, multispot projection from miniature lasers. Charge-coupled device (CCD)-based imaging of the geometrically calibrated, time-sequenced spot array — a moving "pushbroom" — enables temporal 3-D reconstruction of obstacles and near terrain. We obtained 97–98 percent positive spot detection with no false alarms, operating in direct daylight conditions over variable surfaces without difference imaging.
- Various science sorties, in a simulated Sojourner-like Mars Yard at JPL, by an LSR — a 1-meter-long, six-wheeled, 7-kilogram vehicle, carrying a multispectral imager. This vehicular design concept, with planned features of 3 to 4 times stowage volume efficiency, wide-thermal-range operations, low mass to volume and strength ratio, and scalability to larger sizes (e.g., 30–50 kilograms), should benefit future Mars science sample-collection and sample-return operations.

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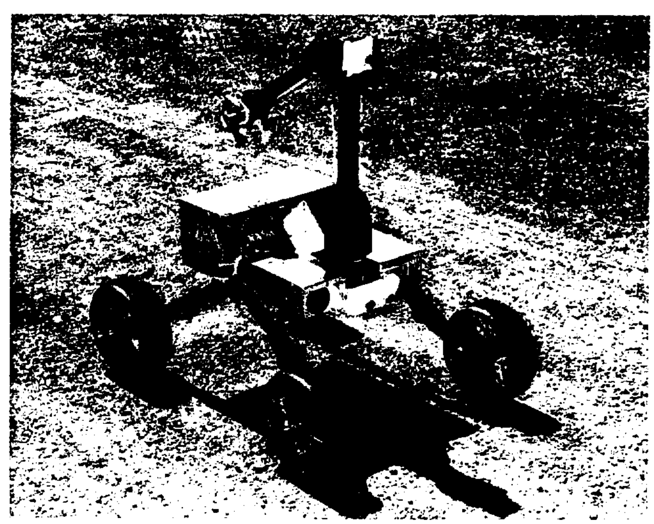
Sample Retrieval Rover

The Sample Retrieval Rover (SRR) is part of the task to increase NASA capabilities for in situ planetary science through developing and demonstrating new rover technologies for low-mass, low-volume, low-power mobile Mars surface operations over diverse terrain and latitudes (see the Lightweight Survivable Rover description). A first rover prototype — the SRR — for the Mars Surveyor Program sample-return mission (MSP '05) is in development. The SRR would retrieve, in as little as one diurnal cycle, previously cached material in the near proximity of an Earth-return ascent vehicle.

The task has designed, implemented, and demonstrated an SRR weighing less than 8 kilograms (samples and containment: 1 kilogram; cache-handling mechanization: 2 kilograms), in simulated near-field operations (10–100 meters) about an ascent vehicle. This assumes local-area navigation to a known location, cache recognition and localization, robotic sample container pickup, and transport.



The Sample Retrieval Rover (SRR-1) during early field trials. The attached light, strong MicroArm 2 is used to pick up and transfer a sample cache onto SRR-1.

All major components of the ~5-kilogram vehicle have been fabricated and integrated with simulated field operations in progress. SRR operation is highly autonomous — once a direction to the target science rover cache has been established, SRR proceeds under beaconed guidance to the near area, visually localizes the science rover in aspect and range, plans a terminal trajectory, visually acquires an accurate position of the cache (sample repository on science rover), and executes visually referenced inverse kinematics control of a small, strong, all-composite, 3-degrees-of-freedom, 1-kilogram robotic arm (MicroArm 2) to transfer the cache onto the SRR platform.

The SRR vehicle incorporates a number of novel architectural features, among them are

- Fully collapsible running gear and wheels (the latter a second-generation, field-hardened design with Kevlar coating and spring steel growsers) enabling it to stow in about 1/3 its operating volume.
- Implementation of both the running gear and robotic arm (lower joints shown only) of a new high-density 3-D machinable composite developed at JPL (see the description of the Planetary Dexterous Manipulator task).
- An actively controlled and posable shoulder joint, allowing vehicle stance and ground clearance to be best configured to the task at hand (lifting a heavy load, running fast over open terrain, etc.).

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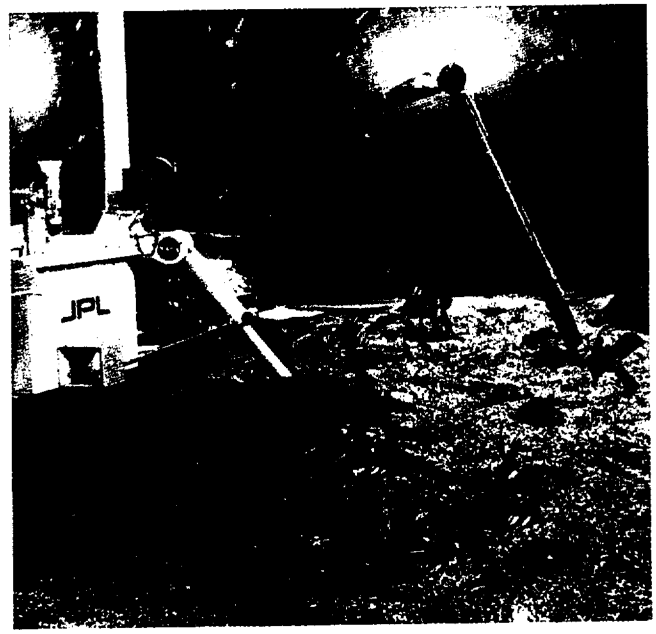
Planetary Dexterous Manipulator

This task develops robotic concepts and enabling technologies for planetary surface exploration. Planned mission applications include sample-selection and sample-return functions of NASA's Mars Surveyor Program. The concepts and technologies, used on future landers and rovers, will enable scientists to dexterously probe, expose, view, acquire, and cache samples of interest. Such in situ robotic science/sample return will advance knowledge of Martian geologic and biologic evolution, climate, and resources.

Ongoing work defines and demonstrates small, dexterous arms for rover science and sample cache returns. Earlier work developed a lander robotic arm concept (Mars Volatiles and Climate Surveyor — MVACS) for the Mars '98 mission. The robotic science operations under investigation are diverse and require well-coordinated advances in robot mechanization and sensor-



The MarsArm II sampling robot prototype. In the foreground, the LSR-1 vehicle with MicroArm I, a small, all-composite robot approximately 30 percent the scale of MarsArm II with the same science end-effector functions.

based intelligent robotic control for remote unstructured, uncertain environments. Control challenges include synthesis of autonomous robotic behaviors that embed basic manual skills of a field geologist, task-adaptive contact interactions with highly variable media, visually guided positioning and placement of instruments, probes, and sampling heads, and generation of 3-D sensing techniques.

The major lines of technology development are

- High-strength, high-mass manipulators with integral microsensors.
- Light, agile sampling effectors with active tooling.
- Durable, all-composite structures and fabrication processes.
- Low-mass, miniature, high-torque density motors.
- Advanced robot-control paradigms for sampling.
- Integration of these concepts with mobile science.

These mechanical innovations are potentially applicable to wide-ranging Mars climates, from equatorial to near-polar latitudes. Research and development involves ground-laboratory simulations of envisioned Mars science sampling scenarios, including stand-alone evaluation of new components and materials in representative Mars environmental conditions.

Science requirements include dexterous robotic operations for viewing; analytic probing; instrument emplacement; material extraction and preparation; sample exposure, acquisition, manipulation, and containment; and visual localization and pickup of a stored sample cache for transfer to an ascent vehicle and return to Earth.

Accomplishments include

- Composites — Innovated a strong, machinable, 3-D carbon composite that can be processed to intricate robotic parts by conventional shop practice. The composite has 50 percent the mass density of aluminum with improved material interface properties. Also developed and performed preliminary mechanical and thermal characterization of high-strength, 2-D composite systems optimized for robotic design applications.
- Actuators — Created and demonstrated high-power, rotary ultrasonic motors (USMs) as potential mass/volume–optimal solutions for a wide class of planetary robotic (and small spacecraft) applications. USMs provide high torque at low/no speed, high efficiency, and high holding force.
- Planetary Sampling — Conceived, developed, and demonstrated for simulated Mars sampling tasks (soil and rock science) a new all-composite, force-sensing, USM-actuated, scalable, lightweight, robotic arm and effector, MarsArm II.

The MarsArm II is a 4-degrees-of-freedom, 4-kilogram, 2-meter sampling robot prototype of all-composite construction. The robot carries a 1-kilogram, multifunction science end-effector that can dexterously scoop, grasp, expose, and closely view surface and near-surface rocks and soils. Once a remote science user visually designates and selects a sampling objective (such as "trench along this line and angle, grasp this designated object, locate the arm camera here"), MarsArm II uses built-in position, force, and vision sensors to monitor, guide, and adapt its motions, which proceed autonomously under task-based intelligent control. A precursor MarsArm I hybrid 2-D, composite-link–aluminum-joint robot concept was selected for NASA's Mars Surveyor '98 science sampling operations.

The task is developing, integrating, and operating a small, all-composite rover sampling arm; evaluating new high-torque ultrasonic motor designs; and advancing 3-D composite strength and reliability. The effort includes characterizing the motor and material technologies for relevant environmental conditions, and demonstrating the arm in representative dexterous sample selection and/or sample- return processing tasks.

The LSR-1 vehicle (see Lightweight Survivable Rover task) has been fully integrated with MicroArm 1 and self-calibrating, visually guided, inverse kinematics controls developed for functions such as trenching, rock-abrasion, close-up viewing, sample pickup and manipulation, and sample caching. These autonomous sampling behaviors — which are "point-and-click"–designated by an operator — incorporate underlying force-referenced control of the sampling arm and its instruments and tools with the environment. MicroArm 2, demonstrating robot construction of a new, higher strength, 3-D machineable composite, has been developed and will be demonstrated in Sample Retrieval Rover field tests.

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Exploration of Small Bodies

Comets and small bodies, such as asteroids, are important targets for future exploration. Small-body missions involve landing on and anchoring in an extremely low-gravity body and sampling its surface and subsurface — operations never before attempted. Cometary surface terrain is predicted to be extremely rough. These bodies are thought to be aggregated interstellar submicroscopic dust grains with coatings of volatiles, ices, and organics. Compared with cometary surfaces, asteroid surfaces may include both significantly harder rocks and a dusty regolith, and higher demands may be placed on lander leg and anchoring designs compared with comet landers. Task objectives are to develop the mechanisms and control strategies to perform landing, anchoring, surface and subsurface sampling, and sample manipulation.

The low-gravity environment of small bodies allows for free fall and unpowered landing, but requires ways of absorbing impact energy as well as attaching the lander to the surface and reacting to sampling forces. Passive energy-absorption systems such as crushable materials, as well as anchoring systems such as rocket-deployed spikes, are being developed and demonstrated.

A three-legged lander was developed using new-technology damping struts. Each leg assembly is made of three high-efficiency damping struts, culminating in a surface-conforming footpad. For full-scale drop tests, the 45-kilogram lander was suspended above a simulant testbed and dropped from 1.2 meters to achieve 5 meters per second landing velocity at impact. The lander was instrumented with accelerometers at the feet and on the base body. The goal was to limit the g-forces at the body to less than 30 g's. The tests established 60–130 g's at the feet; while landing forces seen at the base body were limited to 10–20 g's.

The energy-absorber damping strut looks like a standard shock absorber design, but rather than using a viscous fluid, the energy absorber uses a cutting blade that slices through polyurethane foam as the damper is compressed. This provides an extremely low-rebound strut whose energy absorption can be tailored by varying the foam density and cutter surface area. A multilegged lander using this strut system will be capable of absorbing energy in a multitude of vectors.

Embedding an anchor into the target surface requires a high specific energy source capable of accelerating a 100-gram projectile to 100 meters per second. An integrated winch mechanism in development comprises a force-feedback-controlled winch, a pyrotechnic accelerator, and a tethered anchor. The system fires a winch-tethered anchor from the pyrotechnic accelerator. A self-sealing pyrotechnic unit is in development; the first-generation unit achieved baseline velocity. During the testing, the anchors were accelerated into several comet simulants: polyurethane foam, plaster, Bishop tuff, and Coconino sandstone.

After the anchor embeds in a substrate, the winch controls the tether tension. A winch mechanism would be located on each foot of the lander; as each foot encounters the surface, an anchor is fired from the respective foot. As the lander bounces from the surface in reaction to the landing forces, each winch pulls the lander back to the surface. Force-feedback control keeps the lander from wrenching the anchors from the surface, and preloads the lander to the surface for sampling operations.

For surface and subsurface sampling, low-mass, low-power mechanisms for sample acquisition are being developed with concurrent development of sensors and control methods, enabling autonomous operation in materials of unknown composition. A compact drilling and sample system in development uses a 2.2-kilogram drill that consumes less than 30 watts during drilling. Low mass is achieved by eliminating the need for a drill tower and incorporating state-of-the-art bearings and gears. The bearings use ceramic balls to eliminate the need for additional lubrication and allow cryogenic operation. The tungsten carbide gears will be made of titanium carbon nitride in the next-generation design. "Smart drilling" via software control is achieved through the modulation of thrust and rotation speed. The motors have been successfully dyno tested at 110 kelvins. Normal drilling operation rotates the tip of the removable drill bit to a closed position that prevents acquisition of shaving samples during drilling. At target depth, the drill can be rotated in the opposite direction, opening the chamber to draw in a sample, then again rotating in the original direction to close the chamber. The sample can then be extracted and deposited into a bit receptacle.

Once a sample is acquired, it must be delivered to onboard science instruments for in situ analysis. To accomplish this, systems for sample handling and sample preparation in a microgravity environment are being developed.

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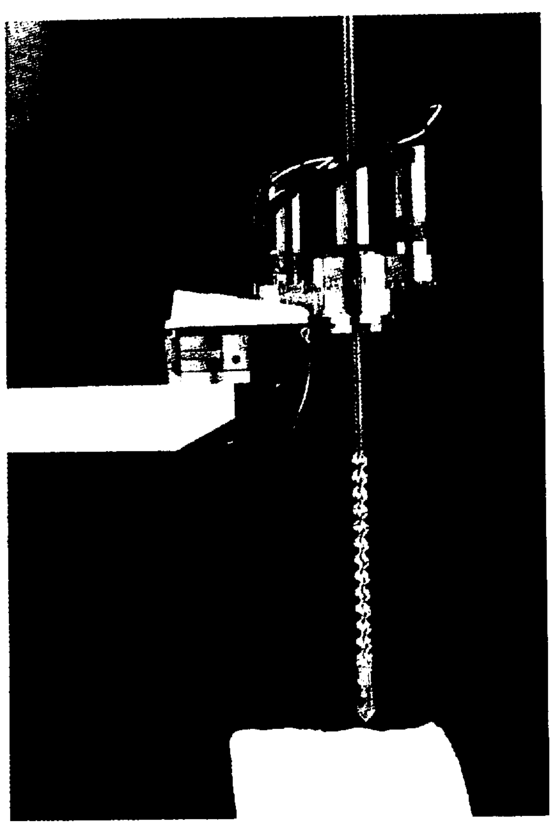


A compact, low-mass drilling/sampling system has a 1.5-centimeter-diameter drill capable of 1-meter-deep sampling.

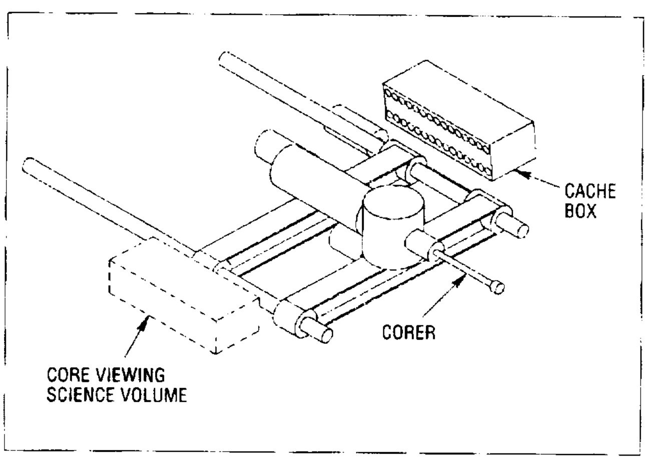
Rock Internal Inspection and Selection System

There is a wide consensus in the scientific community that autonomous rock coring will be a key technology need for 2001 and 2003 Mars missions. This task will develop a miniature remote rock-sampling and curation system in the time frame needed to infuse the new technology into the Mars Exploration 2001 and 2003 missions. Technologies will be developed to acquire small samples of a rock, perform in situ inspection of the interior surface, and cache or reject the sample based on remote curation. The system will be miniaturized for integration with a self-propelled Mars rover of the 45-kilogram class.

The technology thrusts for the Rock Internal Inspection and Selection (RIIS) task are

- Develop a miniaturized rock-sampling system.
- Develop a miniaturized rock-curation system.
- Develop a method of safely storing selected samples to cache.
- Integrate this system with the rover mobility chassis, and develop the control algorithms and strategies to allow autonomous remote operation.

A complete demonstration will be performed to showcase a Mars rock sample acquisition, selection, and cache system operating from a mobile rover science platform. The task will build on hardware deliverables from Honeybee Robotics, currently engaged in developing a miniature rock-coring mechanism under a two-year NASA Small Business Innovation Research grant. Honeybee will be responsible for delivering the rock sample acquisition portion of the system; JPL will develop a multiple-axis carriage mechanism to enable physical integration to the rover chassis.



A rock sample acquisition and cache system.

The carriage will provide the required degrees of freedom to allow remote sensing of the rock sample (for selection of the most scientifically significant) and robotic manipulation to allow the selected samples to be cached. The mobile science platform is currently in development under the JPL Long-Range Science Rover task. When integrated with the Long-Range Science Rover testbed, the RIIS system will enable JPL to investigate the strategies needed to allow autonomous operation of rock sampling from a compliant base such as a small rover. Required investigations include

- Mobility to a rock to be sampled.
- Identification of rock surfaces to core drill within the allowable operating volume.
- Assessment of surfaces that are an acceptable risk to drill.
- Determination of allowable applied forces and torques among the rock, the rover, and the soil.
- Fault-tolerance strategies to prevent or recover from drill jamming.

Leveraging the technology development being performed under the Exploration of Small Bodies task, JPL will develop the closed-loop electronic controller for the RIIS system. The RIIS system will be tested at the component-assembly level against relevant terrestrial analogs of predicted Martian rocks, and then will be integrated with the Long-Range Science Rover testbed for full end-to-end characterization testing.

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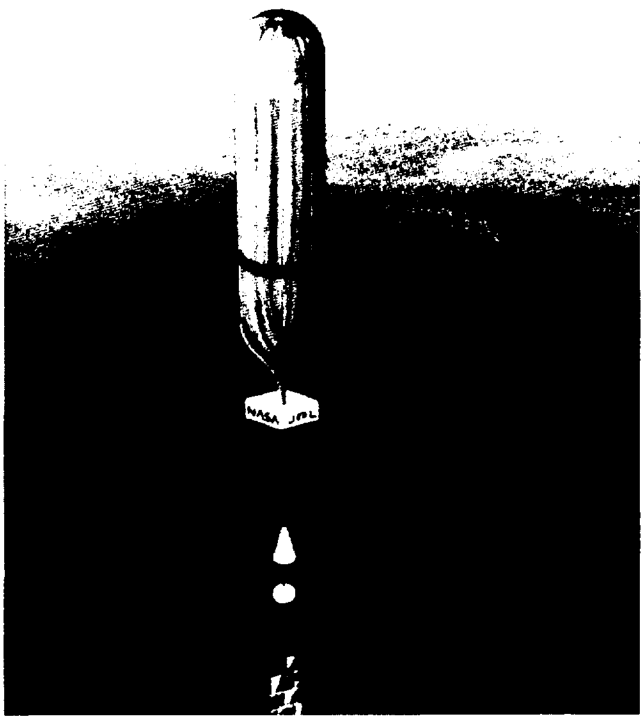
Aerobots

Planetary aerobots, or aerovehicles, are an innovative type of lightweight, low-cost telerobot — one that can fly and navigate in planetary atmospheric environments. Emphasis includes aerobots to enable suborbital mapping of terrain regions and which could transport and deploy microrovers at different, geographically separate land sites for potential Mars, Venus, and Titan deep-atmosphere missions. The challenges of flying a planetary aerobot are in providing



The atmosphere and environment of Venus present unique and difficult challenges to scientific missions of any significant duration.

mobility and autonomous navigation in a constantly changing three-dimensional environment, one in which the robotic vehicle is almost never stationary. These challenges include real-time determination of the location and state of the aerobot, vertical motion control of the aerobot, and prediction and planning for global-scale path trajectory. One type of aerobot involves a robotic balloon concept incorporating buoyancy control. The altitude-control concept employs phase-change fluids such that a planet's atmosphere is used as a giant heat engine to provide the energy to ascend and descend at will, allowing the vehicle to visit multiple sites of scientific interest. This concept has been demonstrated in a free-flying terrestrial prototype.

The temperature at the surface of Venus is roughly 460 degrees Celsius, at a pressure of 92 atmospheres. Constructing a probe that can survive such extreme temperatures and pressures for a short time is difficult, but it has been done in previous Venus missions such as the Russian Vega mission. Higher in the atmosphere, pressures and temperatures are low enough for contemporary hardware. Aerobots offer the revolutionary capability to repeatedly visit the surface of Venus for several hours at a time and then rise high enough in the atmosphere to cool off. No previous technology, such as passive balloons, probes, or landers, can provide this capability.

Global-path planning requires a global wind model that describes the variation of the winds with altitude and location on the planet. This involves developing an adaptive wind model with two levels:

- A moderately detailed local wind model, updated with local onboard wind estimates.
- A coarse planetary-scale model based on the current understanding of Venus global wind circulation features.

It has been demonstrated in simulation that aerobot path planning and sensor-based motion control can achieve descent, downrange, and cross-track adjustments leading to a landing within 30 kilometers of a target at a distance of at least 500 kilometers, using Venus-applicable sensing, control, and models.

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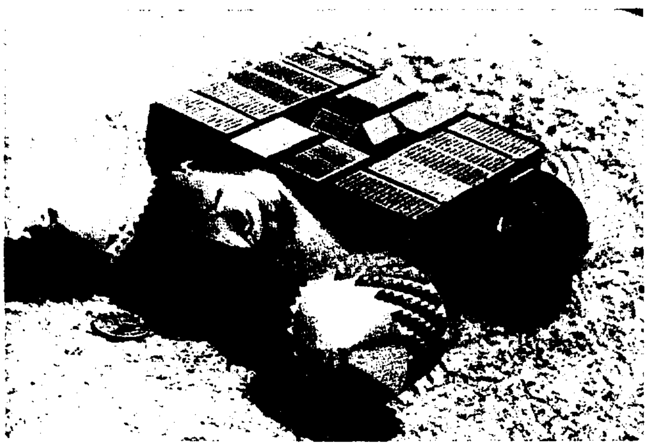
Nanorovers

The nanorover task is a technology-development effort to create very small (10–100 grams), scientifically capable robotic vehicles that can easily fit within the mass and volume constraints of future asteroid, comet, and Mars missions. Important technology elements of this task include

- Miniaturization of all rover systems, including science payload.
- Computer/electronics design for operation without thermal enclosure and control to survive ambient temperature ranges of −125 to +125 Celsius.
- Miniature actuator usage and control in thermal/vacuum environments.
- Mobility and navigation in low-gravity (1/100,000 that of Earth) environments.
- Sensing and autonomous control of rover operations.



The versatile nanorover can traverse cement, gravel, grass, and loose sand. For size comparison, a U.S. 25-cent-piece can be seen just below the wheel at left in the photograph.

The current nanorover prototype consists of a four-wheel mobility chassis designed so that each wheel strut can be positioned independently. The nanorover can pose its body in any orientation to perform various tasks; for example, pointing science instruments at features of interest. Each aluminum wheel (~6 centimeters in diameter) contains a drive motor and helical cleats on the outside to increase performance for skid steering (turning in place). The chassis is designed around two science instruments: a multiband camera system for gathering images, and a near-infrared point reflectance spectrometer (1–2.5 micrometers) to provide mineralogical information. The onboard computer is designed around radiation-hardened components. The nanorover is designed to be completely solar powered, requiring only 1 watt, including an RF telecommunications system for communications between the rover and a lander or small-body orbiter for relay to Earth. The power source is 500 grams of commercial, nonrechargeable, replaceable lithium batteries, with energy density of 750 joules per gram.

The nanorover

- Can operate upside-down, intentionally flip over, recover from accidental overturning, place its body flat on the ground (for sensor placement), run low to the ground on severe slopes or under barriers, rise up on struts for highest possible vantage point and stair climbing, lift wheels and set them atop obstacles, and articulate to keep all wheels providing maximum traction.
- Incorporates ultralow-power active pixel sensing, CMOS imaging technology, ultralow-noise analog input for advanced sensing (e.g., thermal infrared), and ultralow-mass commercial RF digital communications.

Specifications for the current nanorover are

- Weight, 2 kilograms; width, 28 centimeters
- Stowed configuration, 28 centimeters long, 7 centimeters high (operational configuration, 25 centimeters high)
- Run time (fully charged battery)
  —Operating cameras and sending data, 35 hours
  —Moving at 1 meter per second (maximum speed), 5 hours
- Maximum height of traversable step, 20 centimeters
- Maximum width of traversable ditch, 20 centimeters
- Maximum traversable slope, 50 degrees
- Operating temperature, –55 to +125 Celsius
- Vibration limits, 15 g's RMS; shock, 60 g's.

The nanorover has been selected as a technology experiment on the Japanese asteroid sample-return mission MUSES-C, scheduled for launch in January 2002. For this mission, the nanorover will be deployed to the asteroid surface to gather close-up imagery and spectral data, then relay the data through the MUSES-C spacecraft back to Earth.

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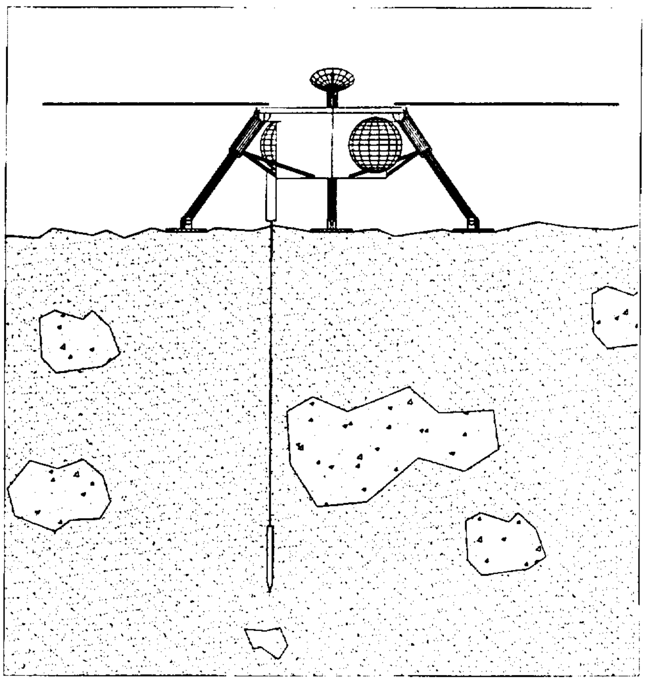
Subsurface Explorer

The objective of the Subsurface Explorer (SSX) task is to create a robotic vehicle capable of maneuvering in the expected regolith (e.g., soil, permafrost) of planets, such as Mars, and small bodies, such as comets. The purpose of the SSX system is to penetrate to depths of meters, to hundreds or even thousands of meters (depending on material properties) and make in situ measurements of soil composition and chemistry. Longer-term development will involve subsurface exploration techniques to depths of tens and hundreds of meters for both lander-based and roving systems, and vehicles for penetrating ice layers (100–10,000 meters) and moving through potential underground bodies of water.

The goal of the prototype development effort is to construct a self-contained vehicle that can reach depths much greater than those achievable with any reasonable-mass traditional drill rig attached to a surface lander.



Prototype penetration system to explore the deep subsurface (more than 10 meters) of planetary and small bodies.

The body of the prototype vehicle is ~1 meter long and ~5 centimeters in diameter. The front half of the vehicle contains a percussive hammer mechanism. A closed gas system will compress the working gas and then rapidly release it into the hammer chamber, propelling the hammer into the anvil or body of the vehicle with very high energy. Material selection for components of the explorer vehicle is critical to ensure strength, durability, and wear resistance as the hammering action encounters the surrounding surface and subsurface material. The impact of the hammer will overcome the frictional forces on the vehicle's outside surface caused by the surrounding material, and will force away material from the nose of the vehicle, moving it forward.

The science package of in situ instruments is located behind the percussive mechanism. The package is spring mounted to prevent damage caused by the high impacts of the hammering. Instruments being explored include microscopic imaging and laser Raman spectroscopy of material against the body of the vehicle, which can be done via a sapphire window in the wall. Behind the science package are the control/communication avionics and tether deployment mechanism. A very thin tether, deployed from the vehicle, provides both power (high voltage) and communication to and from the lander. The tether is effectively buried behind the vehicle as it goes.

Missions under consideration for the SSX include the Mars 2007 mission (after initial sample return), where the vehicle could be used to penetrate deep into the surface material to search for liquid-phase water; and comet-exploration missions, where the SSX could analyze pristine material near the core.

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Robot Survival in Harsh Environments

Closely related to the robotics technology being developed for planetary surface exploration are concurrent developments in complementary technologies required to achieve robot survival in harsh environments. One of the key challenges of Mars exploration is to survive the harsh environment on the surface, where the daily temperature variation can range from below −100 degrees to above 20 degrees Celsius. Mission duration requirements of one year or more are a closely related challenge. The extreme temperature cycling can cause failure of critical robot components and systems due to such damage-accumulation failure mechanisms as fatigue cracking in motors and other components, cyclic growth of flaws, and decohesion or delamination of bonded surfaces. Other damage-accumulation failure mechanisms that may adversely impact robot service life include sensor degradation, mechanical wear, structural fatigue due to prolonged operation, lubricant leakage or migration, and chemical degradation. Such damage-accumulation failure mechanisms must be identified to prevent failures of critical components and systems during the mission service lifetime. In addition to these types of hardware failures, there are concurrent possible failure mechanisms in the onboard software embedded in the robotic systems that provides the various levels of autonomy in performing the mission on the planet surface.

The requirement for survivability drives the need for relatively low-mass, low-power devices and systems that are capable of operating under extreme conditions. Current technologies receiving emphasis are

- Low-temperature batteries for achieving increased survivability to meet a variety of mission requirements.
- Thermal control of electronics enclosures using phase-change materials and heat switches.
- Probabilistic physics of failure methodology to achieve system-level robotic vehicle survivability using a combination of various technological options.

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This segment of the Rover and Telerobotics Technology Program includes technology development for on-orbit satellite and large-platform servicing for both free-flying and platform-attached servicing robots. Target applications emphasize ground control and include such tasks as remote surface inspection of Earth-orbiting platforms using telerobotic systems, and dual-arm autonomous manipulator control for free-flying servicing. The terrestrial spin-offs portion involves tests and demonstrations of space-targeted technologies in realistic settings; included are tasks intended to rapidly move program-developed technology to commercial applications. JPL and industrial partners collaborate to create and demonstrate full-system prototypes that offer solutions to terrestrial problems; such solutions can positively impact significant areas of the national economy.

Muscle Actuators

Electroactive polymers (EAPs) are emerging as new actuation materials with capabilities that cannot be matched by striction-limited, rigid electroceramics, used to perform various tasks such as articulating spacecraft components. EAP materials can be easily formed in any desired shape, can be designed to emulate the operation of muscles, and have unique characteristics of low density and high toughness. EAPs offer unique enabling technologies (potentially including end-effectors and manipulators) as well as shape control of inflatable structures.

This task objective is to develop low-mass, compact, low-cost, low-power EAP muscle actuators, required for collection and manipulation of surface samples from a rover or lander. The near-term objectives are to develop muscles that provide 15 percent larger actuation force than that of the previously developed muscle, and to develop a 2-degrees-of-freedom arm with a grip end-effector driven by EAPs. The overall goal is to establish alternative actuation-enabling technology for missions that place tight restrictions on mass, size, power, and cost.

Compact muscle actuators that employ EAP materials — which are being continually improved and incorporated into the design — are being developed to harness the high displacement at low power, mass, and size capabilities of these materials. To demonstrate performance, an end-effector will be designed and fabricated that emulates the operation of a hand and a miniature manipulator arm that will support and articulate the end-effector. The demonstrator can form a basis for applications to sample-collection tasks, ultradexterous and versatile end-effectors, micromanipulators, inflatable structures, and deployment devices. Because the density of polymers is about 30 to 50 percent that of electroceramics, the EAP-muscles-driven demonstrator is expected to be significantly lighter than electroceramic actuators. The potential use of multifiber in the construction of muscle actuators will provide higher stiffness while assuring resilience and actuation redundancy; i.e., high operation reliability and toughness.

A four-finger gripper actuated by an electroactive polymer. The gripper opens the fingers and lifts a 10.3-gram rock.

Prior emphasis has established a capability to produce and test EAPs and demonstrate a muscle actuator with at least 10 percent contraction actuation displacement. These goals were achieved using a new type of EAP material called ion-exchange, platinum-membrane composite (IPMC) polymers, or "ionomers." Current development focuses on end-effector grip with fingers of encapsulated ionomer having enhanced actuation force. A 2-degrees-of-freedom, EAP-driven manipulator has a dual-sided comb-electrode muscle actuator lifter and a multifinger end-effector gripper. A long-term goal of this task will be to investigate the issue of EAP muscles operation at low temperatures as well as the integration of an EAP-driven, dexterous, multi-degrees-of-freedom arm into a sample manipulation testbed.

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Dexterous Arm Control for the Ranger Flight Experiment

The NASA Ranger Flight Experiment, led by the University of Maryland, is aimed at the development and demonstration of robotic technologies for executing manipulation tasks in space. The Ranger robot incorporates two dexterous 7-degrees-of-freedom manipulator arms mounted on a mobile base. The arms will be used, individually and cooperatively, to perform a variety of manipulation experiments and servicing operations. Based on a recent trade study on dexterous arm control, the configuration-control approach developed at JPL has been adopted for implementation on the Ranger dexterous arms.

Collision-avoidance and base-placement capabilities will enhance the Ranger system and add to the range of tasks that can be accomplished.

The goal of the JPL task is to augment the operational capabilities of the dexterous arms in the Ranger Flight Experiment within the configuration-control framework. There are two specific objectives of the task. The first is to develop the capability of online collision detection and avoidance for the Ranger dexterous arms. This capability does not currently exist in the Ranger baseline control system, and erroneous operator commands can cause collisions between the dexterous arms and the camera and grapple arms, the base, or the task board. This added capability will enable collision-free motions of the arms throughout the work space. It will also cause a reduction in the Ranger operation time, since several possible motions with potential collision are not executed. In addition, this capability will increase the safety of the Ranger during the operation of the arms, a feature vital to the success of the Ranger mission.

The second objective of the task is to provide the ground operator with a software tool for optimal placement of the Ranger base. This algorithm will ensure that both dexterous arms can reach the task site and that the useful work space volume is maximized. The algorithm will take into account the fact that the Ranger base is attached to the spacecraft by the grapple arm. Therefore, the configuration of the grapple arm will also be taken into consideration. At present, the placement of the Ranger base is done by the ground operator in an iterative trial-and-error fashion.

The collision-avoidance and base-placement capabilities will considerably enhance the robustness and reliability of the Ranger control system and will significantly expand the range of tasks that can be accomplished in the Ranger Flight Experiment. A series of technology experiments has been conducted at JPL to demonstrate the efficacy of the collision-avoidance and base-placement algorithms.

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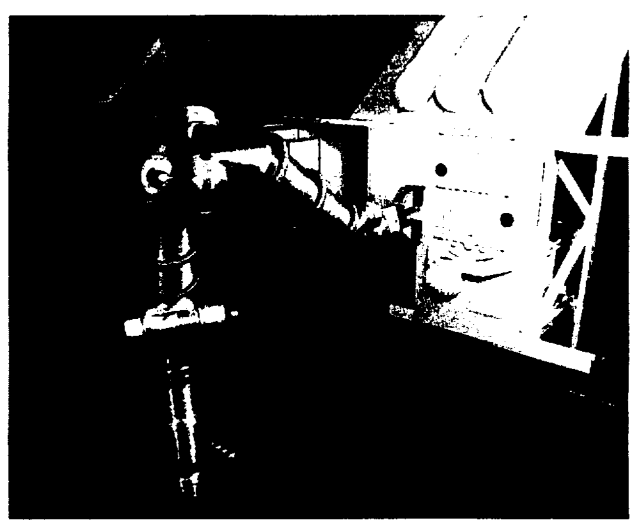
Robotic Contact Control

Reducing the crew Extravehicular Activity (EVA) time spent on maintenance has been identified by the International Space Station (ISS) Program Office as the single most critical factor in enhancing ISS functionality. The number of EVA hours that will be spent by astronauts on routine maintenance and repair activities on the Space Station directly reduces the crew time available to perform science experiments in space — which is a primary goal for the Space Station. During the life of the Space Station, numerous repetitive maintenance and repair operations will need to be performed on a routine and regular basis. These operations include, but are not limited to, in-



Contact control technologies will help automate maintenance and reduce crew EVA time.

specting, identifying, grasping, manipulating, relocating and reinserting orbital replacement units on the Space Station structures, as well as transferring various items to and from airlocks. The capability of the Space Station robotic system to perform these maintenance operations hinges on the development and implementation of robust, reliable robotic contact and motion control systems.

The robotic contact control task is responsive to this need and specifically targets the development and integration of robust robot control technologies that have a high potential to automate the maintenance operations, thereby reducing crew EVA time. Specifically, the goal is to develop and demonstrate advanced contact and motion-control technologies with the enhanced robustness required by Space Station dexterous robots to perform automated maintenance operations.

This task focuses on three challenging research areas:

- Nonlinear end-effector compliance to reduce impact forces and accommodate abrupt changes in end-effector dynamics at impact.
- Adaptive force regulation to enhance contact stability and ensure high-performance force control irrespective of contact surface stiffness.
- Robust motion control to sustain system stability and performance in the face of parameter uncertainties, payload variations, and unexpected disturbances.

The outcome of this effort will be transferred to the Canadian Space Agency for implementation on the ISS robotic system.

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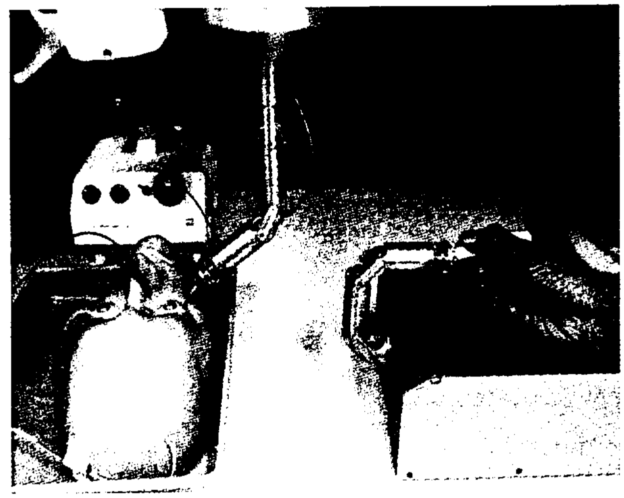
Robot-Assisted Microsurgery

Building on its established NASA technology base in teleoperation and telerobotics, JPL is collaborating with MicroDexterity Systems, Inc. (MDS) to develop a new robotic microdexterity platform with important applications in medicine. The Robot-Assisted Microsurgery (RAMS) workstation enables new procedures for the brain, eye, ear, nose, throat, face, and hand, and is being designed in cooperation with leading microsurgeons. The resulting technology developments have been evaluated in actual clinical procedures, and are being commercialized through a cooperative NASA–industry venture with MDS. JPL developed and demonstrated a proof-of-concept system; MDS provided JPL with user requirements and will perform clinical tests, obtain regulatory approvals, and commercialize the technology.



RAMS workstation with simulated patient. The surgeon manipulates the robotic arm with a hand control.

The RAMS workstation is a 6-degrees-of-freedom master–slave telemanipulator with programmable controls. The primary RAMS control mode is telemanipulation, which includes task-frame referenced manual force feedback and textural feedback. The operator interactively designates or "shares" automated control of robot trajectories. RAMS not only refines the physical scale of state-of-the-art microsurgical procedures, it also enables more positive outcomes for average surgeons during typical procedures — e.g., the RAMS workstation controls include features to enhance manual positioning and tracking in the face of myoclonic jerk and tremor that limit most surgeons' fine-motion skills.

Accomplishments to date include

- Developed a slave arm with 6 degrees-of-freedom in a compact, lightweight package. The arm is 2.5 centimeters in diameter and 25 centimeters long; its base is 17.75 centimeters long and 12 centimeters in diameter.
- Developed the master arm and integrated it with the slave robot. The master arm has 6 degrees of freedom and is 2.5 centimeters in diameter and 24 centimeters long. The size of its base is about 23 × 10 × 17 centimeters. The integrated system includes a VME-based servosystem, kinematics and high-level control, and configuration software and a safety electronics system.
- Delivered a slave robot prototype to the Cleveland Clinic Foundation for external testing. Second prototypes of the master and slave robots and control and electronics systems were also developed. A simulated eye microsurgery procedure was successfully performed using the upgraded second prototypes of the master and slave arms.

In the most recent development, force reflection was added from the slave robot end-effector to the master arm, psychophysical tests were carried out comparing operator performance in using the RAMS system, tests were performed at an external medical laboratory, a dual-arm microsurgery suturing procedure demonstration was done, and a detail design documentation of the RAMS system was completed for transfer to MDS.

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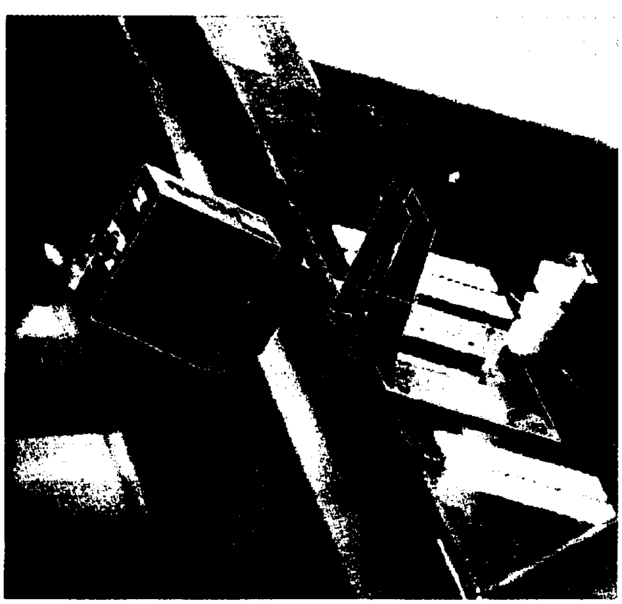
Calibrated Synthetic Viewing

Calibrated Synthetic Viewing (CSV) technology with ongoing technological enhancements is expected to be very useful for space station robotics. CSV provides the operator with calibrated graphic overlays on actual camera video images. Three-dimensional graphic models are intermittently updated through virtual reality calibration that determines the camera calibration parameters and object locations semiautomatically by using model-based edge-matching computer vision algorithms. The algorithms utilize the known geometric object models and their salient edges, and do not specifically require arrays of accurately positioned vision targets. This CSV technology has successfully demonstrated an orbital replacement unit (ORU) insertion task within a 1/4-inch alignment precision using two camera views.



Calibrated synthetic viewing gives the operator graphic overlays, intermittently updated, on video images.

The objectives of the task are to develop, enhance, and evaluate CSV technology; resolve visual occlusion and limited viewing within the harsh space lighting environment; demonstrate reliable ORU insertion with high-precision (1/4-inch) alignment for space station onboard and ground control; and transfer the technology to the NASA Johnson Space Center (JSC) Automated Robotic Maintenance for Space Station (ARMSS) testbed.

An initial version of CSV was completed and delivered to JSC with the key technical elements of

- Edge-based camera calibration and object localization.
- Graphical user interface for interactive camera/model initial adjustment and model/image edge selection and deselection.
- "Weighted average" local edge detector.
- Simultaneous update of camera calibration and object localization (a new key element to enable high-precision alignment).
- Semiautomatic intermittent model update (another new key element to enable high-precision alignment).

Preliminary experiments were performed for alignment precision analysis and JSC was provided support for CSV integration and experiments at the ARMSS facility. With CSV interface to the ARMSS robot controller, video switch, camera control, and video frame grabber completed, JSC conducted an initial experiment with teleoperation mode when the ORU was about 20 and 10 inches away from the receptacle. At the 10-inch distance, the alignment precision was about 1/2 inch.

Most recently, the task demonstrated a remote power controller module (RPCM)–like ORU insertion with ORU/receptacle array under harsh space lighting conditions, and delivered the enhanced CSV technology to JSC. Other items include

- Adding a point-matching operator interface for easier, faster initial operator data entry.
- Devising an effective strategy to cope with harsh space lighting conditions.
- Developing an algorithm for robust edge matching against false matches using a sequence of previous images.
- Developing an interactive "task-level" model building to handle undefined models.
- Performing quantitative error analysis and evaluation.

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This segment of the Rover and Telerobotics Technology Program — typically about 20 percent of the total program — develops technologies in areas of national importance, in support of non-NASA sponsors. Examples are microrobots for urban terrain operations and stereo vision for autonomous ground vehicles. These technologies have important concurrent applications to NASA missions.

Microrobots for Urban Terrain Operations

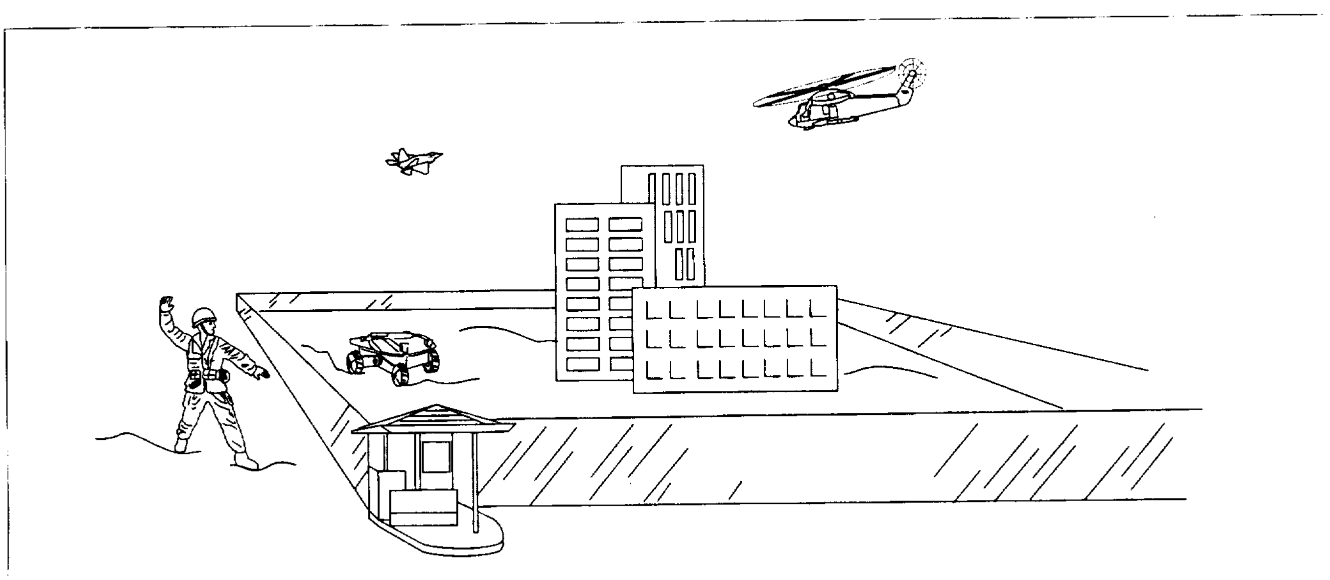
Mobile, stealthy, microrobot sensor platforms — small and cheap enough to be carried and deployed by individuals — can revolutionize the information-gathering process in urban terrain operations. JPL, in collaboration with its partners at the U.S. Army Research Laboratory, Oak Ridge National Laboratory, and the University of Southern California, is developing such microrobots, leveraging from its technology base in microrovers for planetary exploration.

Robots in general, large or small, are very useful for military missions. They repeat tasks precisely and are immune to fatigue, hazards, and emotions. Microrobots complement larger robots owing to these characteristics:

- They can perform rapid maneuvering in constricted urban spaces to which larger robots cannot gain access.
- Access and penetration are enabled by variable configuration with reduced footprint.
- Possession of human-pack portability to cross difficult terrain and overcome obstacles.
- Their small, innocent look makes them hard to detect or interdict, especially from overhead.
- They are easy to insert, recover, sterilize, or destroy.
- Low cost leads to cheap, robust, multiply-redundant, collaborating assets.

In outdoors operation, microrobots would be used to get to targets through narrow conduits and small gaps in guarded areas, but would remain primarily outdoors. Microrobots could perform indoor reconnaissance for localization of targets, people, and materiel, requiring building entry, interval navigation to avoid furniture, negotiation of hallways or air conditioning ducts, moving up and down stairs, etc.

Microrobot locomotion will be provided by a unique wheel-on-struts vehicle with four wheels on "posable struts." Each



A generic outdoor reconnaissance profile with application of specialized sensors integrated with outdoors navigation.

strut can be rotated through 360 degrees, enabling the vehicle to stand tall, crouch low, right itself after flipping over, climb stairs, and roll and somersault over rubble. The microrobot configuration is derived from the JPL nanorover vehicle.

Perception for reconnaissance will be performed by integrating visible and thermal-infrared imagers and an acoustic/vibration sensor. The proposed visible imager is the active pixel sensor (APS) camera; the infrared imager is JPL's cooled quantum-well infrared photodetector (QWIP), which can be implemented in a palm-size, 1/2-kilogram package. The acoustic/vibration system will build on microseismometer technology developed in JPL's Microdevices Laboratory. Thermal imagers will very effectively detect people at night and can detect trip wires due to emissivity differences between the wire and the background.

The effectiveness of the urban microrobot is being demonstrated in two scenarios. In a building-clearing operation, for example, the vehicle may be tossed in a doorway, pointed down the hall, and commanded to scurry along the wall until side-looking laser sensors detect a doorway or branching hallway. Before crossing such a space, the vehicle would stop and listen with the acoustic/vibration system; a second behavior would dash into the open, take video, and dash back into cover, or extend a small boom with the cameras into the open to achieve the same purpose; lastly, the vehicle would conduct stealthy reconnaissance of the new area. Analogous outdoor scenarios include driving and hiding along the curb of a street to look around the next intersection, driving in a ditch and pausing occasionally to listen, or being deployed to use the video motion-detection capability, acting as a wing-man to cover the soldier's flank.

The microrobot under development would dramatically improve the effectiveness and survivability of individual combatants operating in restrictive areas. The vehicle developed by this effort will be the vanguard of a new generation of miniature, mobile, intelligent sensor systems that contribute to dominant battlefield awareness and successful small-unit operations.

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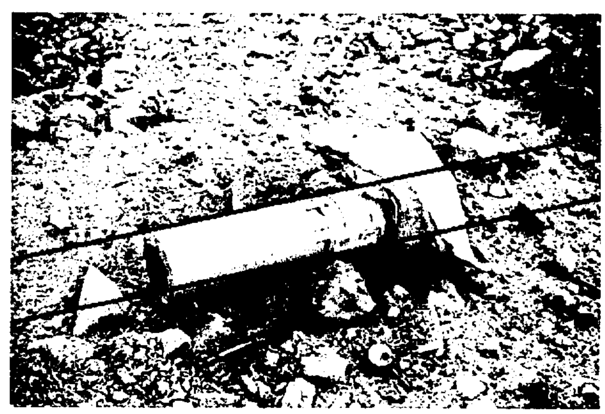
Ordnance Recognition

JPL is performing research in the area of ordnance recognition for the semiautonomous clearing of test ranges. In the current scenario, unmanned ground vehicles (UGVs) survey a test range identifying possible locations of unexploded ordnance for immediate neutralization.

Current research focuses on the recognition of ordnance through the extraction of parallel lines from image edge maps. In close-range recognition, the edges of the ordnance are detected and parallel lines are extracted from the edge image.

The method used to extract the parallel lines from the edge image is called RUDR, for "recognition using decomposition and randomization." In this application of RUDR, a series of single edge pixels is sampled from the edge map. For each such pixel, analysis is performed to determine whether the pixel belongs to a pair of parallel lines, and, if this is the case, the parallel lines are stored. A low probability of failure can be achieved after sampling a relatively small fraction of the edge pixels.



Location of ordnance using edge-detection techniques.

Previous work included detecting large ordnance in range imagery by extracting cylinders from the range data computed from passive stereo vision. Passive stereo techniques are used to compute a depth map of the scene, which is also rendered as a three-dimensional plot of the points determined to lie on the cylinder. Initial work in this area suggests that visual texture, as well as image edges and range data, is useful in localizing ordnance.

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Wide Field of View Stereo

The wide field-of-view (WFOV) stereo system is a JPL-based task in the Department of Defense's Unmanned Ground Vehicles Project (UGV). WFOV is a real-time system that produces dense range maps from a stereo pair of cameras mounted on a High-Mobility Multipurpose Wheeled Vehicle or HMMWV ("Hum-Vee"), the military's modern-day Jeep equivalent.

One portion of data from the WFOV system. This is the left image from a stereo pair with overlays indicating positive and negative obstacles. (The system displays overlays in colors, but are shown here in shades of gray.)

From what the camera sees, images are extracted that include color overlays to indicate both the locations of positive obstacles and the leading edges of negative obstacles; stereo disparity (related to distance from the cameras), and elevation maps of the range data. In all cases, the colors span the rainbow, with red representing low values and violet representing high values.

The range data are being used by higher-level vehicle-control systems for autonomously navigating around local obstacles that are encountered during battlefield maneuvers. The system is being integrated into the UGV vehicles at the Lockheed Martin Corporation.

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While the JPL Rover and Telerobotics Program has built a record of substantial achievement, important technical and programmatic challenges remain. The following are near-term goals:

- *Enable next-generation affordable rover missions to Mars (for example, as part of the Mars Surveyor Program).*
- *Reduce landed mass over the Mars Pathfinder rover of at least a factor of two (demonstrate feasibility of a less-than-5-kilograms rover).*
- *Achieve higher science return in rover missions by enabling many short-to-medium range traverses, active and passive power management, and effective science site exploration and sampling. Such tasks would include confirming and mapping science targets, exposing and retrieving fresh rock and other samples, and accurate deployment and pointing of instruments. Products are to include*
  - *— Long-range science rover capable of traversing tens of kilometers in natural terrain and performing sample selection and acquisition, providing the baseline for a 2001 mission.*
  - *— Sample retrieval rover capable of acquiring previously cached material in near proximity to a companion ascent vehicle.*
  - *— Nanorover to be a flight article for the MUSES-CN comet sample-return mission.*

The following are long-term challenges:

- *Develop self-sustaining (longer than 5 years) robots capable of global-scale (more than 5000 kilometers) movement and navigation in rough terrain, for opportunistic adaptive exploration and search for fossils and other signs of life on planetary surfaces.*
- *Develop low-mass, maneuverable robots for deep (more than 1 kilometer) subsurface scientific data and sample extraction. Products are to include a subsurface explorer using an all-percussive piledriver, capable of penetrating more than 1 kilometer in to the subsurface, and carrying and deploying a microscopic imaging camera and Raman spectrometer.*
- *Affordable coordinated robots that can deploy, assemble, and construct laboratories and facilities in planetary orbits and on surfaces.*
- *Autonomously coordinated planetary surface, subsurface, and atmospheric many-robot operations; autonomous synthesis of integrated conclusions from different robotically acquired scientific data types.*

An important future goal is to broaden the range of applications of telerobotics in space. Emphasis on mobile robots for surface operations has resulted in significant demonstrated opportunities in flight experiments and missions. Telerobotics technology, however, can enable a much broader range of missions, such as autonomous robots for sample return from planetary, cometary, and asteroid missions. Synthesizing new classes of robot configurations for such missions and evaluating the corresponding benefits also pose an important future challenge.