# The Evolution of Space Robotic Exploration

## Manipulation, Mobility and On-board Intelligence


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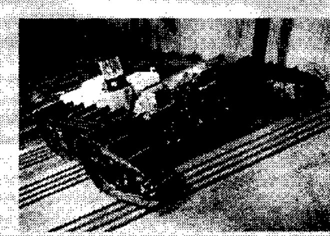

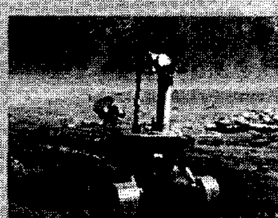

**The University of Reading, England**
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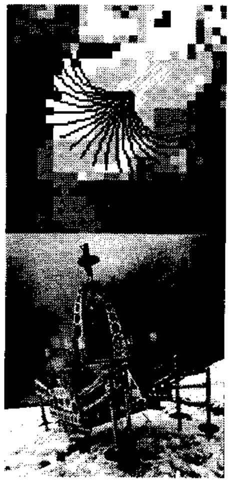
# Outline

- Space Robotics & Mobile Planetary Exploration
- Operational Challenges & Future Vision (s…)
- Surface, Aerial and Subsurface Domains
- Technology Needs & Performance Metrics
- Emerging Robotic System Architectures
- A Path Ahead: Moon, Mars, and Beyond
- Human, Robotic and H/R Exploration

# Planetary Surface Exploration

*(Reference: NExT Study on Space Robotic Capabilities)*

## *Surface Mobility*



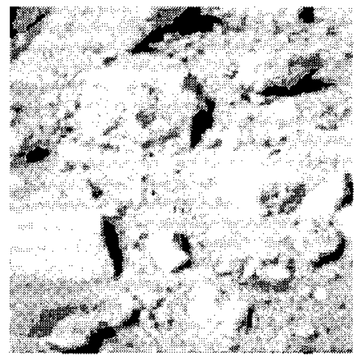
**Mobile Autonomy**

Terrain assessment, path planning, visual servoing

**Mobility Mechanization**

Extreme terrain access, energy efficiency

## *Science Perception, Planning & Execution*



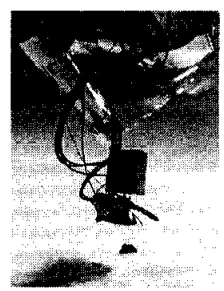
On-board and ground tools; data analysis, target selection, operations planning and execution

## *Human-Robot EVA Interactions*

Tele-operation and human supervision of robotic explorers

Robotic work crews

## *Instrument Placement and Sample Manipulation*



Position sensors, collect and process samples

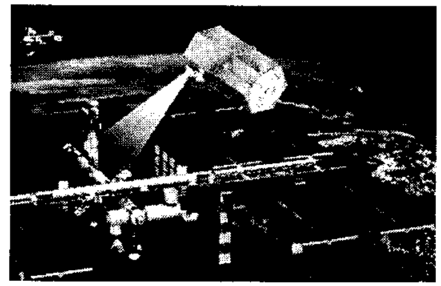
# In-Space / On-Orbit Operations

*(Reference: NExT Study on Space Robotic Capabilities)*

## *Assembly*

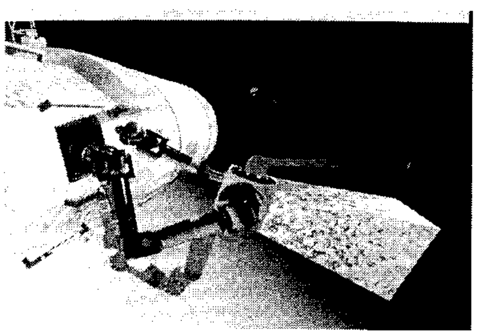
Transporting and mating of components; making connections; assembly sequence planning and execution; assembling small structures

## *Inspection*



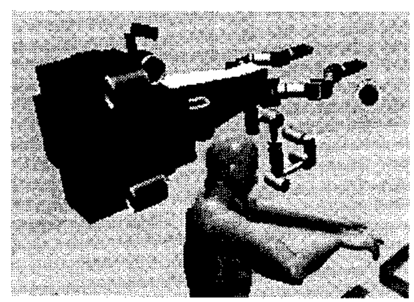
Visual inspection of exterior spacecraft surfaces; path planning and coverage planning; automated anomaly detection

## *Maintenance*



Change-out of components; accessing obstructed components; robotic refueling

## *Human EVA Interaction*



Monitoring and documenting EVA tasks; preparing a worksite; interacting with astronauts; human-robot teaming

# Related Challenges—EDL and Sample Return

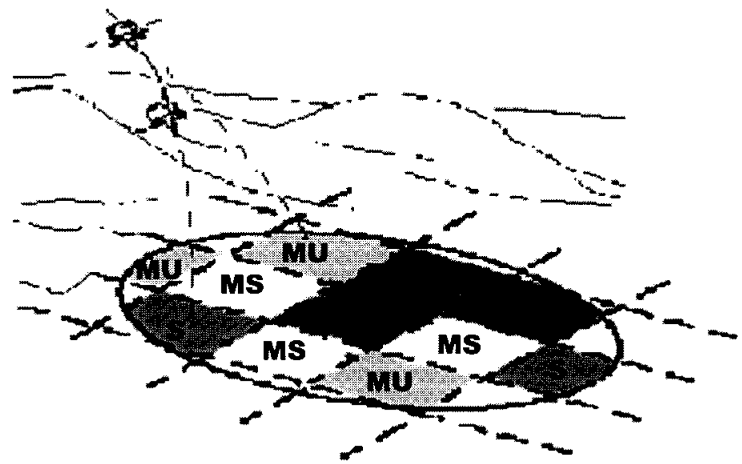
## *Precision Safe Landing, In-Orbit Rendezvous & Sample Capture*

*Develop capability for safe landing on a planetary surface using multiple sensors and appropriate on-board intelligence.*

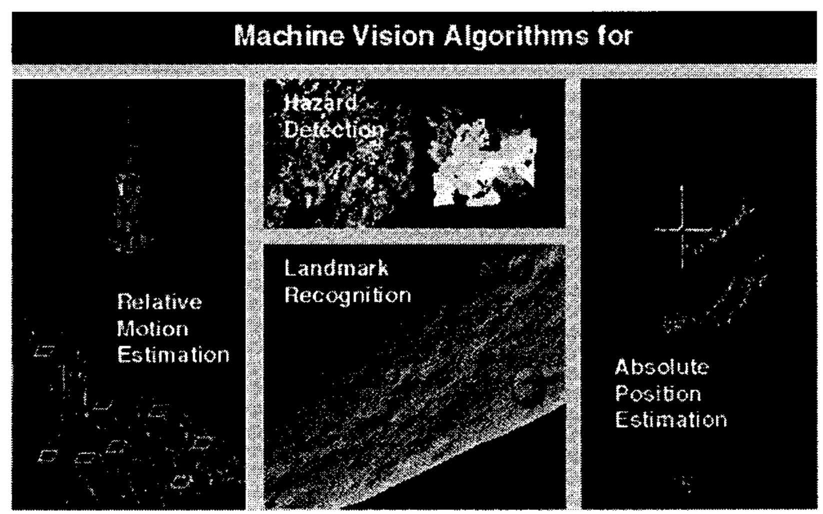
- ***Site Risk Assessment***: The safety of potential landing sites will be assessed independently by onboard sensors, and integrated to form a multi-grade representation of the landing site safety.
- ***Optimum Site Selection***: Based on the site safety map and the spacecraft constraints, the optimum landing site will be selected and the spacecraft will be re-targeted to the new site.

*Develop the capability to precisely localize a spacecraft and control its position and velocity with reference to both natural and artifactual objects*

- ***Feature Tracking & Position Estimation***: Sense, extract, and track in real-time features of interest (planetary surfaces, small bodies, other orbiting space-craft), to predictively control spacecraft trajectory with reference to same




Onboard risk assessment and site selection
U= Unsafe, MU= Moderately-Unsafe,
MS= Moderately-Safe, S=Safe



# Mission Opportunities and Needs (Decadal)

- The recent Space Studies Board/NRC Decadal survey sets priorities for solar system exploration missions that will require advancement of aerial, surface, and subsurface robotic capabilities
- These New Frontiers missions (non-Mars and < $650 M) include Lunar Sample Return, Venus In Situ Explorer with expected technology feed-forward to later Mars and Venus sample returns
- Similarly (for missions > $650 M), Europa Geophysical Explorer is seen as a precursor to a Europa Lander. Cassini-Huygens findings are expected to motivate a sequel Titan aerobot capability, which has figured prominently in Code S planning to date
- Technology drivers at large include on-board autonomy, mobility mechanization & survivability, hard-to-reach mobile/manipulative sampling access, with system-related recommendations for supporting avionics advanced packaging and miniaturization
- The perspective of the Decadal survey is clearly one—given its ten year frame of planning—of advancing autonomous robotic capabilities for space exploration as a precursor to emplacing and sustaining a joint *human-robotic presence* (Lunar, Mars or other sites).

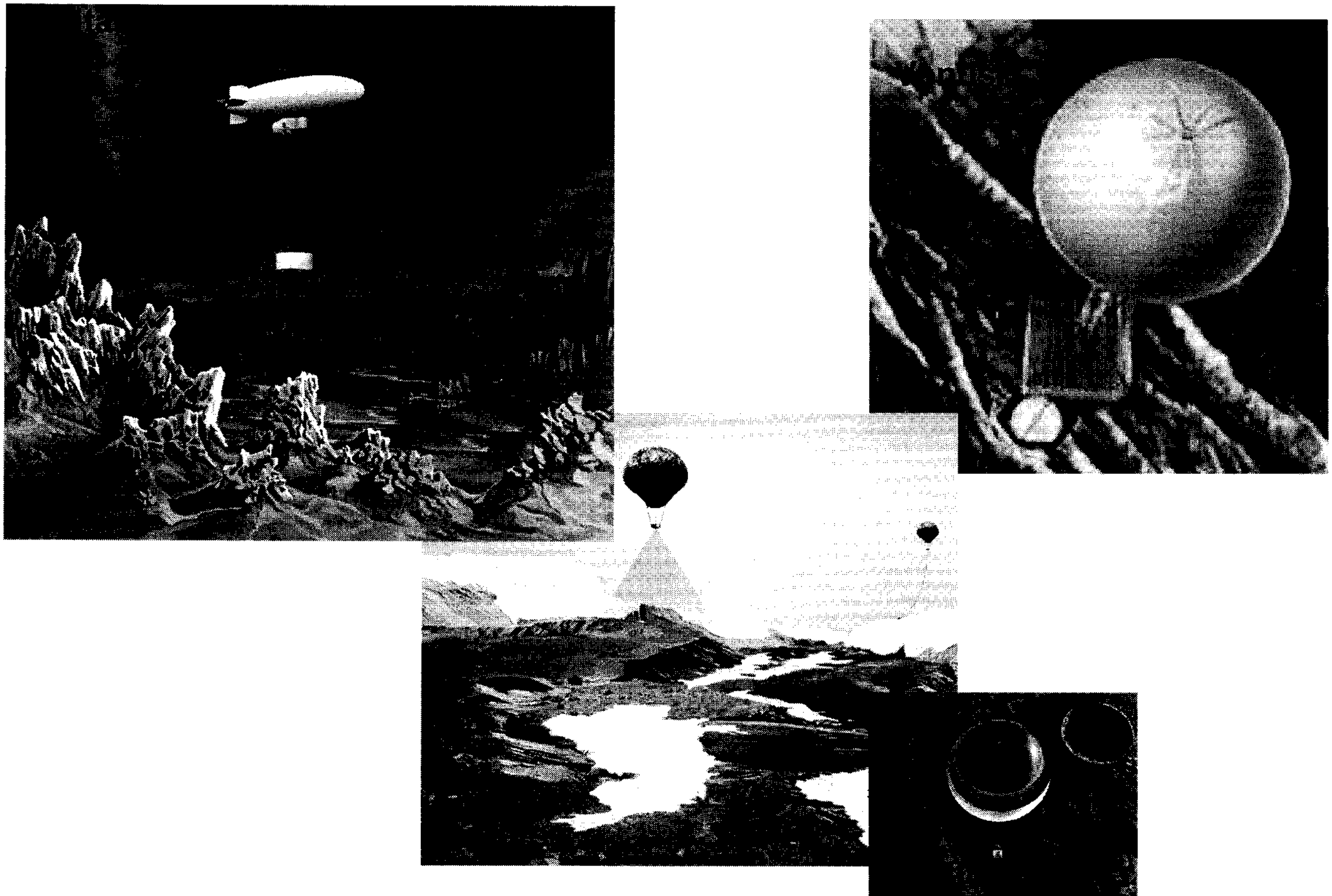
# Mission Opportunities and Needs (NExT)

- The NASA Exploration Team (NExT) has explored an overarching set of mission needs, metrics and roadmaps leading to Technology for Human/Robotic (H/R) Exploration and Development of Space (*THREADS*).
- The scope of this study includes human-robotic system applications in Space Science, Earth Science, Biological & Physical Research, Human Exploration & Development of Space, and Aerospace.
- NExT is a "science discovery-driven" technology innovation model that advocates a "stepping stone approach" to earth/LEO (Space Station), Earth Neighborhood and Accessible Planetary Surfaces (e.g., large optical systems out to 1.5M km, supporting human-robotic infrastructure for assembly-maintenance, sustained planetary surface exploration, etc.), and ultimately travel to 1.5 AU and beyond and *a persistent human-robotic scientific presence.*
- Assumptions in the technology roadmaps are dramatic increases in on-site productivity and intelligence of human-robotic tools, some degree of self-healing/assembly and underlying automated reasoning, "smart sensing" and fail-soft reliability that grounds these assumptions (as well as the extensible and distributed human-machine robotic architectures that would be the basic glue, e.g., "intelligent modular infrastructures").

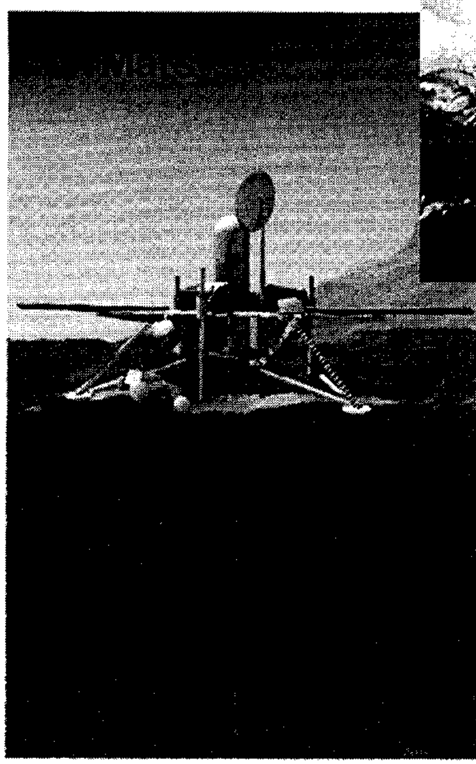
# Examples of Mobile Robotic Systems for Space

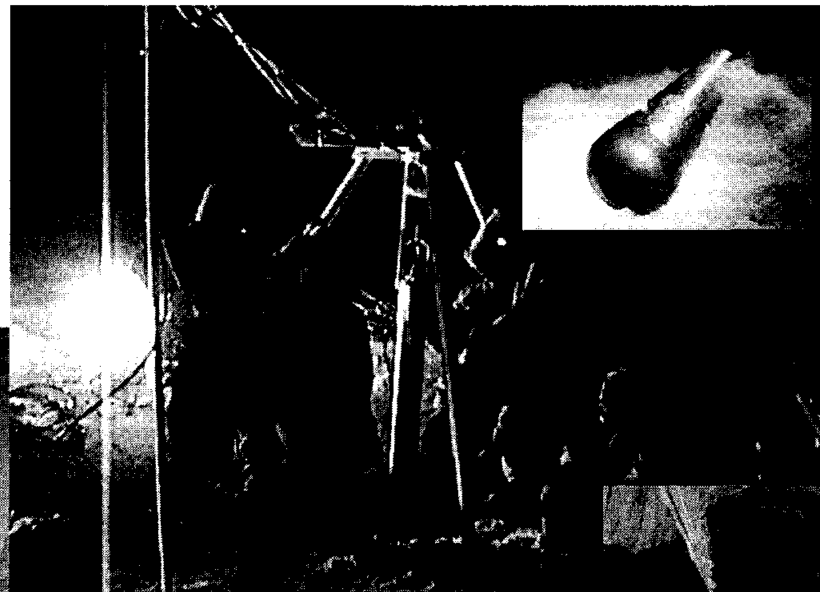
- Aerial Systems *(Venus, Mars, Jupiter, Saturn, Titan)*
  - Fixed-wing airplanes
  - Balloons, blimps ...
- Surface Systems *(Mars, Europa, Titan)*
  - Science rovers (… beyond Mars)
  - Advanced mobility systems (cliffs, craters, etc)
  - Long-duration systems, cooperative assets, robotic outposts...
- Sub-surface Systems *(Mars, Europa)*
  - Gravity penetrators
  - Shallow and deep drills
  - Burrowing devices/moles
  - Directional melters, aquabots (deep ice/water)
- Related Sample Acquisition & Handling *(Mars, Europa, Titan, ...)*
  - Mobile manipulators for instrument and drill placement
  - Precision rendezvous and transfers between mobility elements
  - Sample exchanges between acquisition/*in situ* analysis systems
  - Sample protection and containerization for sample return

# Aerial Exploration

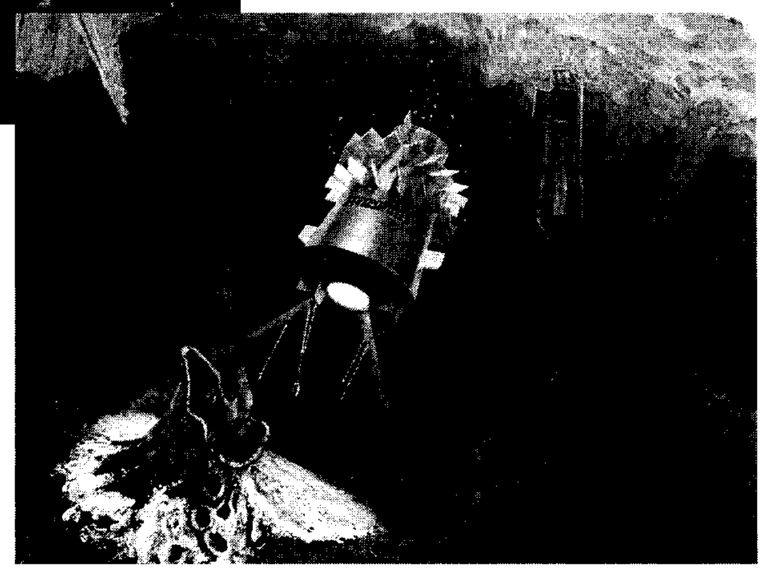


# Subsurface Exploration



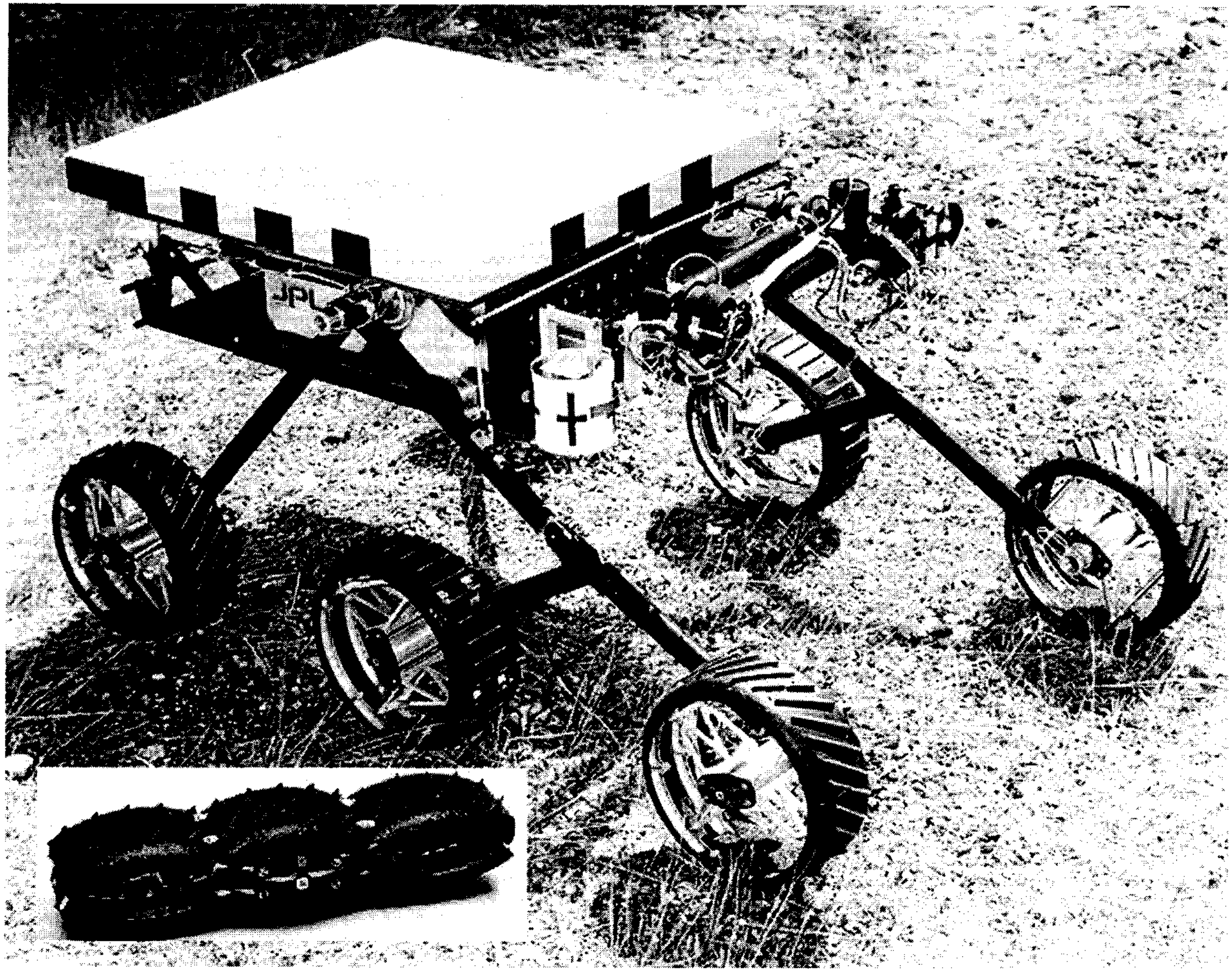


Venus

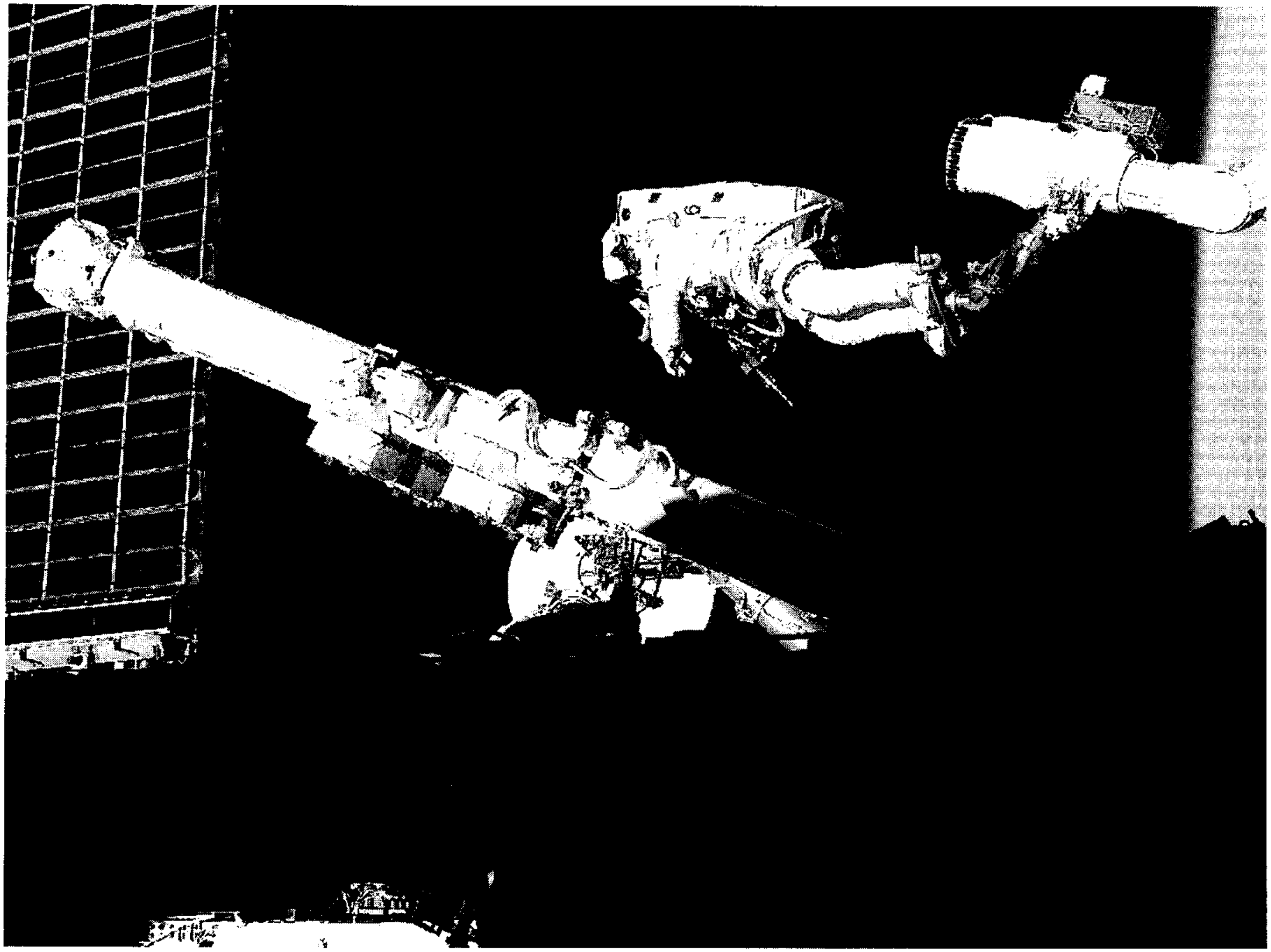


Mars

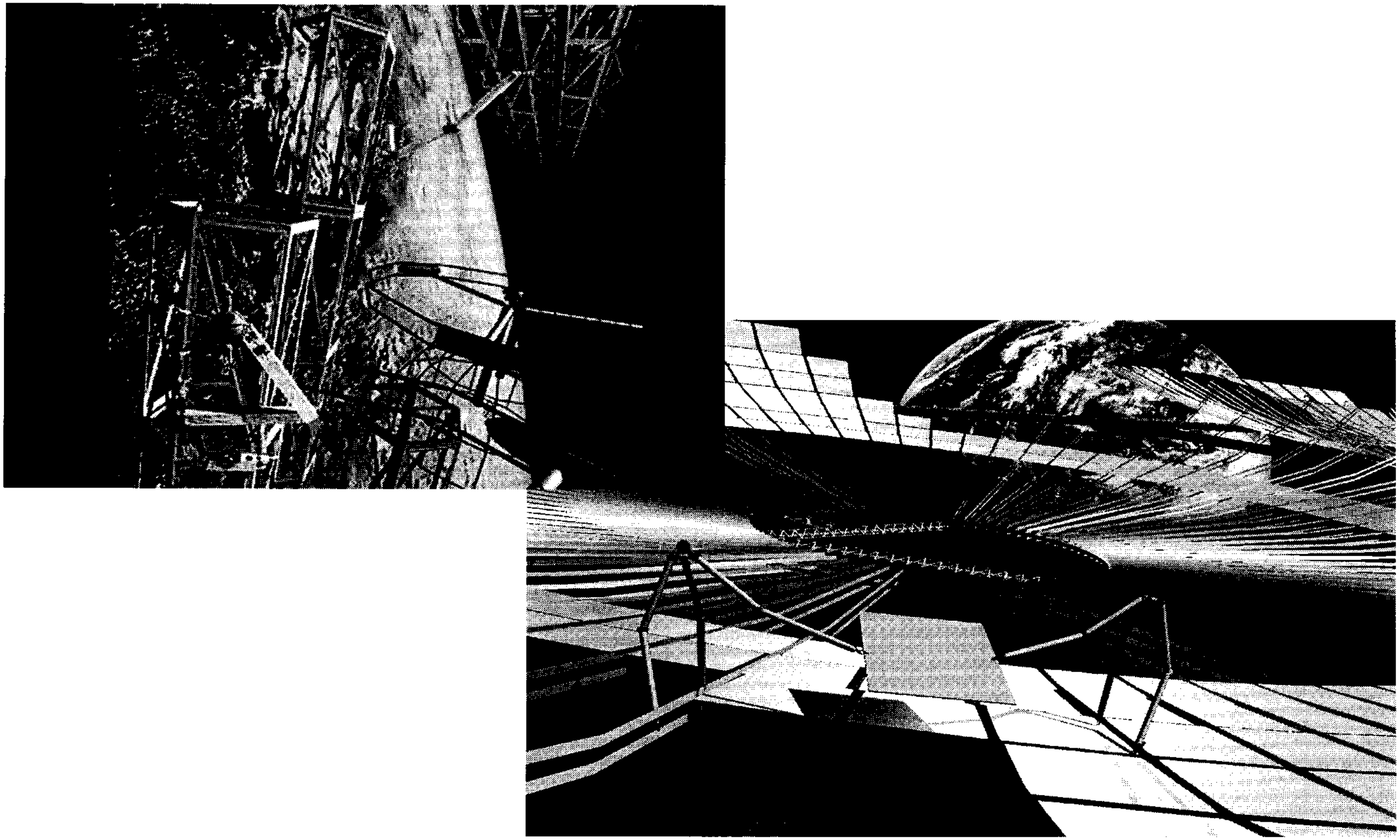
# Surface Exploration



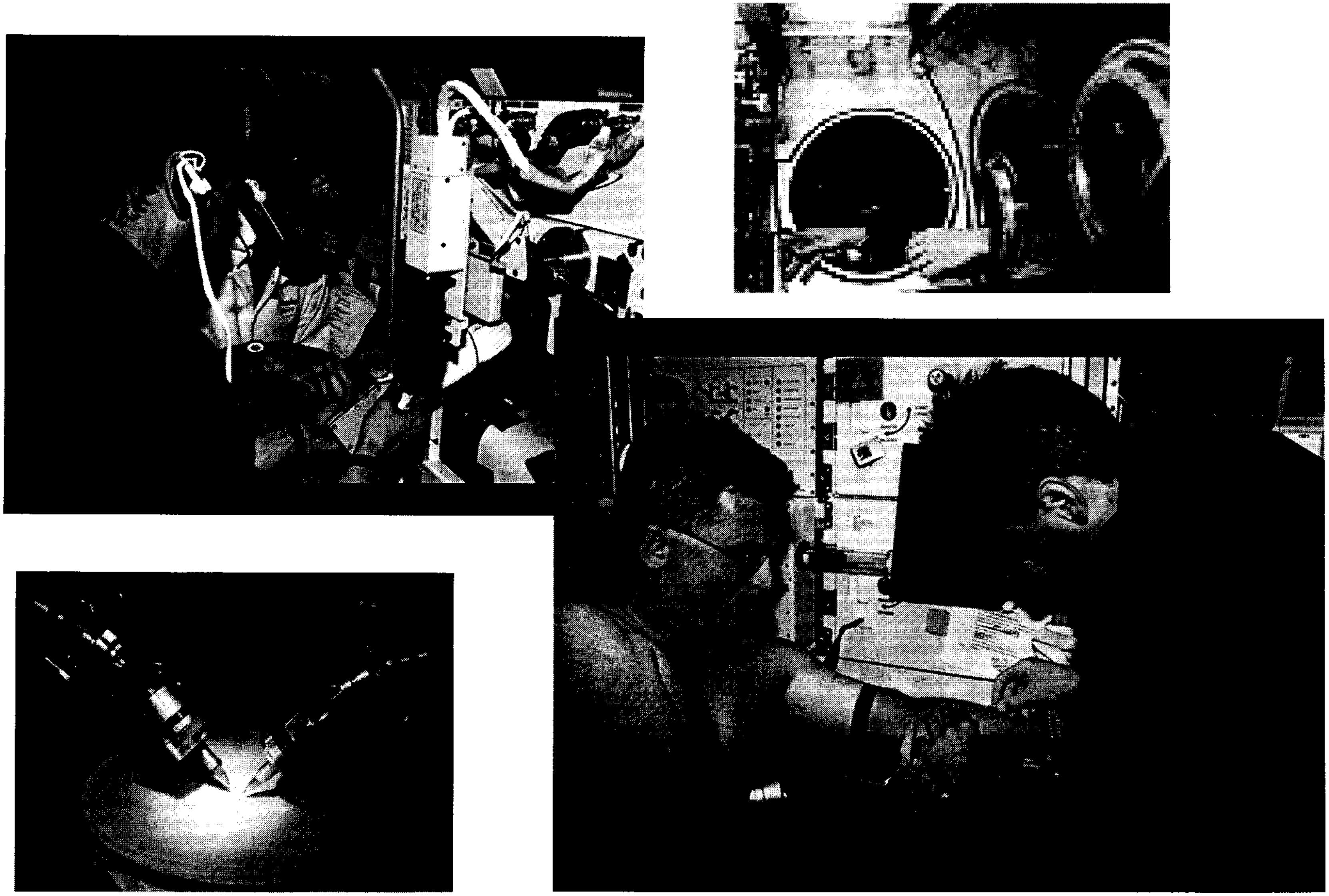
# In-Space Operations



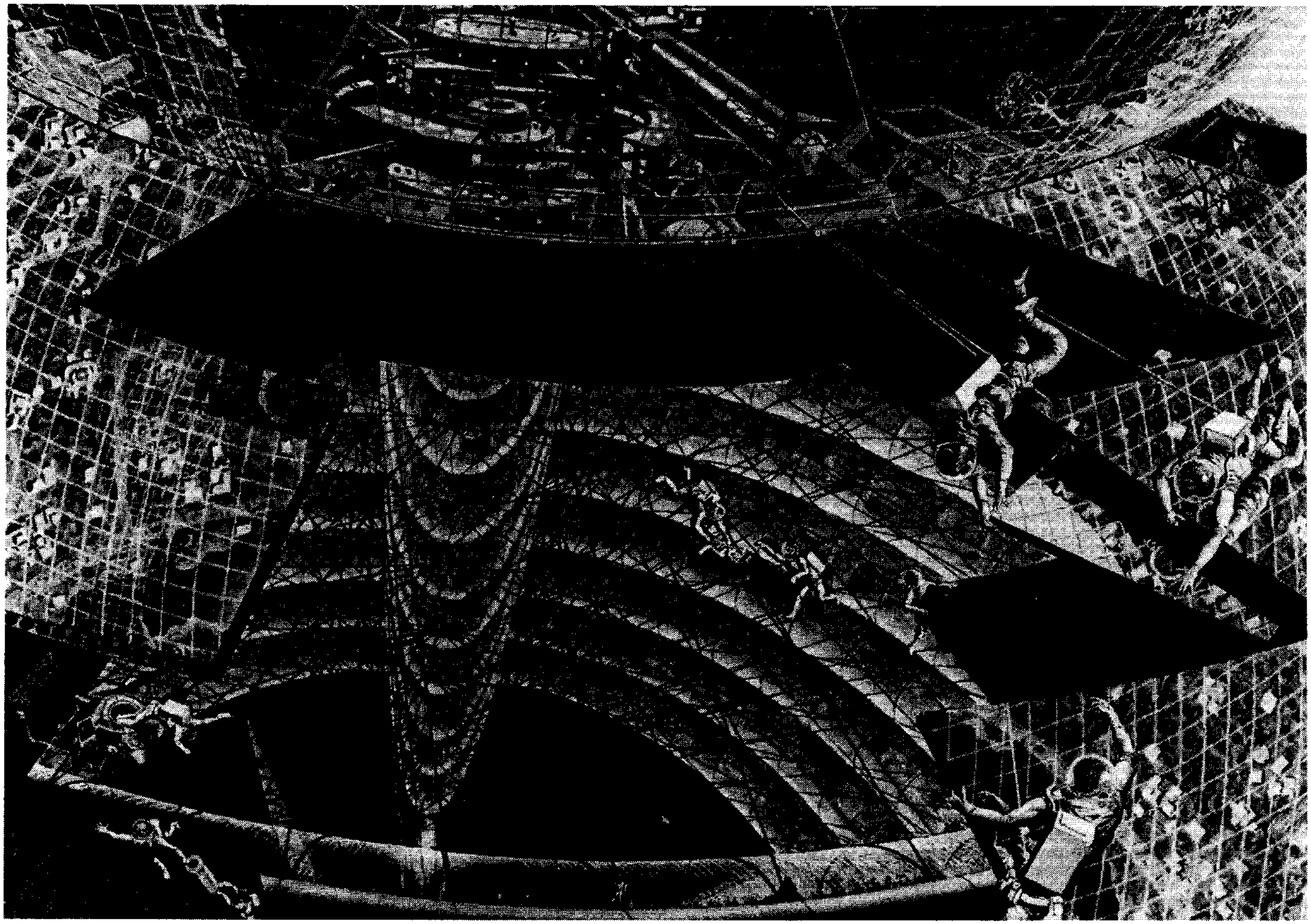
# In Space Assembly



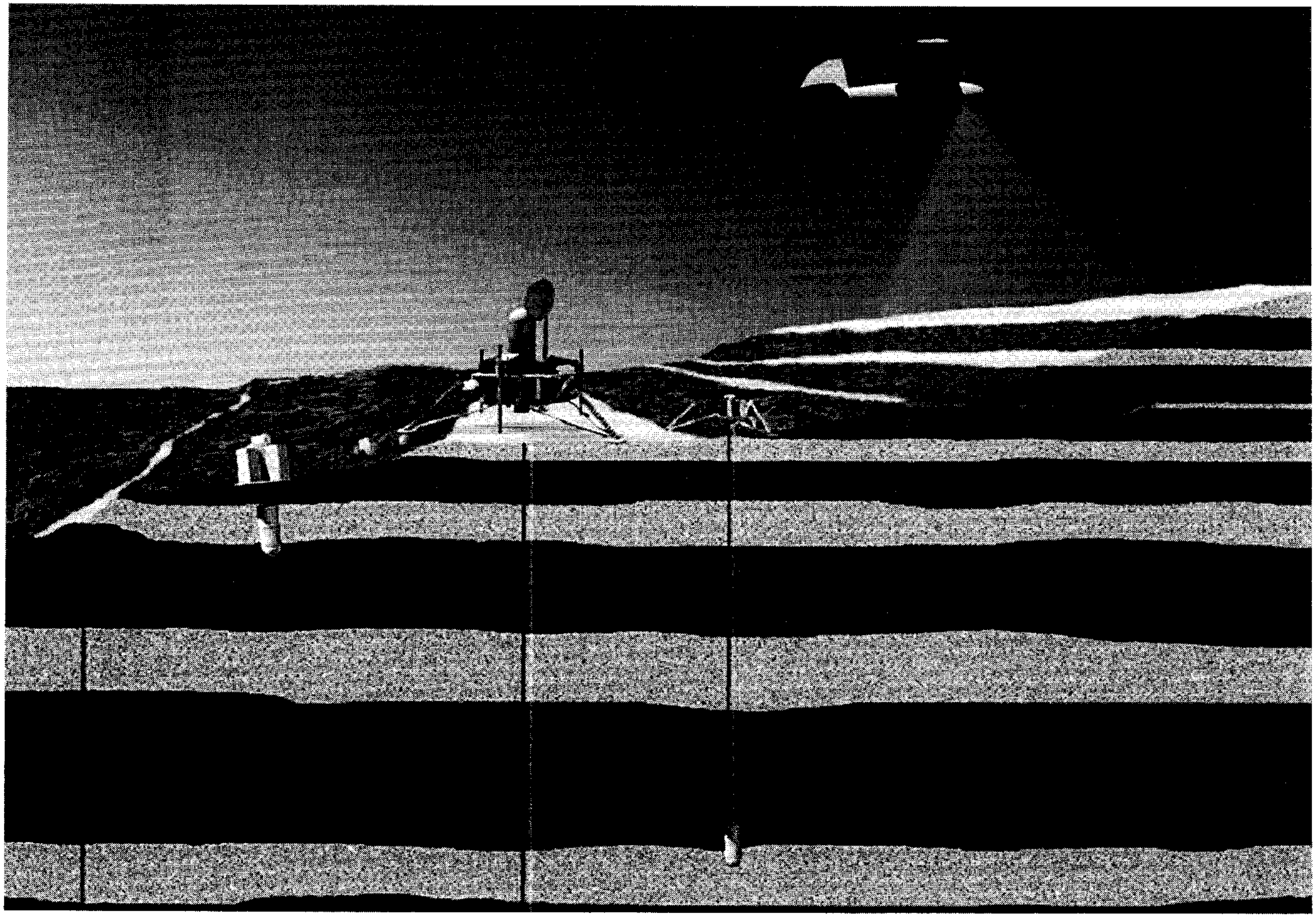
# IVA Robotics



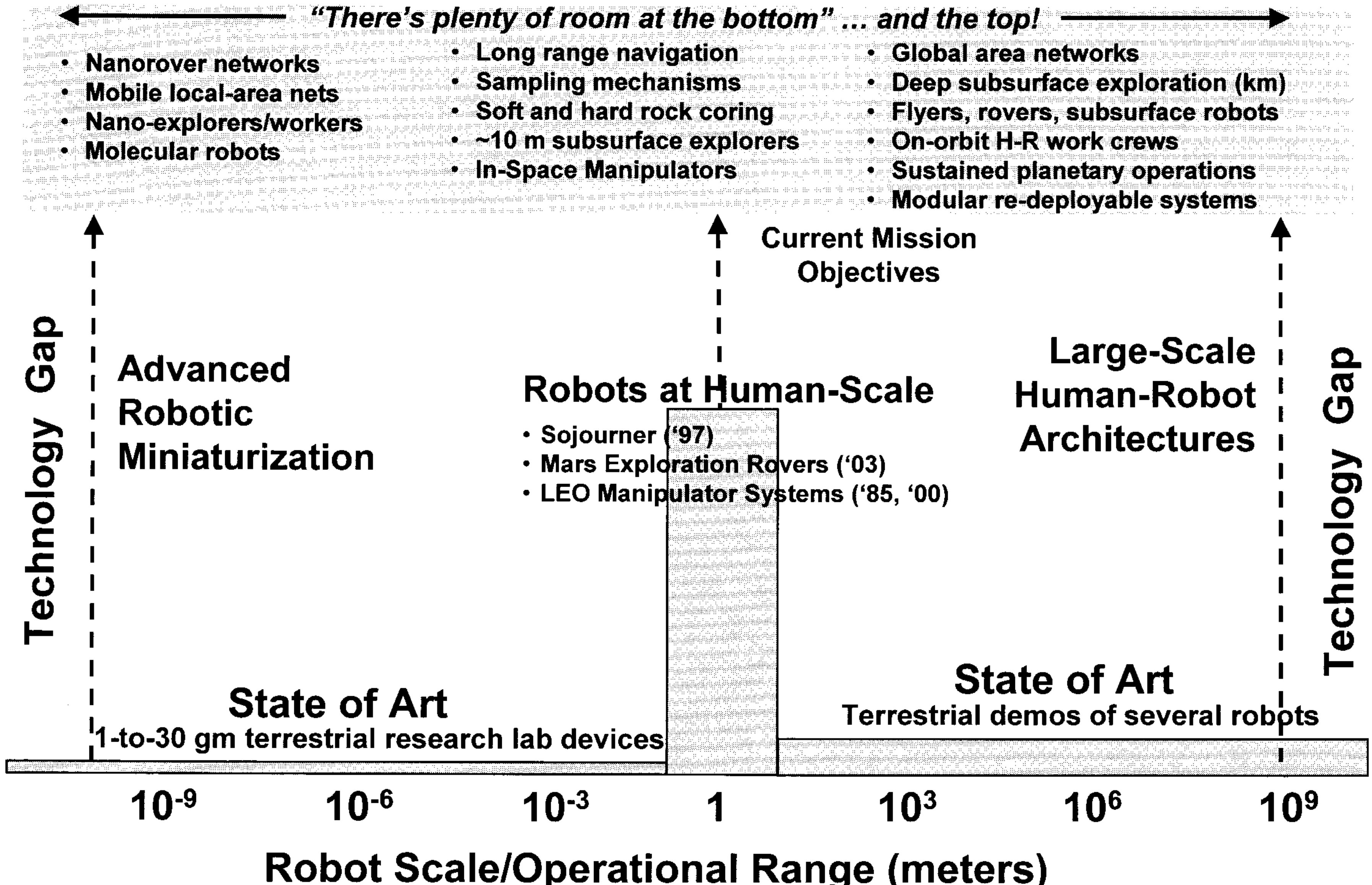
# A Past Vision for Human/Robotic Systems ! ...



# … a More Recent Vision for Planetary Exploration

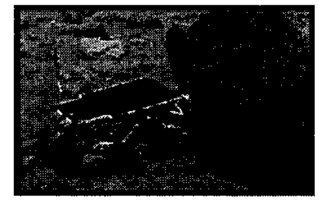


# The Scale, Theatre, & Performance of Space Robotics

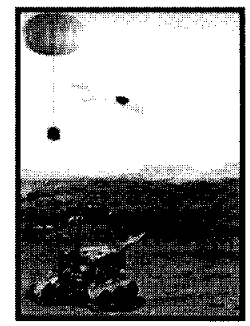


# Challenges—Mobile Space Robotic Exploration

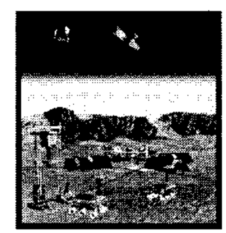
***Enabling and Enhancing Science Return***



- **Extend the range and duration of single missions**
- **Reduce uplink cycles per science target acquisition**
- **Enhance diversity of instrument deployment options**



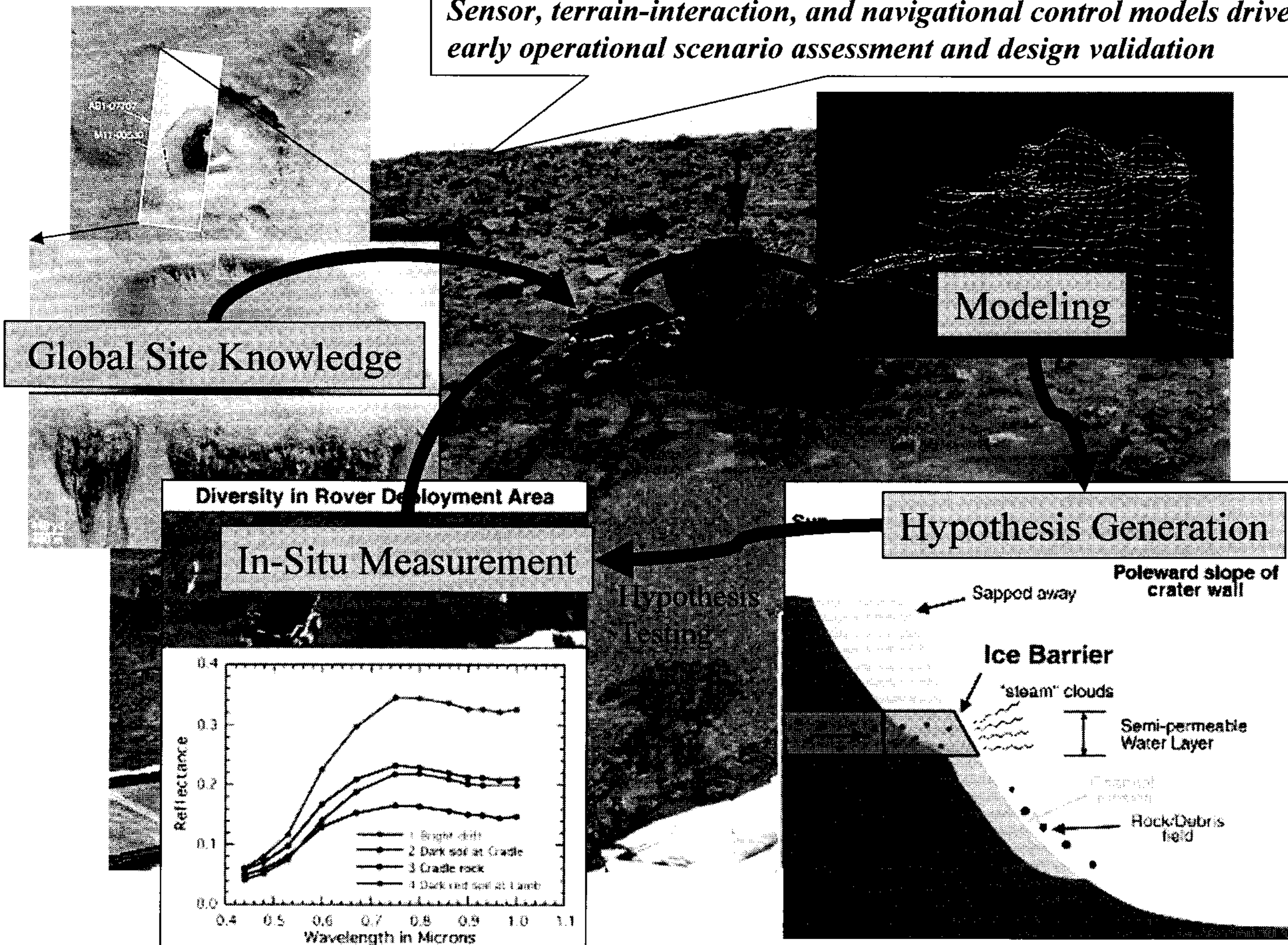
- **Provide mobile access to more featured, adverse terrain**
- **Broaden surface payload landing options (hard and soft)**
- **Access disparate subsurface regions (soil/rock, ice/water)**
- **Span highly variable atmospheres (controlled ascent/descent)**



- **Return pristine surface & subsurface samples for earth analysis**
- **Coordinate aerial, surface, & subsurface assets for global coverage**
- **Increase fidelity of ground simulation, operations & science training**
- **Sustain—ultimately—a permanent networked robotic science presence …**
- **…and implement a meaningful partnership between humans & robots in space.**

# Science Operations on Planetary Surfaces

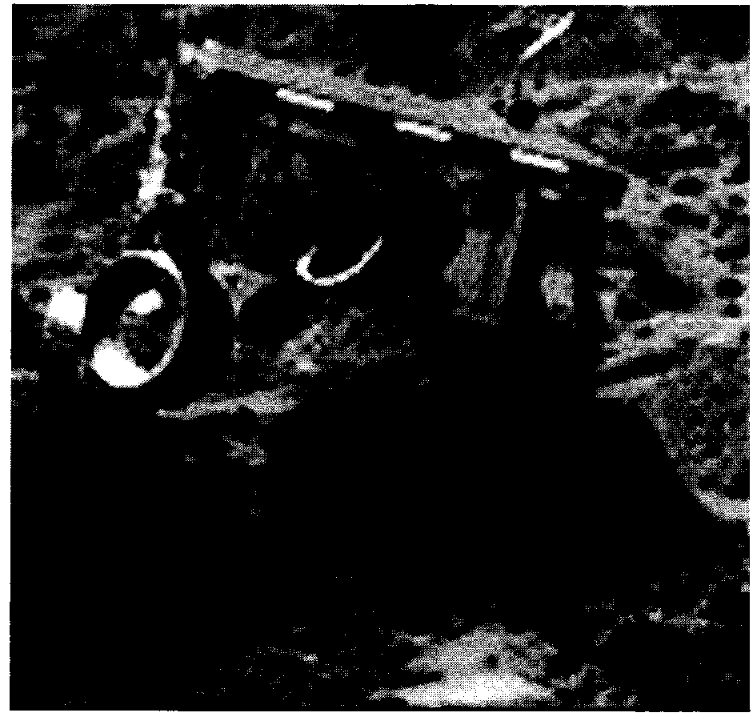
***Sensor, terrain-interaction, and navigational control models drive early operational scenario assessment and design validation***



# Caveat Emptor

## *Human (vs. Autonomous) Control Does Not Always Equal Safe Control*

- **The situation shown to the right occurred when Mars Pathfinder ground operations planners—overriding on-board autonomous navigation—commanded the Sojourner rover into a very rocky area.**
- **"Blind" moves and turns were used, and navigational errors were compounded by noise on rate gyro.**



**Mars Pathfinder/Sojourner (1997)**

# Example: The Mobile *In Situ* Science Operations Paradigm

- A Scientist on Earth would never try to understand geology or biology by staying in one place (hence the notion of "field geology", etc.) ...
- ... given that localized, unequivocal evidence of past processes is rare
- A mental model:
  - Imagine a graduate student in the field with jeep, map, cell phone, GPS, a digital camera/modem on surveyors tripod,...
  - ...and a Professor on the line, able to display the images.
  - what would the Professor ask the grad student to do?
    - take panoramic images
    - "go to" rocks and other points of interest
    - take and prepare samples and conduct analysis
    - take close up images

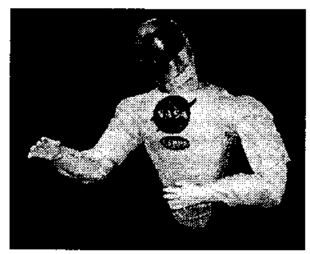
# Space Robotics Technologies & Operational Metrics

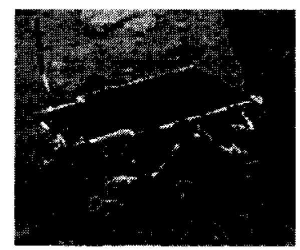
**MANIPULATION**
- EOA speed
- Accuracy
- Precision
- Dexterity
- Power efficiency
- Backdrive-ability
- Thermal stability
- Calibration

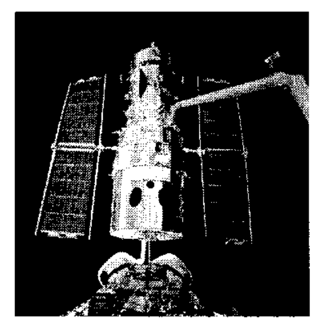
**MOBILITY**
- Ground speed
- Ground pressure
- Traversability
- Localization
- Cone of stability
- Climb rate
- Holonomicity
- Self-rightability

**ON-BOARD INTELLIGENCE**
- Resolution (multi-scale representation)
- Scalability (computational complexity)
- Completeness (search depth, breadth)
- Generalization (of classes, objects)
- Learning (from instances, training, etc.)
- Contingency (recursion, nonlinearity)
- Fidelity (binarization of analog models)
- Robustness (to partial, priced, and contaminated information ...)

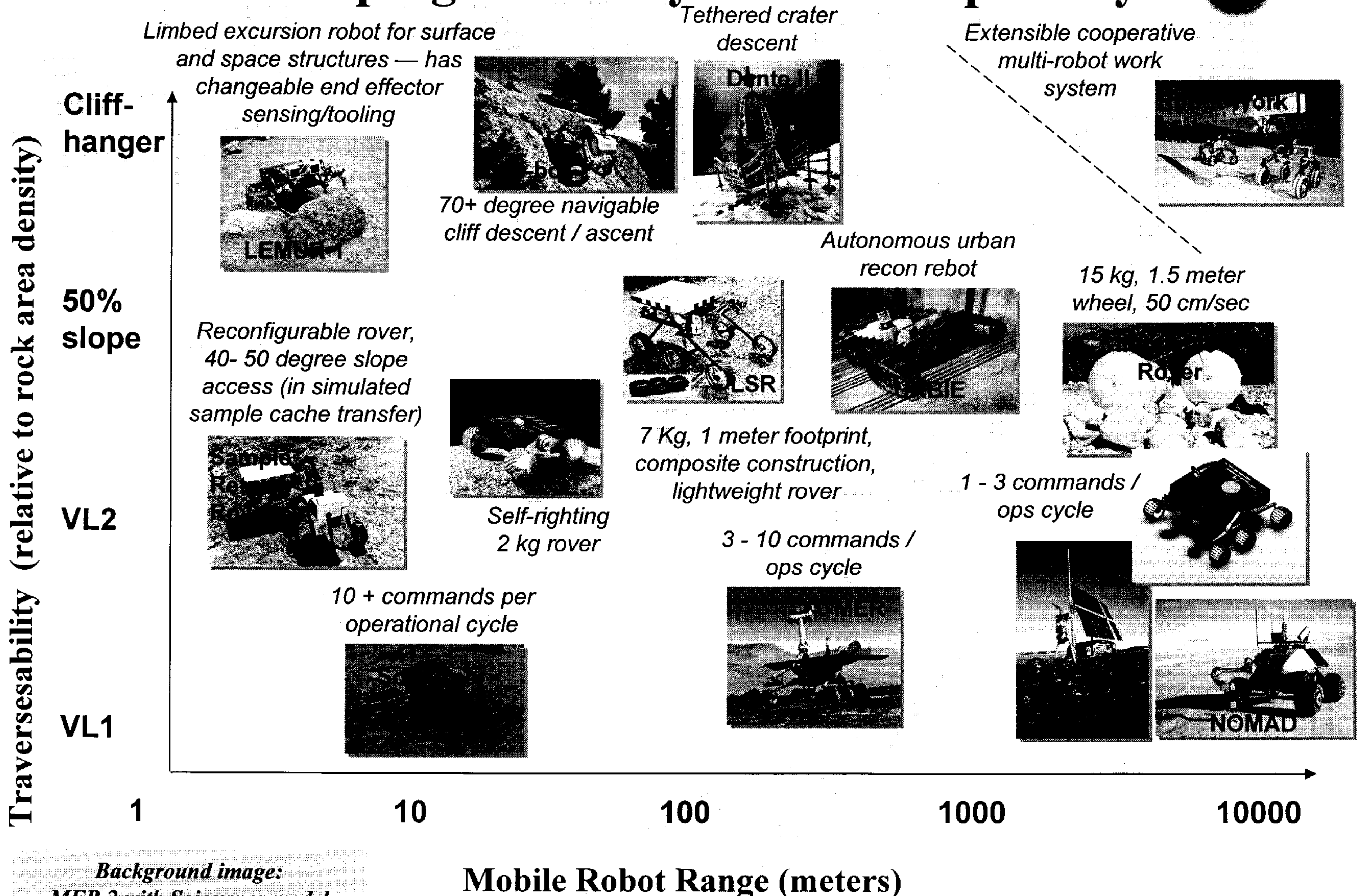
**PERCEPTION**
- Accuracy
- ROC (false positives)
- Calibration
- Weather and dust degradation
- Robustness (wrt. albedo, texture, etc.)
- Fidelity (of featural representation/recovery)
- Color and textural feature discrimination
- Generality (extrapolation, training, learning)
- Computation (Bits/Cycles for given function)





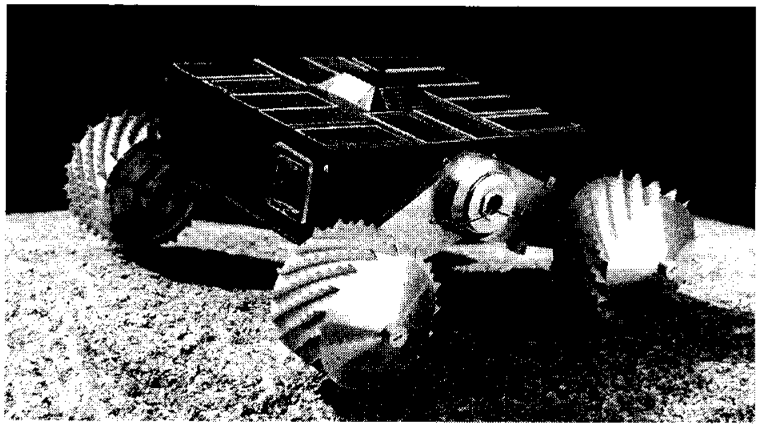


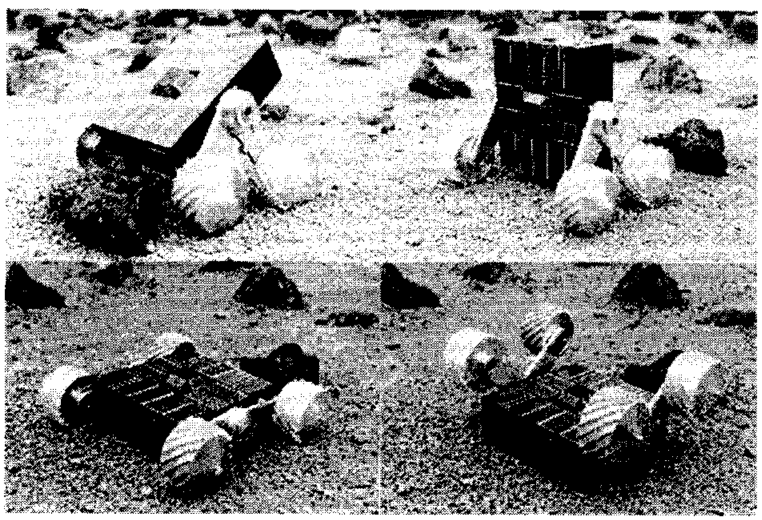
# Developing Planetary Surface Capability




*Background image: MER 2 with Sojourner model*

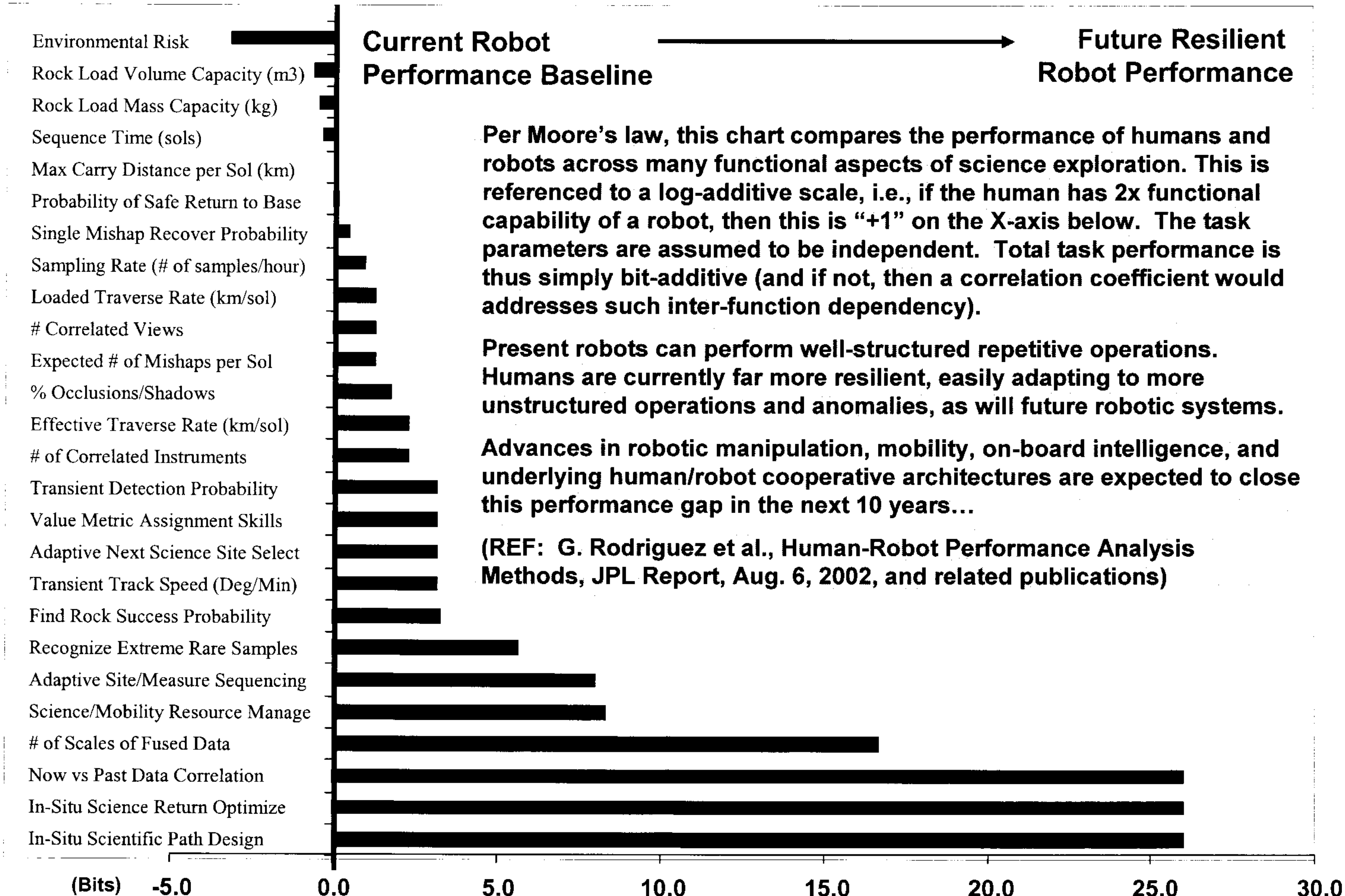
# Miniaturized Mobility (Nanorover)





- Body - 14 cm square
- 4 wheels 6.5 cm diameter
- Wheels on articulated struts
  - can lift wheels and set on top of obstacles
  - capacitive proximity sensing in each wheel
  - right and left-hand helical grousers to assist in skid steering
- 32-bit R3000 processor
- Hi-res Camera (0.3mrad/pix)
- IR Spectrometer (0.8-1.7$\mu$, ~5 nm res)
- Alpha X-Ray Spectrometer
- Total power < 3 Watts
- Total mass <2 Kg
- Designed to survive many cycles from -180C to +125C

# Human & Robotic Performance Comparison




**Per Moore's law, this chart compares the performance of humans and robots across many functional aspects of science exploration. This is referenced to a log-additive scale, i.e., if the human has 2x functional capability of a robot, then this is "+1" on the X-axis below. The task parameters are assumed to be independent. Total task performance is thus simply bit-additive (and if not, then a correlation coefficient would addresses such inter-function dependency).**

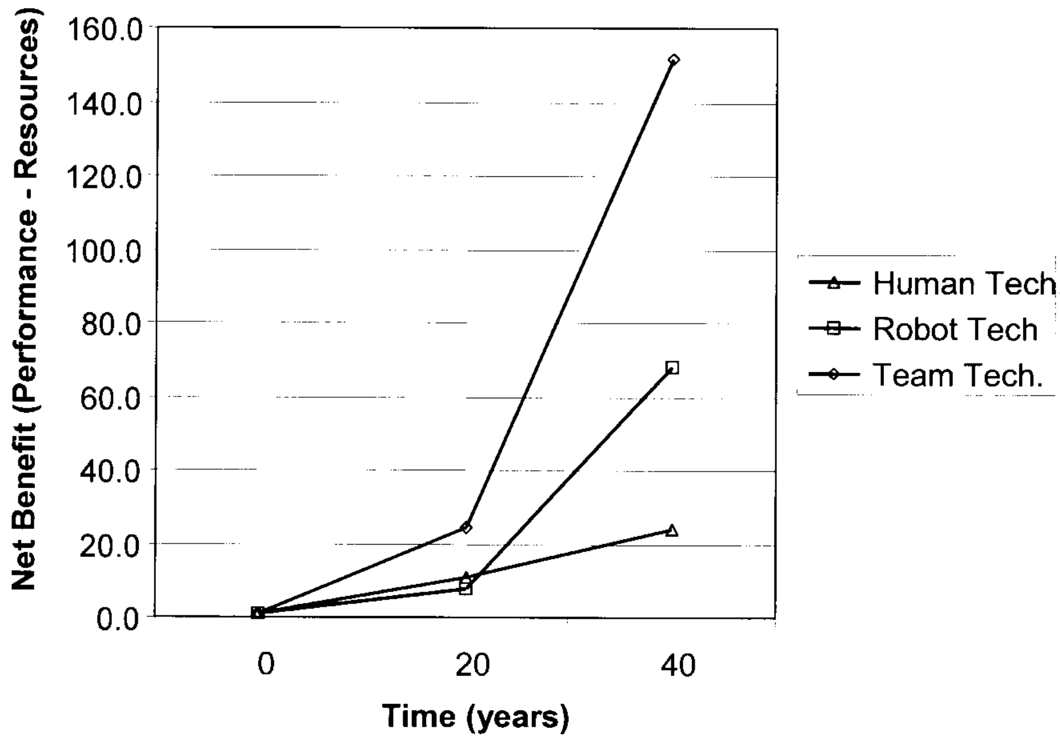
**Present robots can perform well-structured repetitive operations. Humans are currently far more resilient, easily adapting to more unstructured operations and anomalies, as will future robotic systems.**

**Advances in robotic manipulation, mobility, on-board intelligence, and underlying human/robot cooperative architectures are expected to close this performance gap in the next 10 years...**

**(REF: G. Rodriguez et al., Human-Robot Performance Analysis Methods, JPL Report, Aug. 6, 2002, and related publications)**

# It's not "Either-Or" Regarding Humans and Robots

**FAIR-DART Trade Space**
**(Team Cooperation Mode: Autonomous Robot)**




**Human-Robot Cooperation Improves ROI**

This study of L1 orbit telescope assembly demonstrates the potential of human-robot in-space operations to improve NASA ROI as compared to use of either mode alone.

***Moore's Law at Work***

*Y-axis* shows projected improvements in EVA and autonomous robotic performance over time. Projected performance has been characterized with respect to numerous task parameters and estimated human versus robotic capability for each. E.g., for a given task parameter, if the human has twice the functional capability of a robot, then this is "+1 bit" on log-2 scale. Task parameters are assumed to be independent, and total task performance is simply bit-additive (and if not, then a model correlation coefficient addresses such inter-function dependency).

**NOTE**: the result shown here does not assert that EVA is less capable than robotic servicing. Rather, it is shown that projected EVA/technology advances lead to a highly *synergistic human-robotic partnership, one far more productive than results obtainable from human or robotic operations alone*...

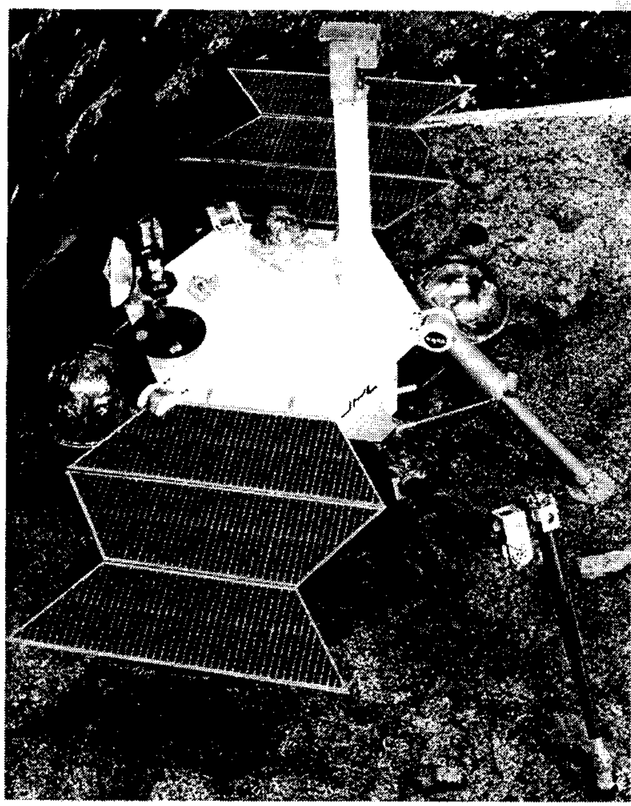
(The initial Condition at 0 Years does not reflect current differences in Human vs Robot Technologies; an estimate of Human EVA of ~20 bits has been obtained from prior studies. The plot for Human technology would have to be displaced upward by this amount in order to reflect such an estimate. Reference: Rodriguez, et al, Human-Robot Performance Analysis Methods, JPL Report, Aug. 6, 2002.)

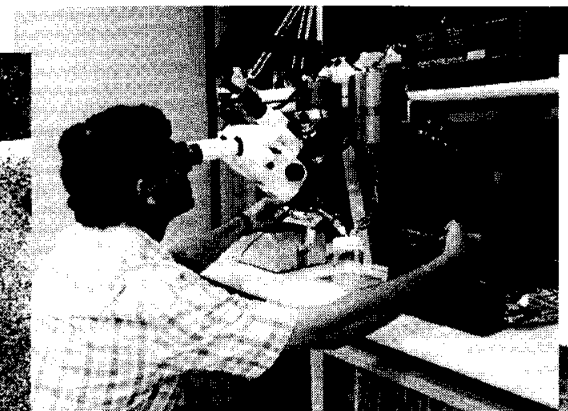
# Mobility R&D at Jet Propulsion Laboratory

- Mobility/robotics is a "major institutional thrust" at JPL
- Products are critically enabling to current/planned missions
- Work/deliverables span basic R&D to flight-mission systems
- Operational foci include aerial/surface/subsurface mobility
- ...with *in situ* science analysis, sampling and sample return...
- ... coordinated with JPL bio-assay/bio-containment expertise
- The R&D program has strong NASA <u>and</u> reimbursable bases
- Work dates to the '60's: rovers, telerobotics, human factors

# Robotics—Fixed and Mobile Manipulation

- There is a long and significant JPL history of teleoperative, telerobotic, and autonomous manipulation technology, as applied to: 1) *surface science* (instrument placement, sample processing & handling), 2) *on-orbit operations* (assembly, inspection, servicing) and relevant human factors, 3) *commercialization* (medical applications of robotics, etc.)



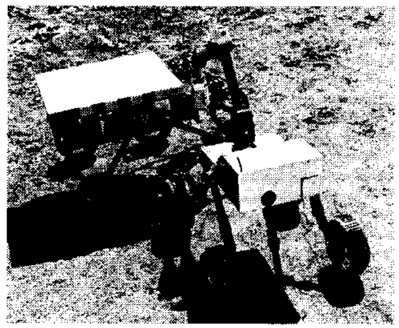


Above: Dual Arm Surgical Tele-Manipulator (RAMS)

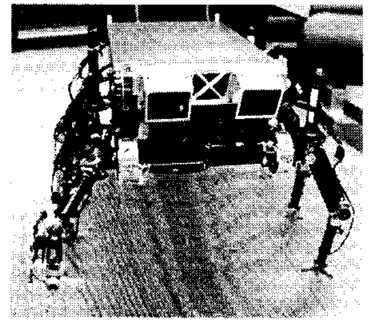
Left: Lander-Manipulator with Camera (Phoenix)

Right: Rover Arm for Instrument Placement (MER)

# Mobility System Development (Examples)



Sample Return Rover



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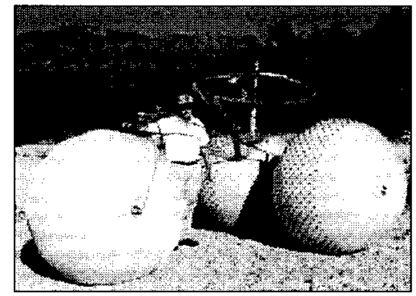
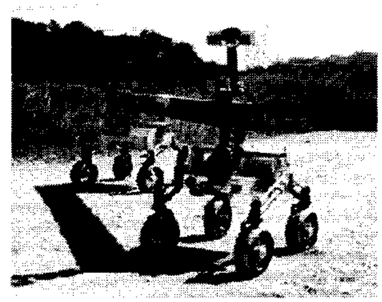
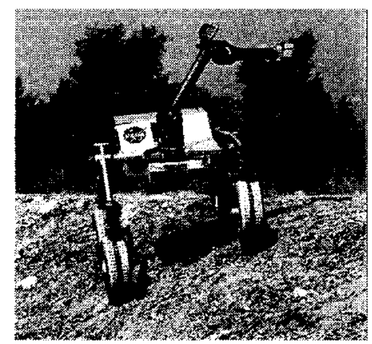


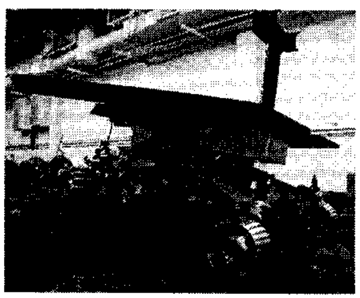
Inflatable Rover



Robot Work Crew

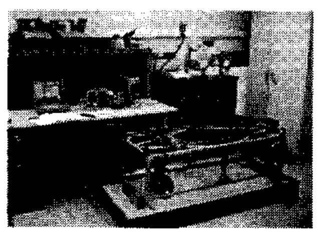


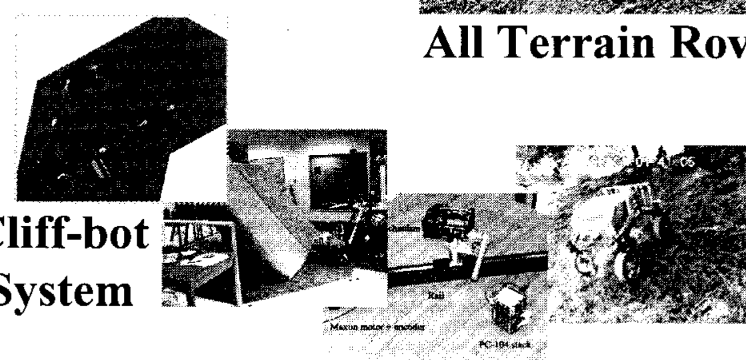
All Terrain Rover



MER Egress Rover

MER Wheel Test Stand





Cliff-bot System

**Planetary Robotics Laboratory**

* http://prl.jpl.nasa.gov

# Field Testbeds & Field Trials

### *Testbed Use*

### *"FIDO (Field Integrated Design & Operations) Rover"*

- Component technology integration and test
- Intelligent Systems (IS) and other initiatives technology product infusion/leverage
- Development and verification of human/robot operation interfaces, planning/visualization
- Quantitative system-level performance evaluation & characterization
- Ground truth, field validation, and science community tie-ins for relevant experiments
- Opportunity for advances in synergistic science operations and on-board science analysis

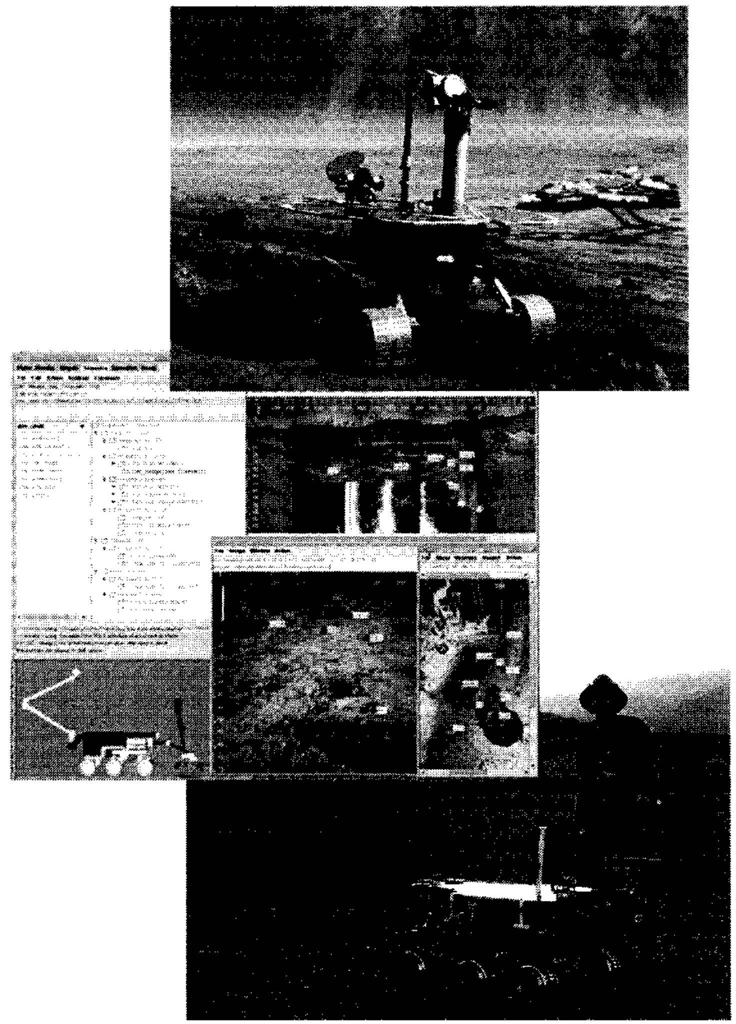
**FIDO Video**

### *Supporting Technology Development*

- Comprehensive control architectures for multiple, interacting, instrumented planetary and on-orbit robotic systems
- On-board intelligence for automated science sequence planning, error handling and recovery; visually referenced mobility and manipulation
- High-fidelity simulations for concept development
- End-to-end capability to emulate science-relevant remote operations, including critical program elements of human/robot interaction & cooperation

# Mission Science and Mobility R&D

- **Mars Exploration Rover (MER)**
  - mission simulations & science training in realistic terrestrial environments for ops & scenario validation
  - *WITS*/Web Interface for Tele-Science selected as the MER science activity planning tool
  - testing interfaces with MIPL for field trial telemetry processing
  - targeted engineering and functional tests (instrument arm, localization repeatability)
  - MarsYard, Arroyo, & field tests in direct support of the MER project
  - product transfers <u>including personnel</u>
- **Mars Science Laboratory (MSL) and later Mars Sample Return (MSR)**
  - advancement of "go-to" capability
  - enablement of visual rendezvous/return
  - development of mobile *in situ* sampling
  - technology benchmarking & reporting



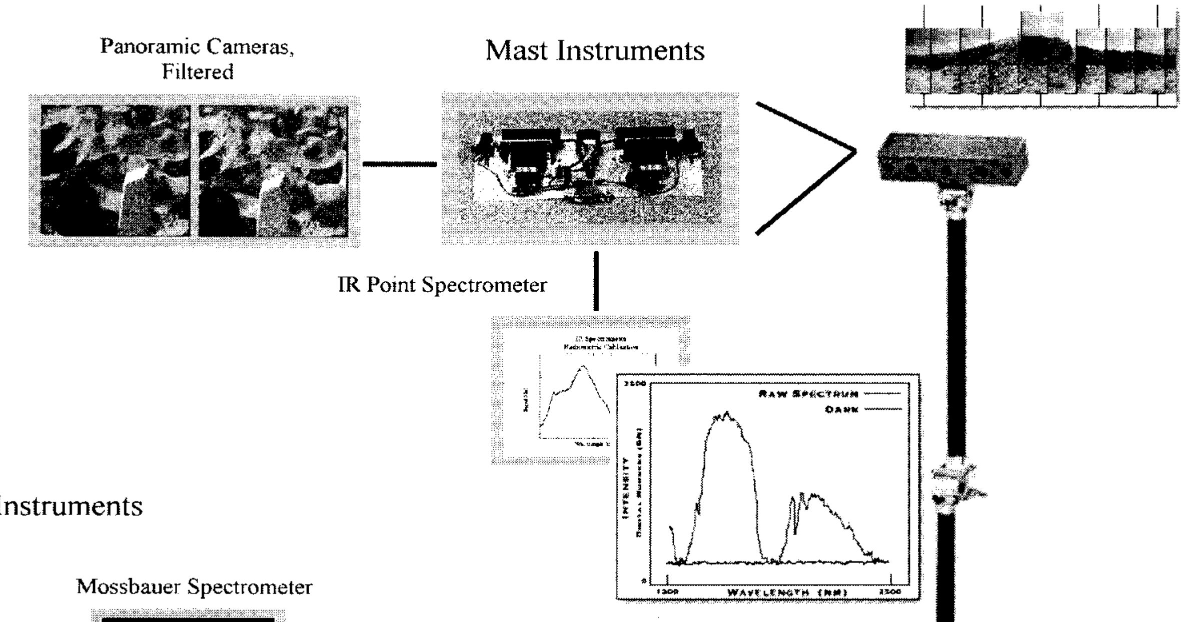
**FIDO (Field Integrated Design & Operations) Rover**

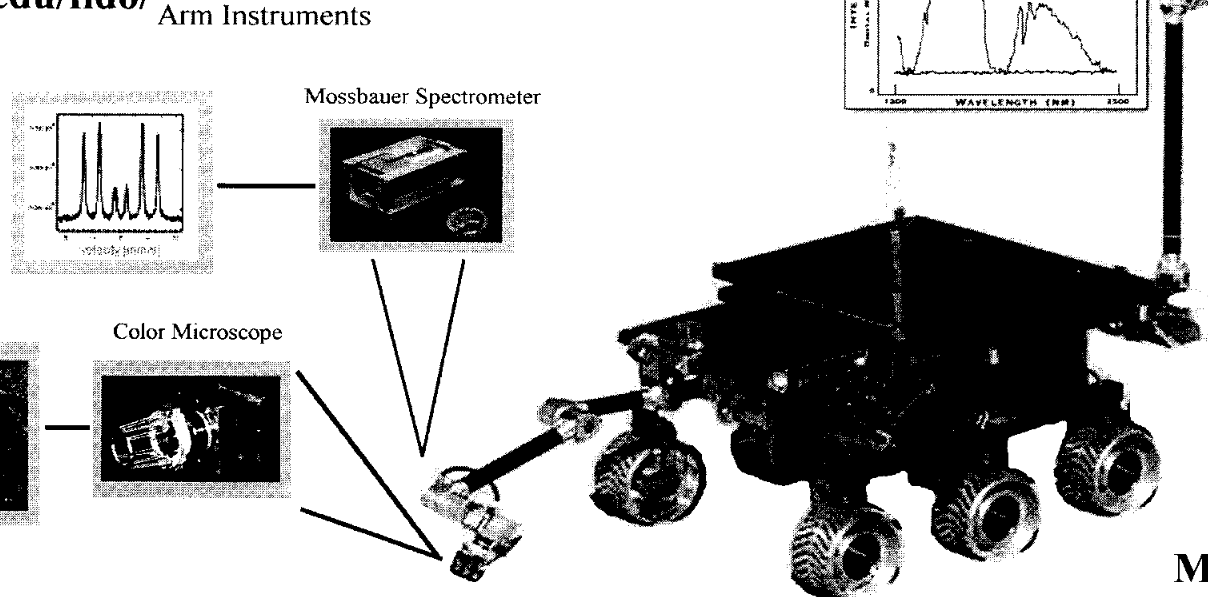
# Field Experiments & Technology Validation

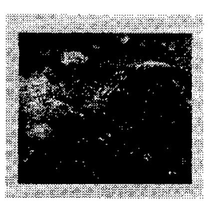
***Integrating Science Operations, Instruments and Mobility***

**Miniaturization and Integration of In Situ Instruments on FIDO**

**SCIENCE**
**http://wufs.wustl.edu/fido/**



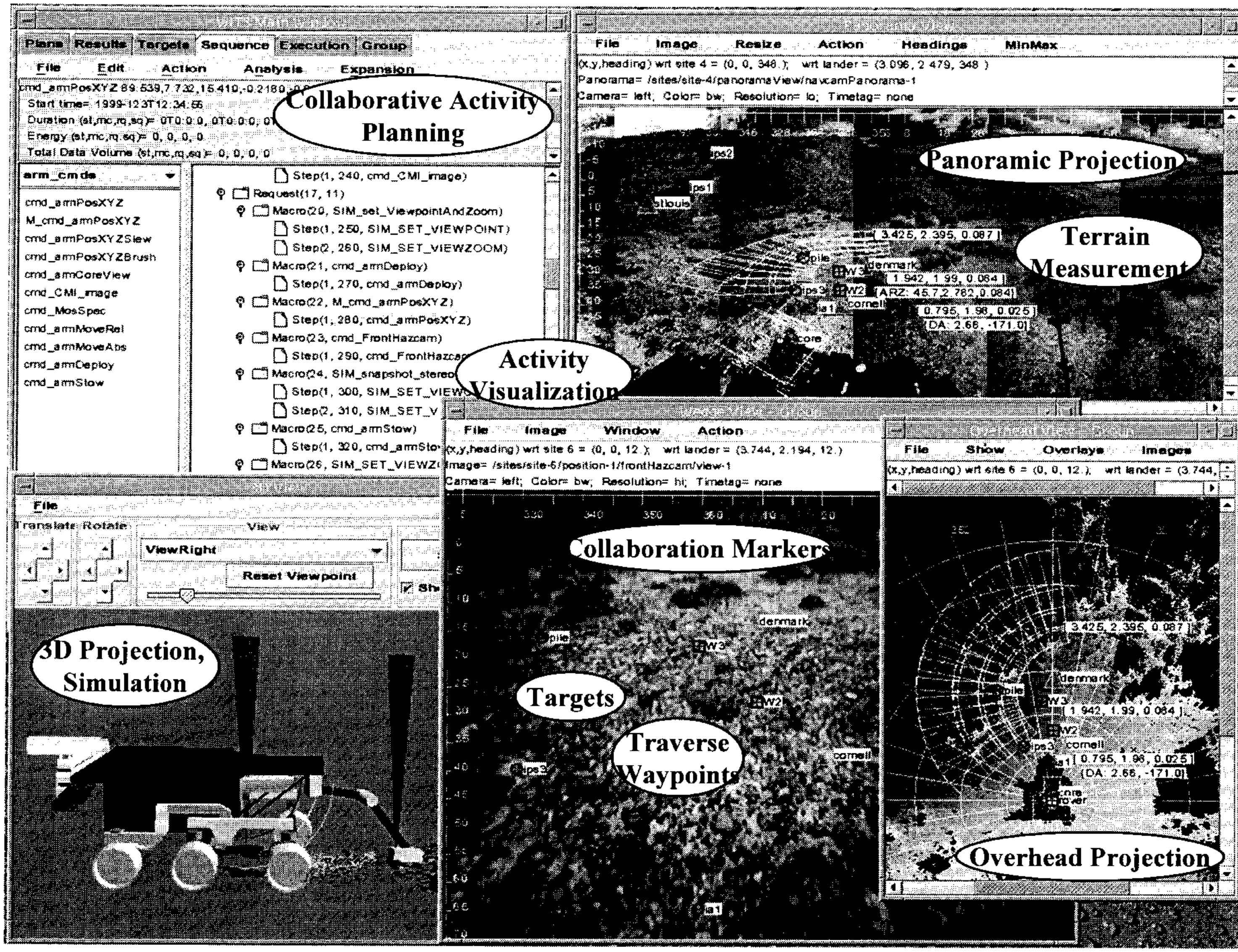



**INSTRUMENTS**
**http://fidoinstruments.jpl.nasa.gov/**

**MOBILITY**
**http://fido.jpl.nasa.gov/**

# Platforms are only Part of the System Solution




***WITS***

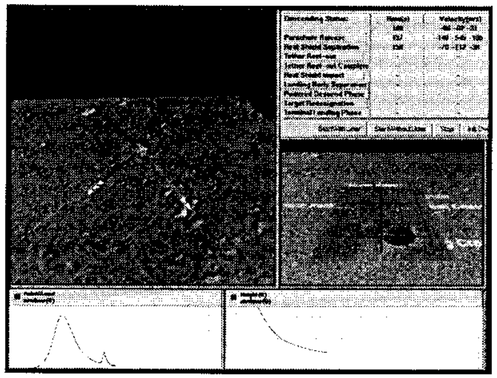
**Web Interface for Tele-Science**

A JPL-developed environment for distributed and collaborative mobile science

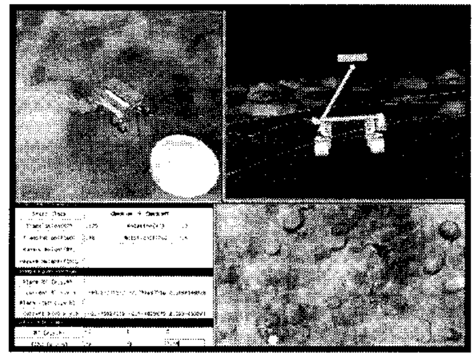
# Simulation

***Supports Mobility System Concept & Mission Development***

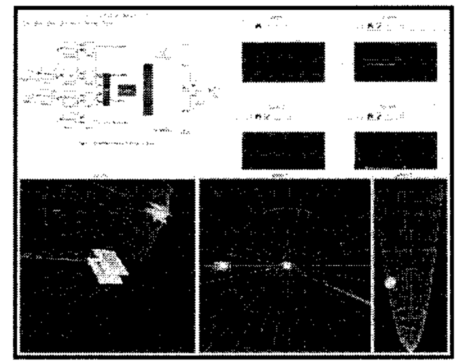
**DSENDS**
Entry, Descent & Landing Simulator



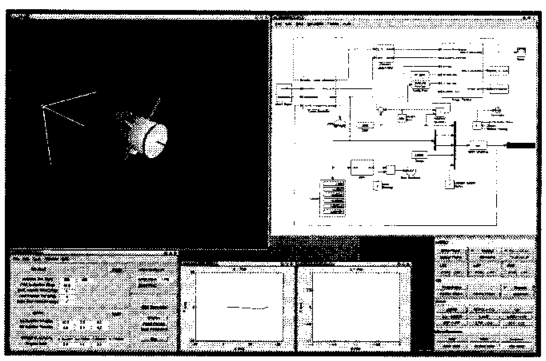
**ROAMS**
Planetary Rover Simulator



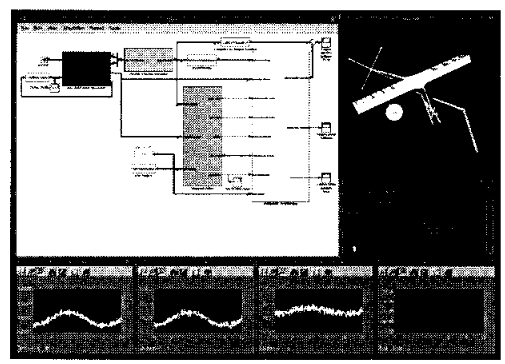
**Formation Flying**
Distributed Real-Time Simulations (Starlight)



## *DARTS Lab*



**Rendezvous & Sample Capture**
(Mars RSC, ST-6, CNES'07)



**Flexible Interferometers**
Integrated Modeling (SIM)

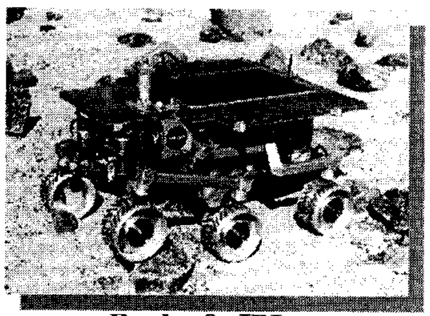
**http://dshell.jpl.nasa.gov/**

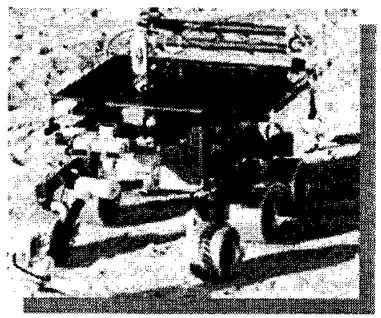
JPL

# Integrated Infrastructure for Mobility System R&D

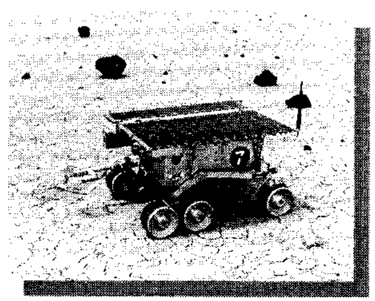
***Infrastructure***

***Hardware*** ***Software***


Rocky 8, JPL


FIDO, JPL

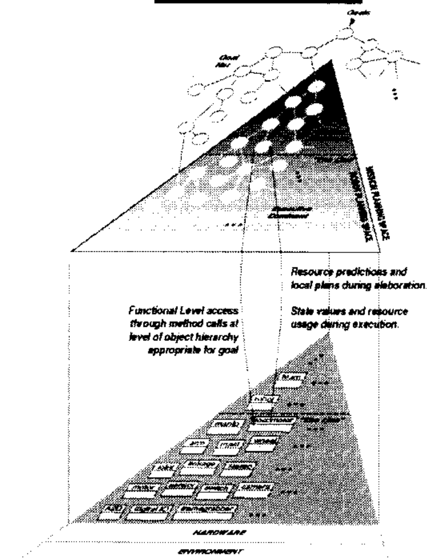

ATRV, CMU


Rocky 7, JPL


K9, ARC

DECISION LAYER

FUNCTIONAL LAYER

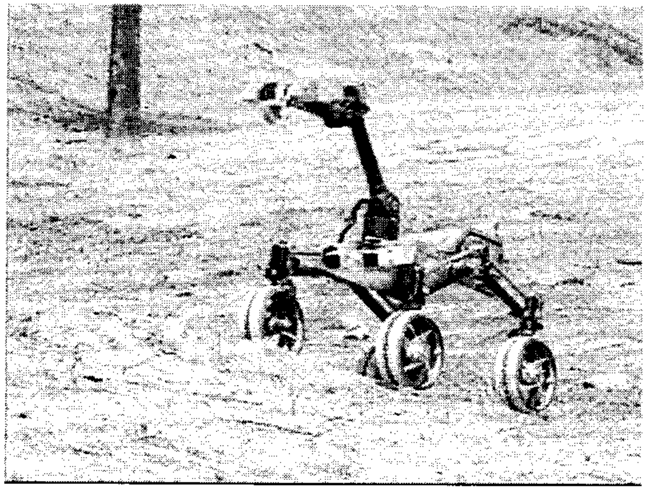



***Coupled Layer Robotic Autonomy Architecture (CLARAty)***

***Current Research Team / Mars Technology Program Tasks***

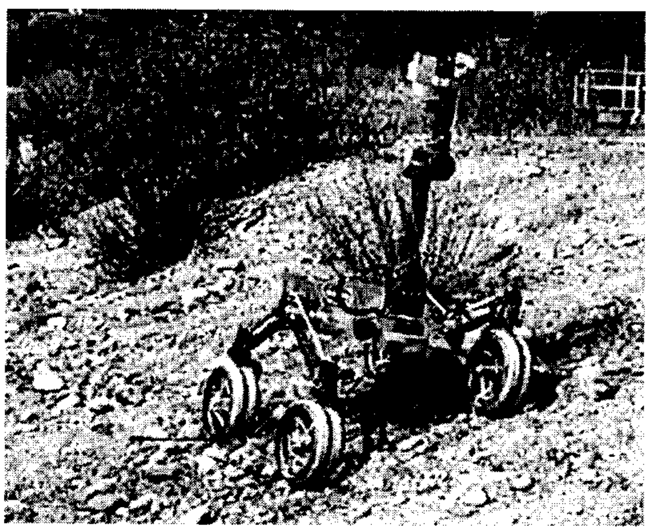
- **JPL** (Driving on Slopes, Visual Servoing, Simulation)
- **MIT** (Terrain Estimation )
- **Univ. of Washington** (Terrain Mapping )
- **ARC** (Autonomous Science, Simulation, Fault Detection)
- **CMU** (Path Planning )
- **Univ. Michigan** (Position Estimation )

# Hardware & Software Innovations Converge



**Rover State Estimation and Predictive Control (JPL)**

- Successfully demonstrated on SRR in Arroyo Seco at slopes of up to $50^o$, wherein fixed-geometry control was shown to fail
- Provides stability with respect to *slip and tip-over*
- Uses visually sensed range map, spline parameterization, and INS for model-based predictive state estimation
- Predictive reconfiguration encoded in a Look-Up-Table: developed via off-line simulation and used online for control of rover

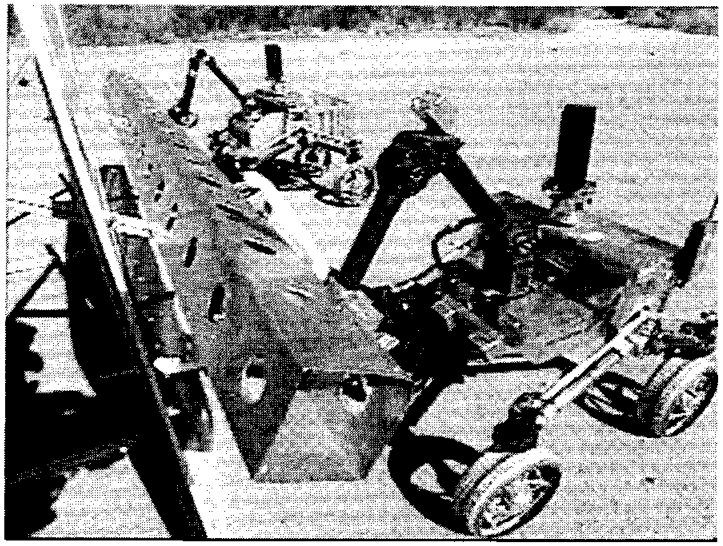


**Physics Based Planning & Reconfiguration (MIT/JPL)**

- Successfully tested in Arroyo: trades off two objective functions for *tip-over* (high priority) and ground clearance (lower priority)
- Uses INS, kinematics, and quasi-static model to stabilize rover in "bounding c.g." volume; reconfigures 2 DOF arm and 2 x 1 DOF shoulders (4 DOFs total)
- Work conducted in residence at JPL by Professor Steven Dubowksy and MIT Ph. D. students (Mech. Engrg.)

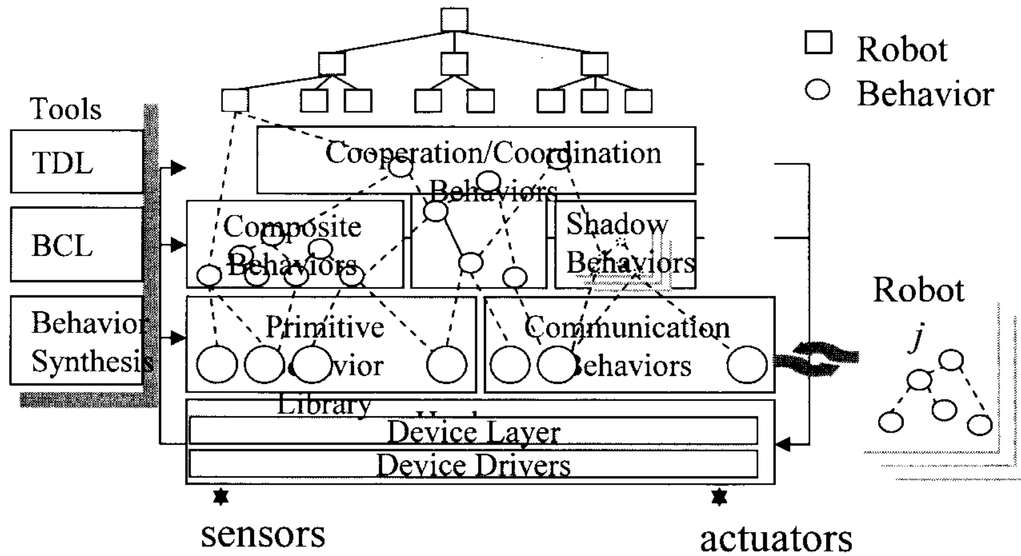
# Toward More Intelligent Robotic Systems

*Architectures for Future Human-Robot Systems—Planetary and In-Space Operations*



**EXAMPLE:** ***Robotic Work Crew***

**Hierarchical task planning, allocation, and monitoring**

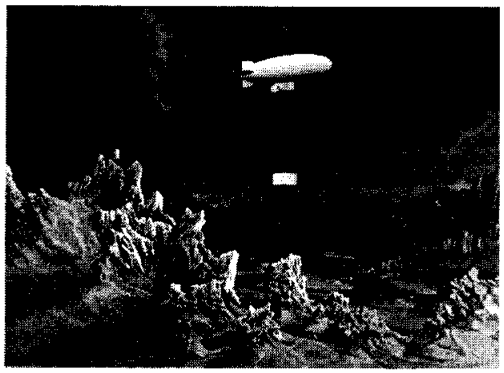



- **M̲ixed I̲nitiative C̲ontrol A̲rchitectures support human and robot multi-agent cooperation**
- **Robots tightly, autonomously coordinate interactions to perform complex physical tasks**
- **Layered autonomy coordinates fast, reactive behaviors and higher level decisions/planning**
- **The human agent/s can be both supervisor and work team participant/s as appropriate**
- **Networked Robotics enables flexible extension, decomposition, & remapping of resources**
- **This provides capability for scaled operations over large areas and multi-task objectives**

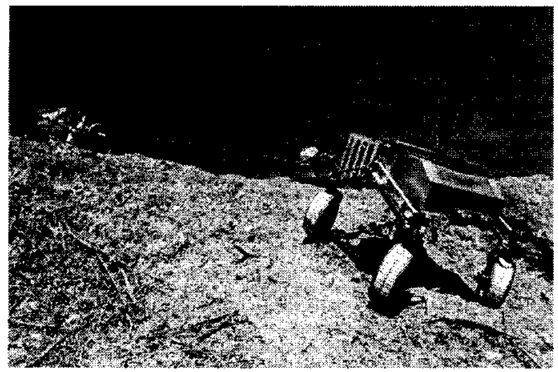
# Autonomous Mobility in Challenging Terrain

*Mobility for High Risk Access and High Value Science*

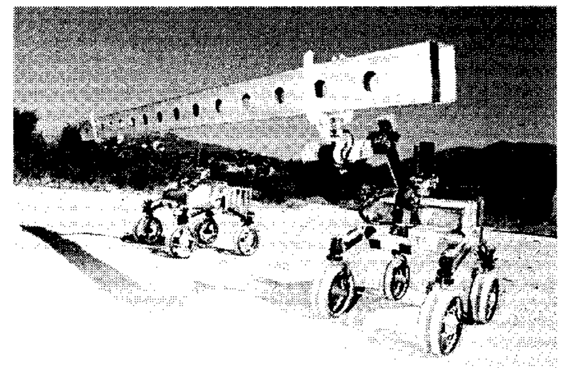
# Advanced System Capabilities



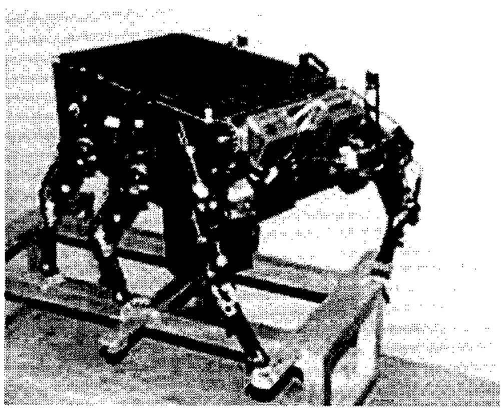
Autonomous Aerial Exploration at Titan



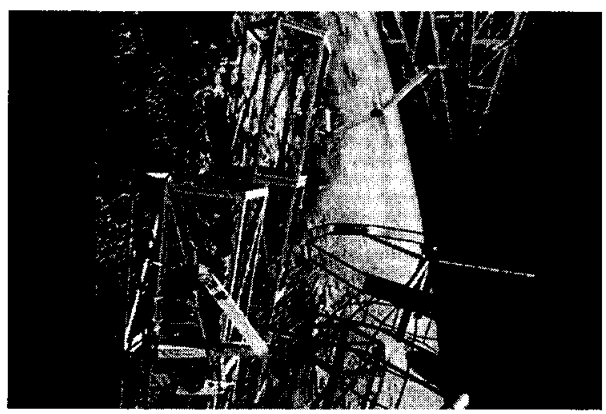
Planetary and Lunar Rough Terrain Mobility



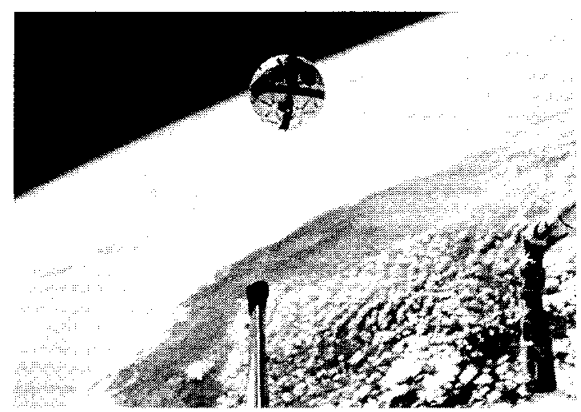
Robotic Work Crews at Moon and Mars



Robotic Maintenance and Repair



In Space Large Structure Assembly

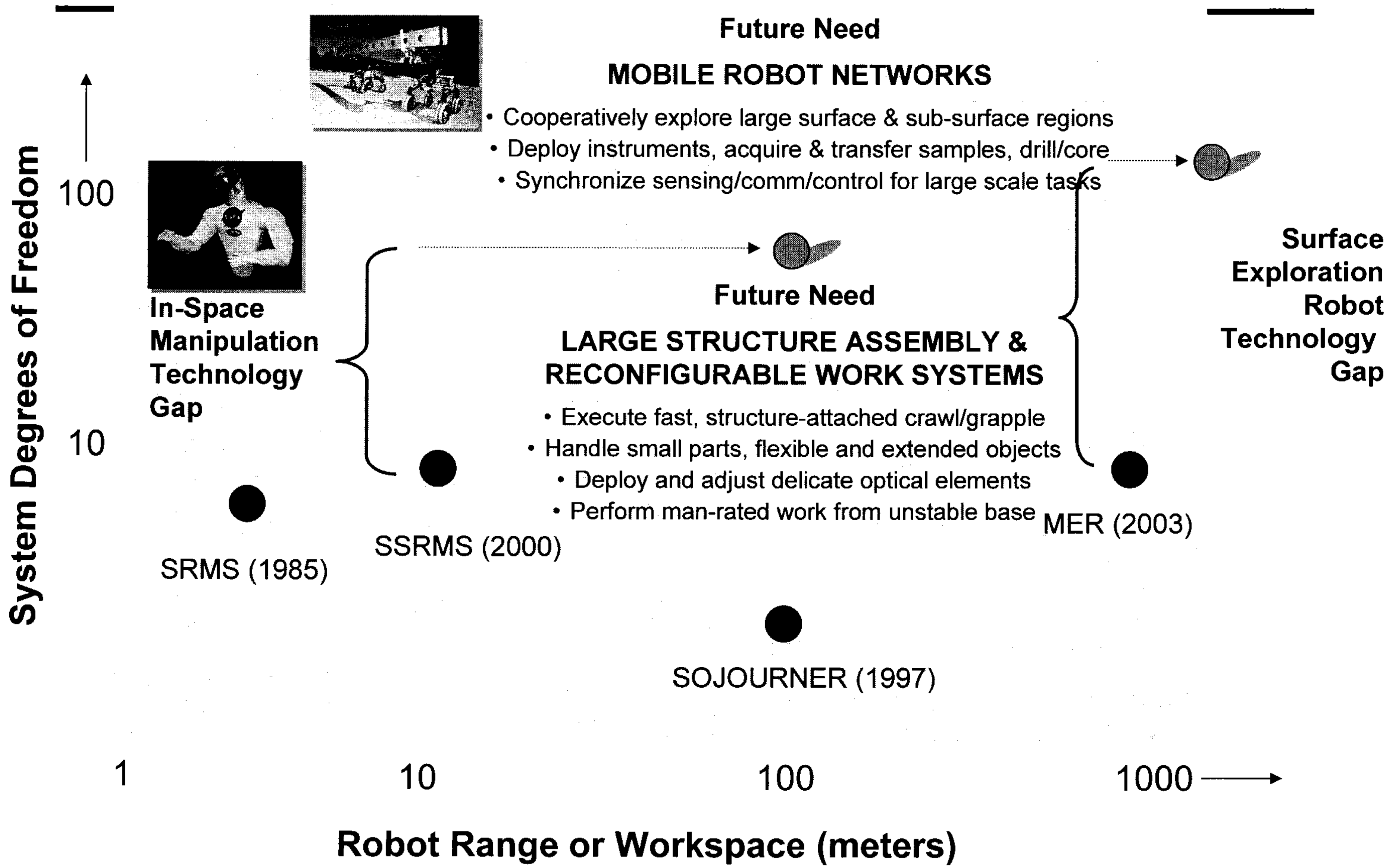


Co-orbital Free Flying Inspection

# Quantified Performance Targets

| Capability | 2003 SOA | 2010 Target | NASA Relevance / Science Impact |
|---|---|---|---|
| **Command cycles per operation for surface mobile exploration** | *Mobility*: ~10 m /command<br>*Manipulation*: ~ 3-5 sols per instr placement (MER) | 1 Km/command<br>1 science measurement per command cycle | Higher autonomy enables **greater science productivity per command**, reduced operator overhead and communications bandwidth requirements |
| **Range of operations (planetary surface)** | < 1 Km linear path (MER) | >1000 Km ^2 via aerial or multi-agent systems | Permits **access to greater diversity** of planetary environments, resulting in greater science productivity |
| **Range of operations (in-space systems)** | Fixed base (SRMS, SSRMS) / 100 m linear track (MSS/ SPDM) | 1 Km^3 work volume | Permits **operational flexibility in maintenance and repair** operations, transportation and assembly of spacecraft systems |
| **Level of dexterity** | Grapple large (>1m^3) Orbital Replaceable Units | Human-level "naked hand" dexterity | Enables **utilization of human-access interfaces** for payload servicing, component **repair or replacement**, access to obstructed components, assembly of structures |
| **Autonomous access to planet subsurface** | 10-100 cm | Autonomous robotic drilling to 100 meters | Enables access for **examination of geologic layering, access to potential resources**, and continued search for pre-biotic deposits |
| **Access to adverse and rugged terrain** | VL1 terrains (Sojourner) | >VL2 terrains, vertical cliffs, crater walls | Enables **access to areas of intense planetary scientific interest** (e.g., close-up examination of cliff/crater wall stratifications and mineralogy) |
| **Multi-robot cooperation including human interaction** | none | Multi-agent servicing systems spanning large work areas and payloads | Permits **more efficient exploration, increases system-level robustness**, risk mitigation via redundancy, **enables human-robotic tasks of large physical scale** |
| **Autonomous visualization & inspection** | none (some teleoperated inspection via SRMS cameras) | Automated inspection of spacecraft exteriors, anomaly detection | Enables **automated detection of spacecraft damage**, identification of mis-assembly, documentation of spacecraft state changes |

# Robotics Capability & Mission Enablement

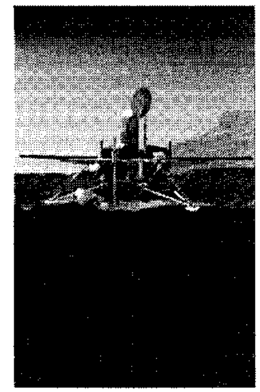


# A Science Vision for Solar System Exploration

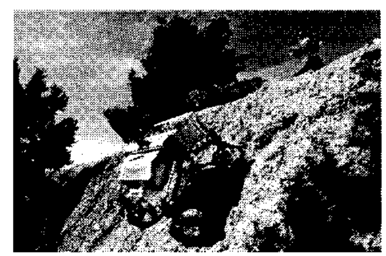
***Mobility, Safe Landing, Sample Acquisition/Handling, Rendezvous and Sample Capture***

- **Rove globally over planetary surfaces and approach local sites (even in extreme terrain) within ~ 1 pixel of planning image with overall system performance comparable to a field scientist.**

- **Access subsurface environments including liquid water aquifers or polar caps on Mars, Titan, Jovian moons like Europa, and penetrate through comet nuclei, and deep into lunar and Mercury polar volatiles, etc.**
- **Fly through atmospheres of Titan, Venus, and Mars to provide superior combinations of coverage and access where possible.**



- **Land safely within ~ 1 pixel of a site based on downlink orbital imagery.**
- **Select, acquire and prepare samples suitable for any in-situ instruments with end-to-end performance comparable to current Earth science processes.**
- **Acquire, loft, rendezvous/capture, and return to Earth pristine samples within appropriate planetary protection guidelines.**



- ***And ultimately, conduct persistent human/robotic teamed exploration of high value planetary and lunar bodies***

# In Conclusion – Mobile Robotics for Space

- In-situ science and sample return from planetary and small bodies such as Mars, Venus, Titan and Europa pose extreme technical and operational challenges to autonomous mobile robots.
- Mobility and mobile manipulation are needed to avoid the kind of situation which prevailed with the Viking landers in 1976: despite a rich array of rocks visible about the landers, no rocks could be reached by the lander arms, and thus no real "hard rock" science was done.
- Future missions will involve surface, subsurface, and atmospheric/aerial mobility. This focuses and defines the need for new technology development in sensing, autonomy and space-relevant mobile robotic hardware-software architectures for solar system exploration.
- Parallel arguments exist for future in-space/on-orbit operations, which will include assembly, inspection & maintenance tasks of increasingly large scale, complexity and duration. These tasks will be enabled by a similar technology base and are expected to similarly couple free-flying mobility, manipulation, and multi-robot cooperation.
- Capability advances will be driven by synergistic hardware-software design (vs. software as an artifact of hardware architecture), and will rely heavily on integrated design/simulation environments to span large system trade spaces