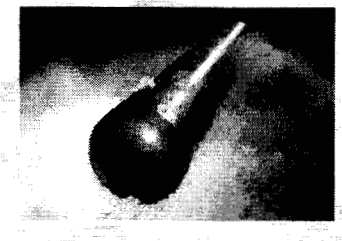
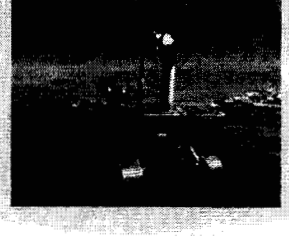
The Expanding Venue and Persistence of Planetary Exploration

... a mobile robotics perspective ...

Dr. Paul S. Schenker



Mobility Systems Concept Development Section
Jet Propulsion Laboratory,
California Institute of Technology



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Outline

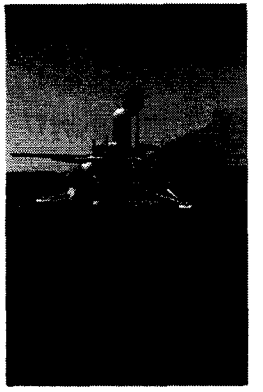
- A Motivational Example
- Operational Challenges to Mobile Robotics
- NAS Decadal Studies and NASA Planning
- Surface, Aerial and Subsurface Domains
- Future Needs & Performance Metrics
- JPL R&D Program for Mobile Robotics
- Some of the Harder Problems Ahead
- Conclusions

A Vision—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 orbital imagery.**
- **Select, acquire and prepare samples suitable for any in-situ instruments with end-to-end performance comparable to current Earth science processes.**

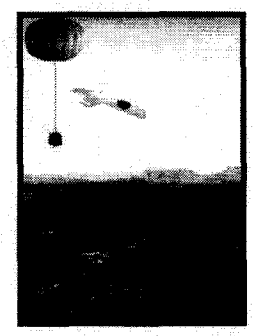
- **Acquire, loft, rendezvous/capture, and return to Earth pristine samples within appropriate planetary protection guidelines.**
- **And ultimately, conduct persistent human/robotic teamed exploration of high value planetary and lunar bodies**

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**

Space Mobility — The Big Challenges

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/soft")**
- **Access disparate subsurface regions (soil/rock, ice/water)**
- **Span highly variable atmospheres (controllable 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 – the NAS/SSES Decadal Report

- 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 Summary

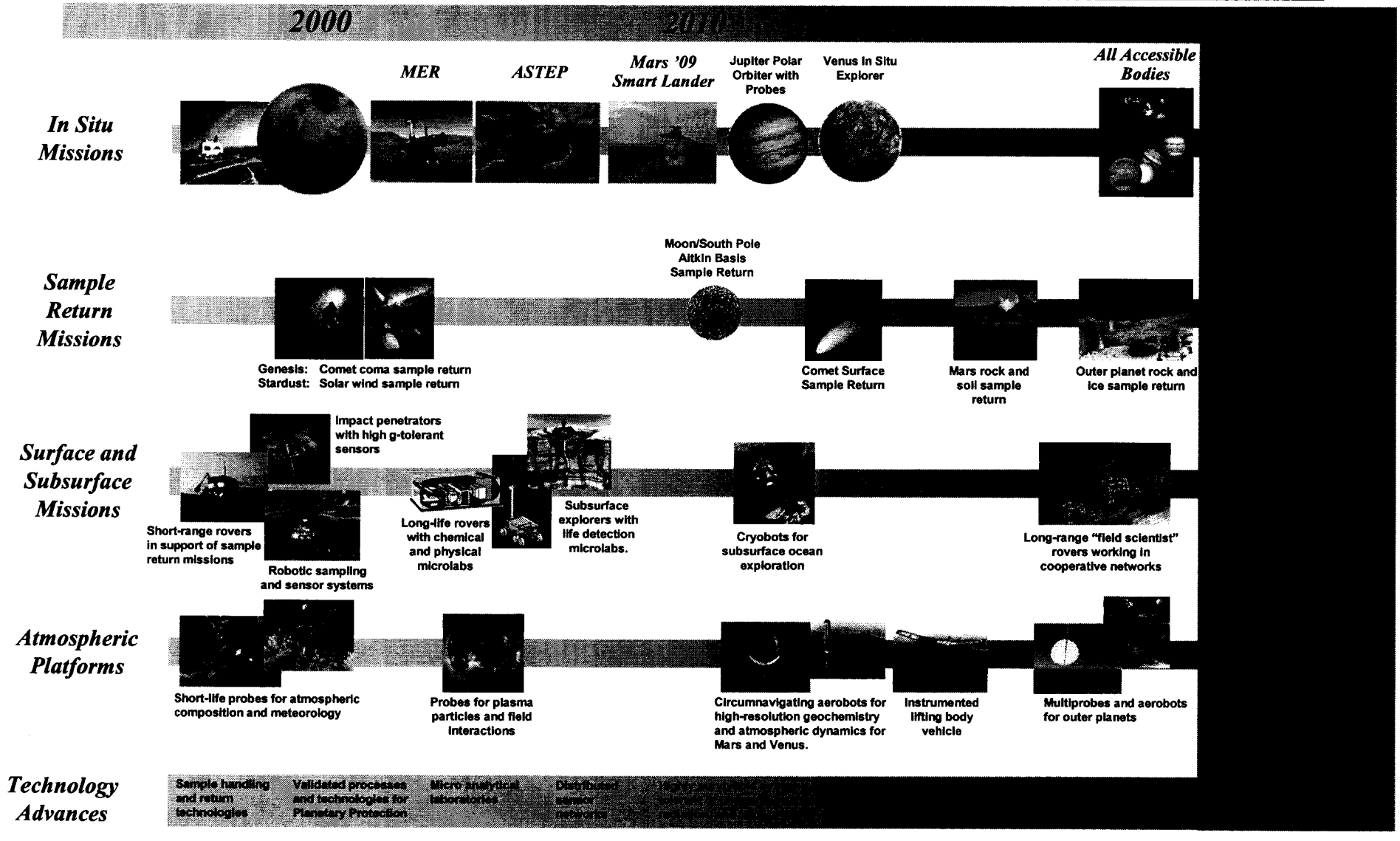
- **The NASA Exploration Team (NExT) has explored an overarching set of mission needs, metrics and roadmaps leading to Technology for Human/Robotic (H/R) Exploration and Development of Space (*THREADS*).**

- **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*).**

A Conceptual Roadmap for Mobility System Development



Mars Missions: 2009 – 2020 Exploration "Pathways"

Under NASA Consideration

Pathway	2009	2011	2013	2016	2018	2020	NOTES
Explore Hydrothermal Habitats	**MSL to Hydrothermal Deposit**	**Scout**	**Astrobiology Field Laboratory**	**Scout**	**Deep Drill**	**Scout**	**All core missions sent to active or extinct hydrothermal deposits.**
Search for Evidence of Past Life	**MSL to Low Lat.**	**Scout**	**Ground Breaking MSR**	**Scout**	**Astrobio. Field Lab or Deep Drill**	**Scout**	**All core missions to mid-latitudes. Mission in '18 driven by MSL results and budget.**
Search for Present Life	**MSL to S. Pole or Active Vent**	**Scout**	**Scout**	**MSR with Rover**	**Scout**	**Deep Drill**	**Missions to modern habitat. Path has highest risk.**
Explore Evolution of Mars	**MSL To Low Lat.**	**Scout**	**Ground Breaking MSR**	**Aero-nomy**	**Network**	**Scout**	**Path rests on proof that Mars was never wet.**

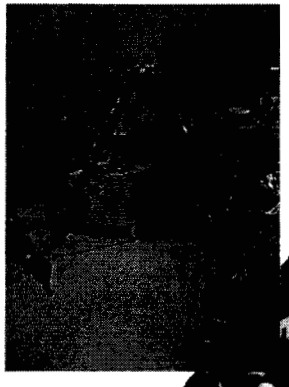
Future Missions and the Enabling Role of Mobile Robotics

Now–2004

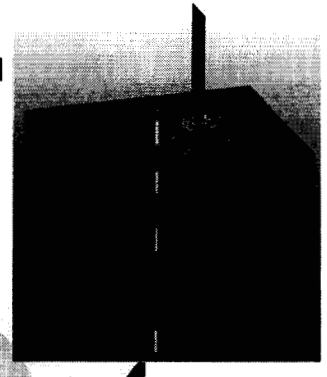
MER Instrument Deployment Device

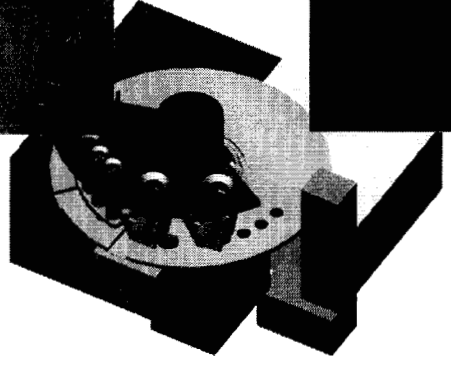
MER Rover Integrated with Instrument Deployment Device

2007–2010

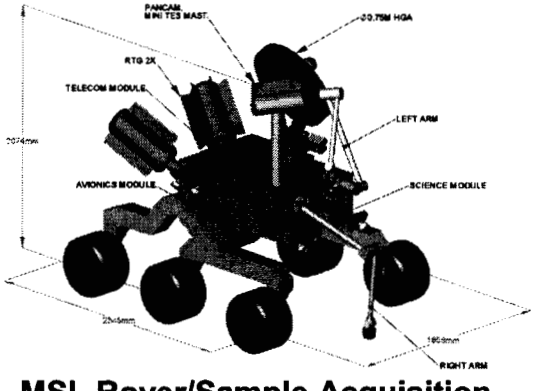


Scouts and Discovery Missions





MSL Sample Preparation/Handling

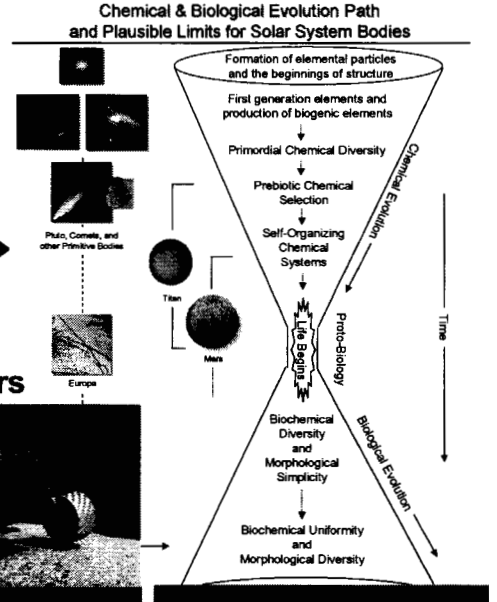


MSL Rover/Sample Acquisition

2011–2020

New Frontiers and Mars Long-Life Rover/Sample Return

Search for Origins of Solar System, its Evolution, and Signs of Past/Extant Life



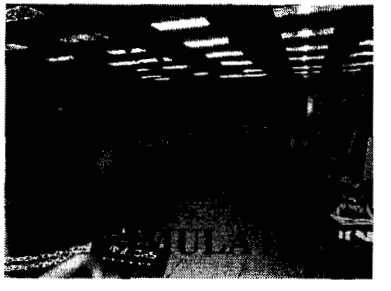
Asteroid Nano-rovers

Lunar/Venus/ Comet Landers

Titan Aerial Platform with Sampling Sonde

Mobility/Robotics R&D at Jet Propulsion Laboratory

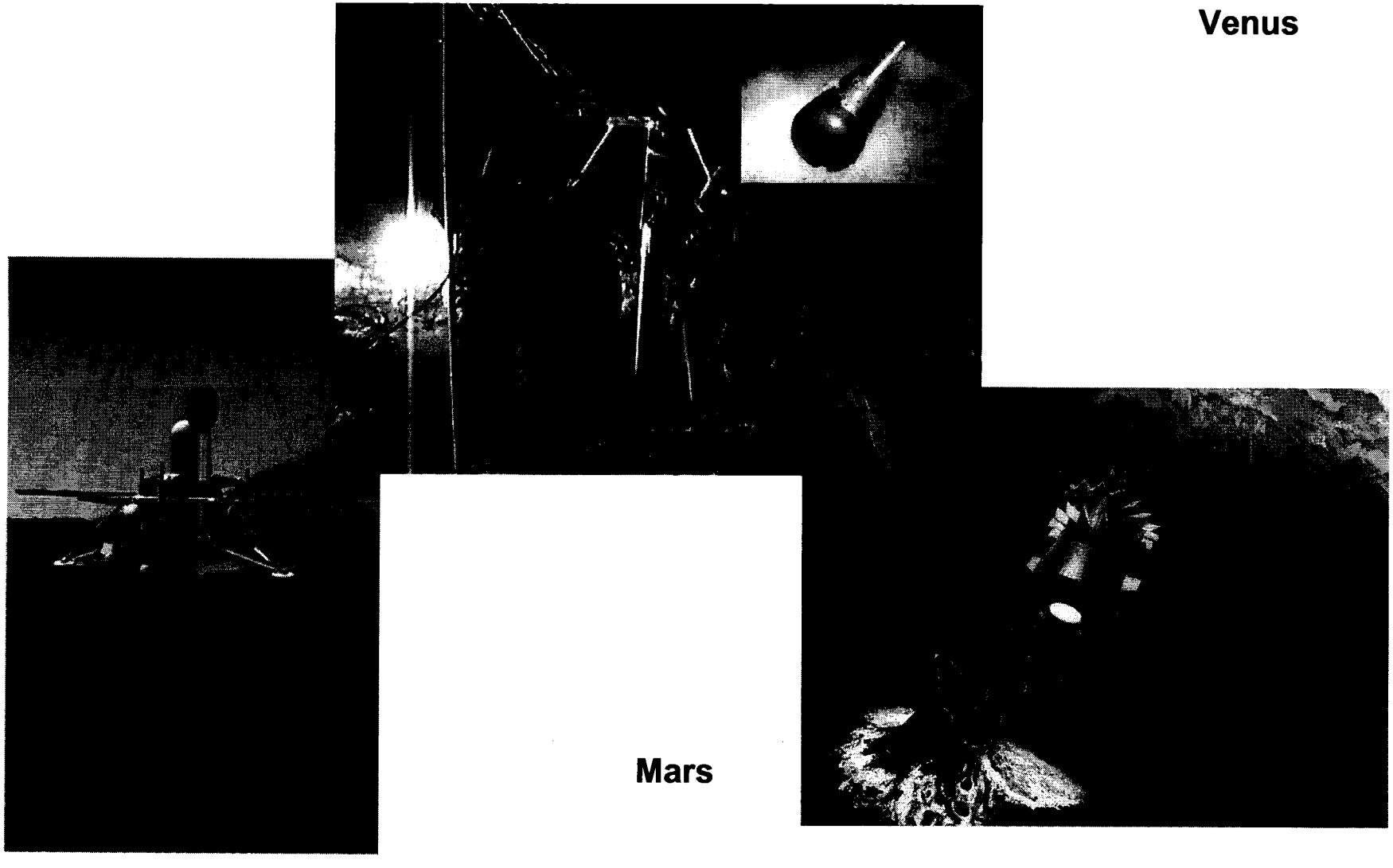
- Mobility/robotics is a "major institutional thrust" at JPL
- Products are critically enabling to current/planned missions
- Work and deliverables span basic R&D to flight-mission systems
- Operational foci include aerial/surface/subsurface mobility
- ...with *in situ* science analysis, sampling and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



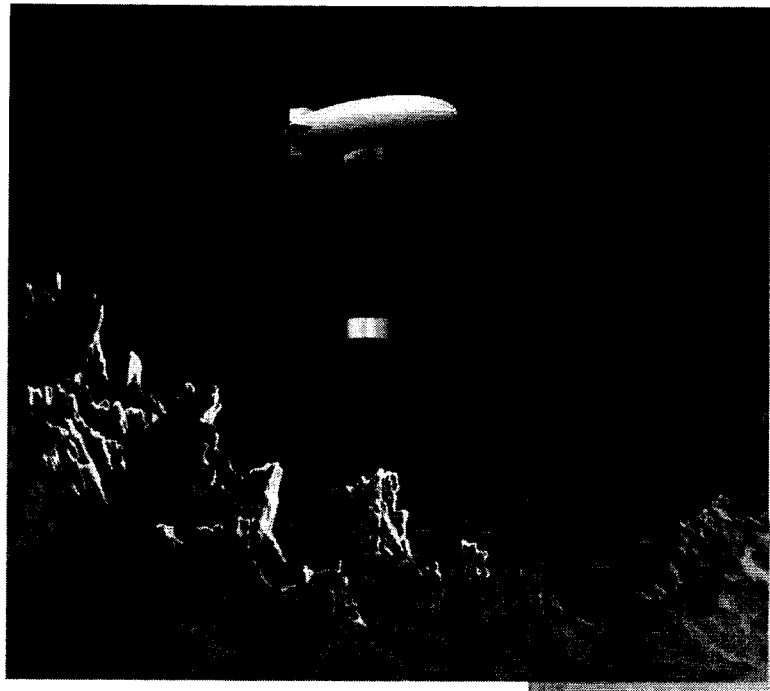
Scope of the JPL Mobility/Robotics R&D Effort

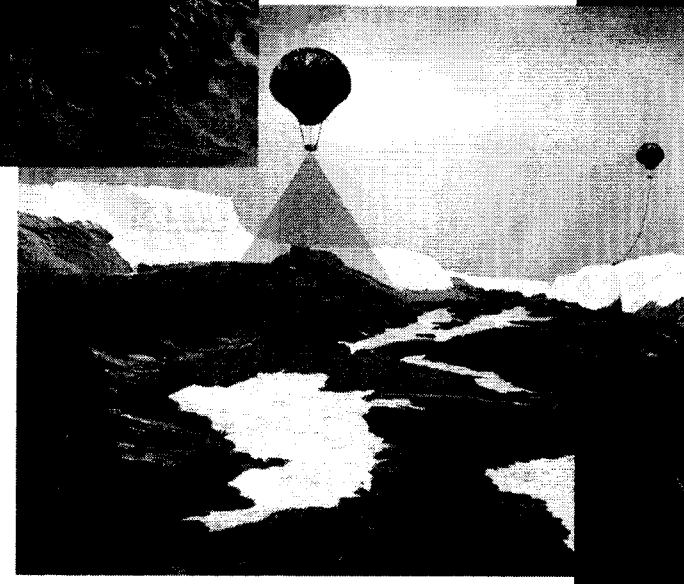
- Scope of current mobility/robotics R&D is ~$ 16M/year, 80+ people
- Emphasis has been "Mars-centric", and is now rapidly expanding
- Interest in Outer/Inner Planets, small bodies, subsurface/sampling
- This is supported by new tasks/technology for aerobots/drills/etc.
- Character of work is TRL 2-6 (6.2-6.3a) and "systems-driven"
- Style of work is theme-oriented technology and system integration
- Collaborations include CMU, MIT, Stanford, USC, Ames/JSC et al.
- Products are demonstrated and validated in realistic field operations
- *The FIDO* rover and *URBIE* are respective NASA/non-NASA examples
- See websites http://robotics.jpl.nasa.gov *and* http://prl.jpl.nasa.gov

Subsurface Exploration — Illustration



Aerial Exploration — Illustration

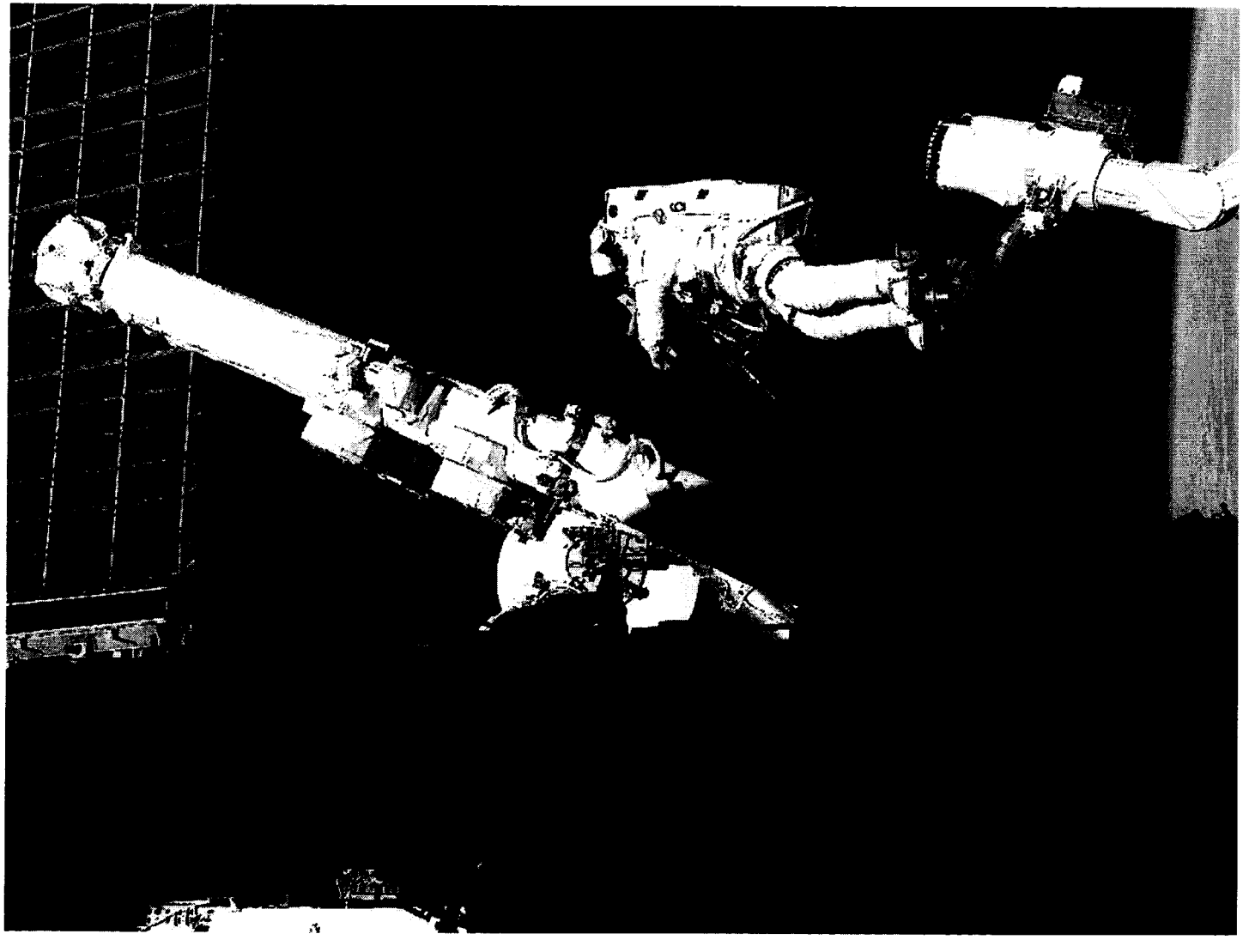




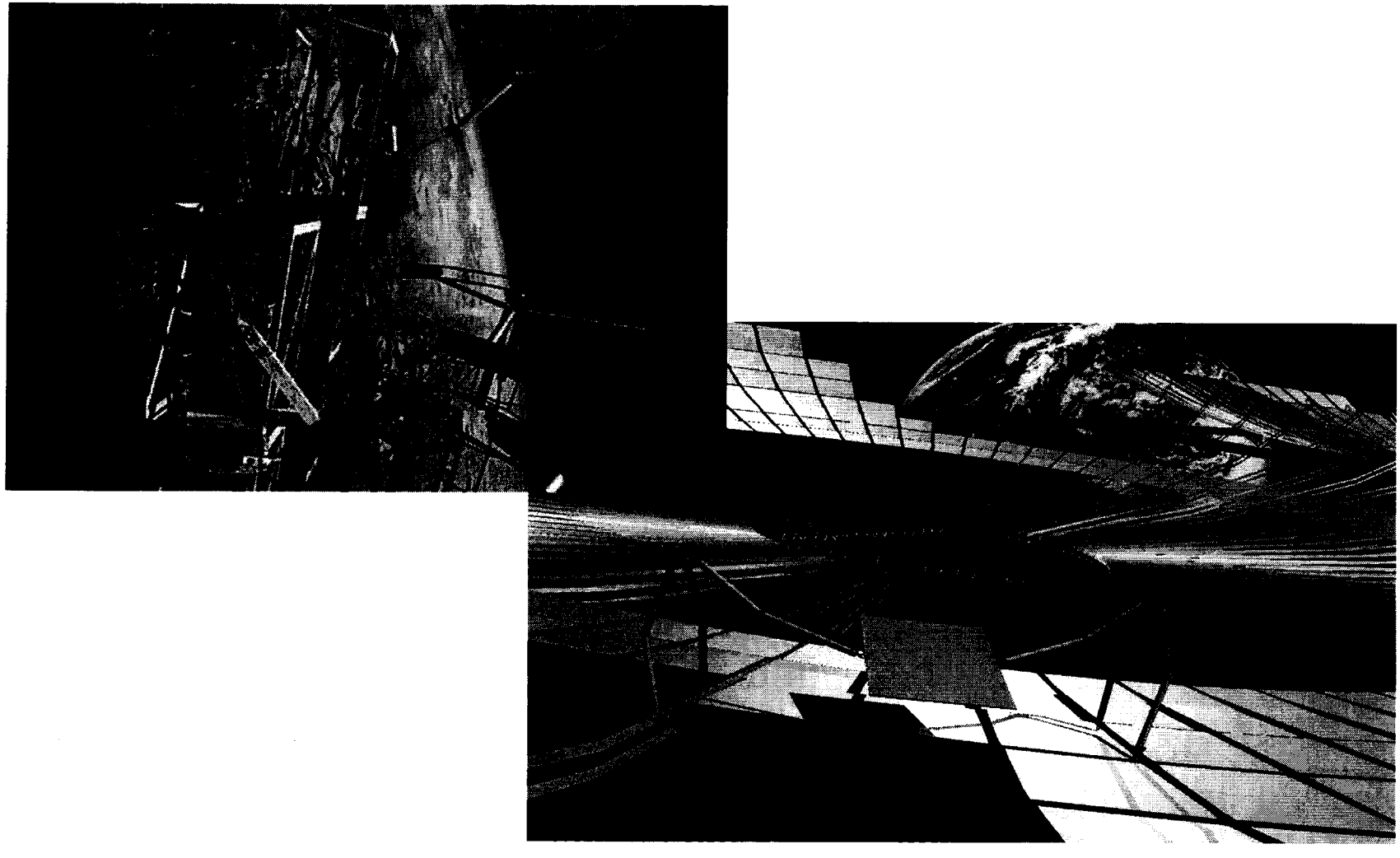
Aerial Exploration — Comments

- **Mars Balloons (mid-TRL)**
  - Aerially-deployed, helium-filled; 1 week to multi-month float lifetimes; order 5 kg payloads for delivered masses < 100 kg
  - Aerially-deployed, CO2-filled, solar heated (Montgolfiere); multi-week lifetime at illuminated poles, 1-2 day elsewhere; order 2-3 kg payloads for delivered masses < 100 kg
- **Titan Balloons/Blimps (low-TRL)**
  - Aerially deployed, helium filled; multi-month float lifetimes; order 20+ kg payloads for delivered masses of 100+ kg; propulsion system for limited (1 m/s) maneuverability; altitude control and surface interaction (sampling) capability
- **Venus Balloons (low-TRL)**
  - Surface launched balloons for sample return missions; zero pressure design, 400+ kg lift capability, 1-2 day float lifetime
  - Aerially deployed, helium-filled altitude cycling balloon for periodic deep atmosphere operation; multi-week operation; order 10 kg payload for delivered masses of 100+ kg.

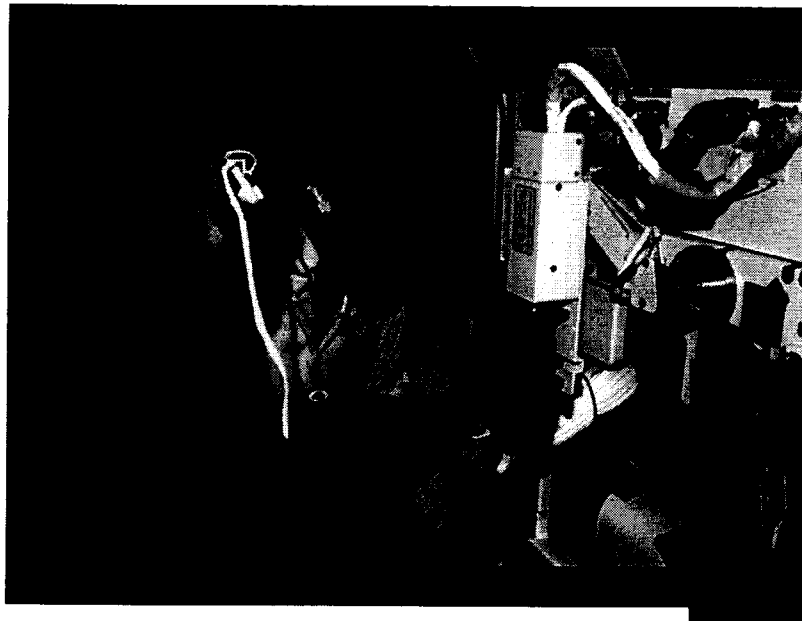
Illustration: In-Space and On-Orbit Functions

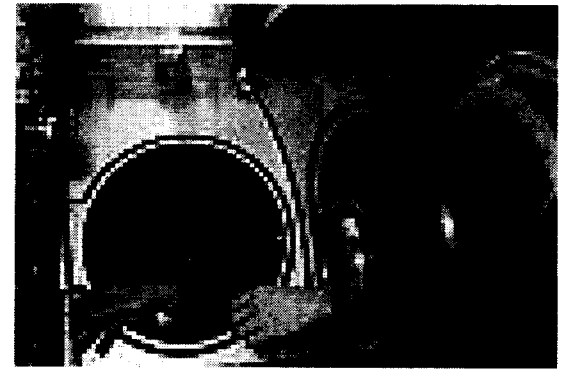


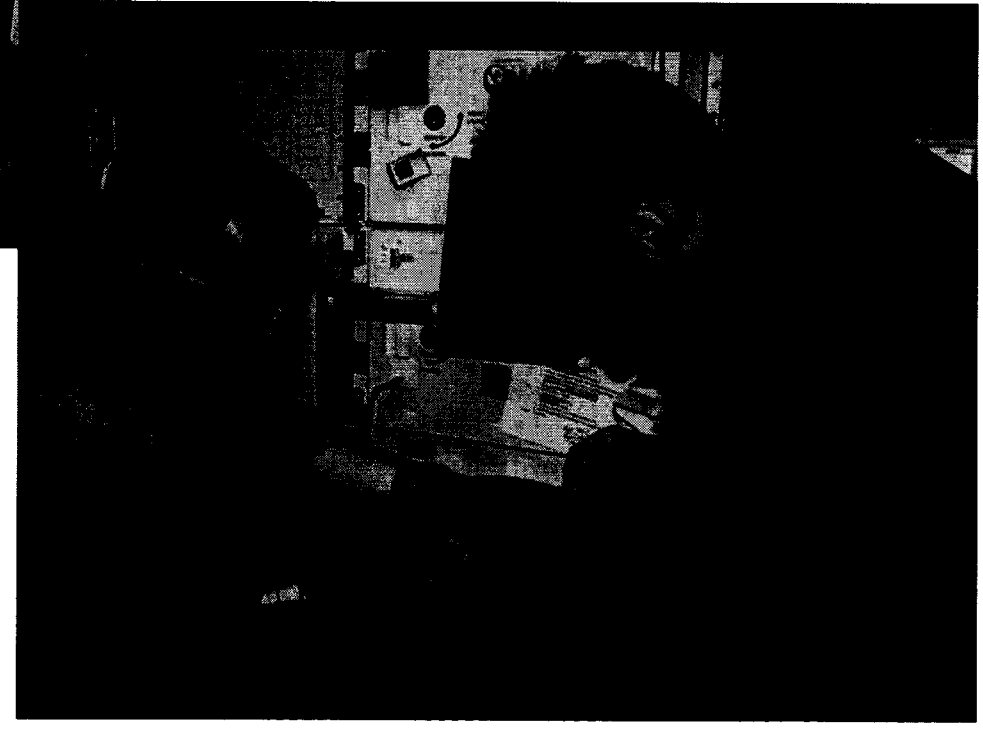
In Space Assembly — Illustration

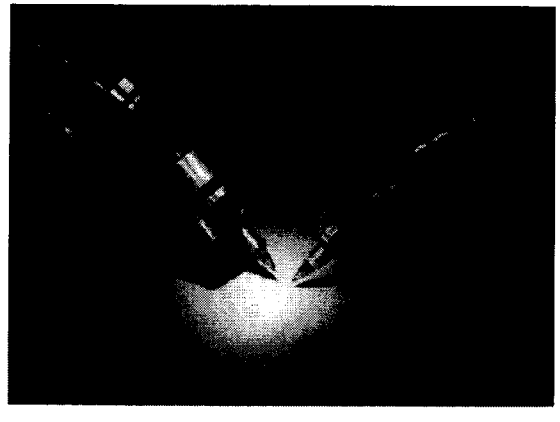


IVA Robotics — Illustration (Glove-box and Medical Procedures)









Mobility Systems Concept Development (Section 348)

Products

- New System Concepts for Mobile Robotic Operations, both NASA & non-NASA Customers
- Enabling Technologies for Autonomous Aerial, Surface and Sub-Surface Mobility
- High-Fidelity Simulation, Integration, and Field Testing of R&D System Prototypes

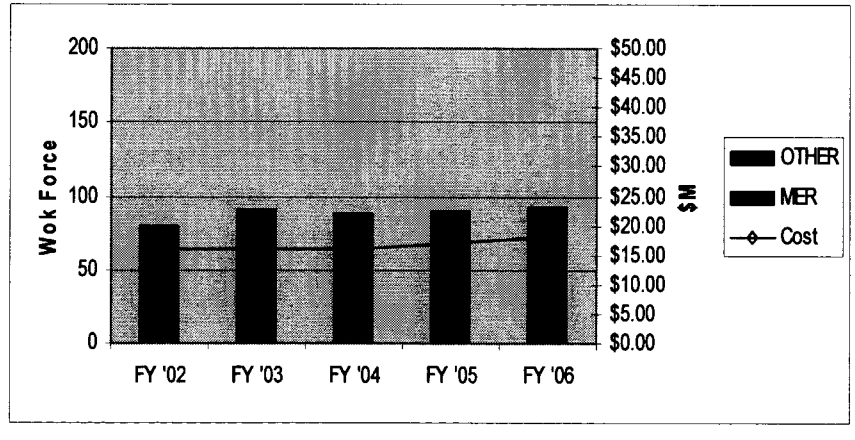
Technical Expertise

- Robotic System Architecture & Engineering
- Rapid Prototyping of New R&D System Concepts
- Machine Vision, Navigation, Control, and User I/F
- Mobile Sample Acquisition, Processing & Handling
- Robotic Modeling & Simulation Environments
- Robotic Software Development & Validation

Technical Challenges

- Long Ranging, Continuous Surface Mobility
- Precision Robotic Navigation & Localization
- Autonomous Science Deployment, "Go-To"
- All Terrain Surface Mobility & Navigability
- Aerobotic Access to the Outer/Inner Planets
- Subsurface Access to Extreme Environments
- Tightly Integrated Delivery of Autonomous Sampling with Micro-Instrumentation

Business Forecast



Manager: Dr. Paul S. Schenker, (818) 354-2681

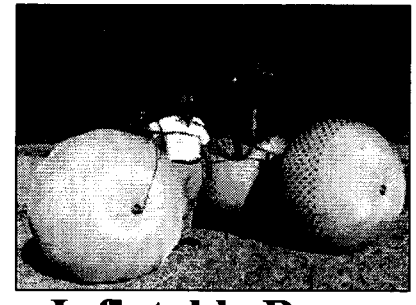
JPL Mobility/Robotics R&D Line Organization

- "Mobility Systems Concept Development Section (348)"
  - Paul S. Schenker, Manager, (818) 354-2681
  - Wayne F. Zimmerman, Deputy Manager, (818) 354-0234
  - Catherine A. Woodall, Business Area Manager, (818) 354-9288
  - Reporting to Leslie L. Livesay, Manager, Avionic Systems & Technology (340)
- Group Supervisors are well-recognized technical area leaders ("groups")
  - Larry H. Matthies: Machine Vision Group (818) 354-3722
  - Homayoun Seraji: Telerobotics Research & Applications Group (818) 354-4839
  - Eric T. Baumgartner: Mechanical & Robotics Technologies (818) 354-4831
  - Brian H. Wilcox: Robotic Vehicles (818) 354-4625
- Each 15-20 person group has roles in component technology and systems
- All groups have fielded working R&D systems and infused flight technology
- This includes a 15 year history of Tri-Service platform/demo developments
- Internal customers include R&TD, Space Exploration Technology Program, Mars Technology Program, MPO (MER, MSL, Scouts)

Mobility System Development in the PRL*

Sample Return Rover

LEMUR



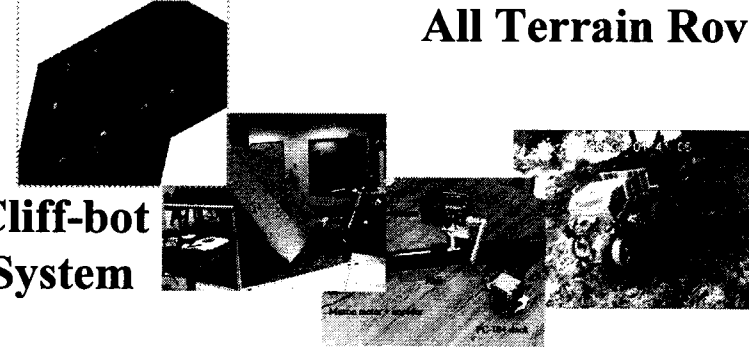
Inflatable Rover

Robot Work Crew

All Terrain Rover

MER Egress Rover

MER Wheel Test Stand



Cliff-bot System

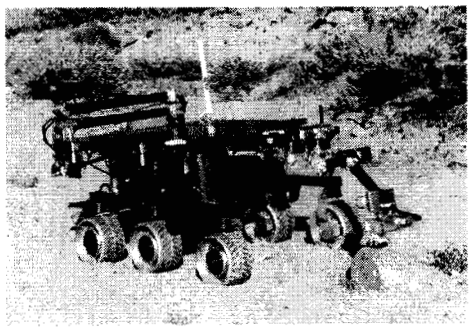
Planetary Robotics Laboratory

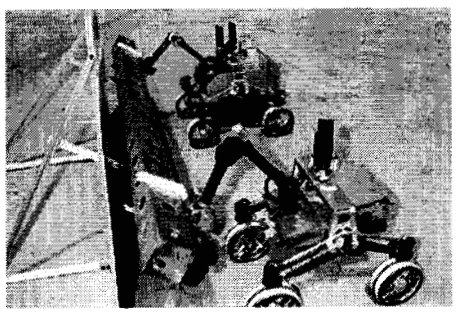
* http://prl.jpl.nasa.gov

Mechanical & Robotics Technology Group

Eric T. Baumgartner, Supervisor, x4-4831

- **Robotic System Development**
  - Full-scale field rover systems (FIDO)
  - Cooperative robotics and outposts (Cliff-bot, Robotic Work Crew)
  - Robotic manipulation systems (MarsArm I/II, various rover-mounted manipulators)
  - Robotic vehicle concepts (FIDO class, SRR class, LEMUR)
- **Group Technical Expertise**
  - Robotic systems engineering, mechanical design, electrical design, vision systems, control systems, real-time computer architecture and design
  - Group members support MER and MSL flight programs, Mars Technology Program, Space Solar Power Program, etc.

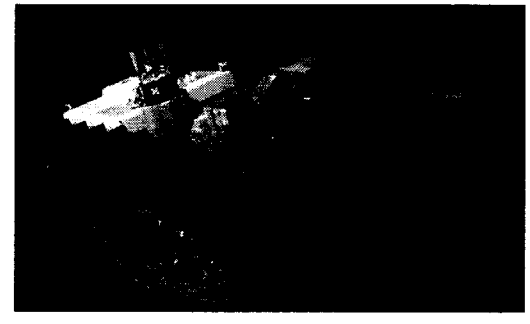




Machine Vision Group

Larry H. Matthies, Supervisor, x4-3722

- **Largely a technology development group, developing sensors and algorithms for perception systems that enable autonomous navigation of rovers, landers, orbiters, and robotic ground and air vehicles for reimbursable sponsors (DARPA, Army). Technology examples:**
  - Stereo vision-based rover obstacle detection
  - Image and lidar-based obstacle detection and velocity estimation for landers
  - Landmark recognition for orbiters
  - Day/night, all-weather perception systems for autonomous, off-road navigation for Army robotic vehicles



- **Technology Transfer to Flight :**
  - MER: rover obstacle detection and avoidance software
  - MER: software uses EDL imager to estimate horizontal velocity (DIMES)
  - Smart Lander: software uses lidar for landing hazard avoidance

Telerobotics Research & Applications Group

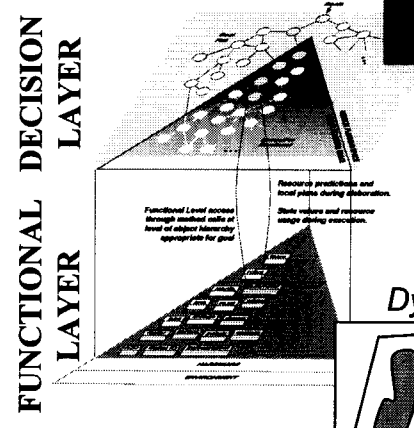
Homayoun Seraji, Supervisor, x4-4839

- **Technology Tasks**
  - Coupled Layer Architecture for Robotic Autonomy
  - Web Interface for TeleScience (WITS)
  - Safe Navigation on Challenging Terrain
  - Autonomous Reasoning for Safe Landing
  - Adaptable Robotic Systems

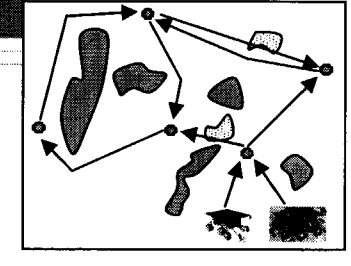
- **Technology Transfer to Flight**
  - MER: Robot Arm Control
  - MER: Science Activity Planner (SAP)
  - MSL: EDL Modeling and Simulation

Simulation (ROAMS)

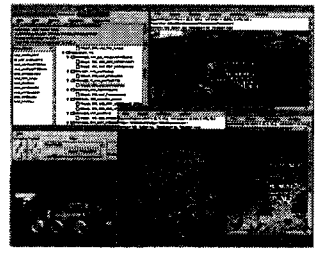
CLARAty



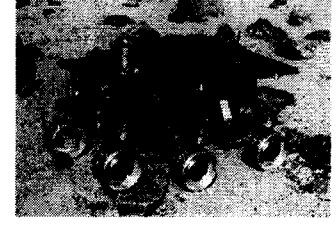
Dynamic Planning



WITS



Rocky 8

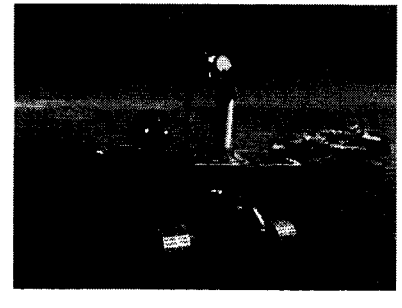


Robotic Vehicles Group

Brian H. Wilcox, Supervisor, x4-4625

- **Robotic Vehicle Research Tasks**
  - Nanorovers
  - Subsurface explorers
  - Special-purpose hardware and software for extreme environment in-situ systems (e.g. ultra wide temperature, ultra miniaturized for balloons and airplanes)

- **Robotic Vehicle System Engineering, with the majority of group currently supporting 2003 Mars Exploration Rover, based on experience with Sojourner, in such capacities as**
  - Flight System Chief Engineer
  - Assembly, Test, and Launch Operations Lead
  - Avionics system engineer
  - Flight software developers
  - Ground Control Software and Mission Operations



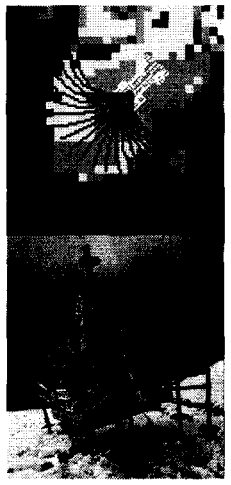
JPL Mobility/Robotics R&D Areas

- **Technologies**
  - 3D visual terrain mapping, analysis, tracking, & visual servo control
  - Autonomous navigation including fused sensing & collision avoidance
  - Landmark/object recognition & precision rendezvous (natural/artificial objects)
  - High fidelity teleoperation & autonomous manipulation (servicing/sampling)
  - On-board reactive autonomy/intelligence for safe, terrain-adaptive mobility
  - Advanced mechanization & actuation design (reconfigurable, miniature...)
  - Advanced materials & structural design (inflatable, composite architectures)
- **Systems Development**
  - Aerial, surface, and subsurface autonomous system prototypes (all scales)
  - Architectures for multi-agent/multi-robot cooperation (robot teams)
  - Advanced simulation environments for mobile systems design/operations
- **Field Operations & Technology Validation**
  - Deep experience base in technology, systems, simulation for remote manipulation
  - User interfaces for distributed work group command-control-communications
  - Extensive field testing, requirements analysis, & V&V of surface systems
  - Close coupling of R&D efforts to the science community in all phases of work
  - Infusion of technology, concept designs, operational approaches, and key personnel to NASA missions

Illustration: Planetary Surface Exploration Operations

(Reference: NExT Study on Space Robotic Capabilities)

Surface Mobility



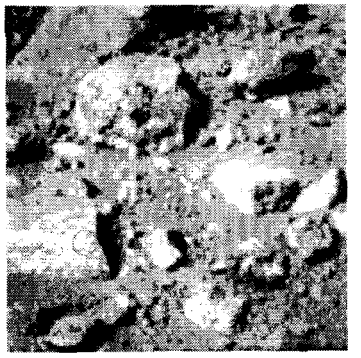
Mobile Autonomy

Terrain assessment, path planning, visual servoing

Mobility Mechanization

Extreme terrain access, energy efficiency

Science Perception, Planning & Execution



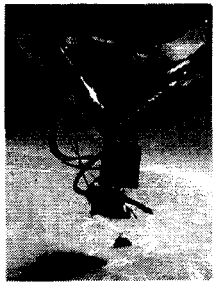
On-board and ground tools; data analysis, target selection, operations planning and execution

Human-Robot EVA Interactions

Tele-operation and human supervision of robotic explorers

Robotic work crews

Instrument Placement and Sample Manipulation

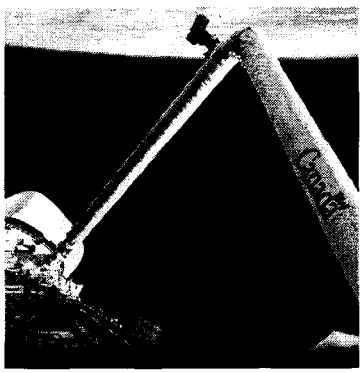


Position sensors, collect and process samples

Illustration: In-Space and On-Orbit Operations

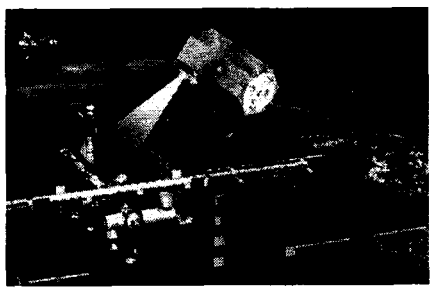
(Reference: NExT Study on Space Robotic Capabilities)

Assembly



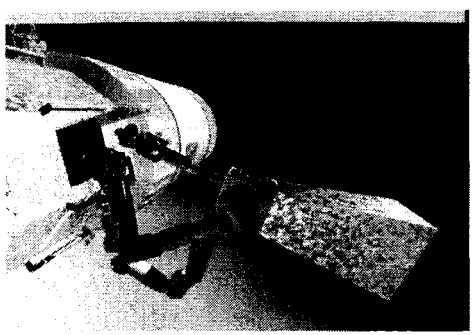
Transporting and mating of components; making connections; assembly sequence planning and execution; assembling small structures

Inspection



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

Maintenance



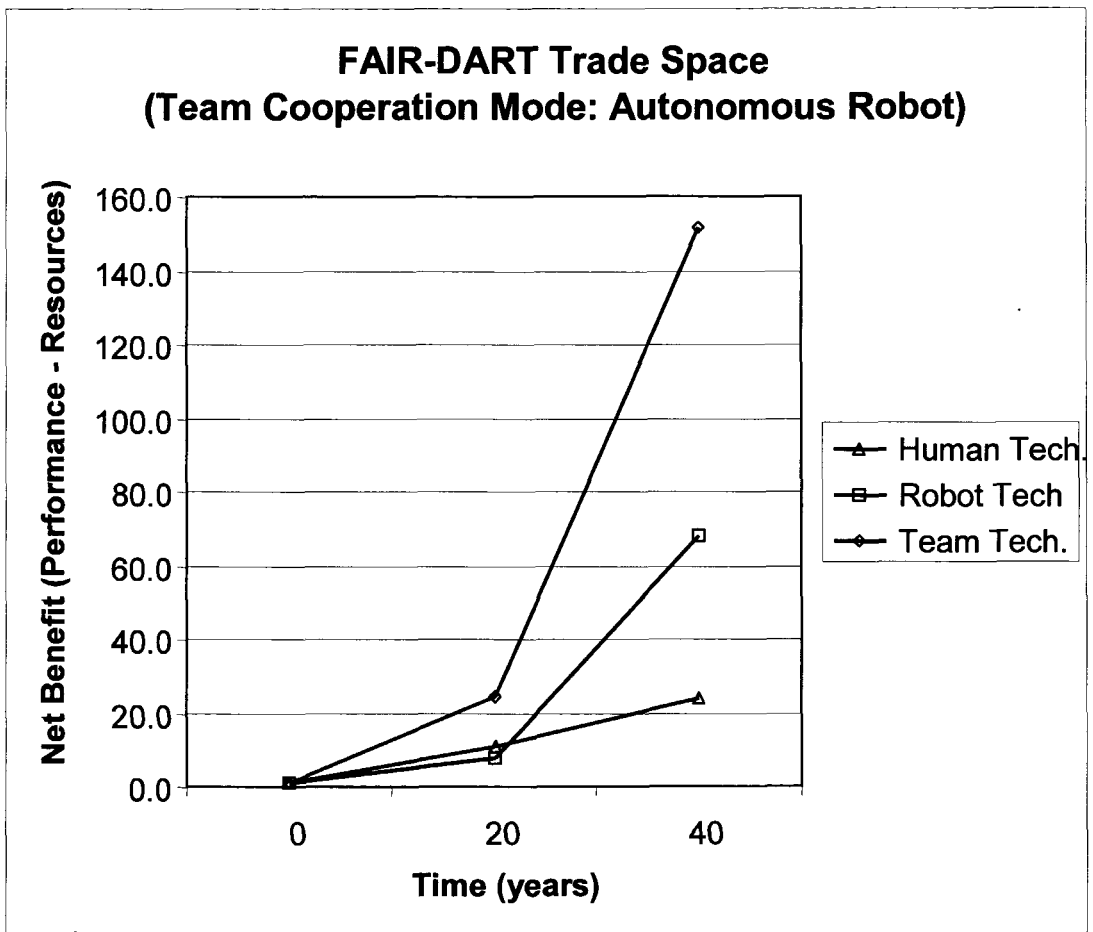
Change-out of components; accessing obstructed components; robotic refueling

Human EVA Interaction

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

A Past Vision for Human/Robotic Systems in Space (30 years ago) …

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



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.)

… A More Recent Vision for Planetary Exploration

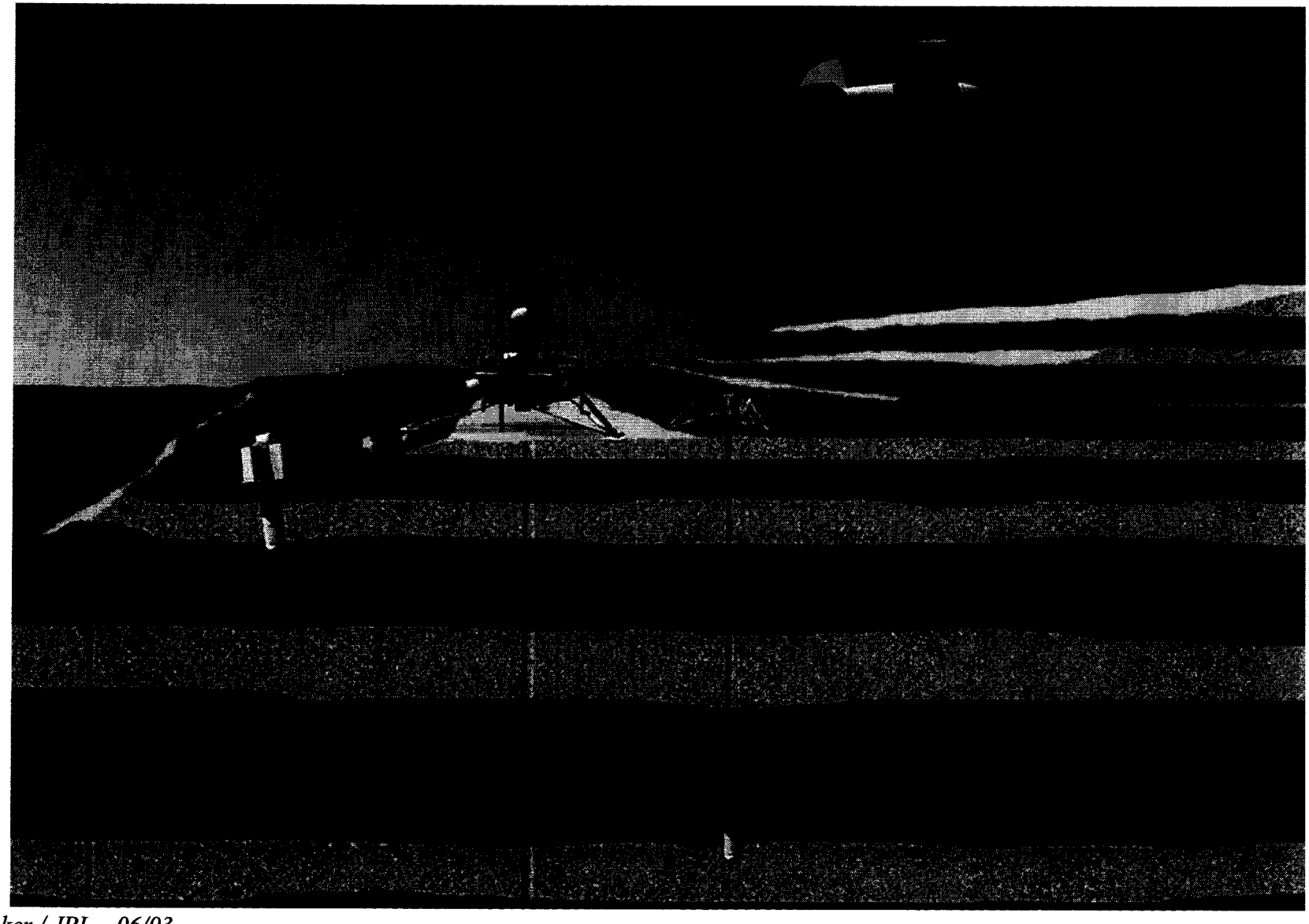
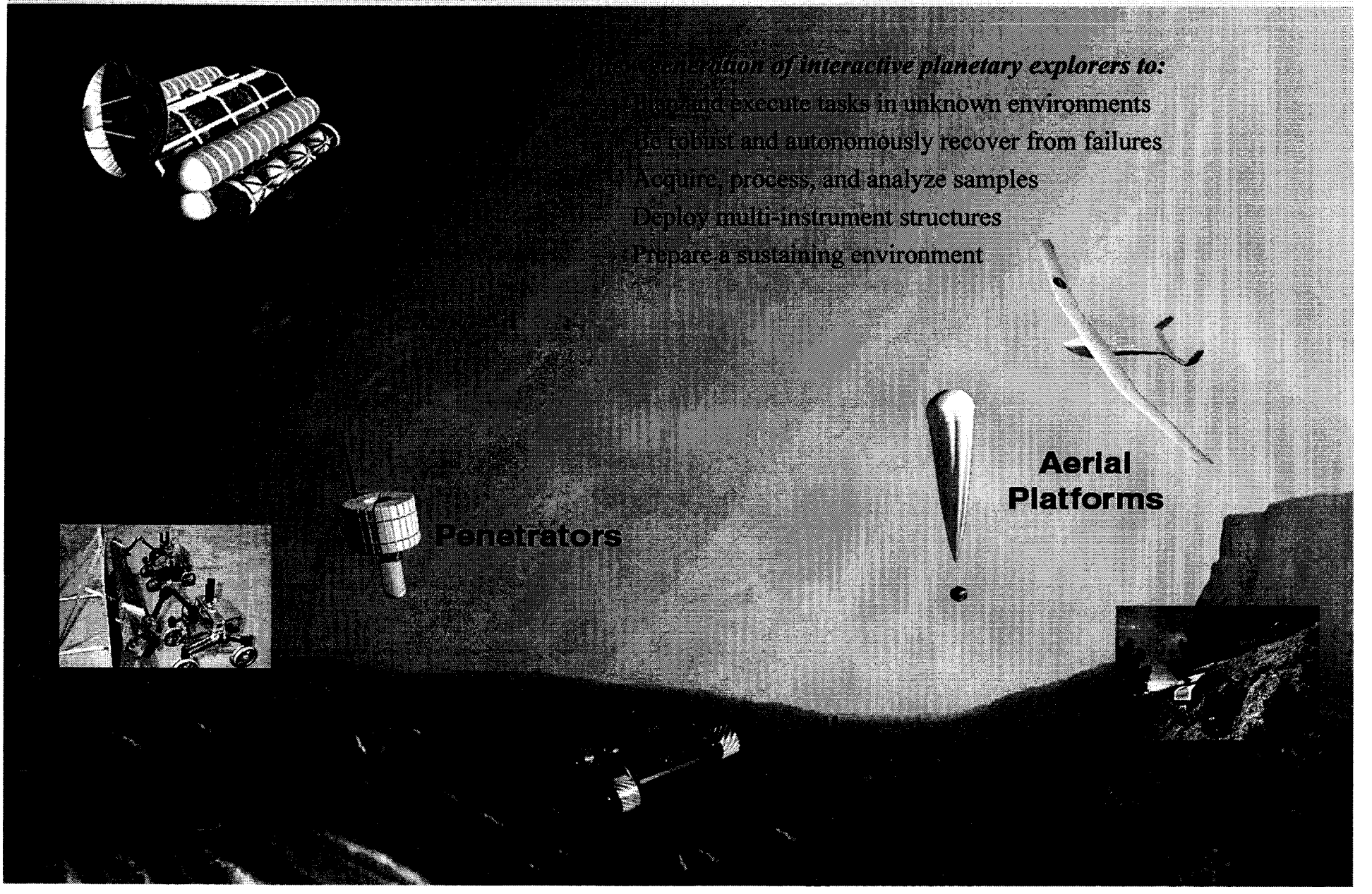
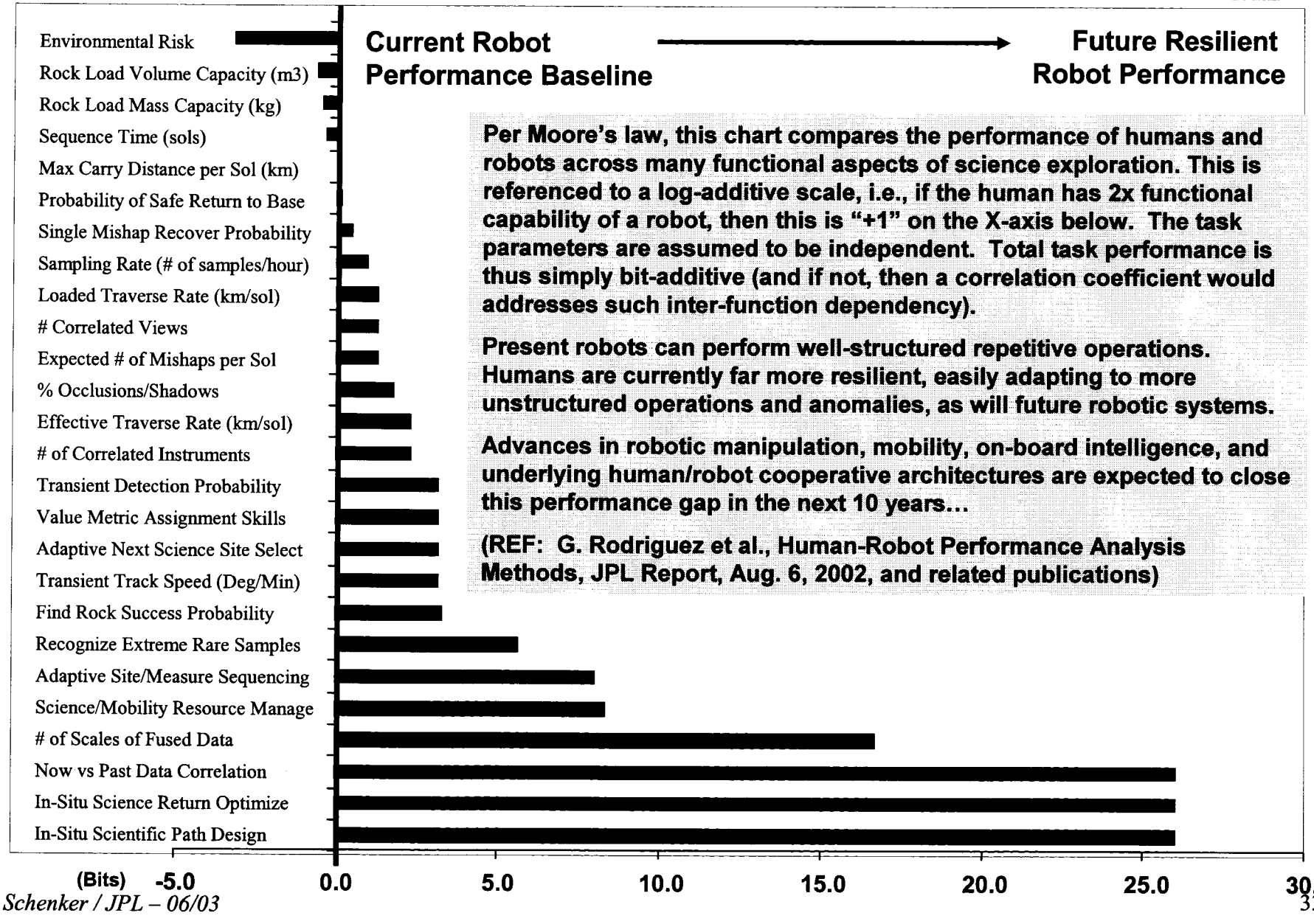


Illustration — Networked Robotic Operations



Human and Robot Performance—Discovery Operations



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)

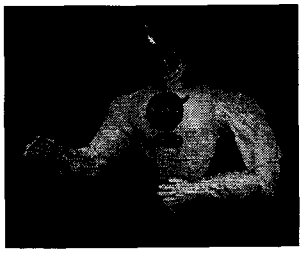
Space Robotics Technologies & Operational Metrics

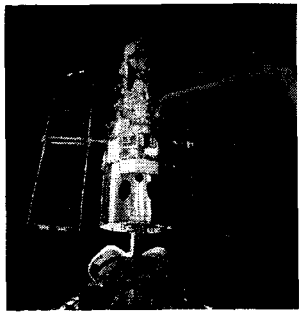
MANIPULATION
- EOA speed
- Accuracy
- Precision
- Dexterity
- Power efficiency
- Backdrive-ability
- Thermal stability
- Calibration

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

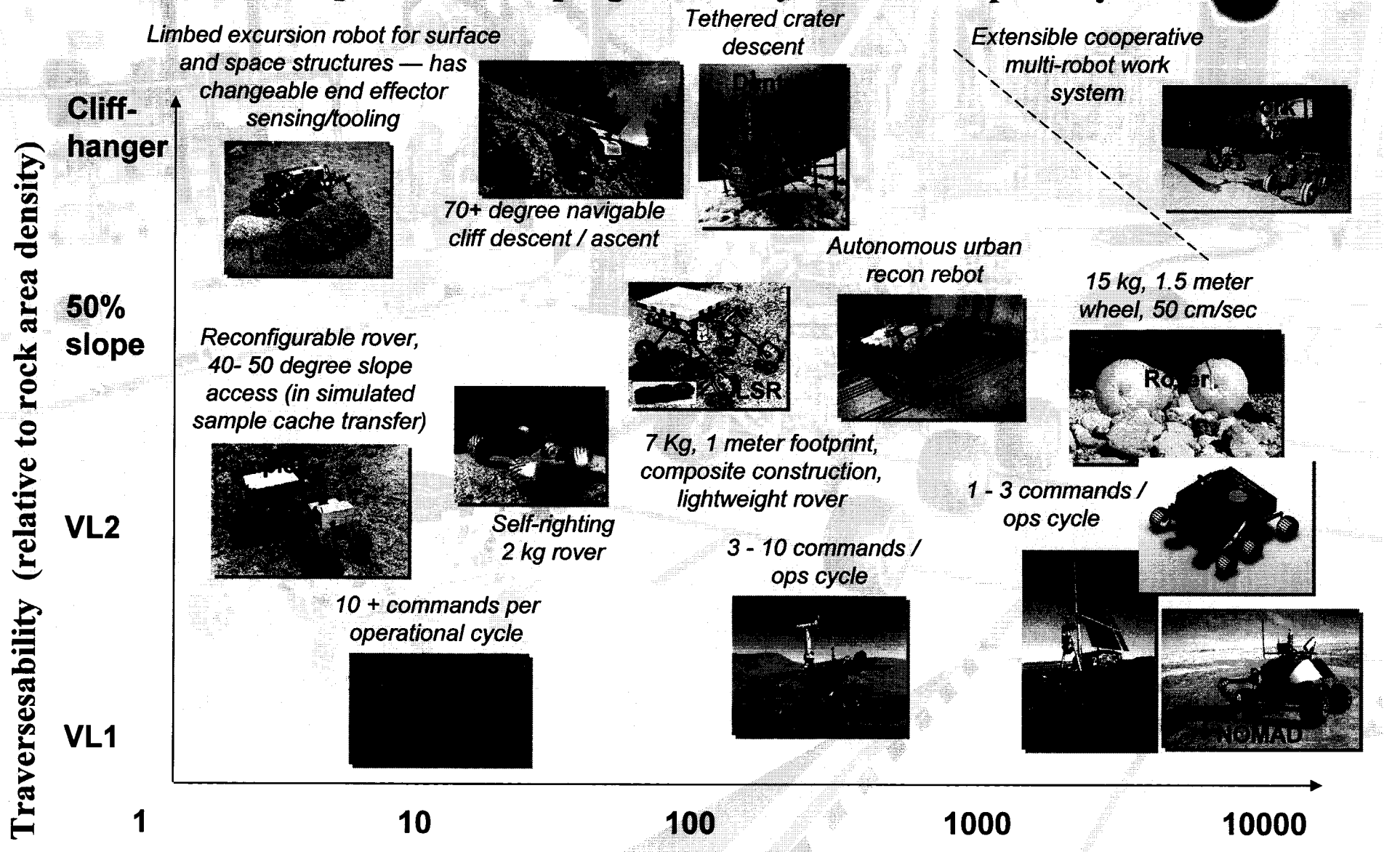
ON-BOARD INTELLIGENCE
- Resolution (multi-scale representation)
- Scalability (computational complexity)
- Completeness (search depth, breadth)
- Generalization (of classes, objects)
- Learning (from instances, training, etc.)
- Contingency (recursion, nonlinearity)
- Fidelity (binarization of analog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





Example — 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"

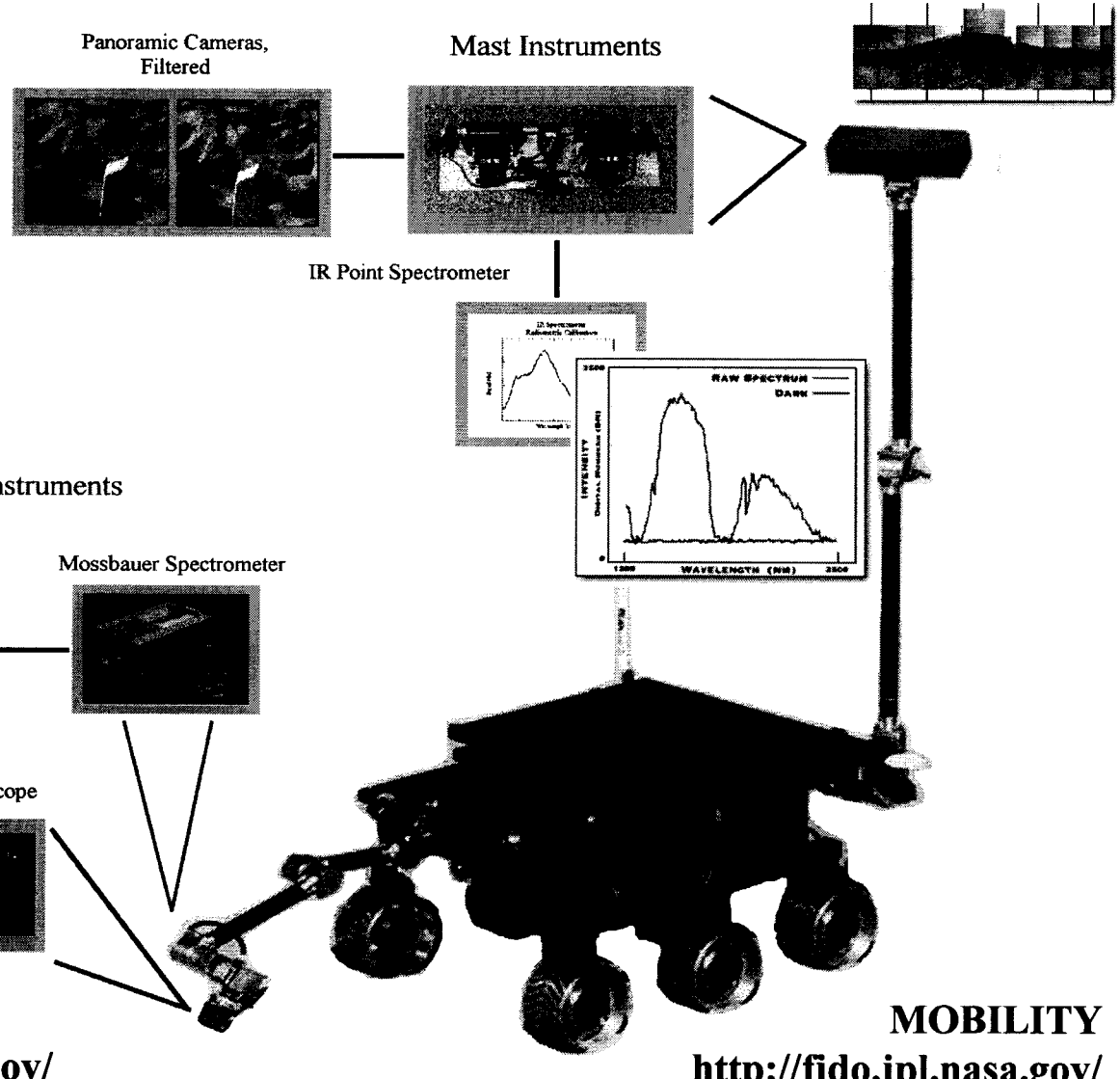
Supporting Technology Development

- 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

Field Experiments & Technology Validation

Integrating Science Operations, Instruments and Mobility

Miniaturization and Integration of In Situ Instruments on FIDO



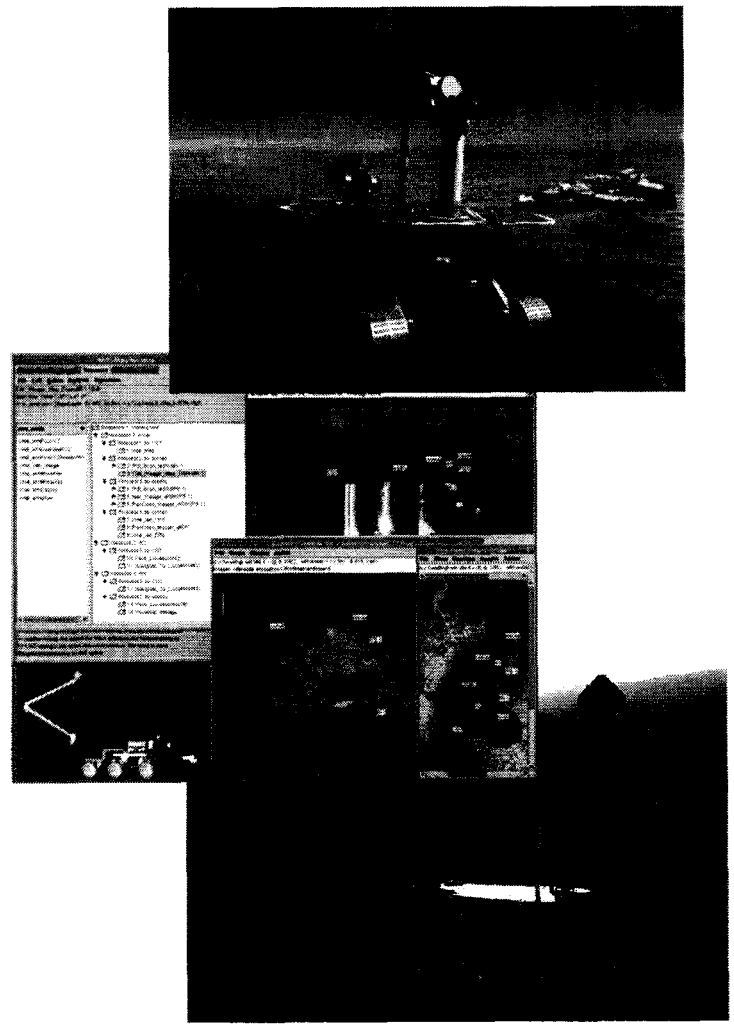
SCIENCE
http://wufs.wustl.edu/fido/

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

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

EXAMPLE: Mission Science Interaction with 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



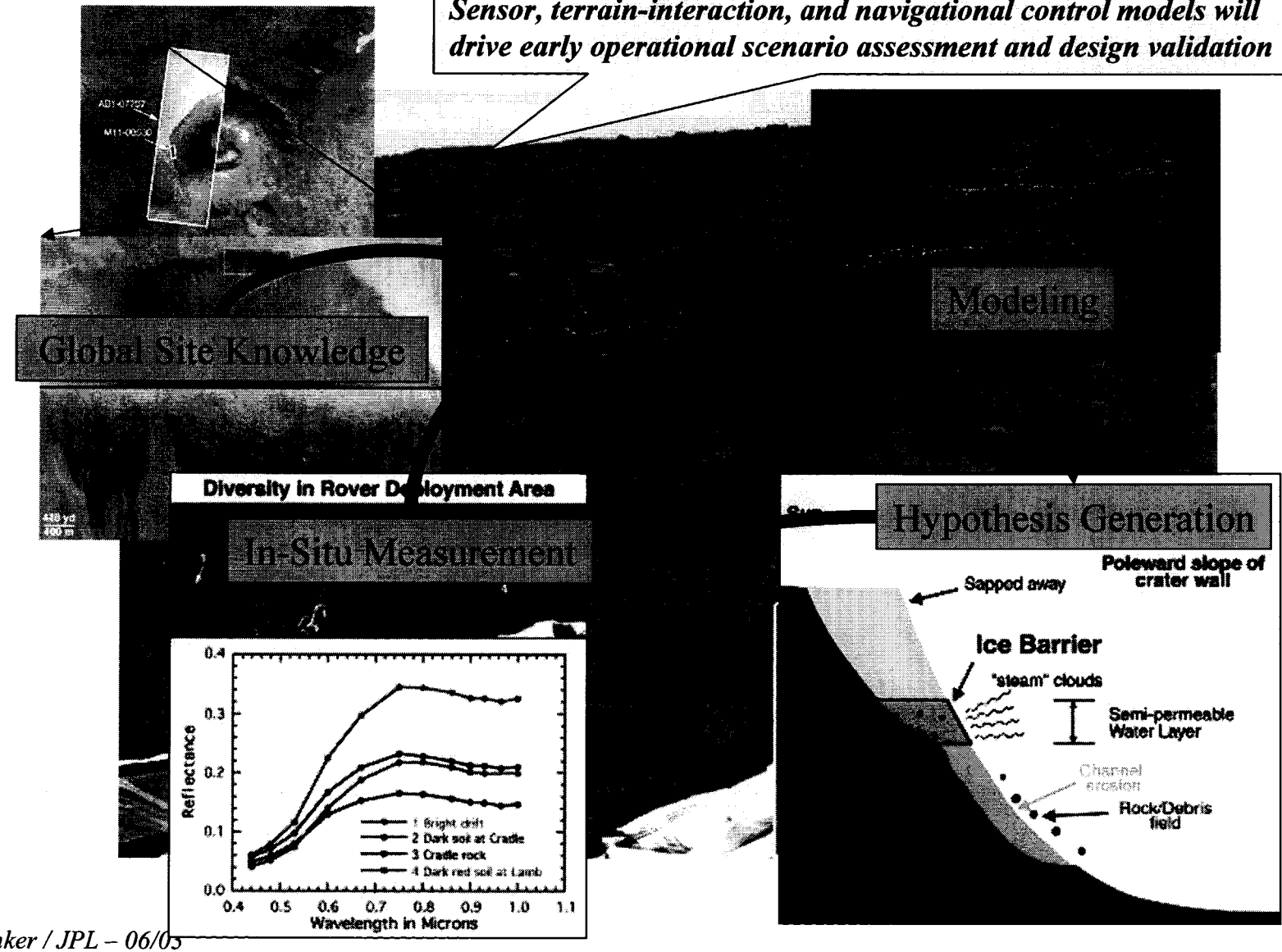
FIDO (Field Integrated Design & Operations) Rover

The Mobile In Situ Science Paradigm

- A Scientist on Earth would never try to understand geology or biology by staying in one place (hence "field geology") ...
- ... given that unequivocal and evidence of past processes is rare
- <u>A mental model</u>:
  - given 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

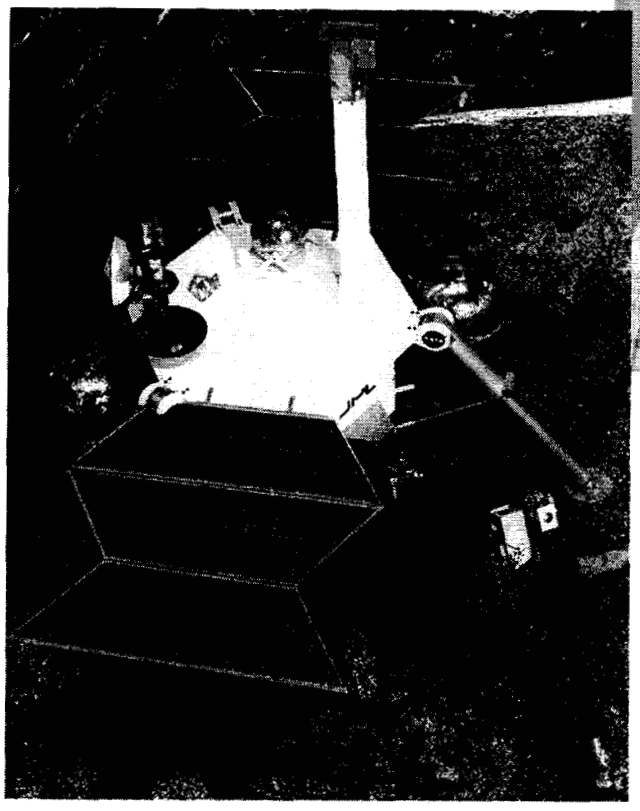
Bridging Robotic Autonomy, Science and Simulation

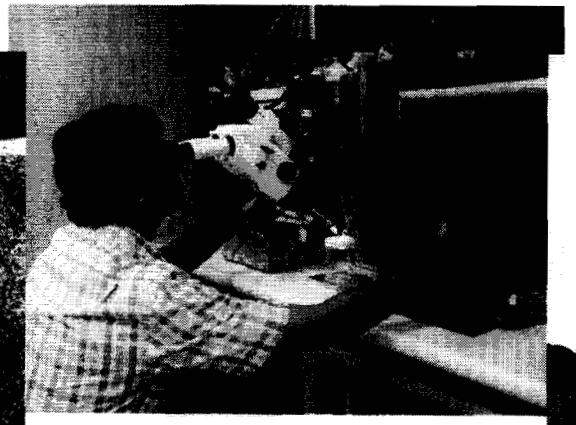
Sensor, terrain-interaction, and navigational control models will drive early operational scenario assessment and design validation



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.)**

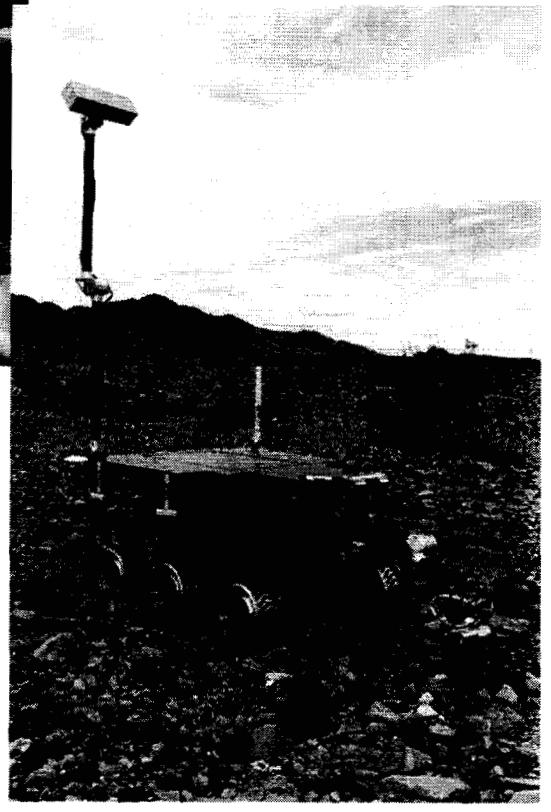




<u>Above</u>: Dual Arm Surgical Tele-Manipulator

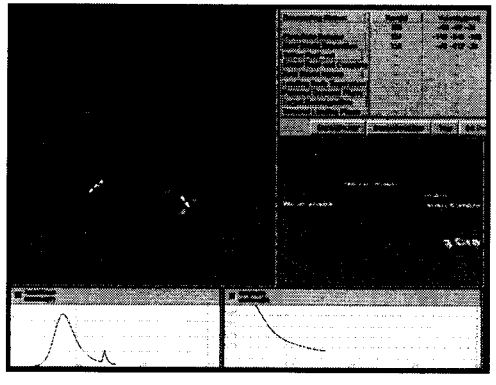
<u>Left</u>: Lander-Manipulator with Camera

Right: Rover Arm for Instrument Placement

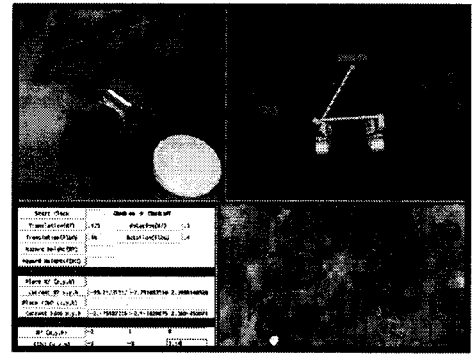


Simulation Supports Mobility Concept & Mission Development

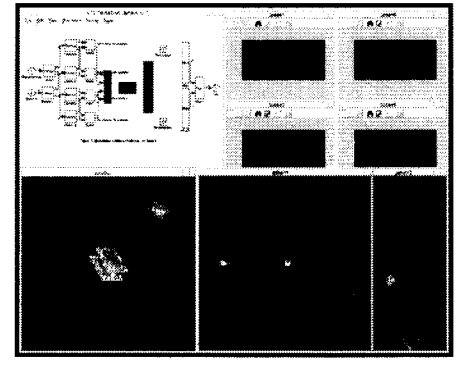
DSENDS
Entry, Descent & Landing Simulator



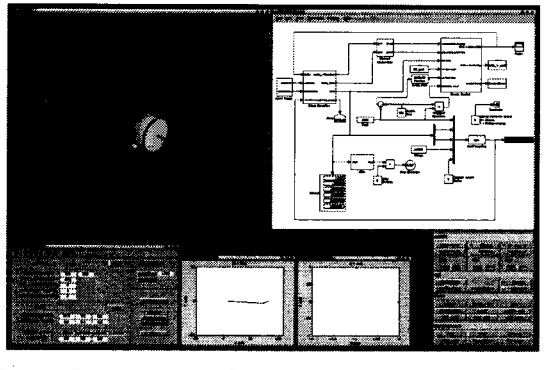
ROAMS
Planetary Rover Simulator



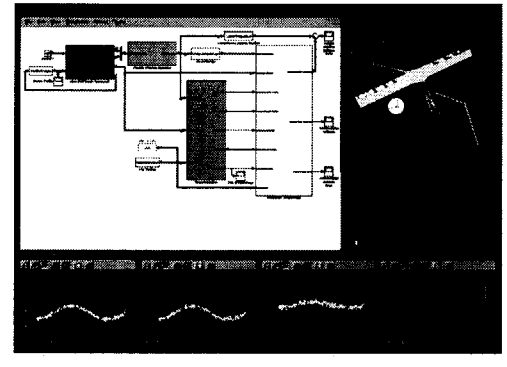
Formation Flying
Distributed Real-Time Simulations (Starlight)



DARTS Lab



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



Flexible Interferometers
Integrated Modeling (SIM)

Mobility Challenges Include EDL and Sample Return

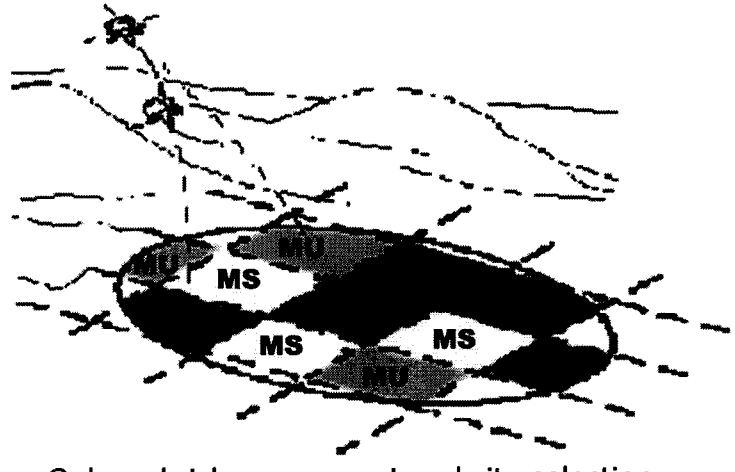
Precision Safe Landing, In-Orbit Rendezvous & Sample Capture

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

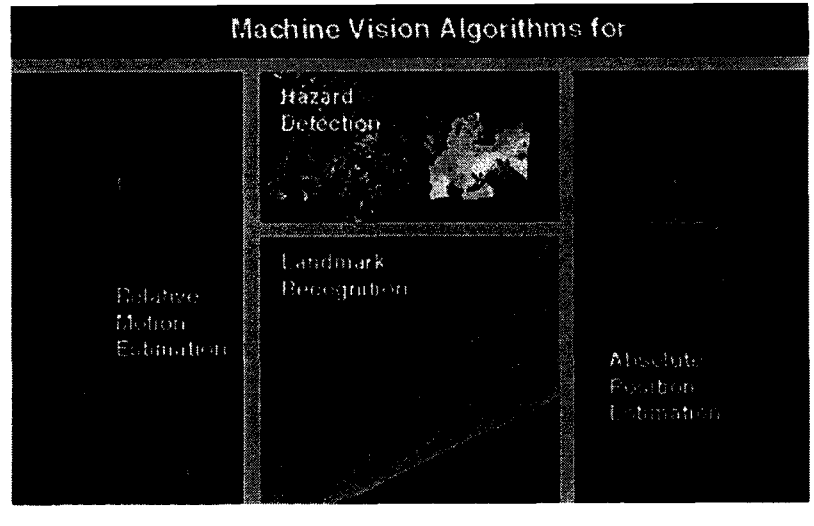
- *Site Risk Assessment*: The safety of potential landing sites will be assessed independently by onboard sensors, and integrated to form a multi-grade representation of the landing site safety.
- *Optimum Site Selection*: Based on the site safety map and the spacecraft constraints, the optimum landing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

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

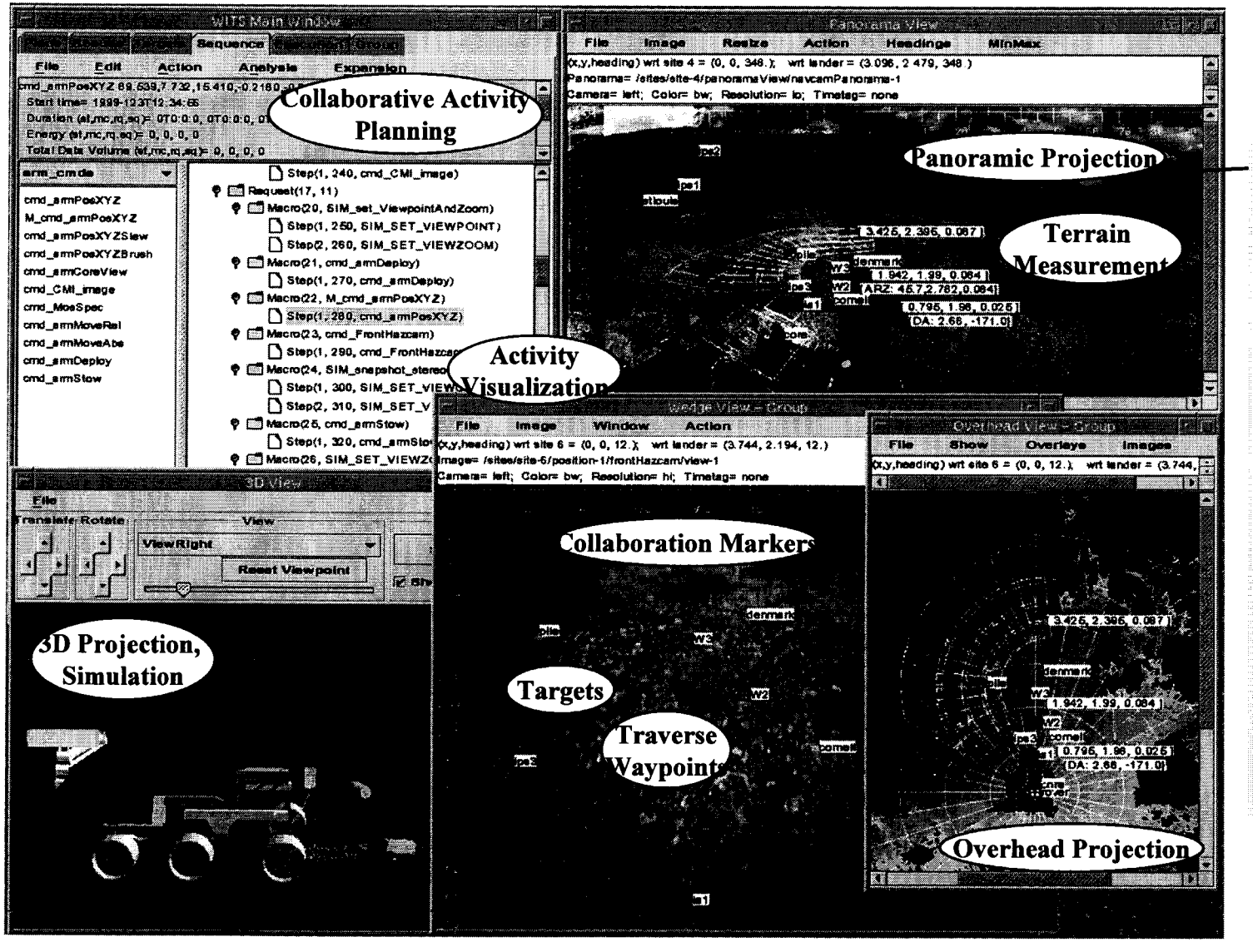
- *Feature Detection & Tracking*: Robustly sense, extract, and track in real-time features of interest (planetary surfaces, small bodies, other orbiting space-craft), predictively controlling spacecraft trajectory with reference to same



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



Platforms are only Part of the Overall System Solution

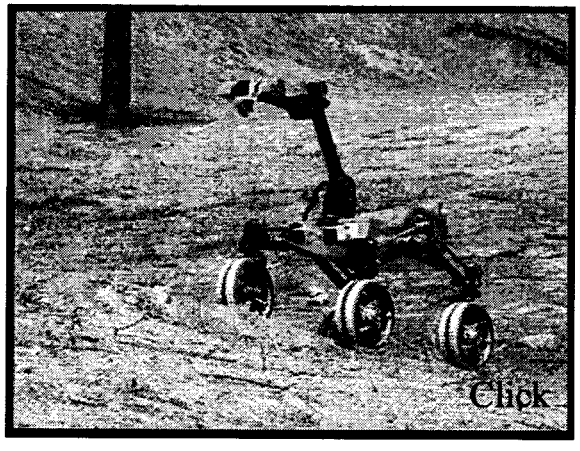


WITS

Web Interface for Tele-Science

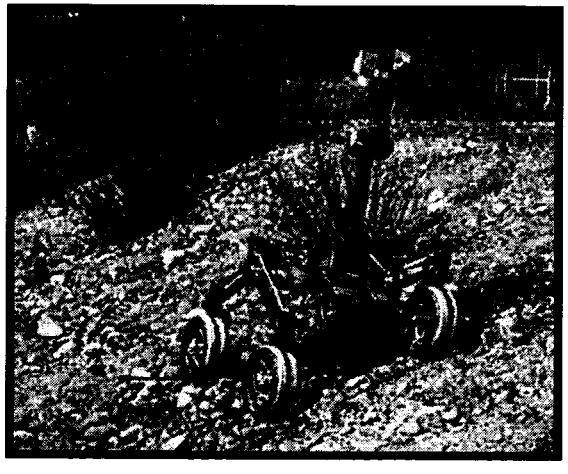
A JPL-developed environment for distributed and collaborative mobile science

University Collaborations (An MIT Example)



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

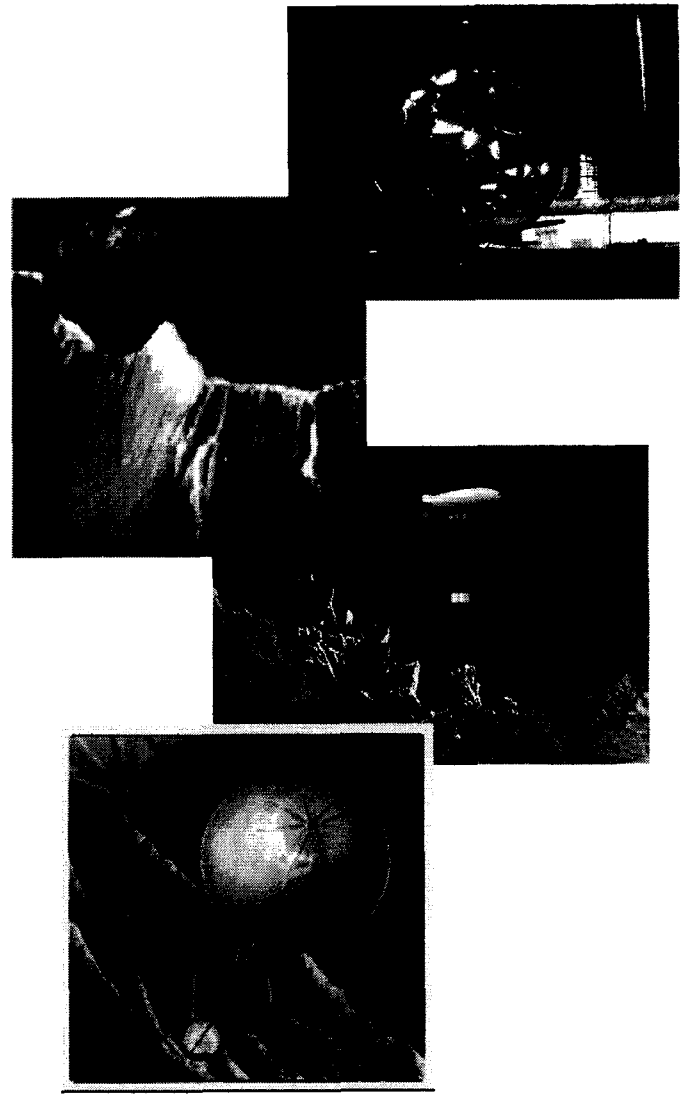


Physics Based Planning & Reconfiguration (MIT/JPL)

- 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.)

Aerial Mobility is an Emerging NASA Emphasis

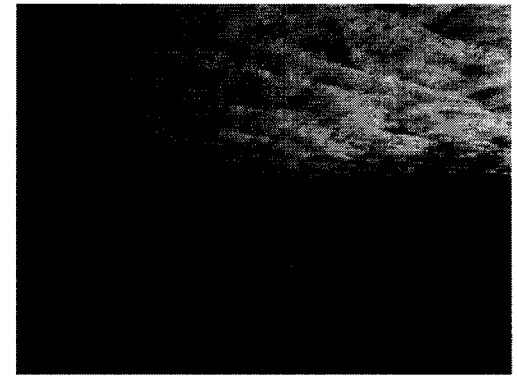
- **Mars Balloons**
  - Aerially-deployed, helium-filled; 1 week to multi-month float lifetimes; order 5 kg payloads for delivered masses < 100 kg
  - Aerially-deployed, CO2-filled, solar heated (Montgolfiere); multi-week lifetime at illuminated poles, 1-2 day elsewhere; order 2-3 kg payloads for delivered masses < 100 kg
- **Titan Balloons/Blimps**
  - Aerially deployed, helium filled; multi-month float lifetimes; order 20+ kg payloads for delivered masses of 100+ kg; propulsion system for limited (1 m/s) maneuverability; altitude control and surface interaction (sampling) capability
- **Venus Balloons**
  - Surface launched balloons for sample return missions; zero pressure design, 400+ kg lift capability, 1-2 day float lifetime
  - Aerially deployed, helium-filled altitude cycling balloon for periodic deep atmosphere operation; multi-week operation; order 10 kg payload for delivered masses of 100+ kg.



There is Continuing Interest in Subsurface Mobility

- **For Mars:**
  - ***1 m*** **access: Already developed (by ASI, ESA), flight ready (e.g. Beagle 2 mole)**
  - ***10 m*** **access: Concepts exist, prototypes are in development, mass/power intensive**
  - ***200 m*** **access: Viable concepts exist, no prototype**
  - ***4 km*** **access: Questionable concepts, no prototype**
- **Other Rocky or Rock/Ice bodies:**
  - **Mars technology does not extrapolate well to other environments: Venus is too hot, icy worlds are too cold; comets/asteroids have minimal gravity (anchoring problems), etc.**
- **Icy Bodies (Europa, Titan, etc.):**
  - **Nothing flight ready**
  - **Technology development underway for melting (cryobot) vehicles**
  - **Earth-based technology for glacier drilling is too heavy to be directly applicable**

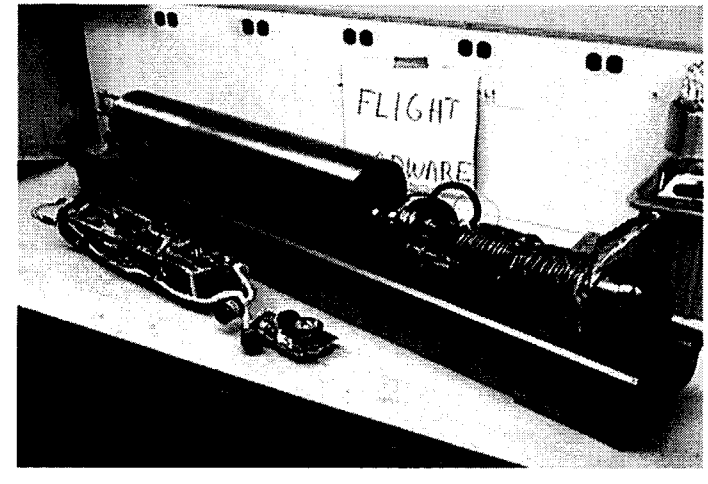
Beagle 2 mole in testing



Typical Earth-Antarctic drill site

Example: Cryobot at Svalbard, Norway (Feb 02)

- Probe successfully penetrated 23m of glacier ice (meets minimum depth requested by Planetary Ice Science community with desire to go max of 200m)
- Technology will be enabling for a Mars '07 Cryo-Scout mission; Penetration rate ~.6-.7m/hr (.75Kw @ the probe), providing further validation of probe modeling results
- Probe successfully penetrated ~12 layers of dust/ debris (dust size 10-60microns based on debris as collected from pump bay post-mission)
- Test environment similar to Mars-like sediment conditions; no Earth probes have achieved this and this must be demonstrated if this technology is to be used for planetary exploration
- Probe performed robustly and degraded gracefully even in presence of failures: 1) Pump bay heater failure resulted in shifting melt control to the passive heaters with pump remaining on (melt rate reduced to .3-.4m/hr); 2) Water jet pump failure resulted in shifting melt control to passive heaters only (melt rate reduced to 1-3cm/hr)

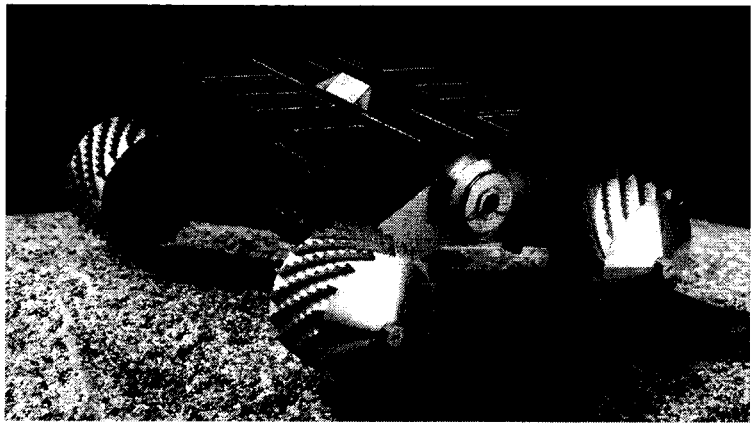


Longer Range Opportunities for Subsurface Exploration*

- **Europa Melt Probes ("Cryobots")**
  - Concepts exist and low TRL prototype testing underway of vehicles that can melt through Europan ice and reach sub-surface oceans
- **Comet Nucleus Sample Return**
  - Concepts exist for anchoring and drilling techniques from 1 - 10 m depth
  - Initial technology development activity has been discontinued
- **Venus Surface Sample Return**
  - Concepts exist for use of high-temperature ultrasonic drills for collection of < 1 m surface samples
  - No current technology development work

*** Cf. NAS Decadal Report**

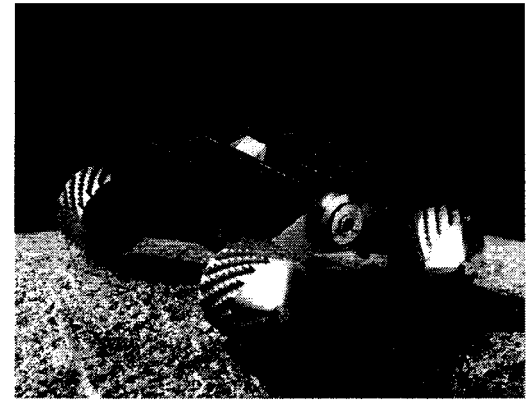
Miniaturized Mobility for Extreme Environments (Nanorover)

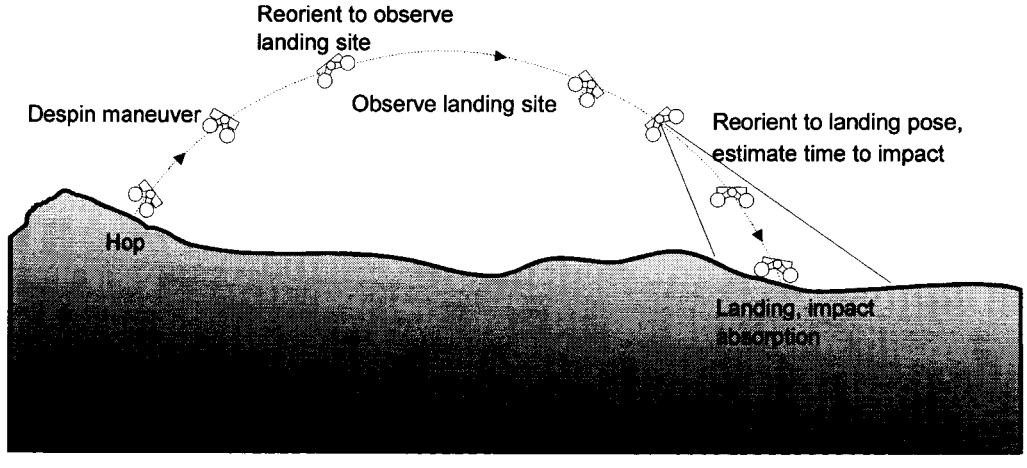


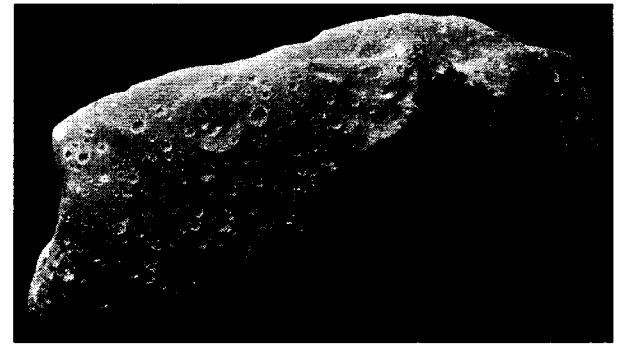
- Body - 14 cm square
- 4 wheels 6.5 cm diameter
- Wheels on articulated struts
  - can lift wheels and set on top of obstacles
  - capacitive proximity sensing in each wheel
  - right and left-hand helical grousers to assist in skid steering
- 32-bit R3000 processor
- Hi-res Camera (0.3mrad/pix)
- IR Spectrometer (0.8-1.7μ, ~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 for Small Body Mobility

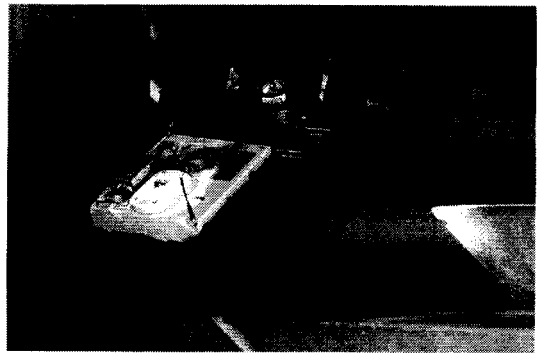
- **Mobility in a Microgravity Environment**
  - trajectory propagation, gravity and dynamics modeling
  - surface interaction modeling (traction, electrostatic adhesion, Van der Waals forces)
  - position and attitude estimation and control
- **Anchoring and Sampling**
  - kinetic anchors and samplers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



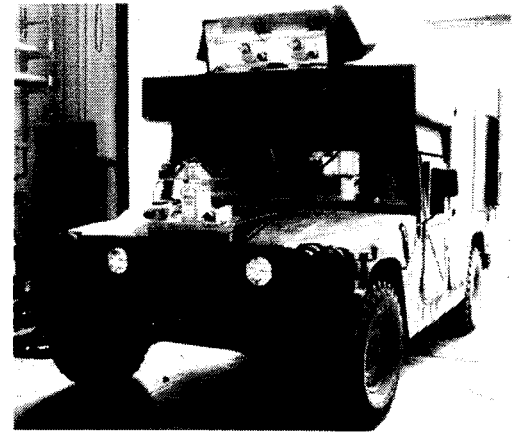




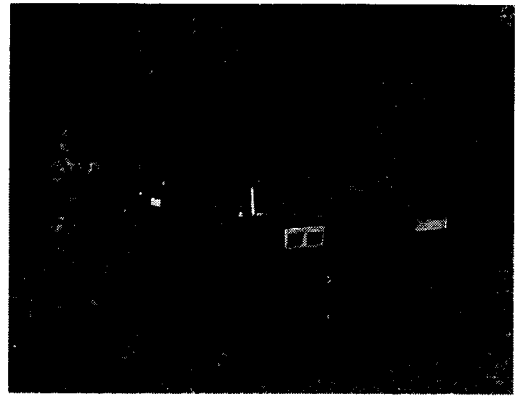
Related DoD R&D Programs at JPL



TMR



ARL Testbed Vehicle



Demo III, CTA

Perceptor

Sensor Trade Studies Enabling More Robust Mobility

- **Range sensing on vegetation:**
  - Stereo
  - Ladar
  - Radar
- **Multispectral vegetation classification:**
  - RGB
  - VNIR
  - Dual band thermal IR
- **Range/color fusion for vegetation classification**
- **Water hazard sensing with:**
  - RGB color and texture classification
  - Stereo or ladar ranging of reflections
  - FLIR brightness and texture classification
  - SWIR multi-spectral classification
  - Visible and NIR ladar attenuation
  - Polarization
- **Sensor penetration of natural and man-made atmospheric obscurants:**
  - Natural: haze, fog, rain, snow, dust
  - Man-made: smoke, dust
  - Sensors: visible, MWIR,and LWIR cameras, NIR ladar, MMW radar
- **Range sensor performance on snow:**
  - Visible stereo
  - Ladar
  - Radar penetration
- **FLIR stereo performance on rain-soaked ground**
- **Detectability of positive and negative obstacles as function of size, distance, and sensor resolution**

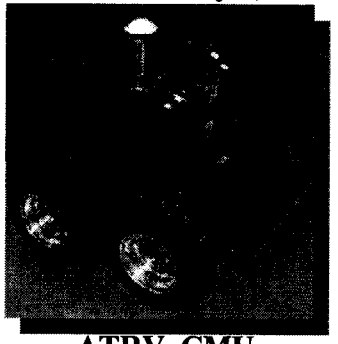
Infrastructure: JPL Rover Technology Development

Infrastructure

Hardware

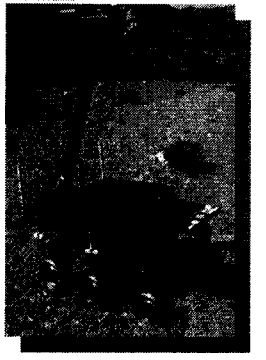
Rocky 8, JPL

FIDO, JPL



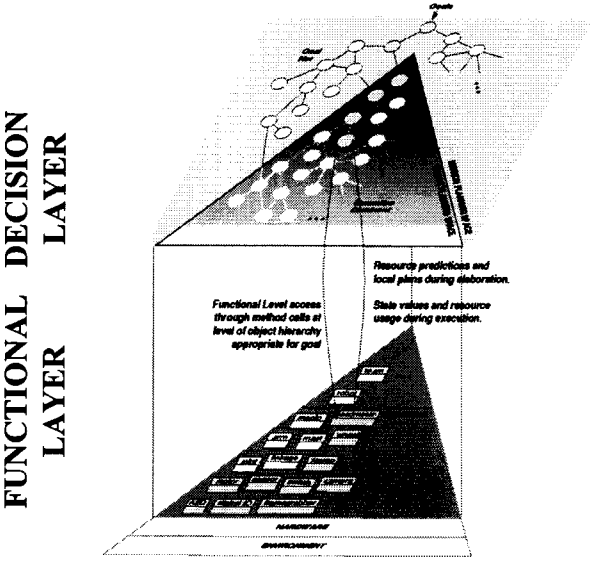
ATRV, CMU

Rocky 7, JPL



K9, ARC

Software



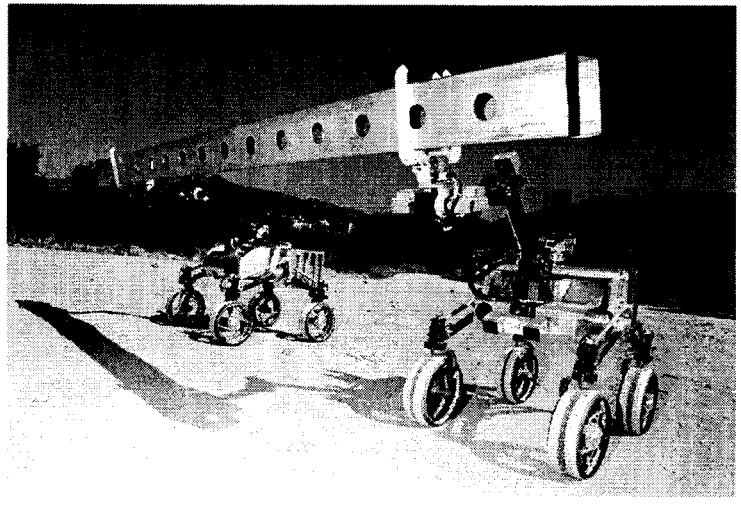
Coupled Layer Robotic Autonomy Architecture (CLARAty)

Current Research Team / Mars Technology Program Tasks

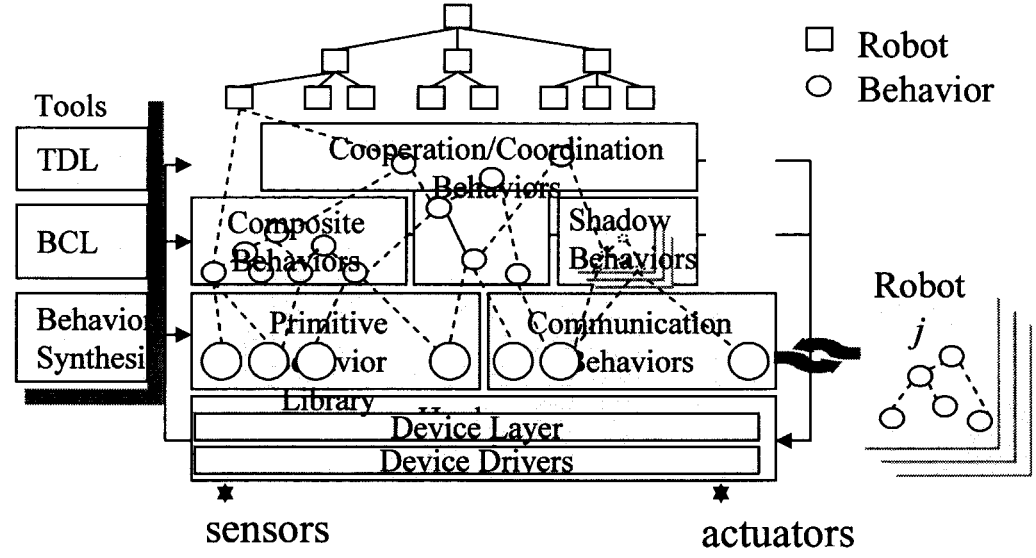
- **JPL** (Driving on Slopes, Visual Servoing, Simulation)
- **MIT** (Terrain Estimation)
- **Univ. of Washington** (Terrain Mapping)
- **ARC** (Autonomous Science, Simulation, Fault Detection)
- **CMU** (Path Planning)
- **Univ. Michigan** (Position Estimation)

Toward More Intelligent & Distributed Mobile Robotic Systems

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



Hierarchical task planning, allocation, and monitoring



EXAMPLE: Robotic Work Crew

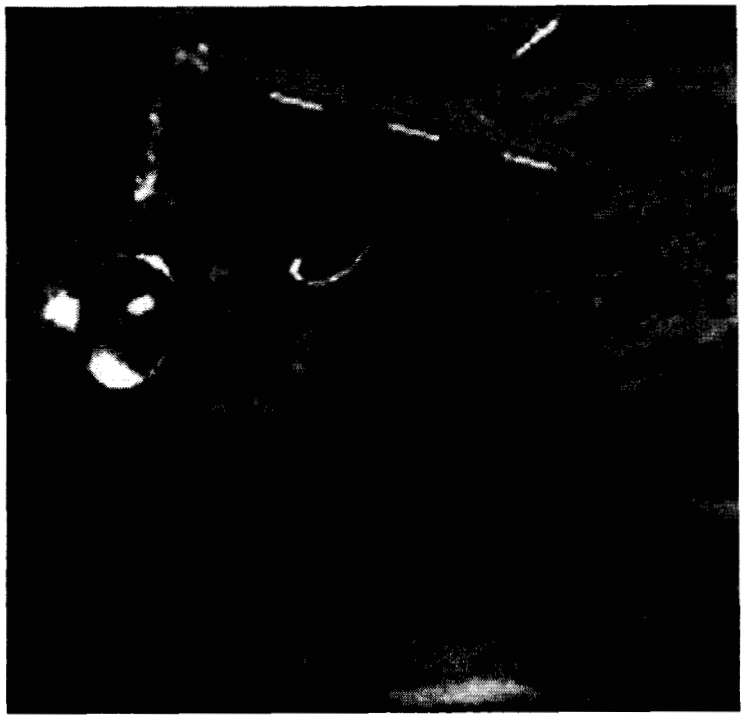
- **Mixed Initiative Control Architectures support human and robot multi-agent cooperation**
- **Robots tightly, autonomously coordinate interactions to perform complex physical tasks**
- **Layered autonomy coordinates fast, reactive behaviors and higher level decisions/planning**
- **The human agent/s 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

CAVEAT: Human Control Does Not Always Equal Safe Control

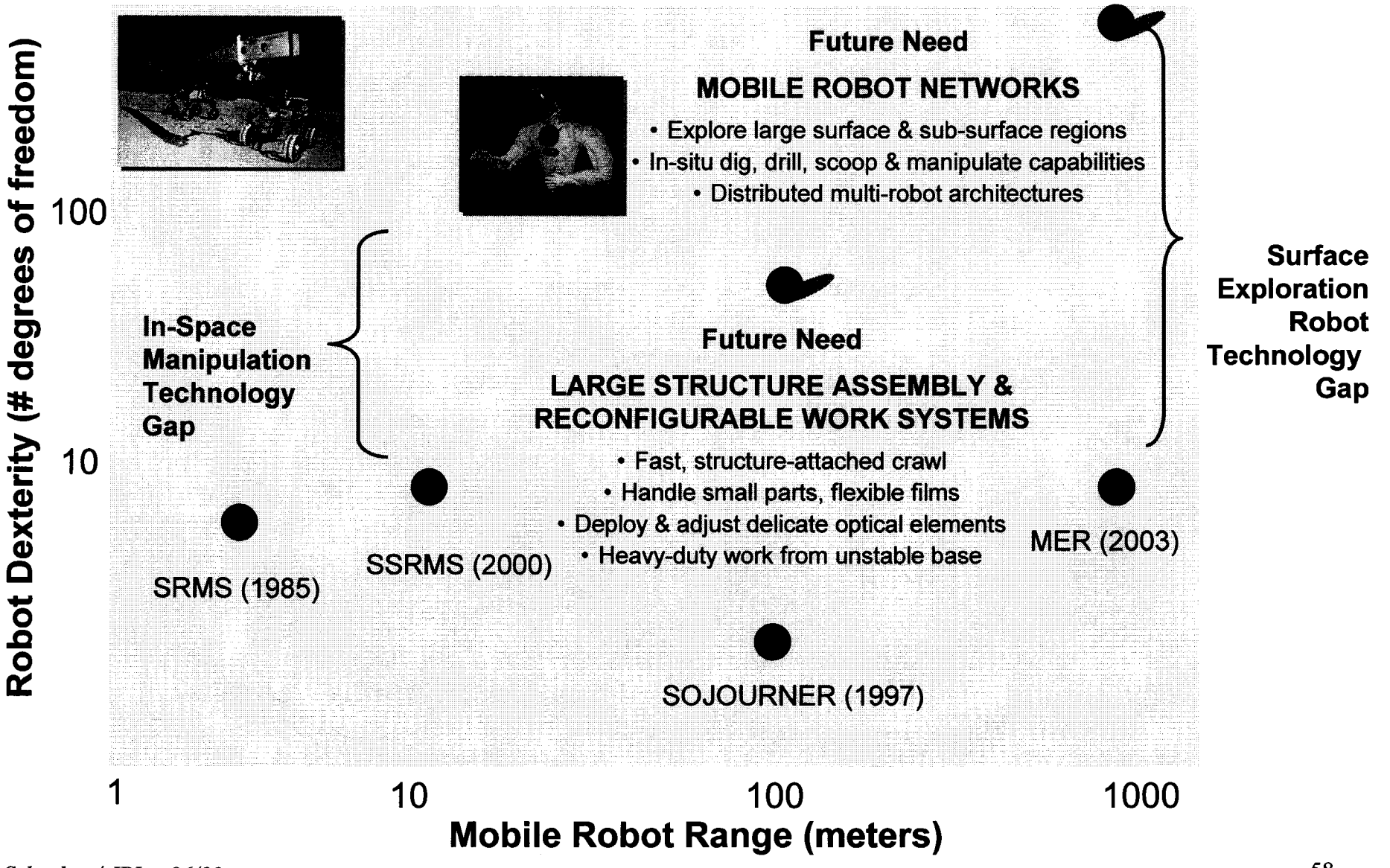
- The situation shown at right occurred when MPF ground operations planners—overriding the autonomous navigation system—commanded Sojourner into a very rocky area.
- "Blind" moves and turns were used, and navigational errors were compounded by noise on rate gyro.



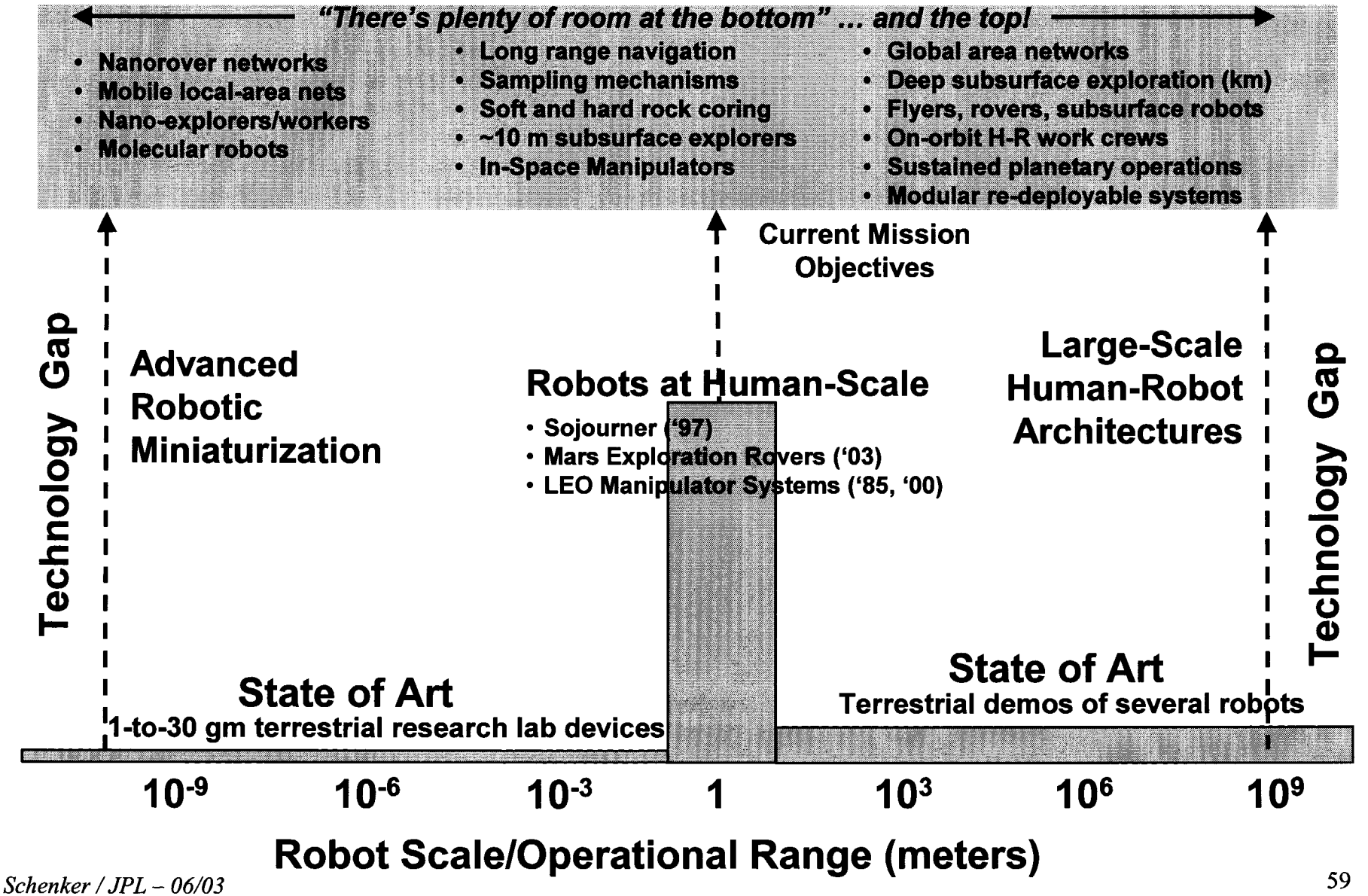
Mars Pathfinder/Sojourner (1997)

Filling Technology Gaps

On-Orbit and Surface Operations Examples



Increasing Scale, Theatre, and Performance of Space Robotics



In Conclusion – Mobile Robotics for Space

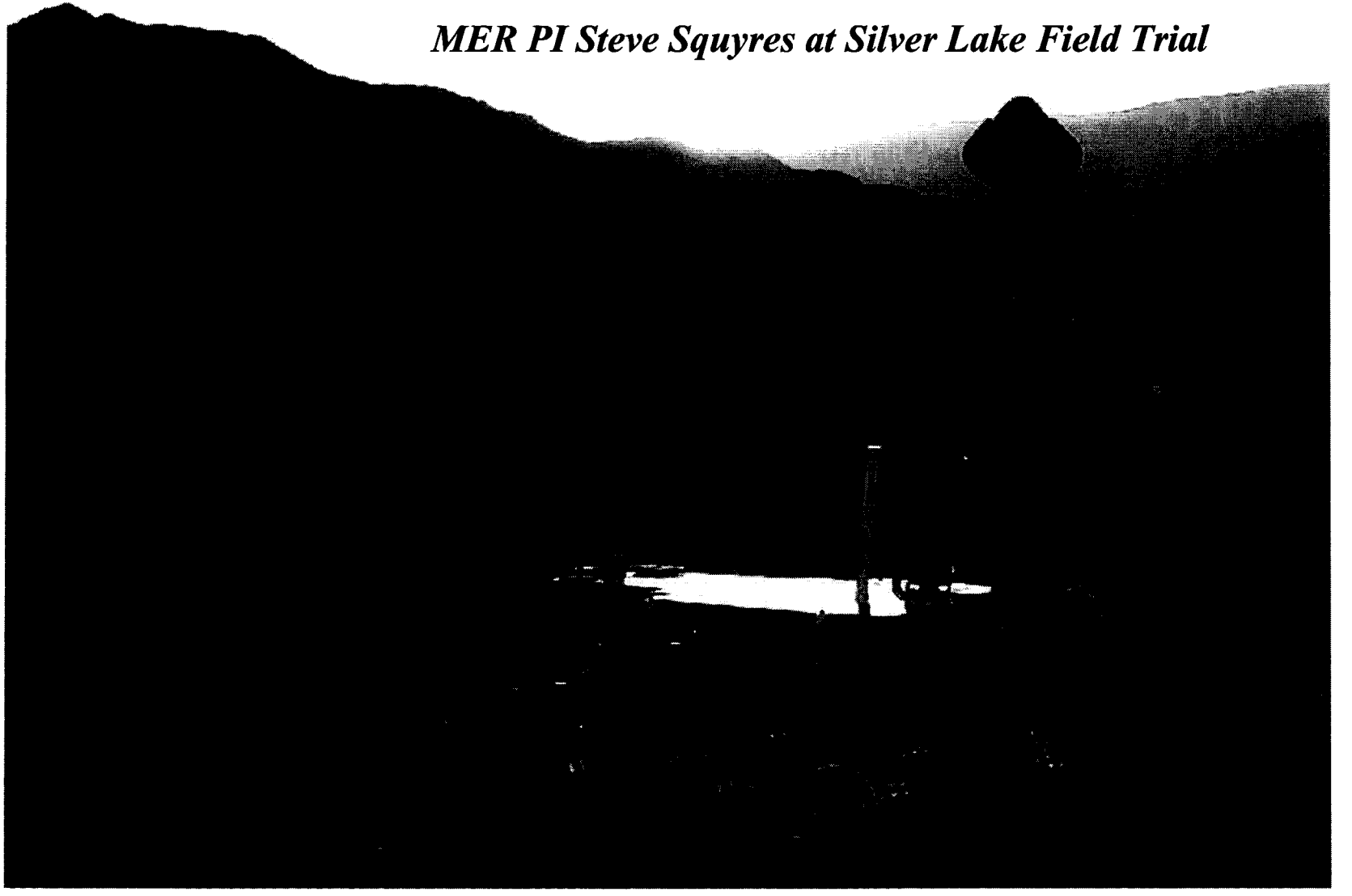
- **In-situ science and sample return from planetary and small bodies such as Mars, Venus, Titan and Europa poses extreme technical and operational challenges to autonomous mobile robots.**

- **Yet, mobility and mobile manipulation is 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 robot hardware-software architectures for solar system exploration.**

- **Parallel arguments exist for future in-space/on-orbit operations, which will include assembly, inspection and maintenance tasks of increasingly large scale, complexity and duration. These will be enabled by a similar technology based and are expected to similarly couple free-flying mobility, manipulation, and multi-robot cooperation.**

THE END

Making the Connection with Science is the End Goal

MER PI Steve Squyres at Silver Lake Field Trial