

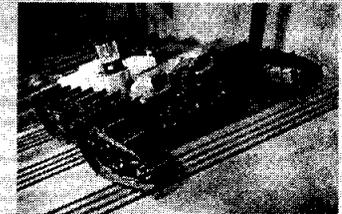


Space Robotics

The Next Generation of Mobile Planetary Exploration

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**The National University of Ireland, Galway
June 24, 2004**



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Outline

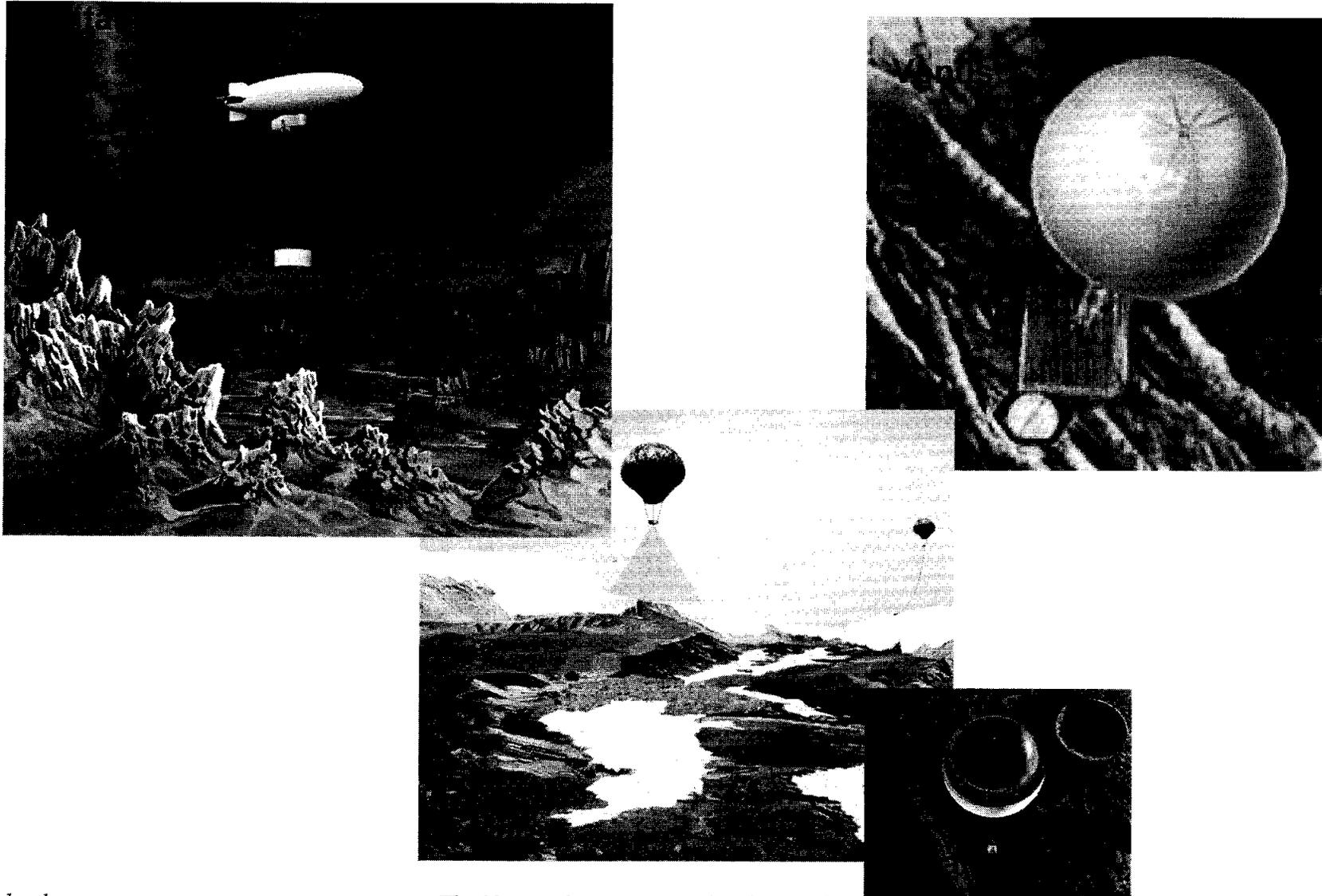
- **Space Robotics & Mobile Planetary Exploration**
- **Operational Challenges & A Future Vision**
- **Surface, Aerial and Subsurface Domains**
- **Technology Needs & Performance Metrics**
- **Emerging Robotic System Architectures**
- **Design Tools & Development Environments**
- **A Path Ahead: Moon, Mars, and Beyond**



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

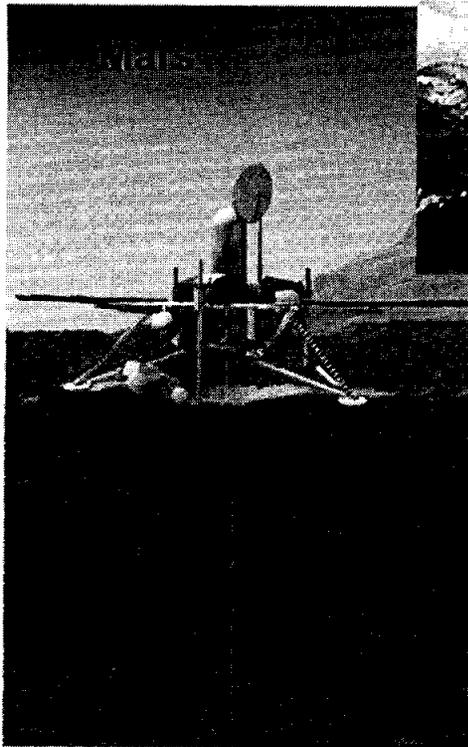
Aerial Exploration



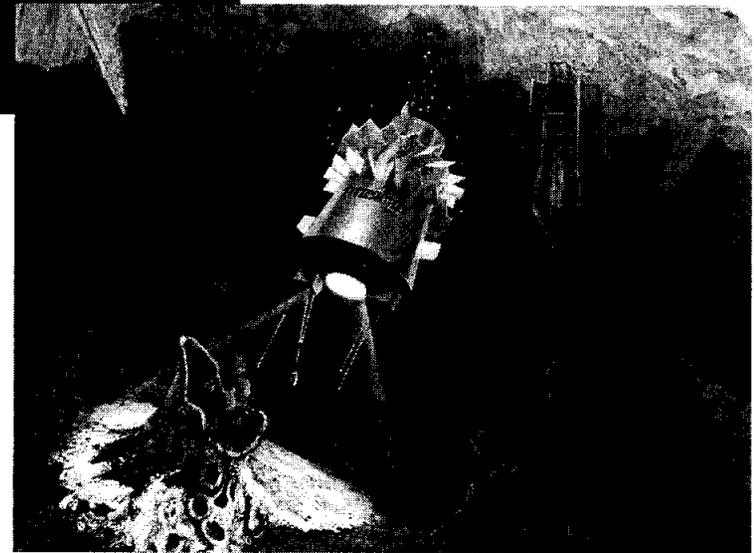


Subsurface Exploration

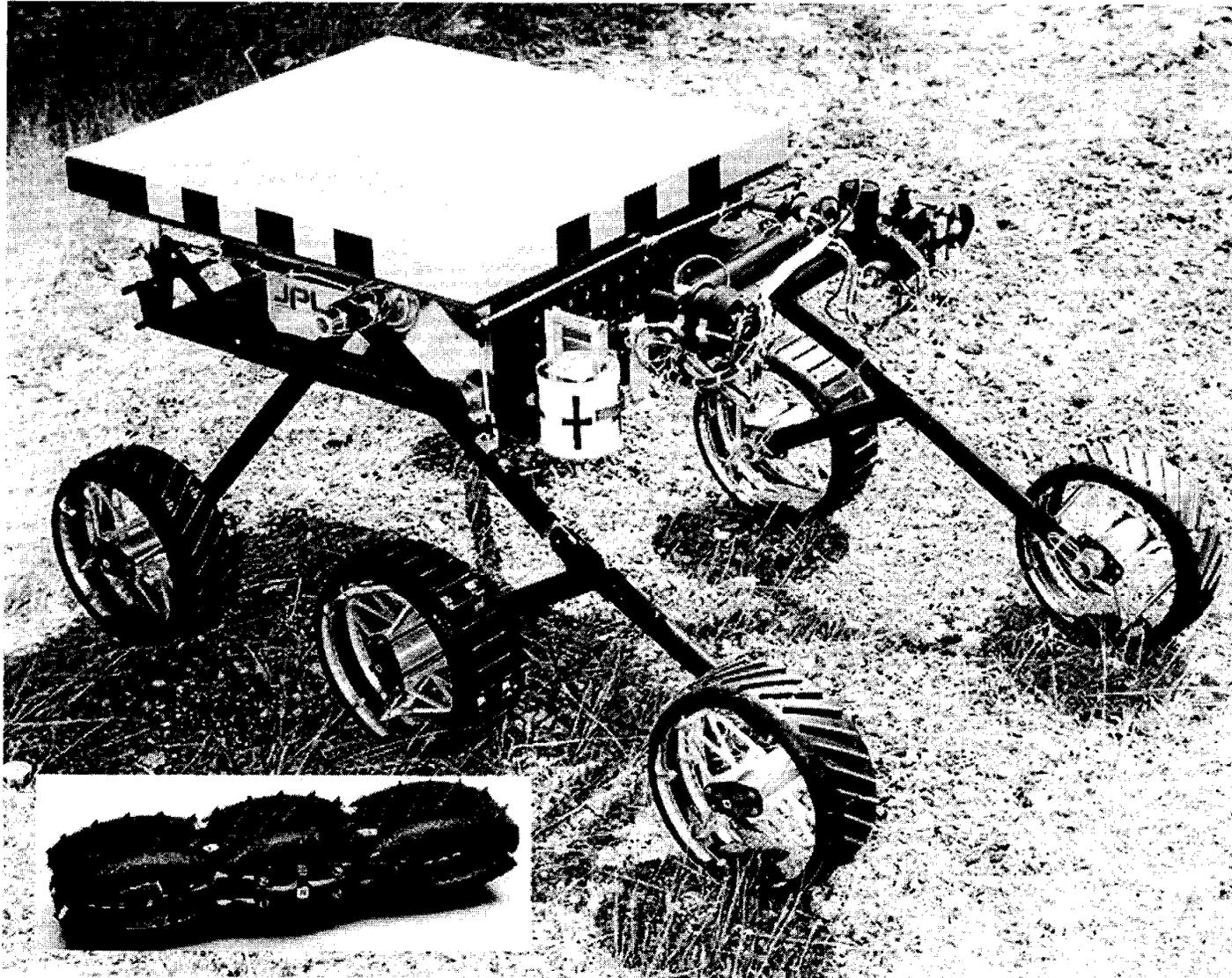
Venus



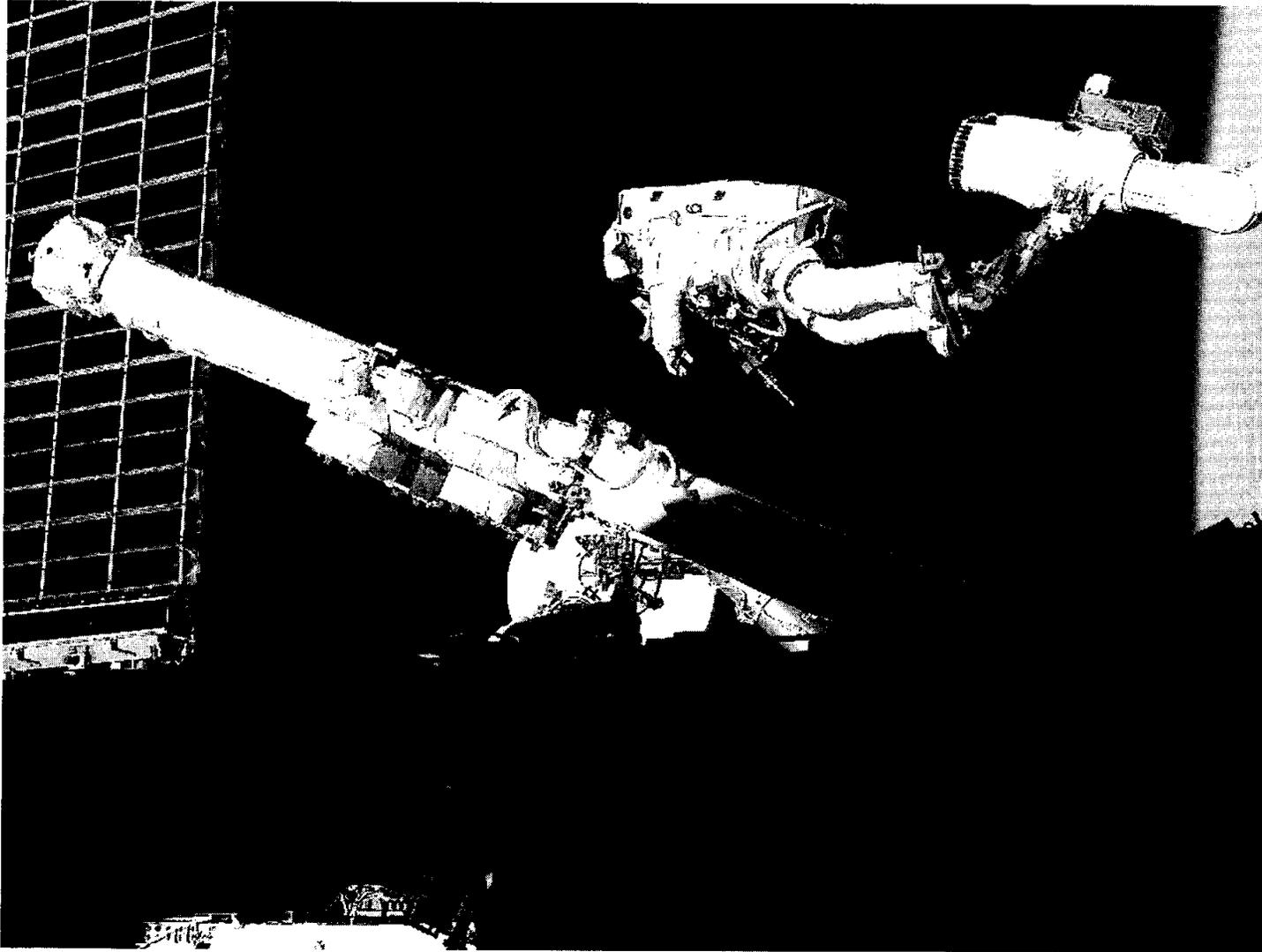
Mars



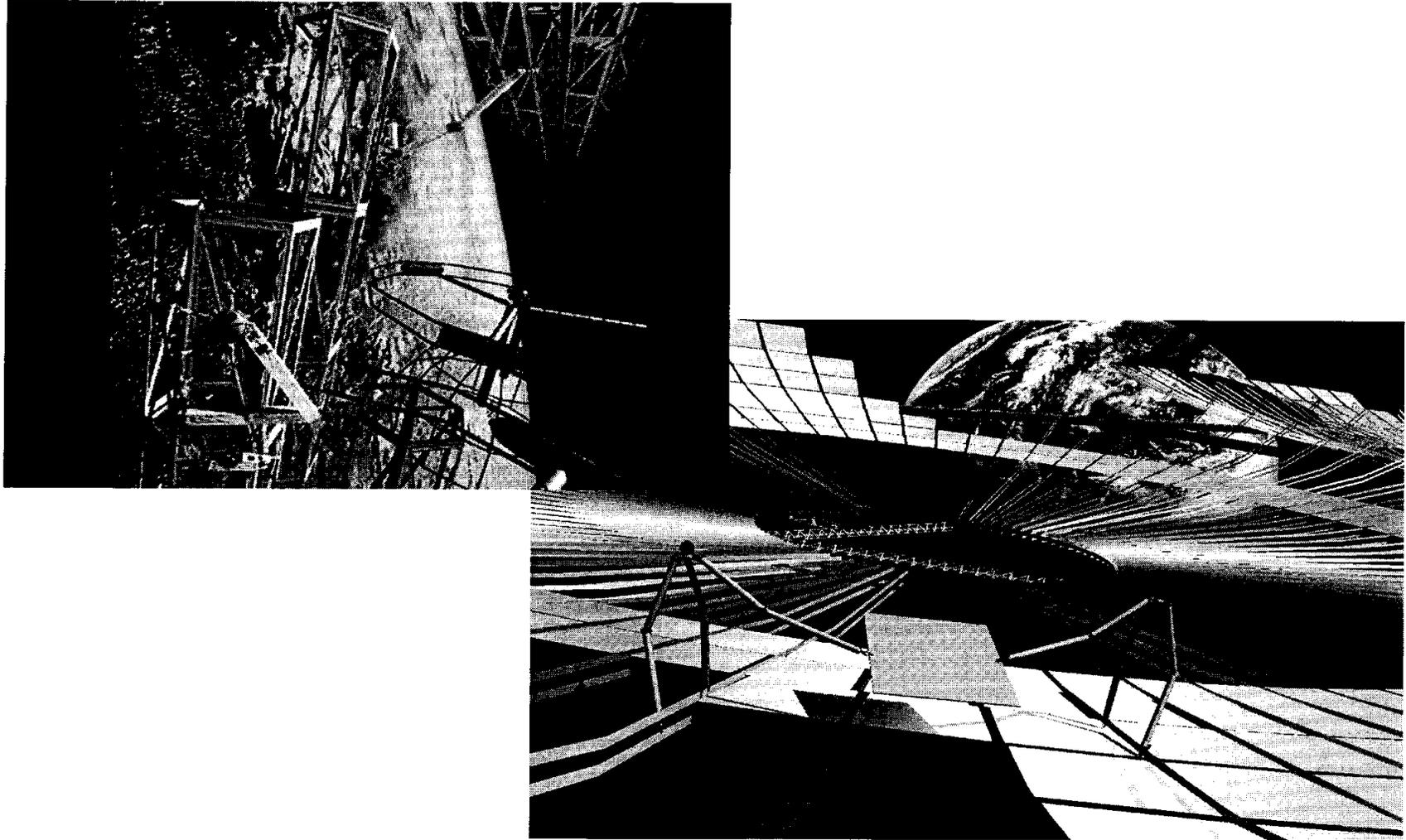
Surface Exploration



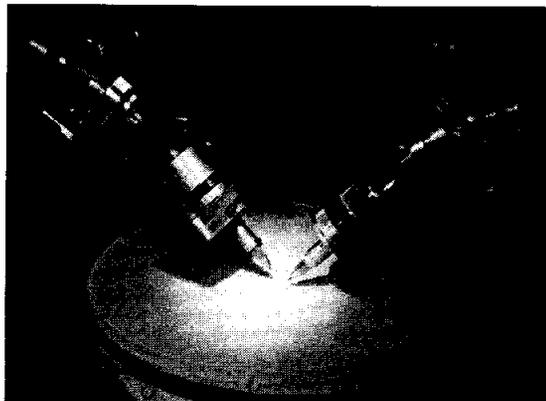
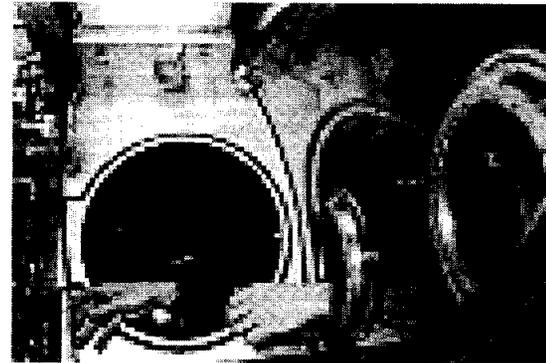
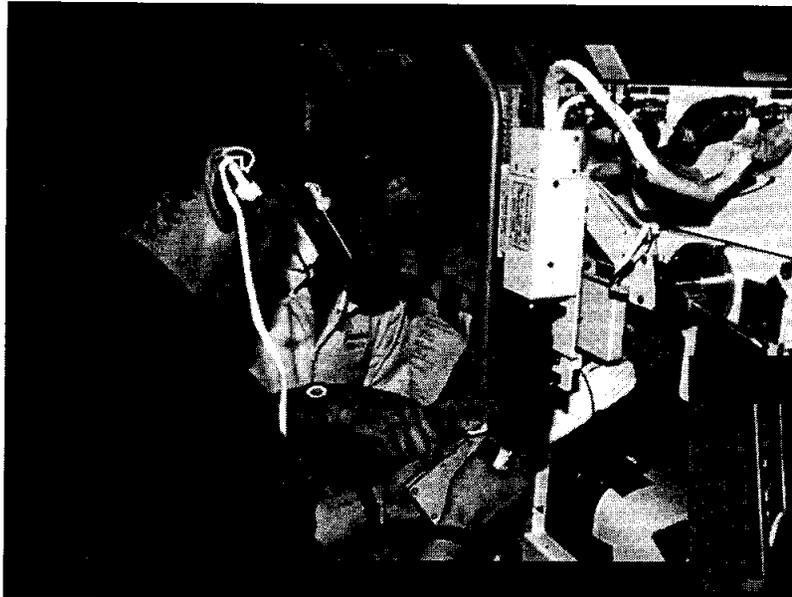
In-Space Operations



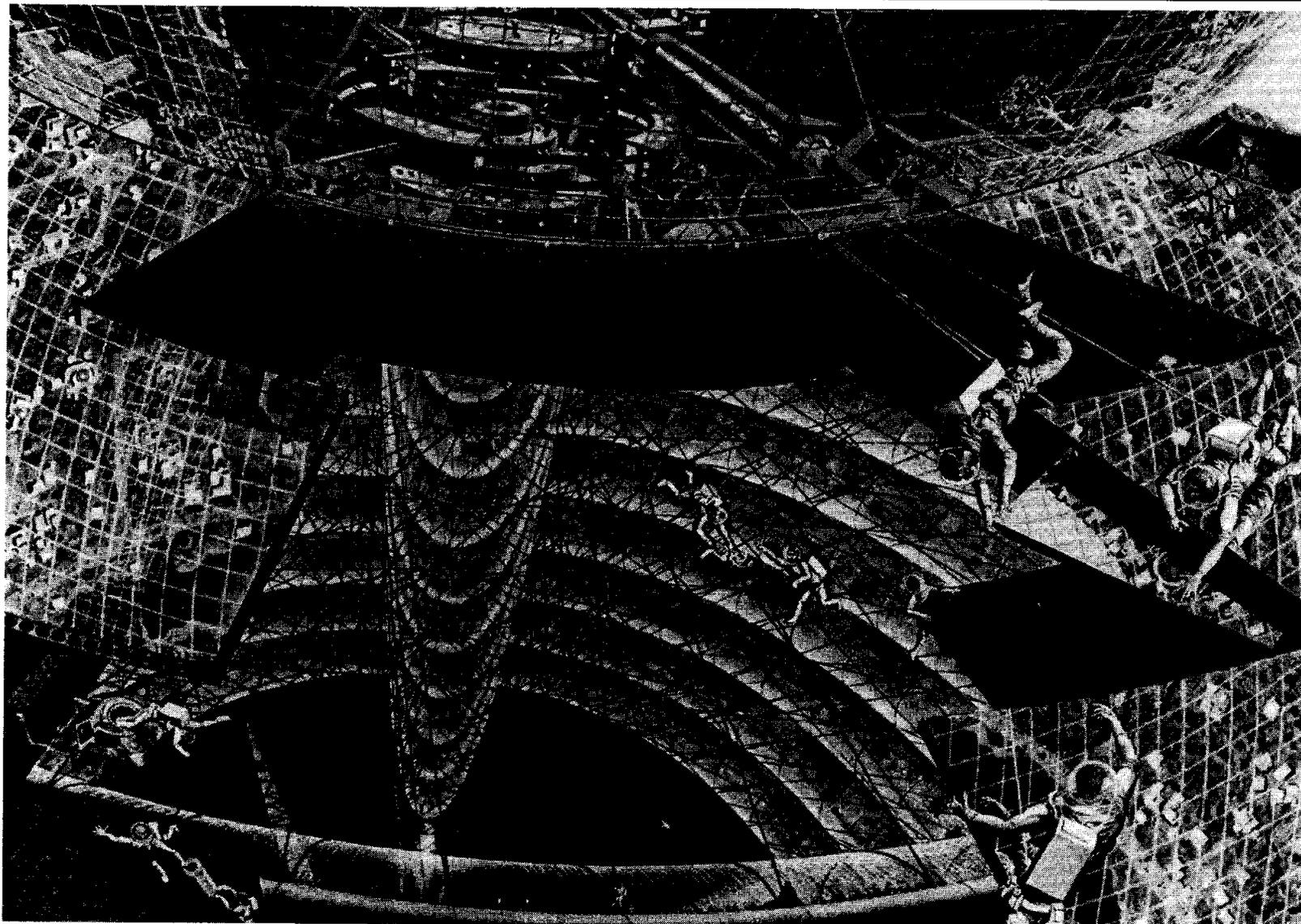
In Space Assembly



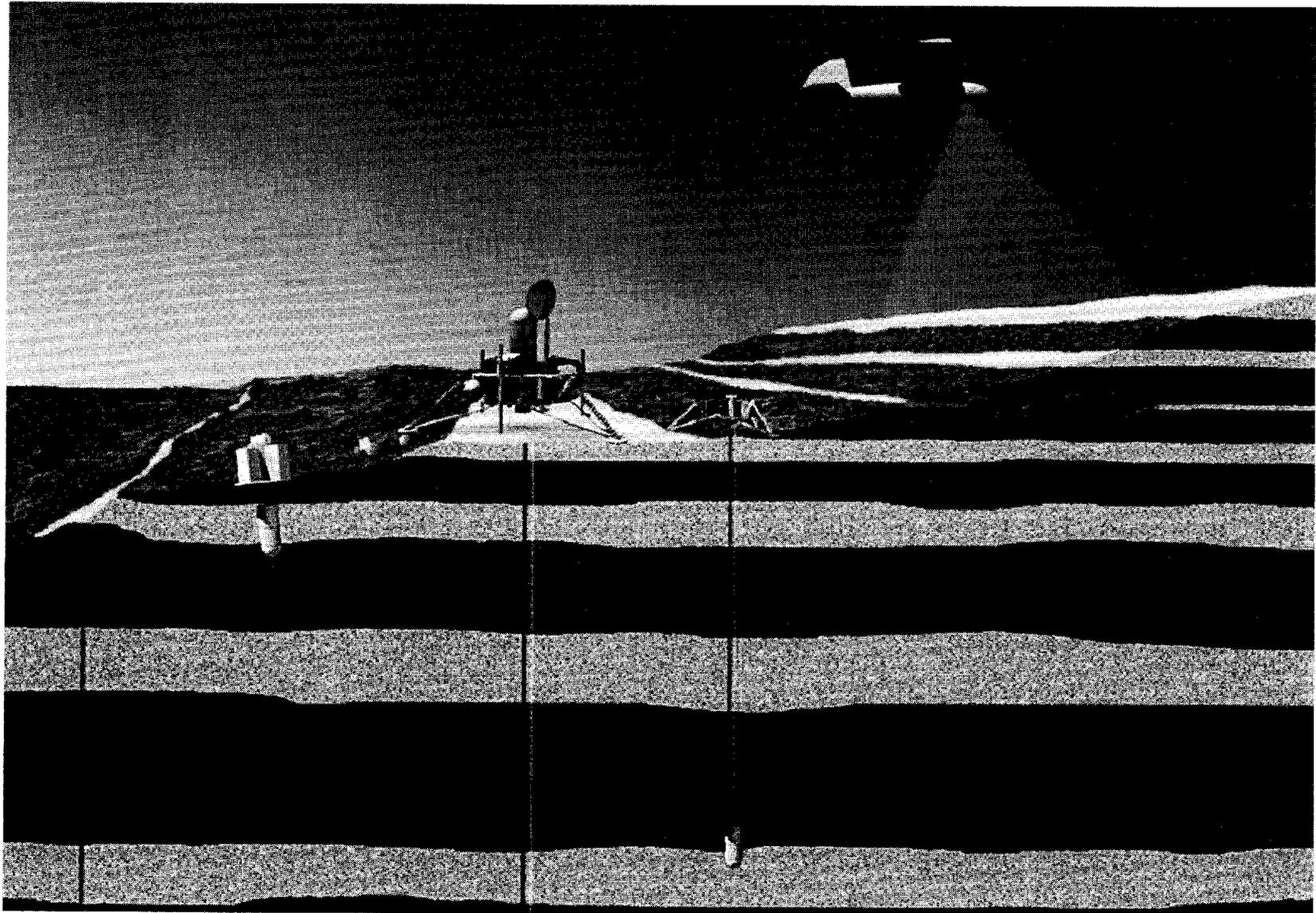
IVA Robotics



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



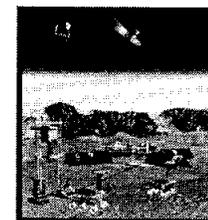
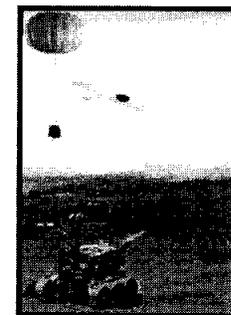
... a More Recent Vision for Planetary Exploration



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.**





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).**

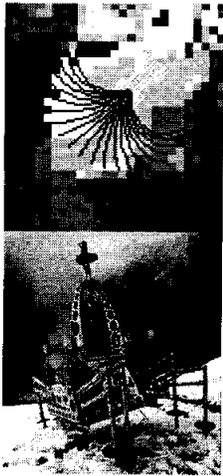
Mission Opportunities and Needs (NExT)

- 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").

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



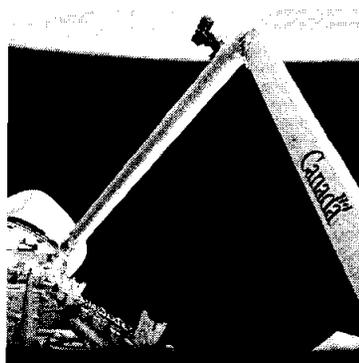
Position sensors, collect and process samples



In-Space / On-Orbit Operations

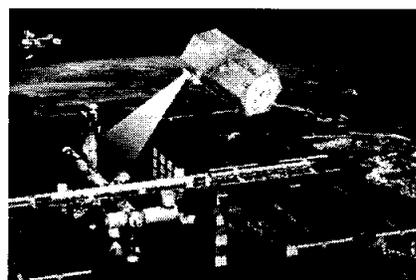
(Reference: NExT Study on Space Robotic Capabilities)

Assembly



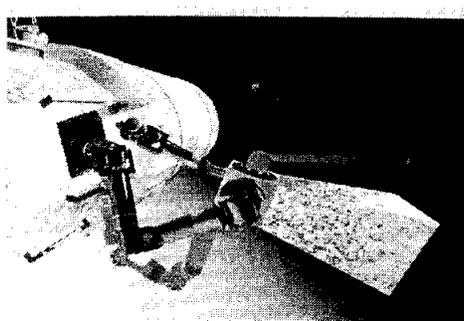
Transporting and mating of components; making connections; assembly sequence planning and execution; assembling small structures

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

JPL Related Challenges—EDL and Sample Return

Precision Safe Landing, In-Orbit Rendezvous & Sample Capture

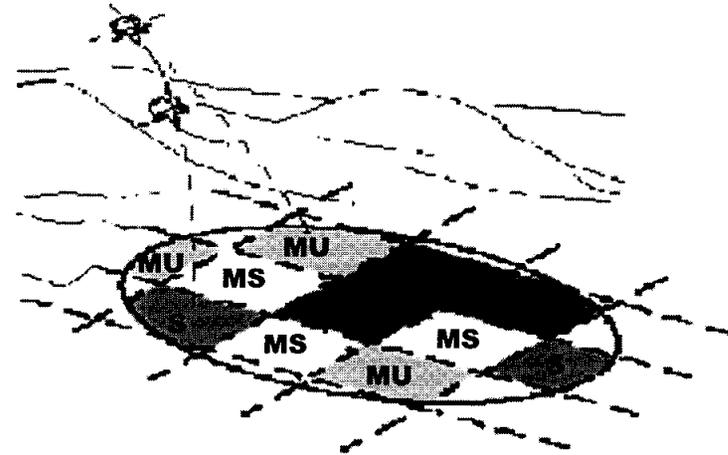


Develop capability for safe landing on a planetary surface using multiple sensors and appropriate on-board intelligence.

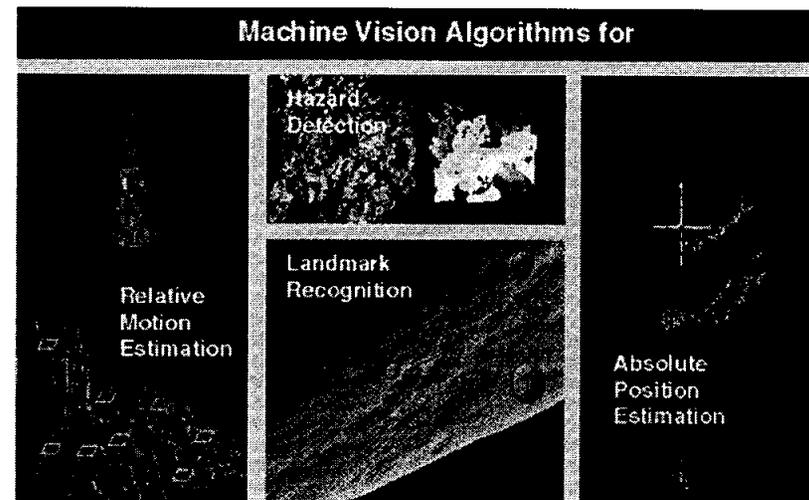
- **Site Risk Assessment:** The safety of potential landing sites will be assessed independently by onboard sensors, and integrated to form a multi-grade representation of the landing site safety.
- **Optimum Site Selection:** Based on the site safety map and the spacecraft constraints, the optimum landing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

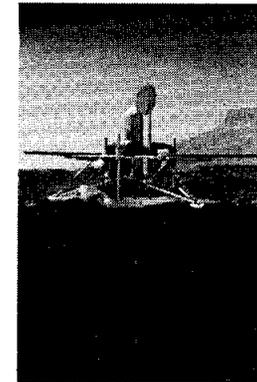




... a Current Vision for Solar System Exploration

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

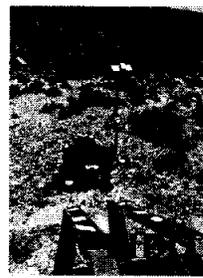
- **Rove globally over planetary surfaces and approach local sites (even in extreme terrain) within ~ 1 pixel of planning image with overall system performance comparable to a field scientist.**
- **Access subsurface environments including liquid water aquifers or polar caps on Mars, Titan, Jovian moons 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**





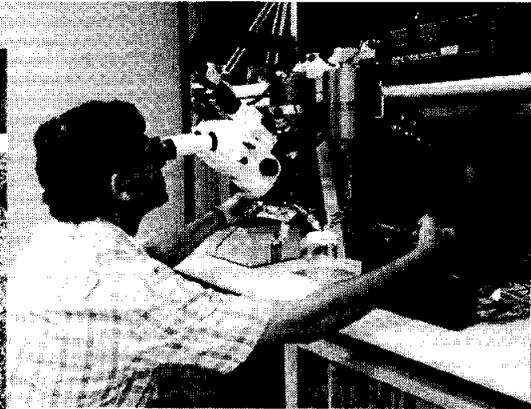
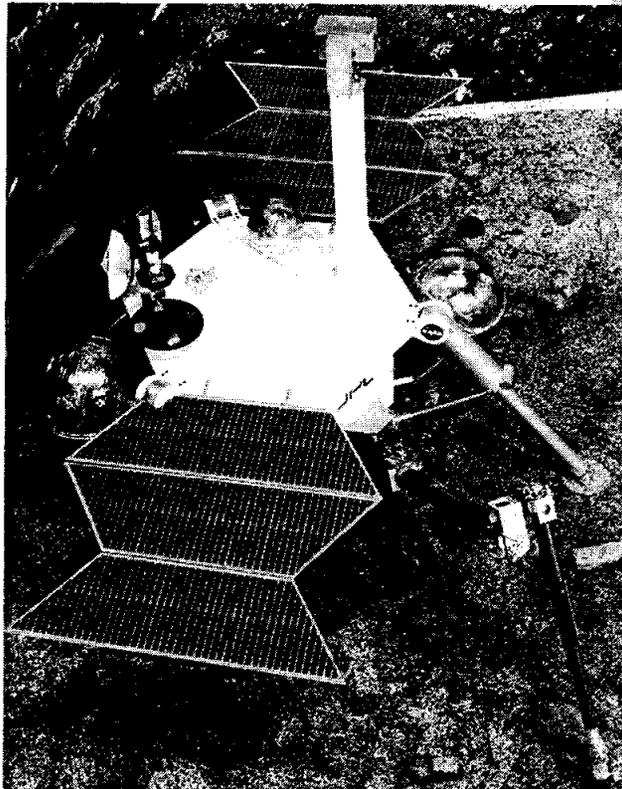
Mobility R&D at Jet Propulsion Laboratory

- **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 and 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.)

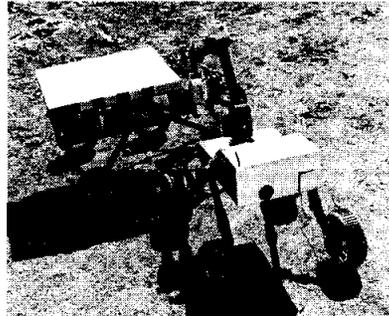


Above: Dual Arm Surgical Tele-Manipulator (RAMS)

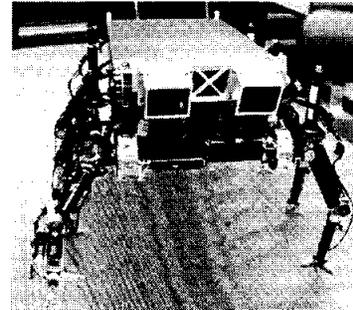
Left: Lander-Manipulator with Camera (Phoenix)

Right: Rover Arm for Instrument Placement (MER)

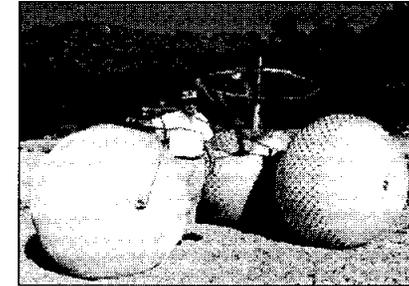
Mobility System Development (Examples)



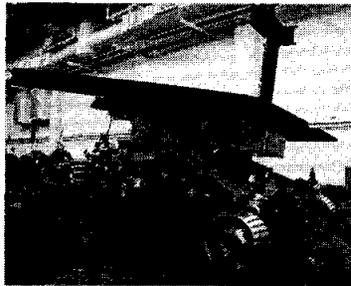
Sample Return Rover



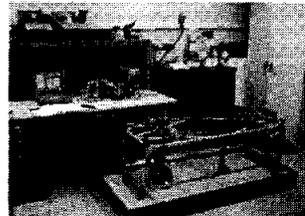
LEMUR



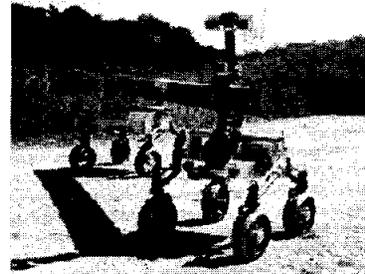
Inflatable Rover



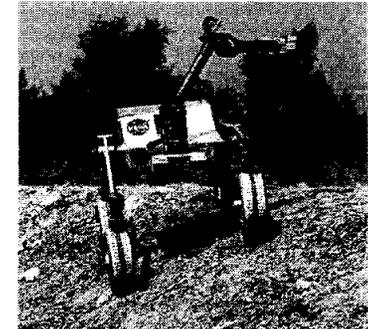
**MER Egress
Rover**



**MER Wheel
Test Stand**



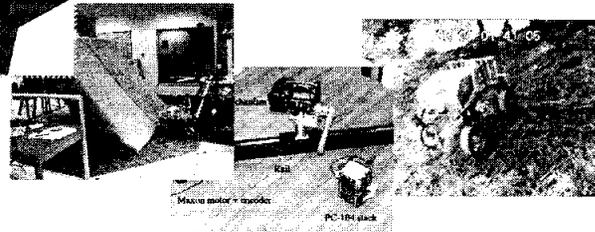
Robot Work Crew



All Terrain Rover



**Cliff-bot
System**

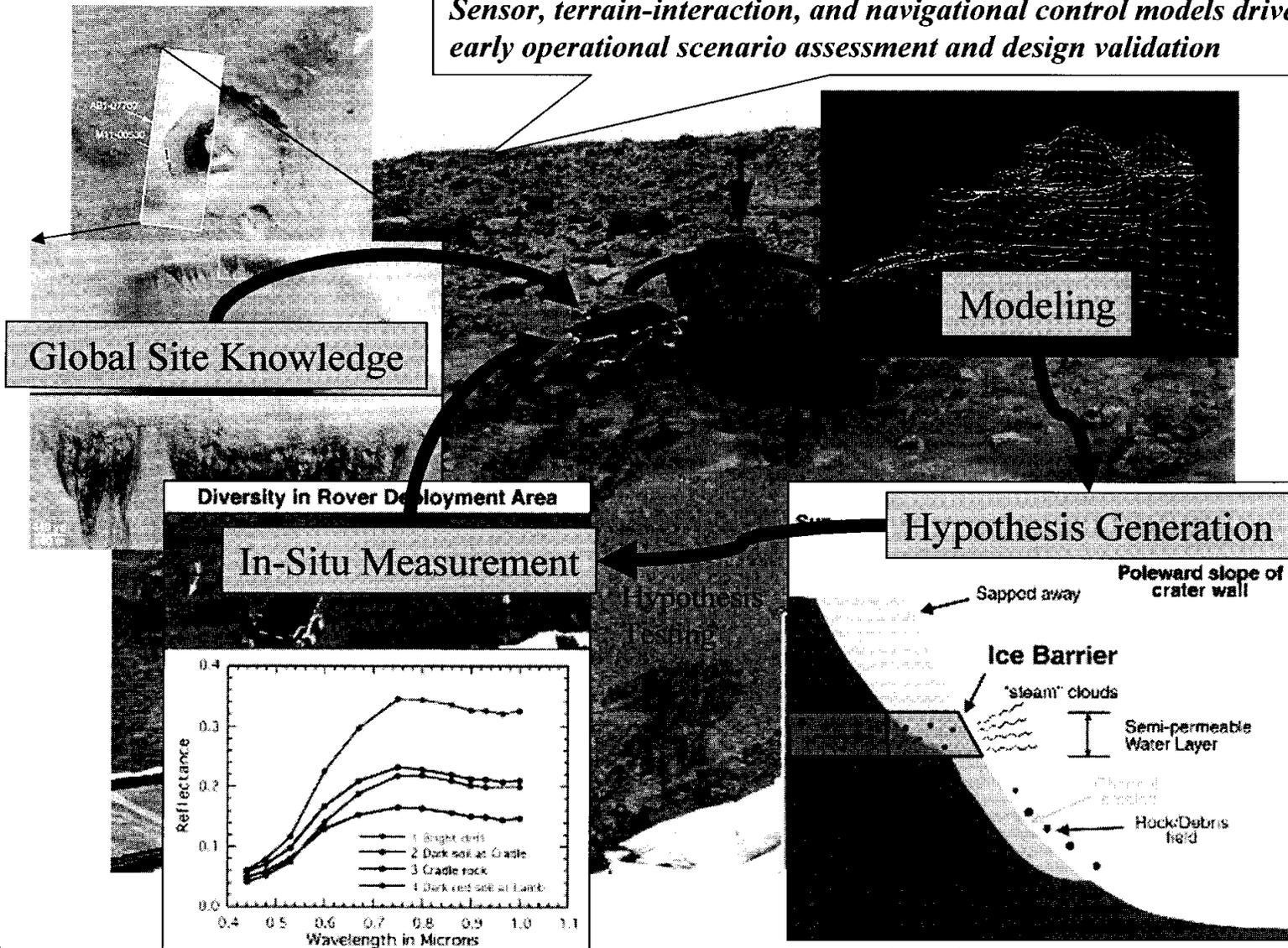


Planetary Robotics Laboratory

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

Scientific Operations on Planetary Surfaces

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





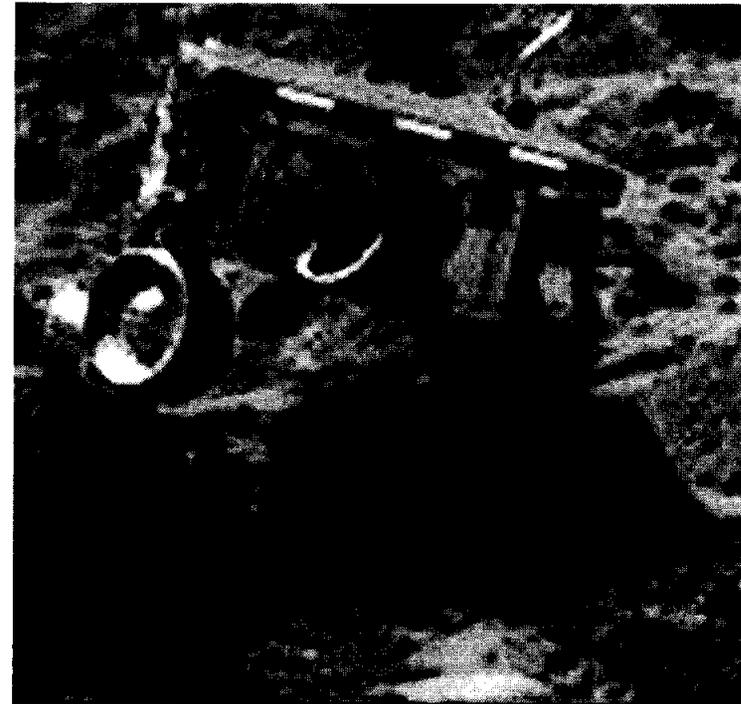
Example: The Mobile *In Situ* Science Paradigm

- **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 a 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 ...**

Caveat Emptor

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

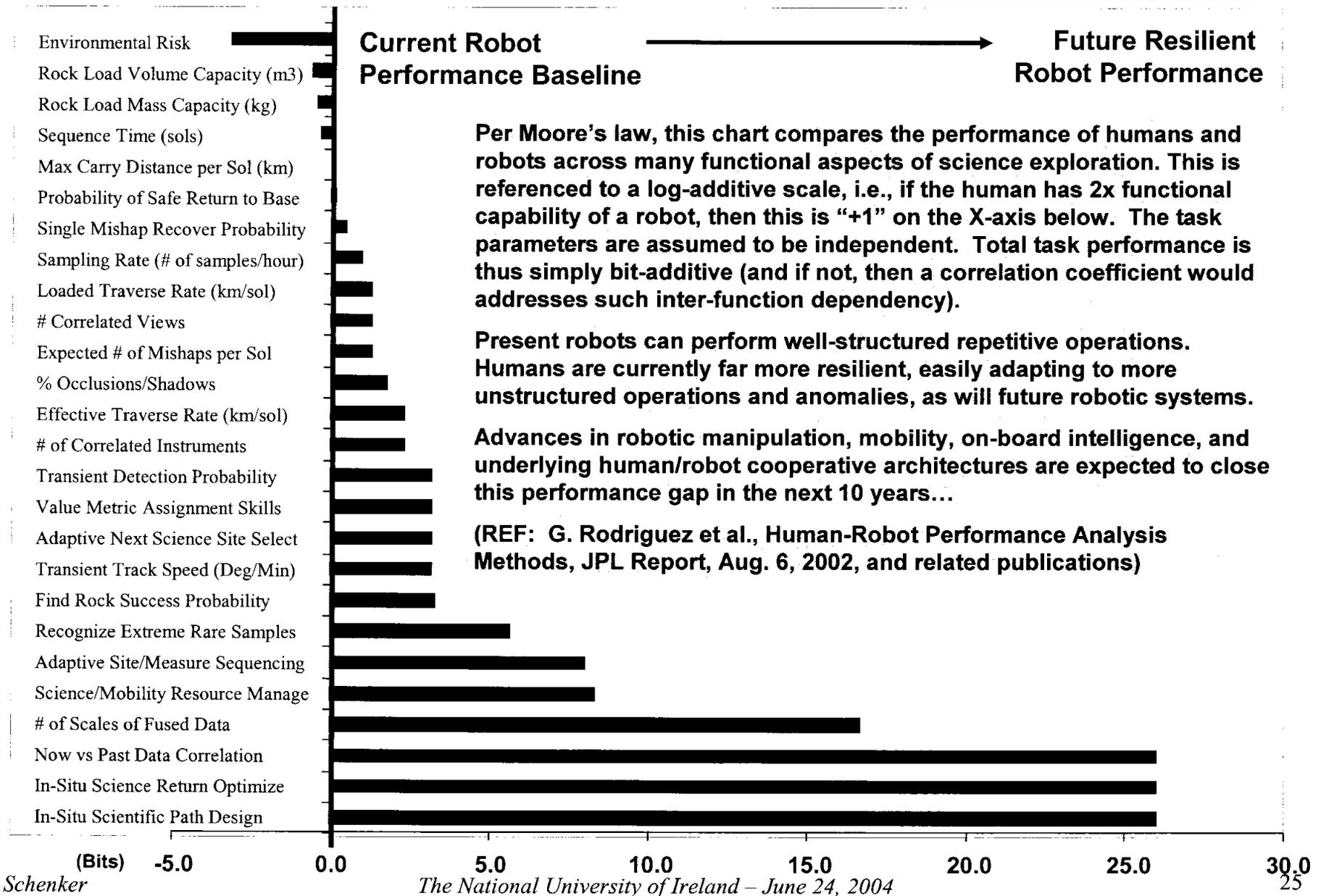
- The situation shown to the right occurred when Mars Pathfinder ground operations planners—overriding on-board autonomous navigation—commanded the Sojourner rover into a very rocky area.
- "Blind" moves and turns were used, and navigational errors were compounded by noise on rate gyro.



Mars Pathfinder/Sojourner (1997)

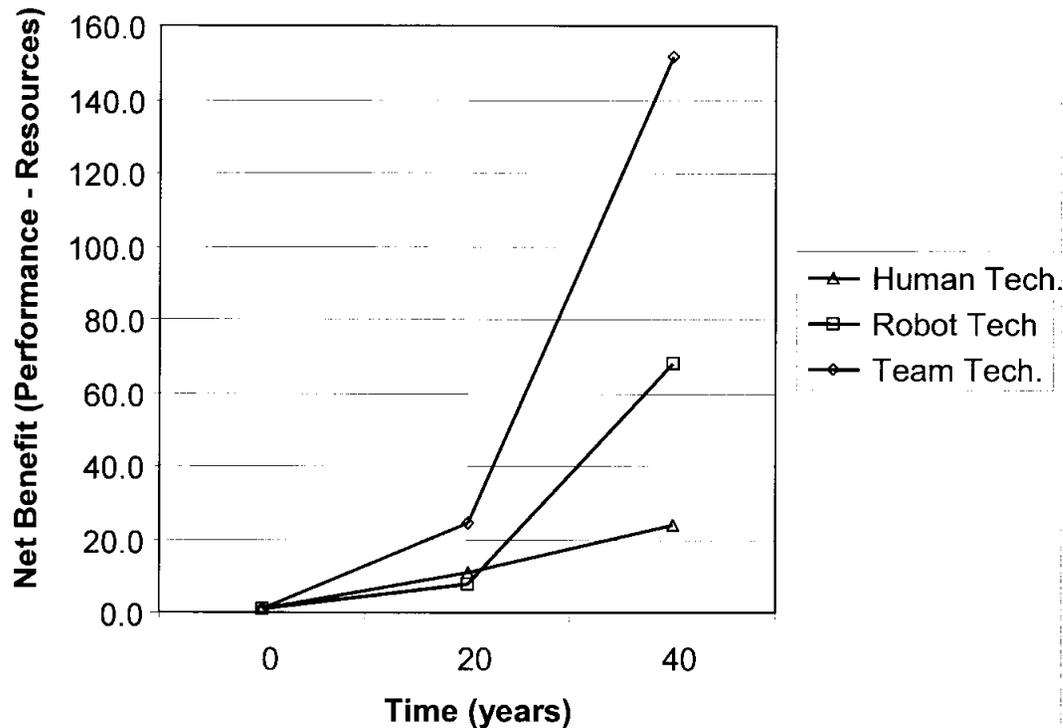


Human & Robotic Performance Comparison



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.)

Space Robotics Technologies & Operational Metrics

MANIPULATION

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

MOBILITY

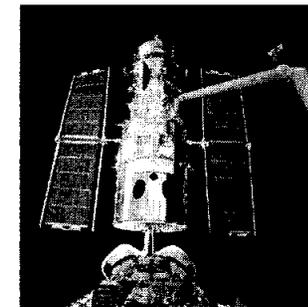
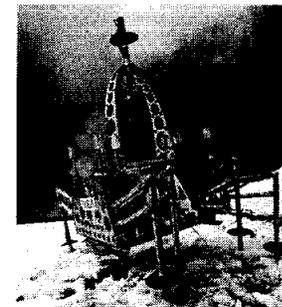
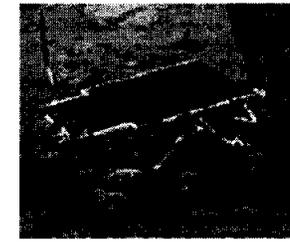
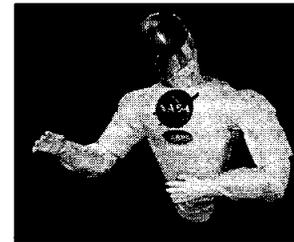
- Ground speed
- Ground pressure
- Traversability
- Localization
- Cone of stability
- Climb rate
- Holonomicity
- Self-rightability

ON-BOARD INTELLIGENCE

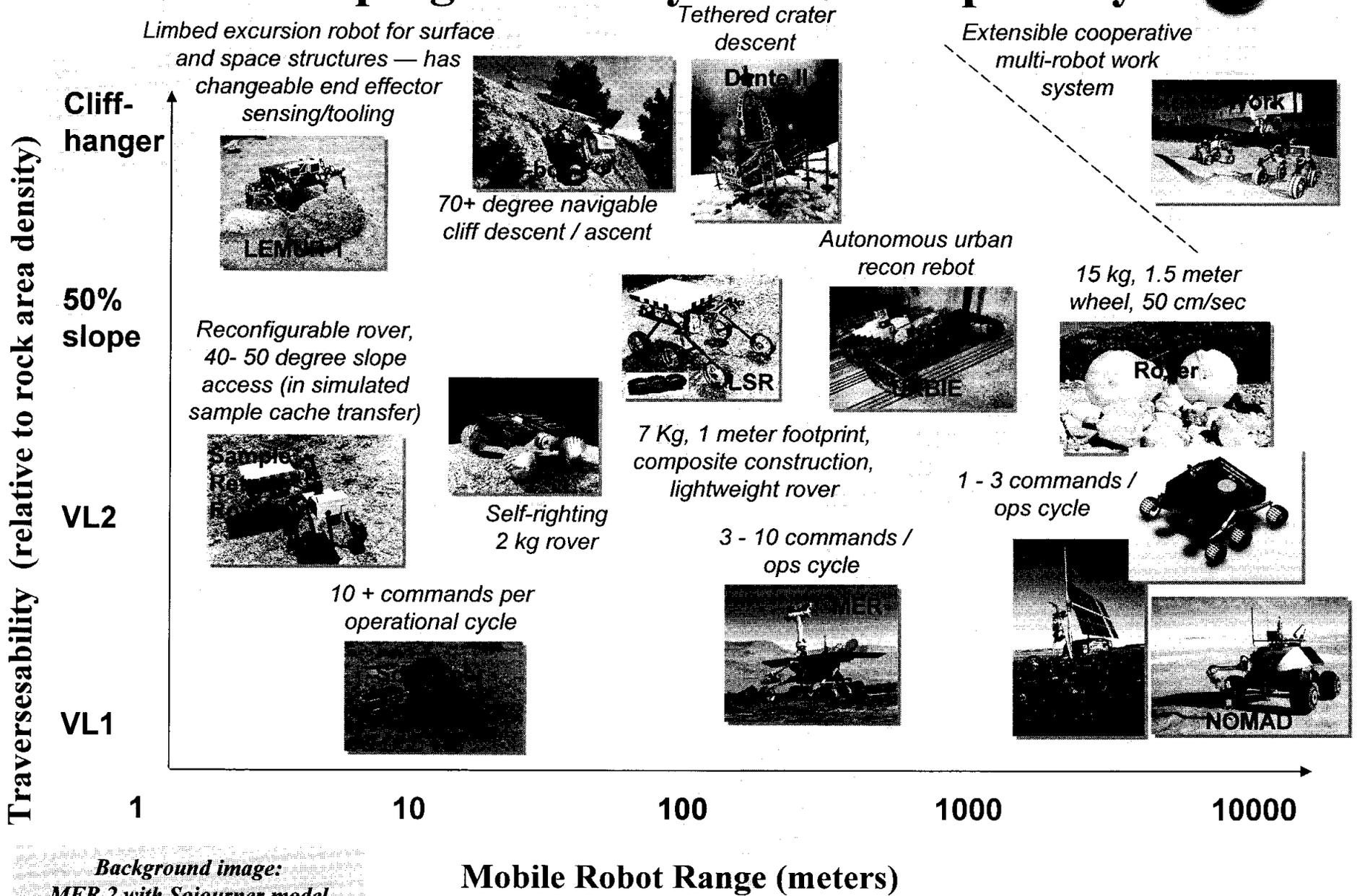
- Resolution (multi-scale representation)
- Scalability (computational complexity)
- Completeness (search depth, breadth)
- Generalization (of classes, objects)
- Learning (from instances, training, etc.)
- Contingency (recursion, nonlinearity)
- Fidelity (binarization of analog models)
- Robustness (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)



JPL Developing Planetary Surface Capability



Background image:
MER 2 with Sojourner model



Field Testbeds & Field Trials



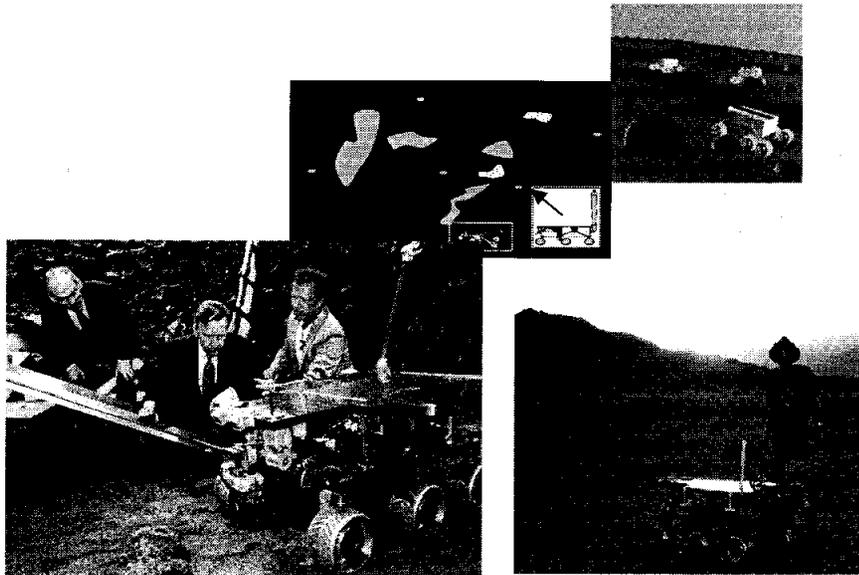
Testbed Use

- 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 (Field Integrated Design & Operations) Rover"

QuickTime™ and a 3iv 54 DF 116 odn decoder are required to see this picture.

FIDO Video



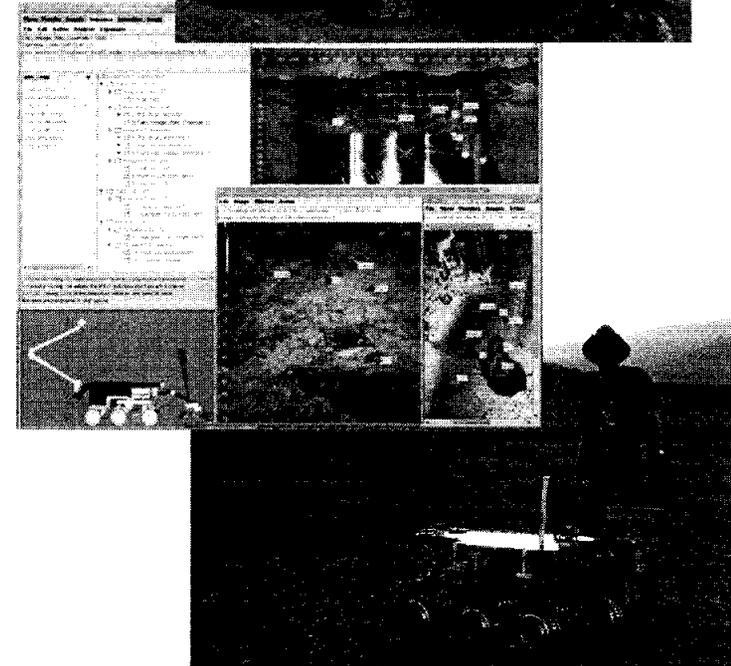
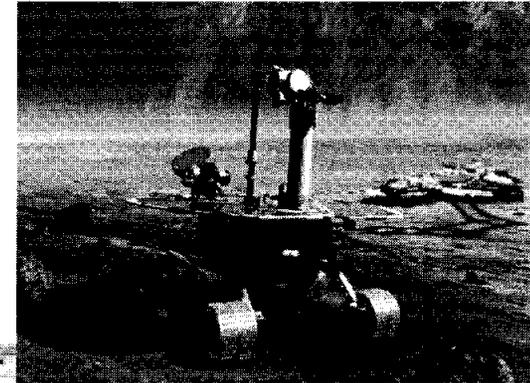
Supporting Technology Development

- 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 including personnel

- **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



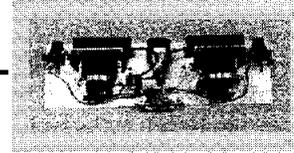
**Miniaturization
and
Integration of
In Situ
Instruments
on
FIDO**

SCIENCE

<http://wufs.wustl.edu/fido/> Arm Instruments

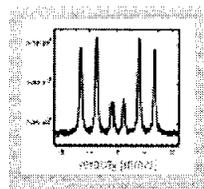
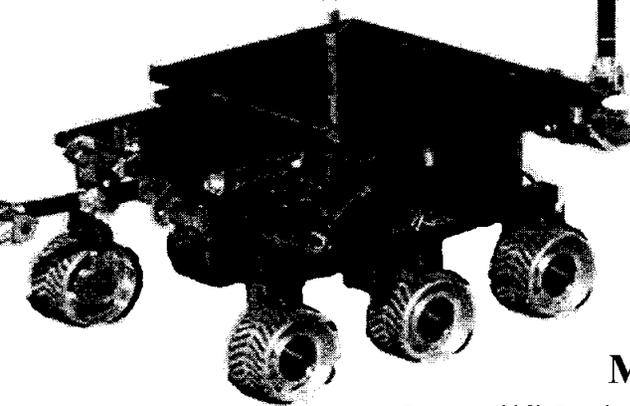
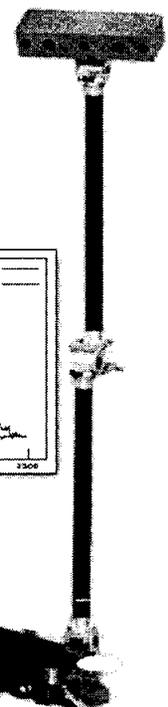
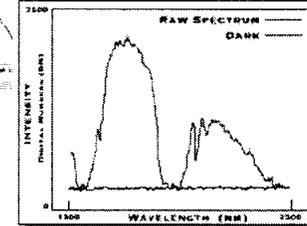
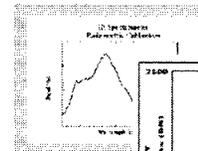


Panoramic Cameras,
Filtered



Mast Instruments

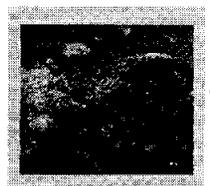
IR Point Spectrometer



Mossbauer Spectrometer



Color Microscope



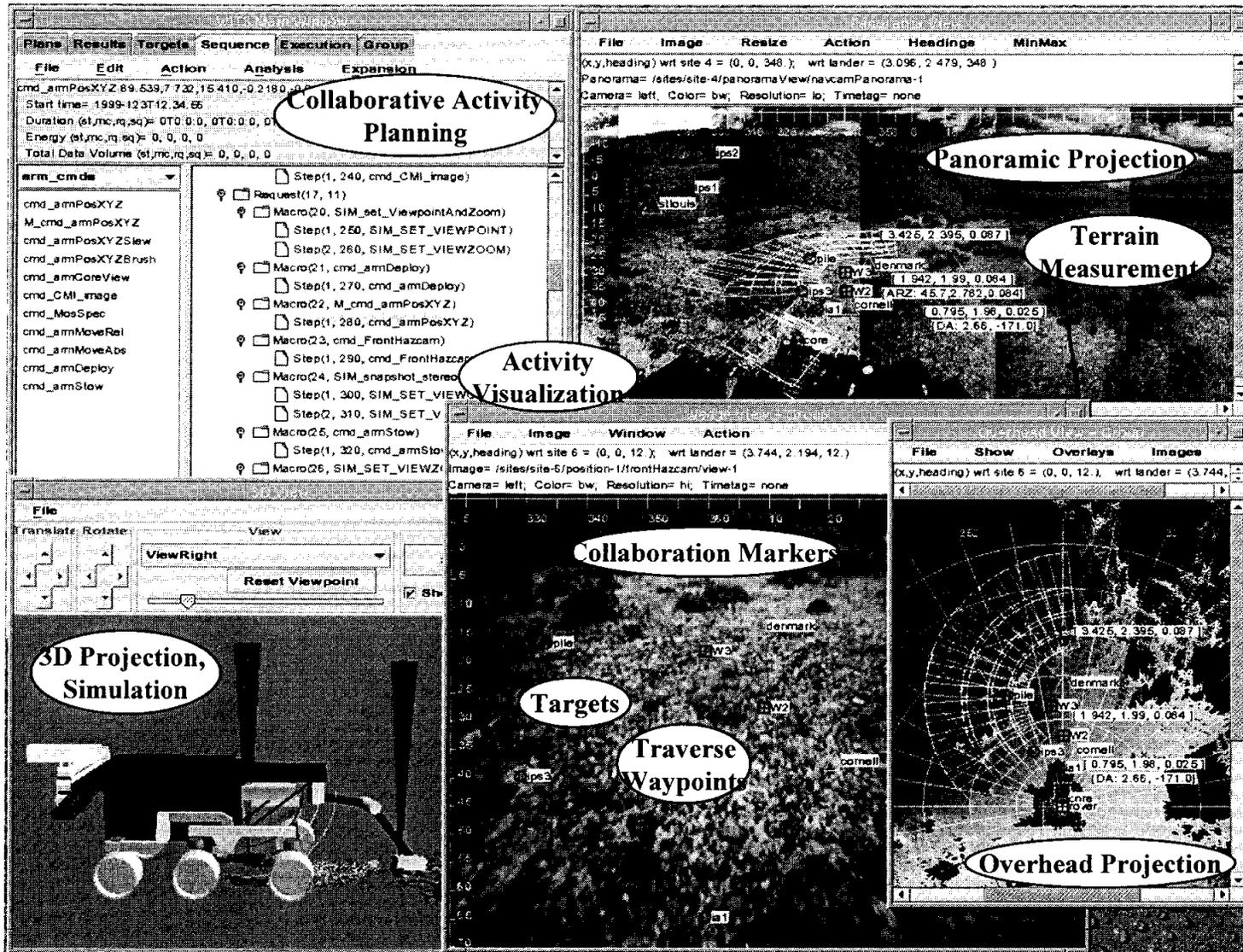
INSTRUMENTS

<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

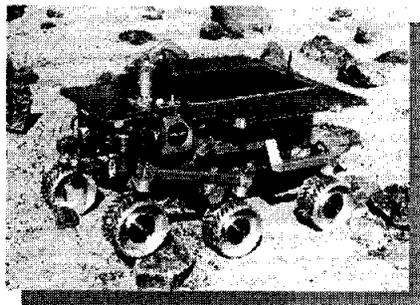
A
 JPL-developed
 environment for
 distributed and
 collaborative
 mobile science

Integrated Infrastructure for Mobility System R&D

Infrastructure

Hardware

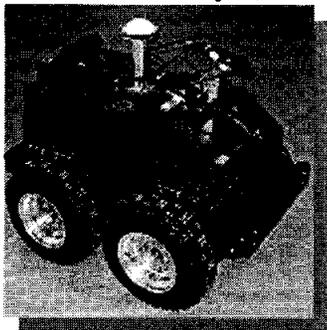
Software



Rocky 8, JPL



FIDO, JPL



ATRV, CMU

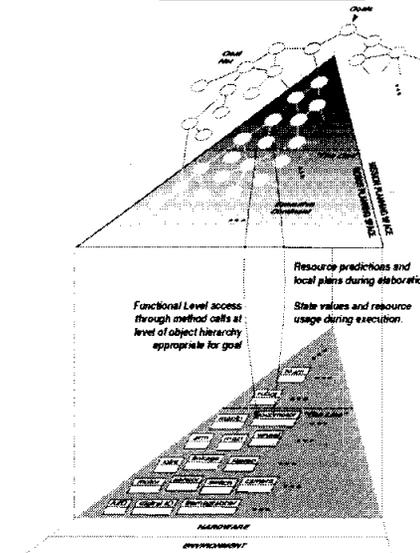


Rocky 7, JPL



K9, ARC

FUNCTIONAL DECISION LAYER



Coupled Layer Robotic Autonomy Architecture (CLARAty)

Current Research Team / Mars Technology Program Tasks

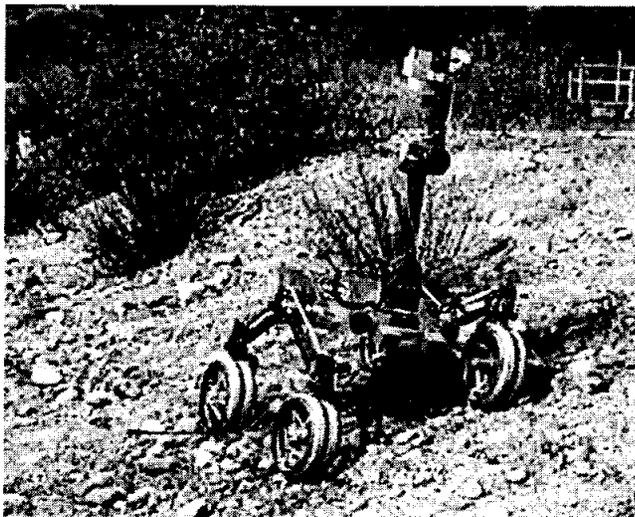
- JPL (Driving on Slopes, Visual Servoing, Simulation)
- MIT (Terrain Estimation)
- Univ. of Washington (Terrain Mapping)
- ARC (Autonomous Science, Simulation, Fault Detection)
- CMU (Path Planning)
- Univ. Michigan (Position Estimation)

Hardware & Software Innovations Converge



Rover State Estimation and Predictive Control (JPL)

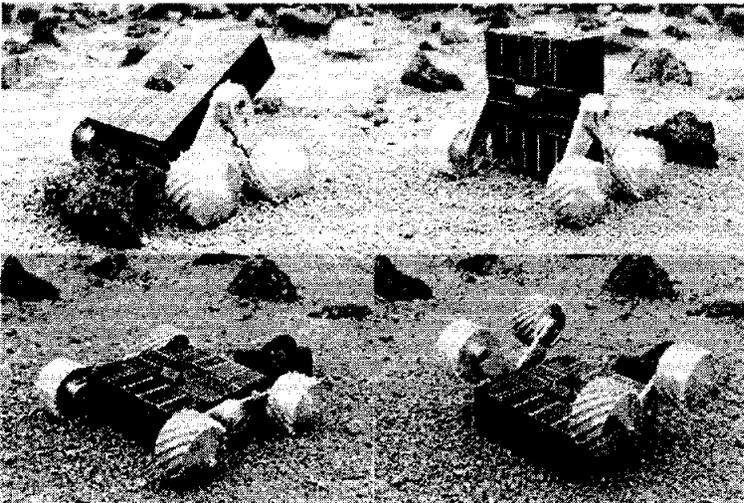
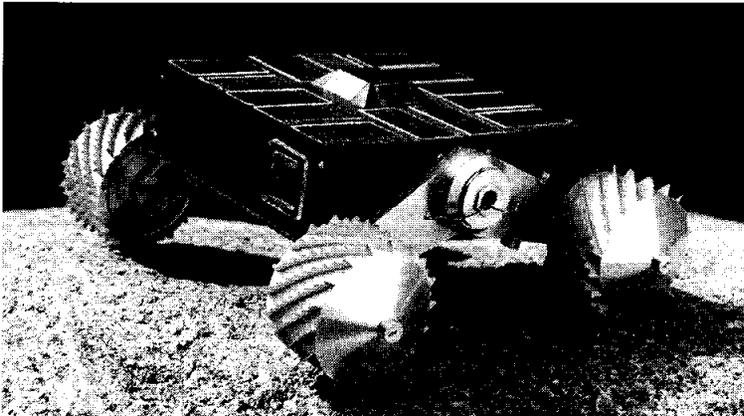
- Successfully demonstrated on SRR in Arroyo Seco at slopes of up to 50° , wherein fixed-geometry control was shown to fail
- Provides stability with respect to *slip and tip-over*
- Uses visually sensed range map, spline parameterization, and INS for model-based predictive state estimation
- Predictive 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.)

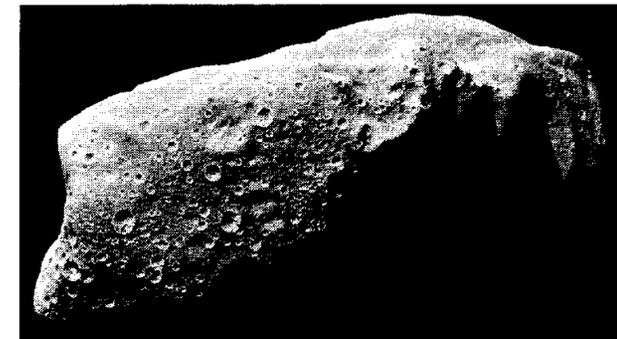
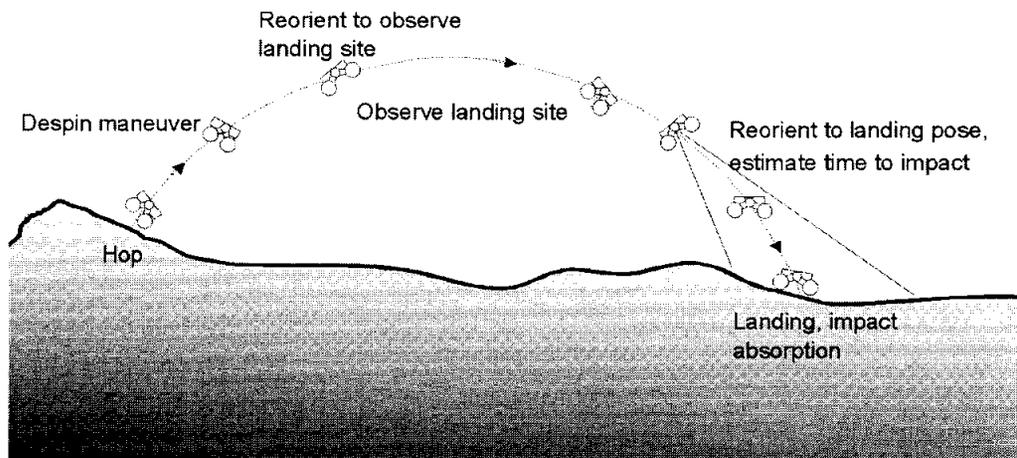
Miniaturized Mobility (Nanorover)

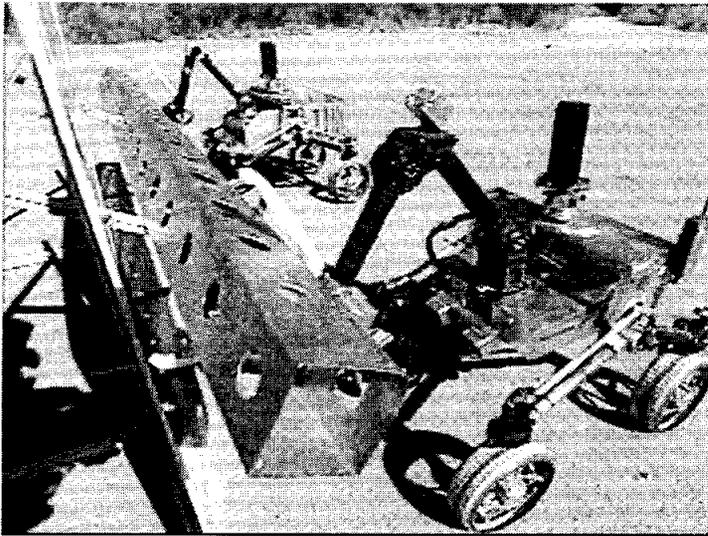


- Body - 14 cm square
- 4 wheels 6.5 cm diameter
- Wheels on articulated struts
 - can lift wheels and set on top of obstacles
 - capacitive proximity sensing in each wheel
 - right and left-hand helical grousers to assist in skid steering
- 32-bit R3000 processor
- Hi-res Camera (0.3mrad/pix)
- IR Spectrometer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

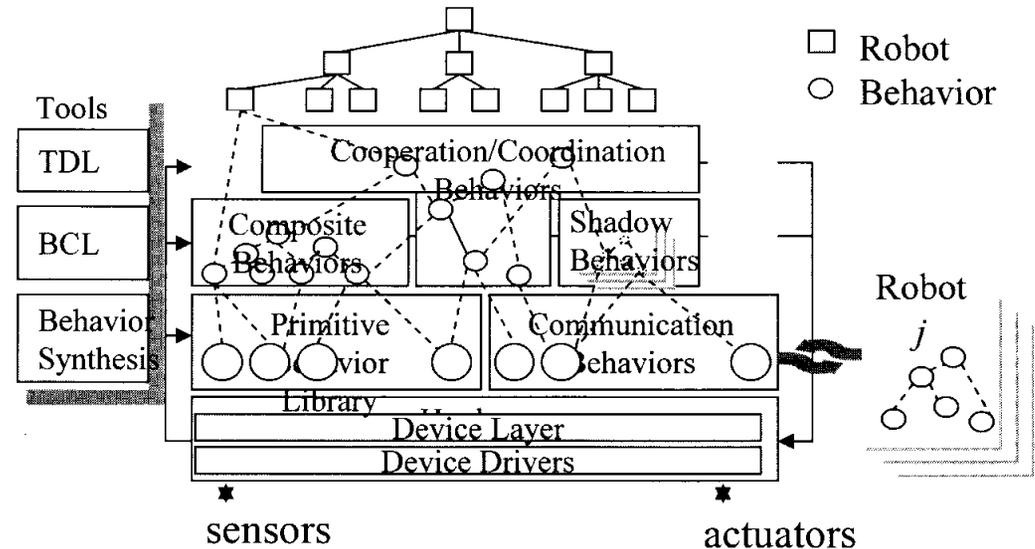
Challenges and Unique Opportunities!

- **Mobility in a Microgravity Environment**
 - trajectory propagation, gravity and dynamics modeling
 - surface interaction modeling (traction, electrostatic adhesion, Van der Waals forces, etc....)
 - position and attitude estimation and control
- **Anchoring and Sampling**
 - kinetic anchors and samplers (nail gun, drive tube)
 - reaction forces for sampling and means to compensate
 - thermal management of sample contamination control





Hierarchical task planning, allocation, and monitoring



EXAMPLE: *Robotic Work Crew*

- Mixed Initiative Control Architectures 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



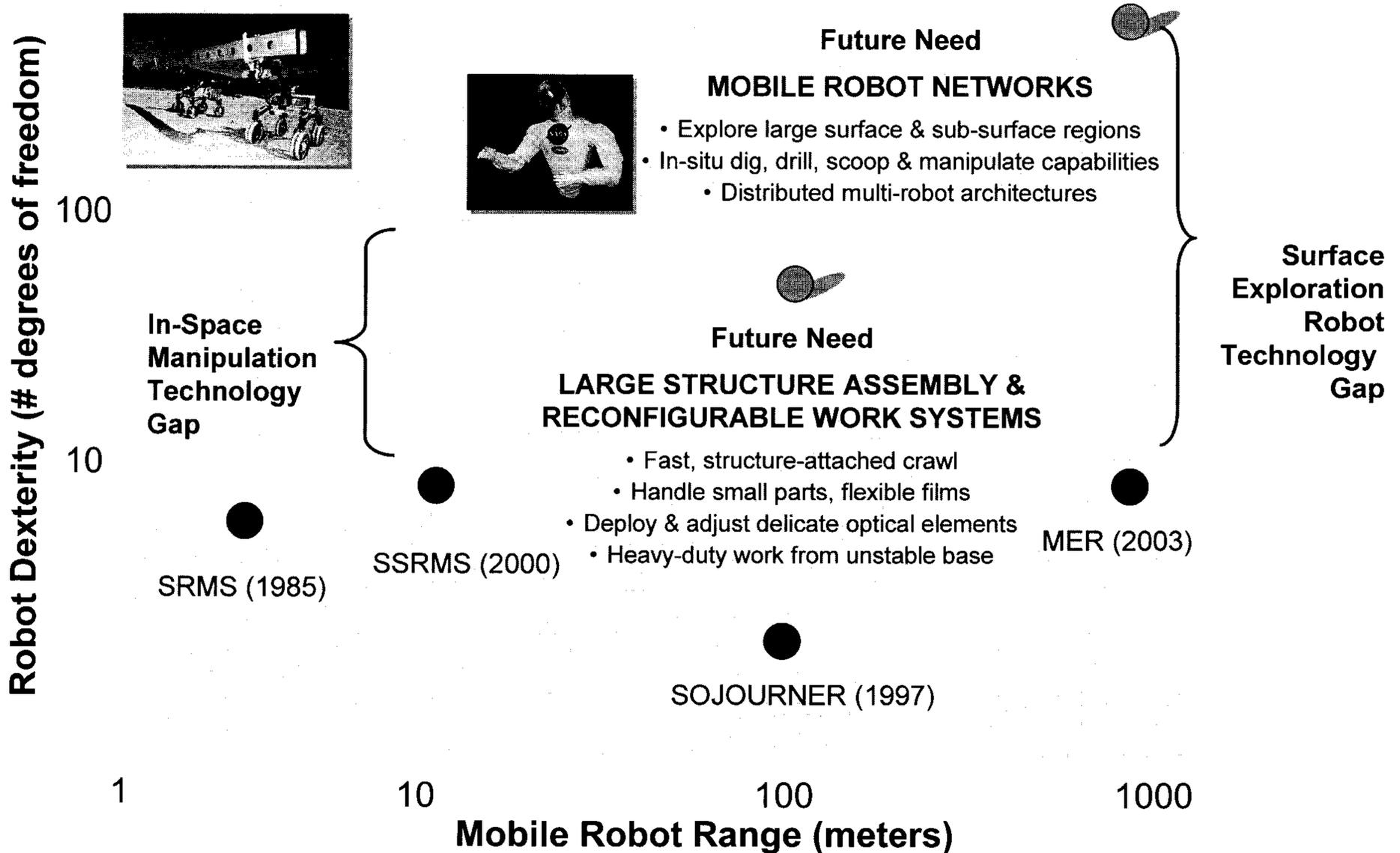
Autonomous Mobility in Challenging Terrain

Mobility for High Risk Access and High Value Science



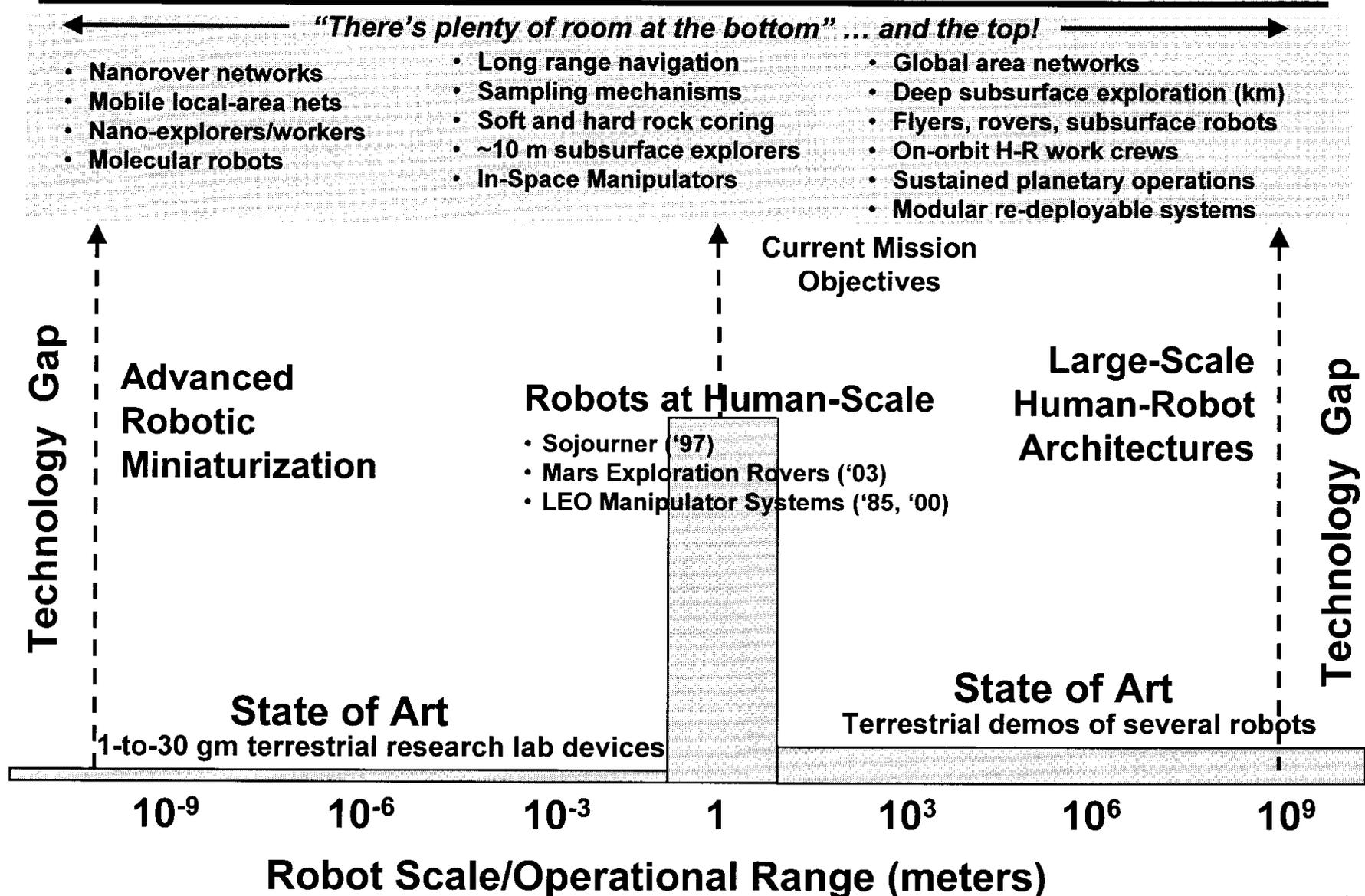
Filling the Technology Gaps

On-Orbit and Surface Operations





The Scale, Theatre, & Performance of Space Robotics





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**