Microbots for Large-Scale Planetary Surface and Subsurface Exploration

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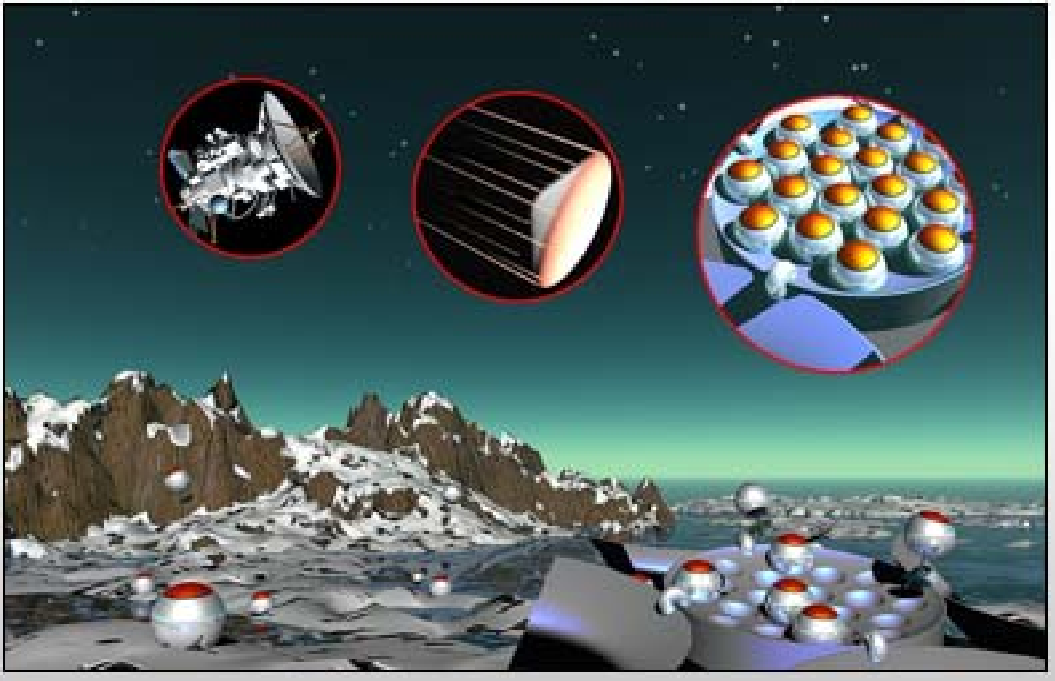
The Mission Concept

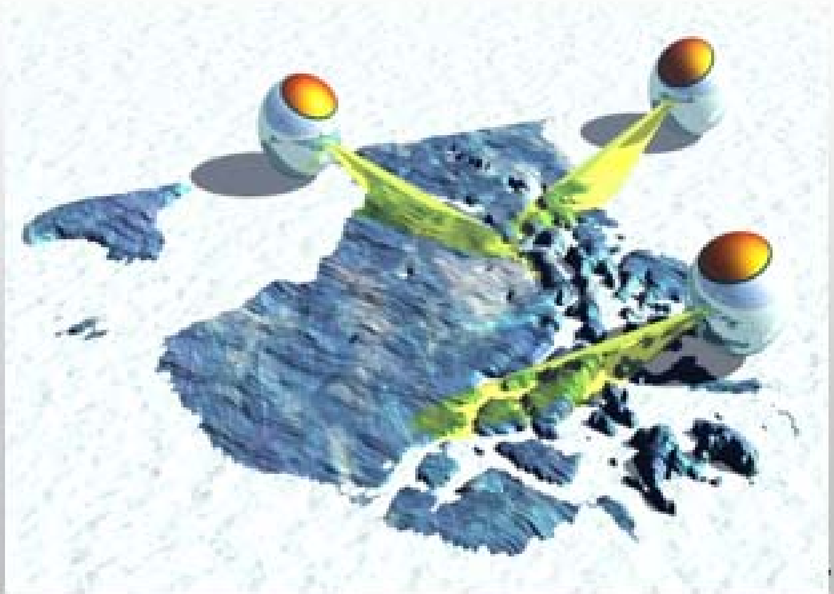
Deploy thousands of small mobile microbots over a planet's surface and subsurface

Allows the scientific study of very large-area surface areas in extremely difficult terrains

Allows the scientific study caves other subsurface domains



The Concept



Small and Light Weight

- ≈ 100mm and 100 grams

Highly Redundant

- 100s-1000s of units for a mission
- Individuals are sacrificial
- Largely constructed of highly durable and lightweight polymers
- Extremely simple and reliable

Highly Agile in Rough Terrain

- Hopping, rolling, bouncing

Autonomous

- On-board power, communications, sensing
- Teams with science-driven group intelligence

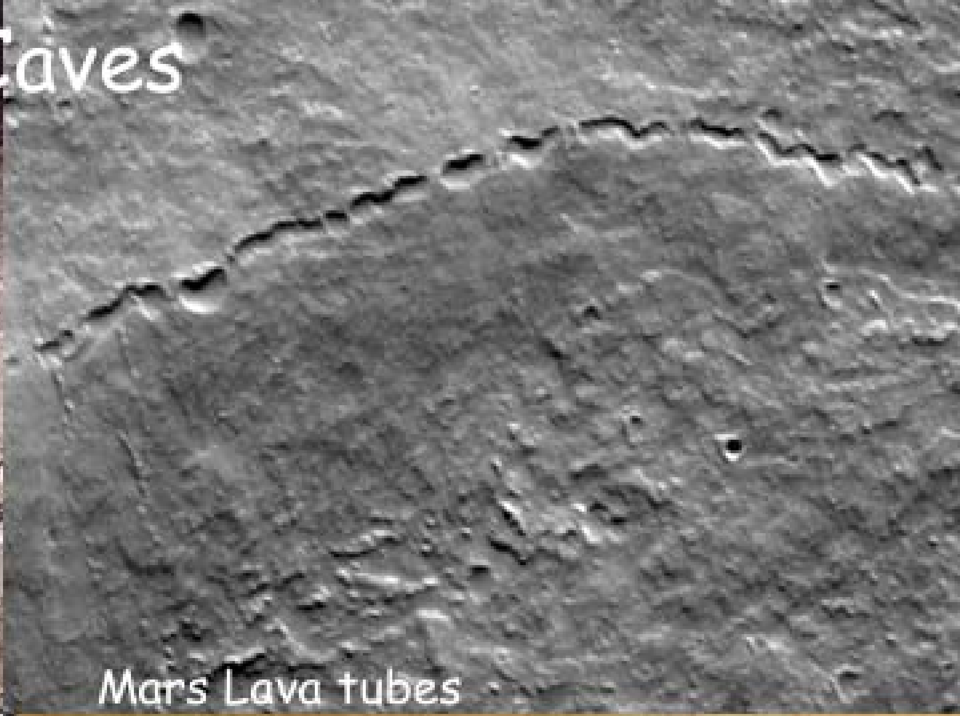
Scientific Motivation

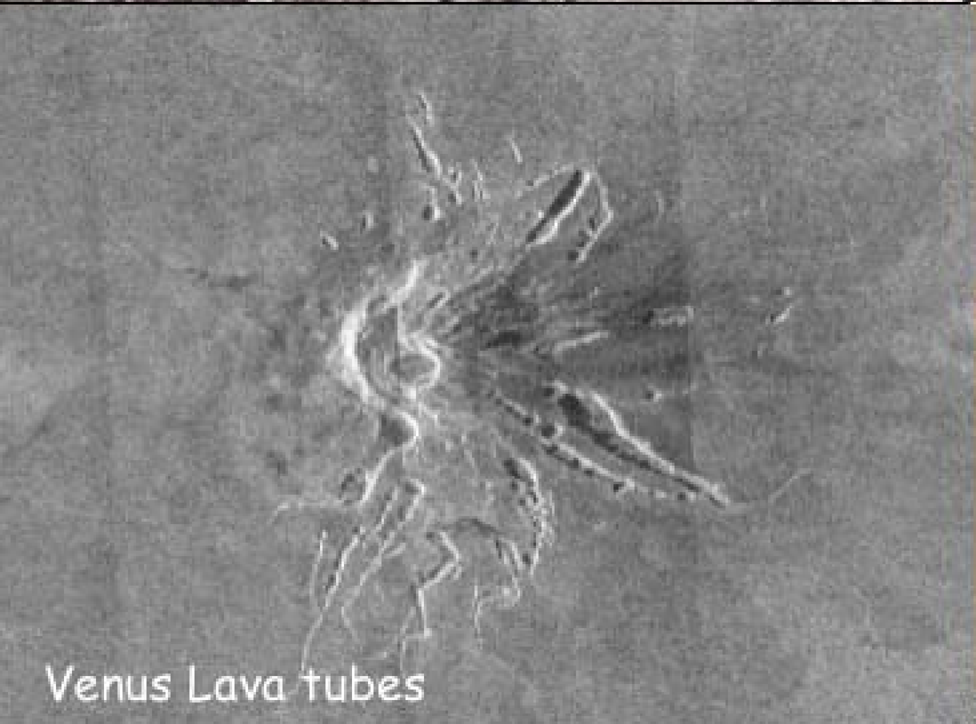
- Caves:
  - Windows into the subsurface
    - *(underlying geology, subsurface ices/water, etc.)*
  - Repositories for materials
    - *(biological traces, climate signals, unique minerals, etc.)*

- Surface terrains
  - Icy surfaces
    - *(e.g. permafrost, polygons, rocky deserts, etc.)*
  - Volcanic and rocky surfaces
    - *(e.g. lava flows, canyons, rock underhangs, etc.)*

Scientific Motivation- Caves

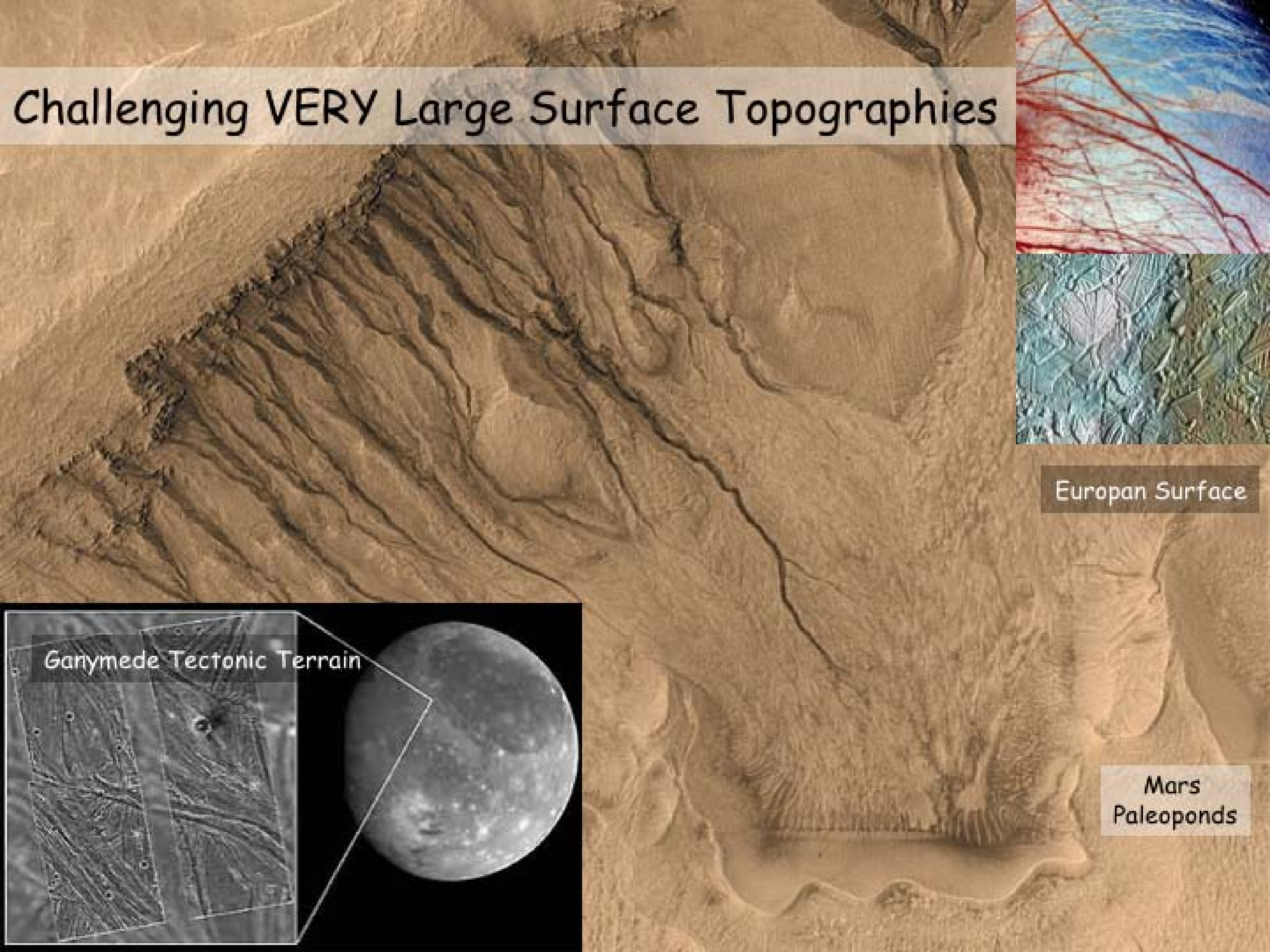

Lunar Lava tubes


Mars Lava tubes


Venus Lava tubes


Io Lava tubes

Challenging VERY Large Surface Topographies



Planetary Surfaces and Caves Present Challenging Terrain

Preliminary Field Testing - New Mexico Lava tubes

- Breakdown floors vs. sediment floors
- Wedging issues in different terrain
- Size optimization of microbot units

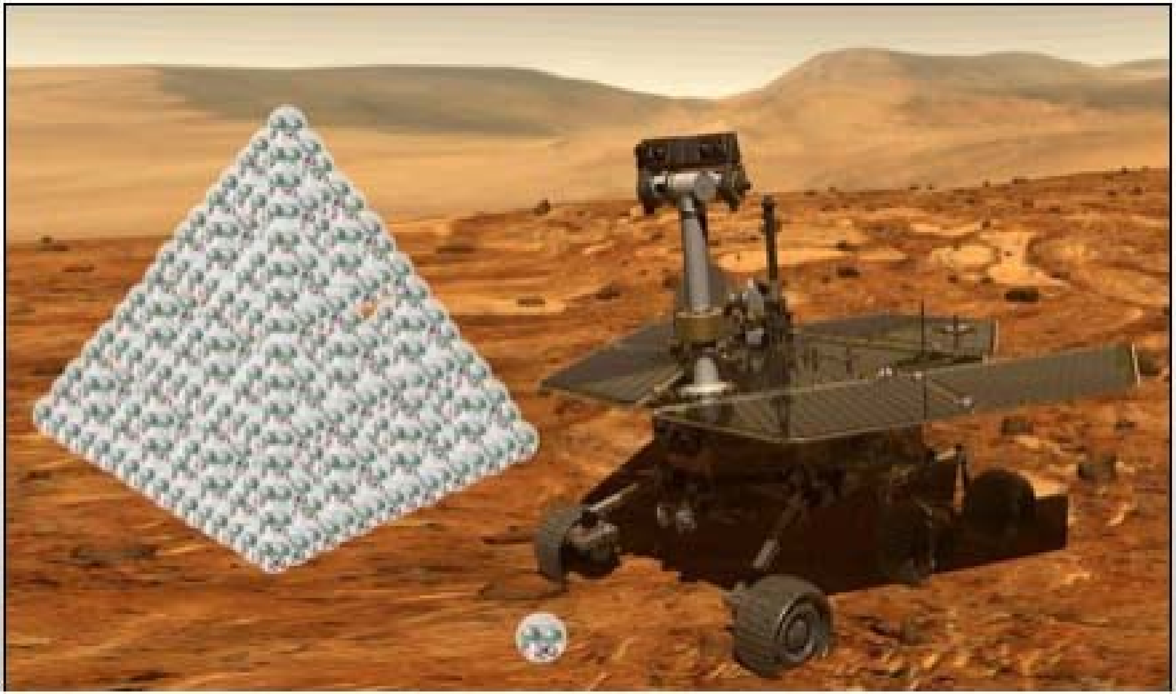
REMots - A New Paradigm for Exploration of the Bodies of the Solar System

Future Planetary Missions will Need to Explore:

- Very Large Surface Areas
- Access complex subsurface topologies
- Traverse very rough terrain

ReMotes provide:

- Strategy flexibility
- Multiple applications
- Multiple planet types
- Multiple terrain types

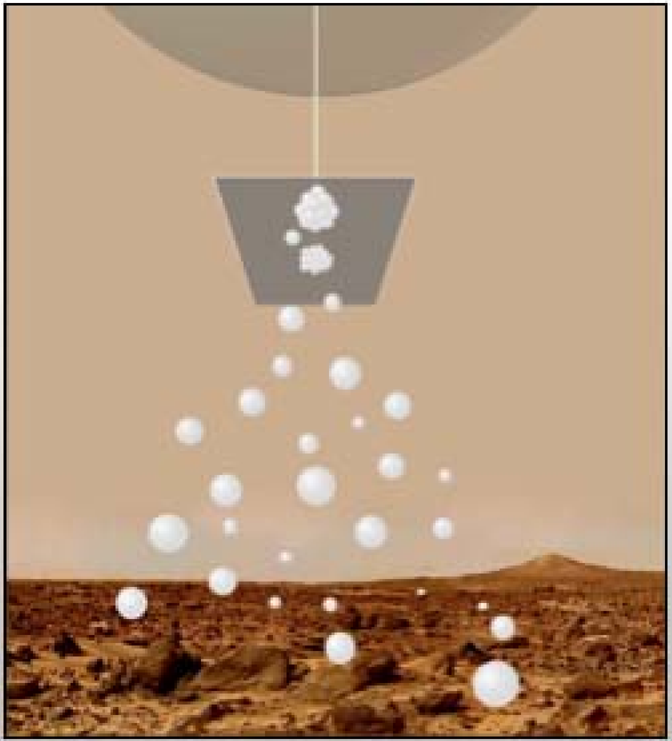


...at comparable volume and mass to existing linear sampling strategies!

1000 REMotes would have the same launch volume and weight as the Spirit

REMots - A New Paradigm for Exploration

Deployment and Communication Concept

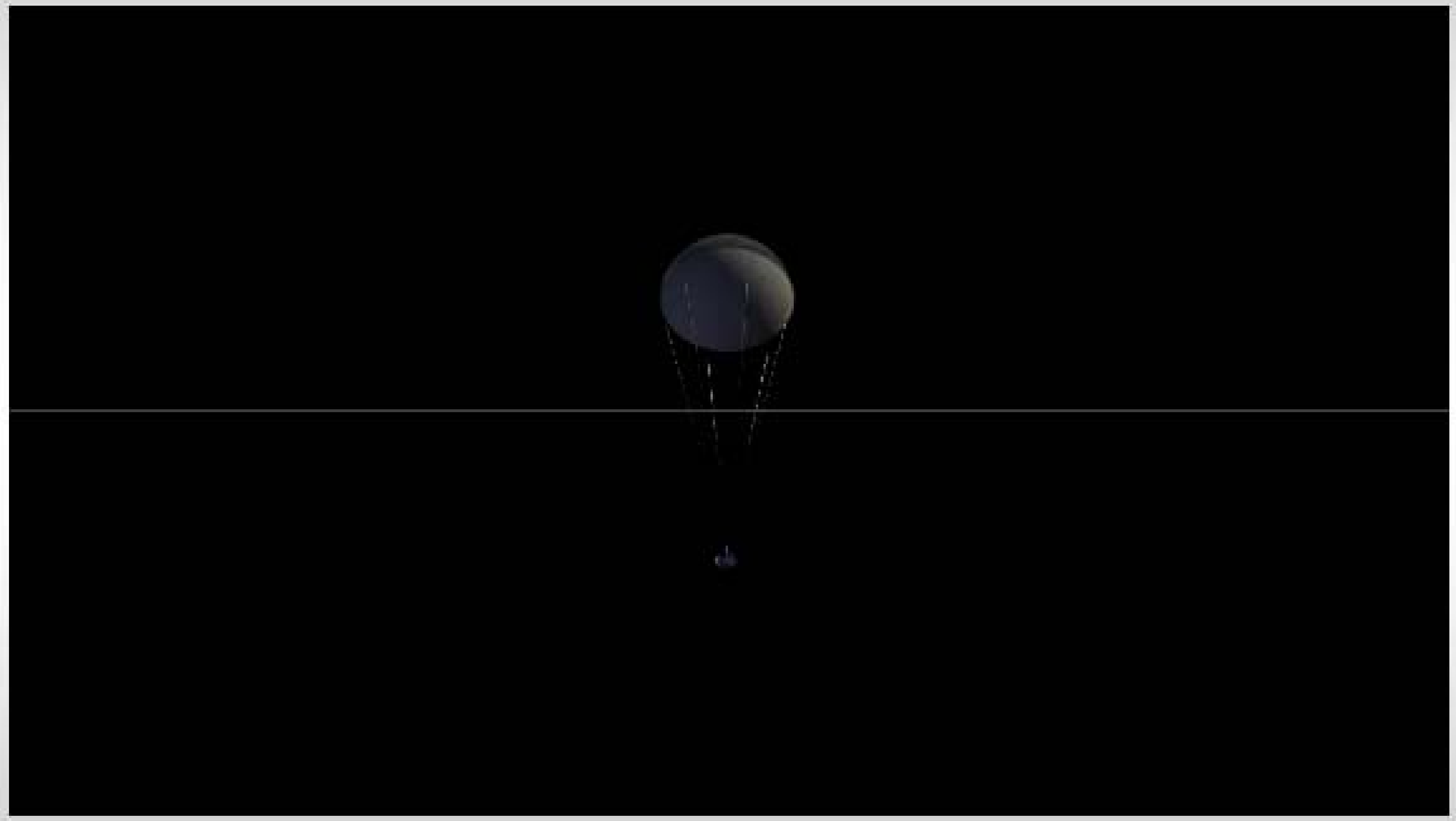


Deployed by orbiter
    Airbag landing

Deployed from a balloon or aerial vehicle
    Low altitude drop landings

Microbots Communicate via:
    "Trail of breadcrumbs" (LAN) to lander or to aerial vehicle or orbiting satellite

Deployment



Reference Missions

A Mar surface exploration mission - 135 sq kilometers (50 sq miles) in 30 Sols

A Cave exploration mission - 1 Km in 5 days (WEEBUBBIE CAVE-Australia)

Microbot Subsystems

Mobility

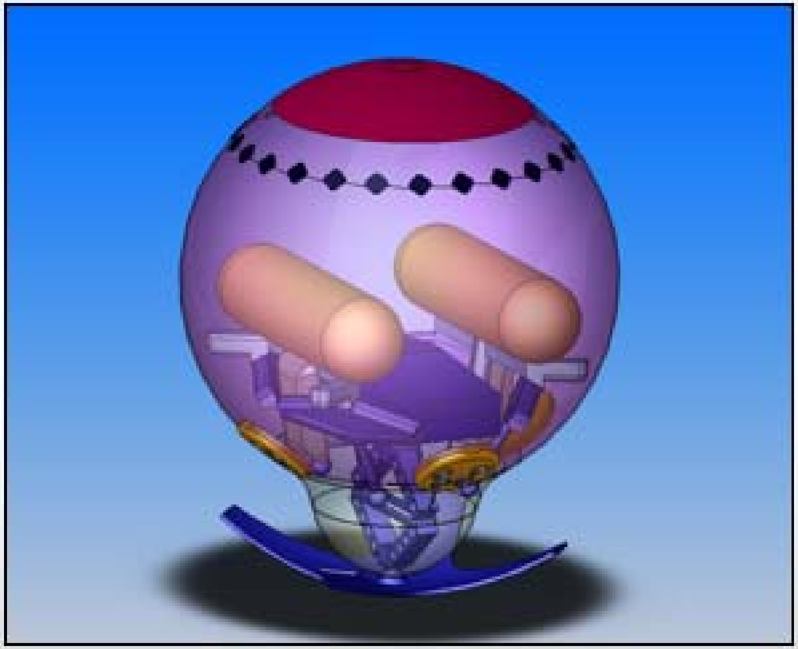
- Bi-Stable EPAM "muscle" actuators
- Directed or non-directed hopping

Power

- Hyper-efficiency micro fuel cells

Sensors

- Micro-scale imagers, environmental sensors, gas analysis sensors, spectrometers



Communication and control

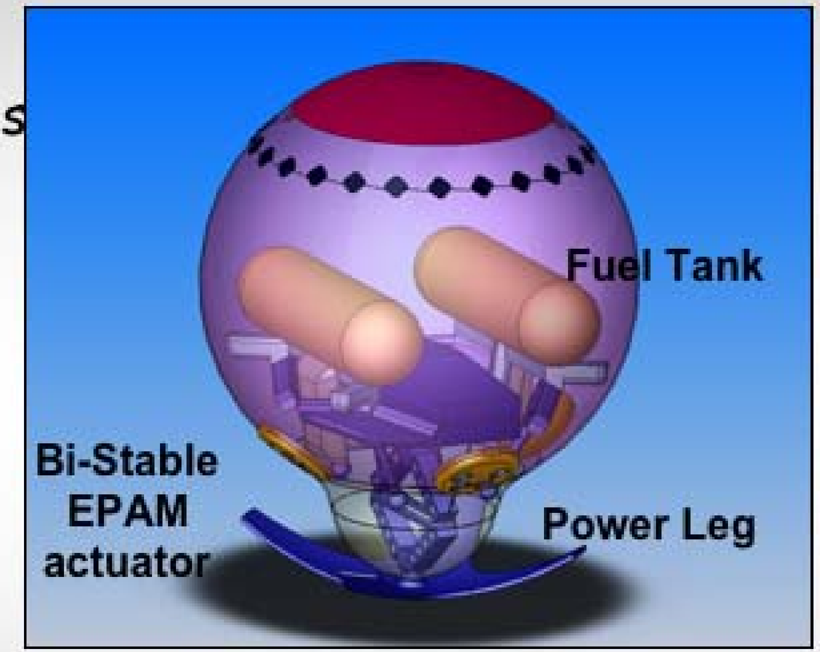
- Surface/subsurface LAN
- Collective group behavior

Mobility and Power

Mobility and Power

- All Polymer Bi-stable "muscle" actuators
- Directed or non-directed hopping, bouncing, rolling
- High-efficiency fuel cells

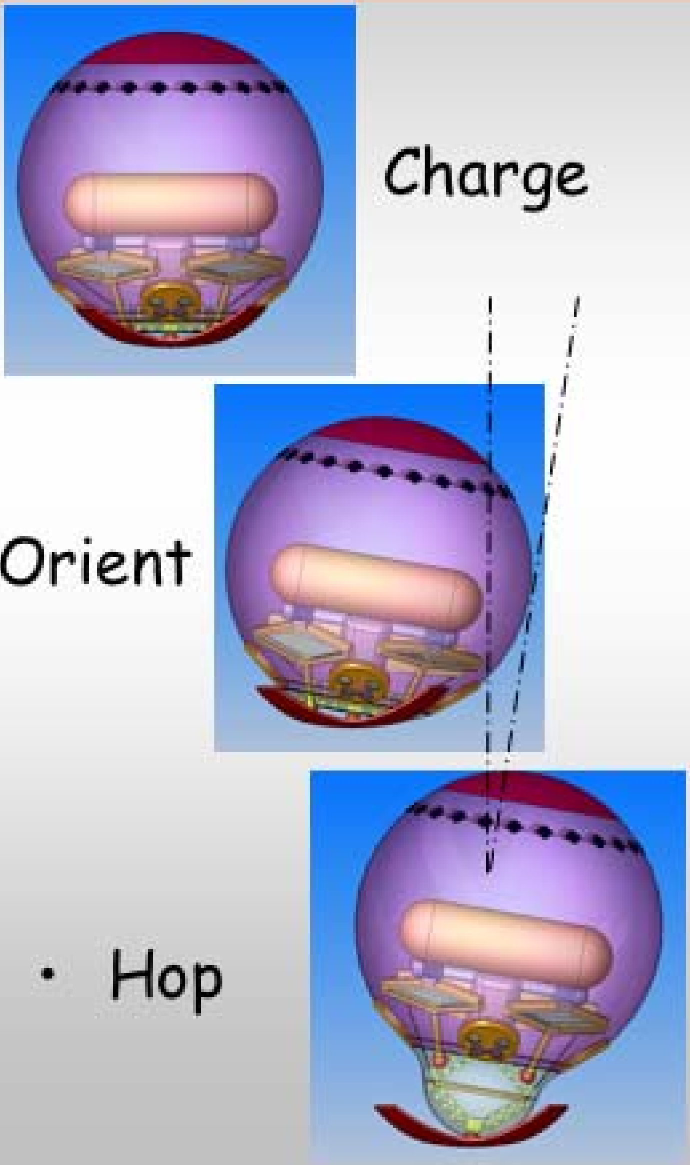
Mass (Total)	150 g
Diameter	10 cm
Hop height (Mars)	1.5 m
Distance per hop (Mars)	1.5 m
Avg. hop rate	6 hop/hr
Max. hop rate	60 hops/hr
Fuel use	1.5 mg/hop
Peak power	1.5 W



Predicted System Parameters based on the reference missions

Mobility and Power

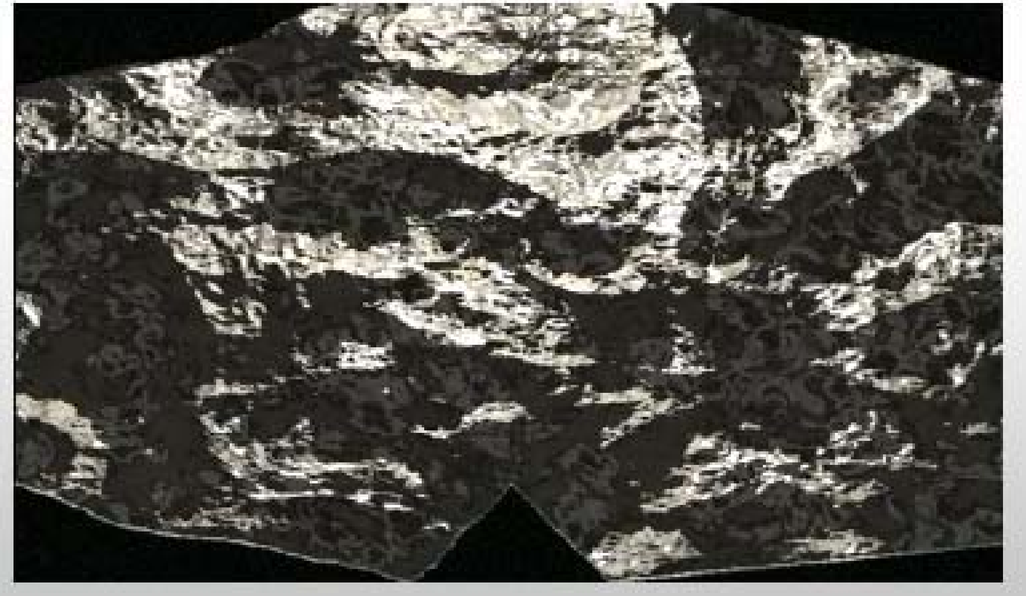
EPAM "muscle" actuators - Directed or non-directed hopping, bouncing, rolling



Charge

Orient

- Hop



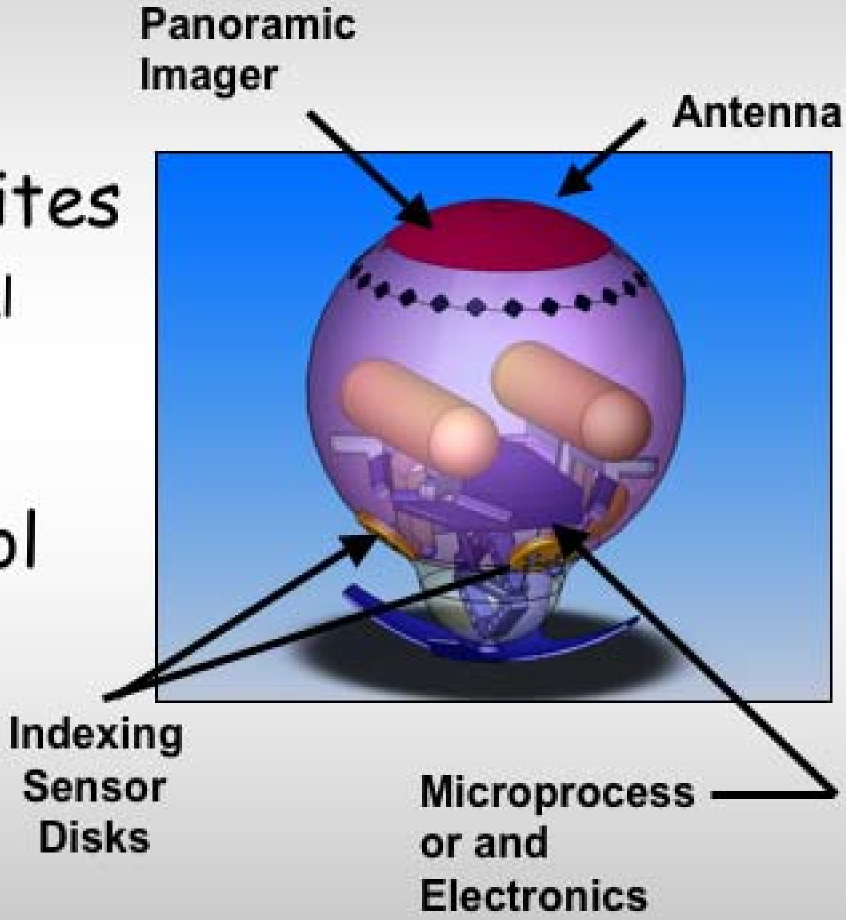
Sensors and Communications

Heterogeneous sensor suites

Micro-scale imagers, environmental sensors, gas analysis sensors, spectrometer, etc.

Communication and control

Surface/subsurface LAN



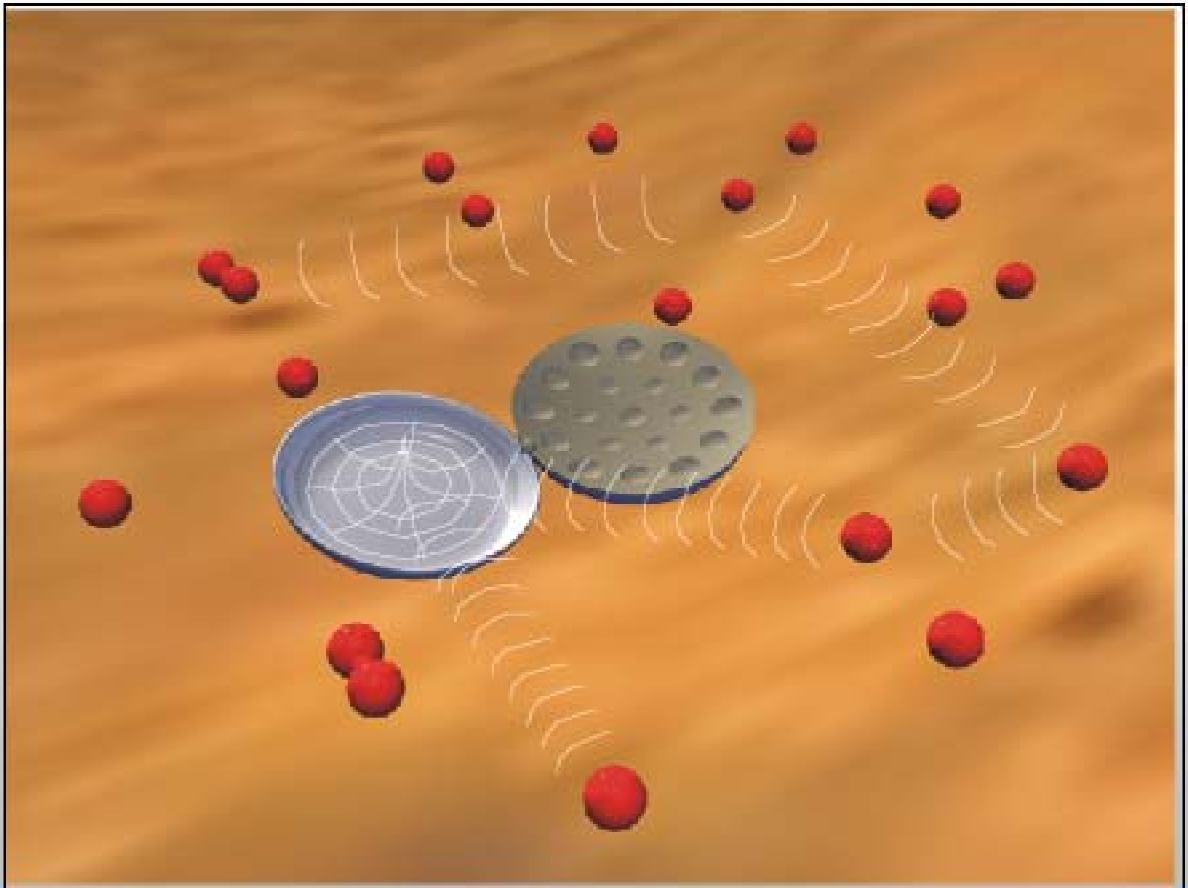
Sensors and Communications

Communication and control

Surface/subsurface LAN

Collective group behavior

Microbot surface LAN



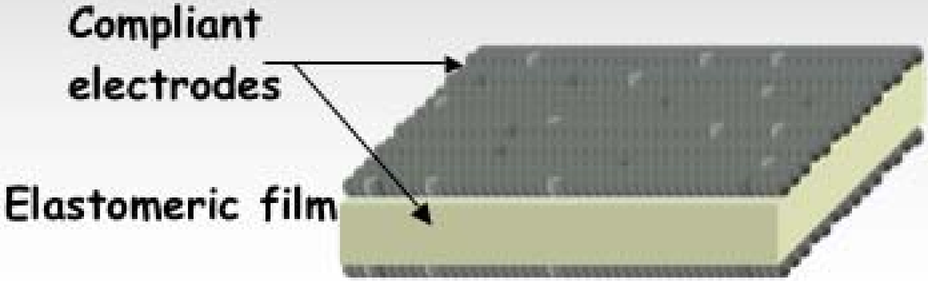
Key System Components

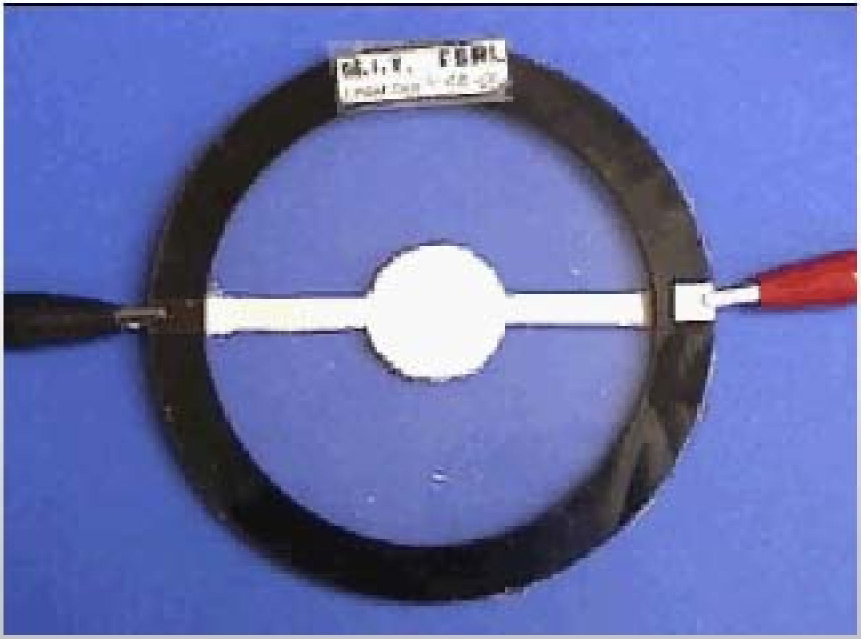
Actuation

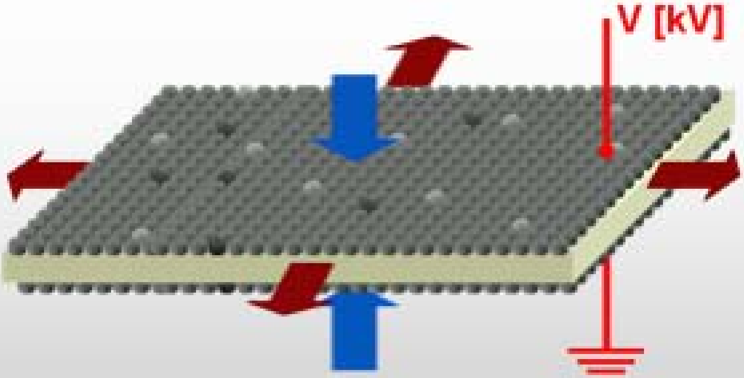
Actuator: Electroactive Polymer Artificial Muscles (EPAMs)

- Simple
- Lightweight

Basic Operating Principle



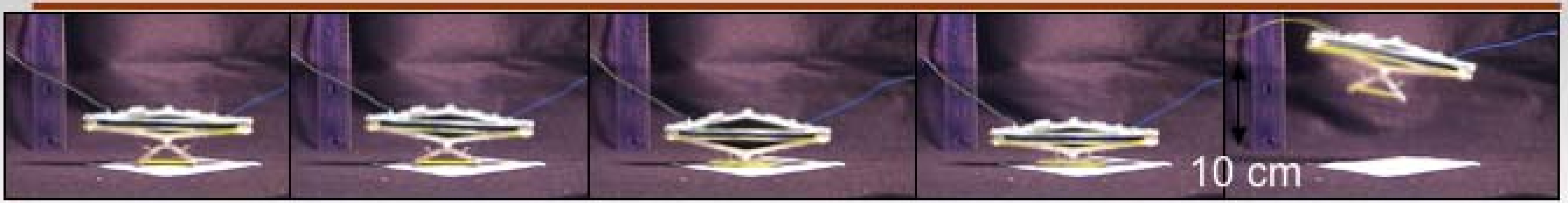




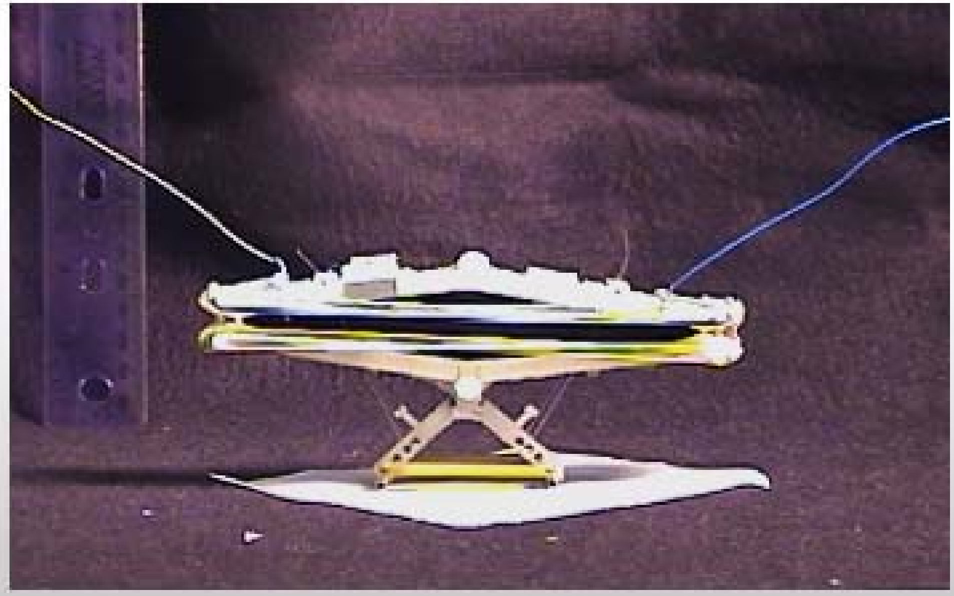
Actuation

MIT actuator performance
- Large strains (up to 200%)
- Micro-amp currents
- 1000:1 force to weight ratio
- Dynamic response: 10 Hz
- Energy efficiency: > 70 %

Actuation



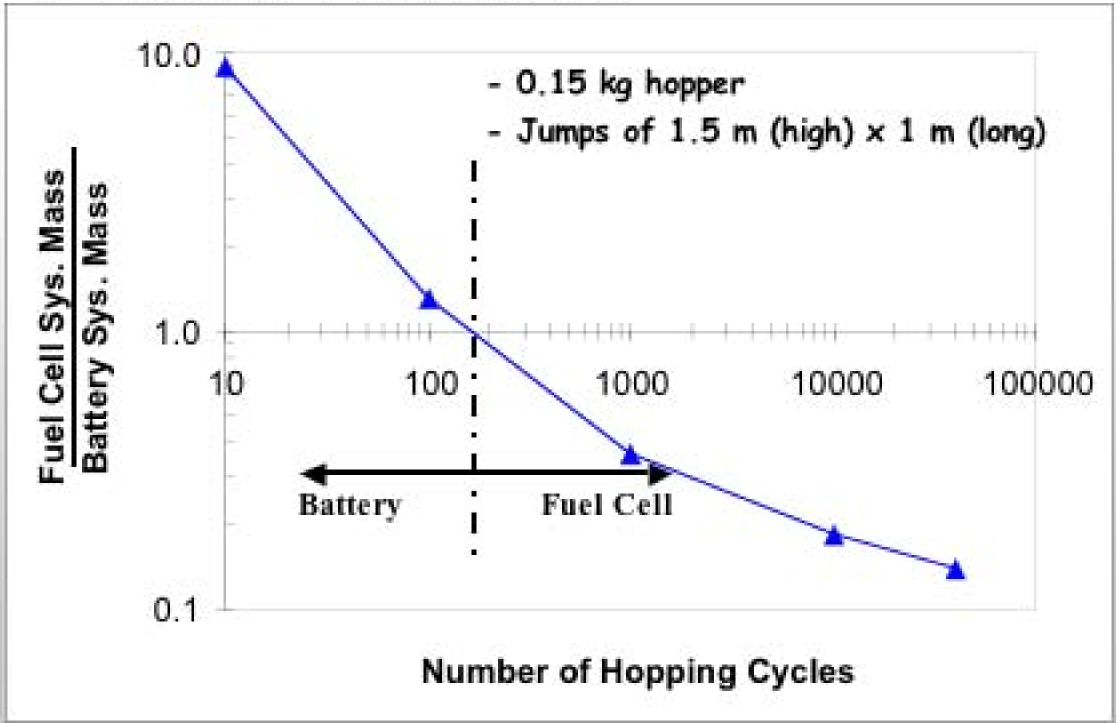
- Indexing Actuator Concept
  - Simple
  - All polymers - light weight and inexpensive

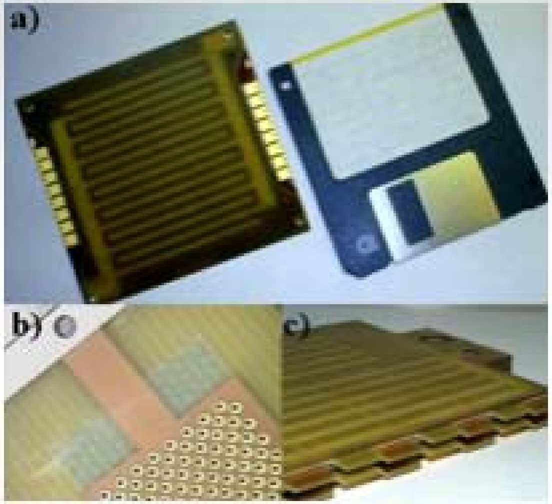


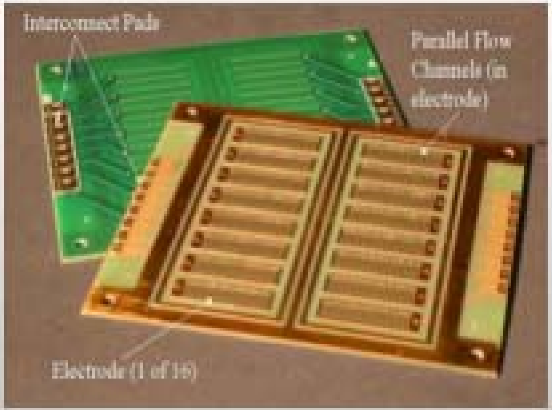
- Experimental Prototype:
  - 110 x 50 x 15 mm
  - Mass: 30 g
  - Jump height ~ 100 mm (1g)

Power

- **Fuel cells result in long system range**
  - Surface mission: 30 days*6 hops/hr ~ 5000 hops
  - Cave mission: 1 km penetration ~ 1000 hops
  - Fuel consumption (H_2+O_2): 1.5 mg / hops
  - Peak power: 1.5 W
  - Embedded in structure







PCB Fuel Cell power (Fritz B. Prinz, Stanford)

Sensors and Computation

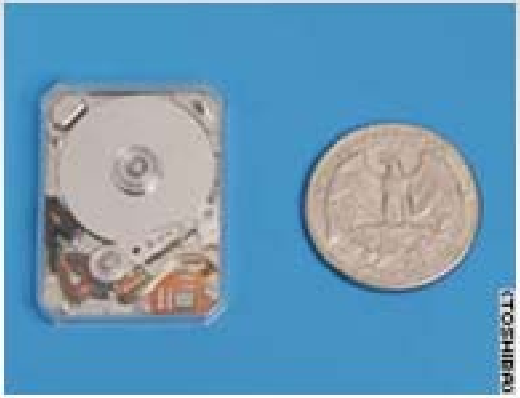
Key Exploit - Micro-sensors and micro-computational components (currently under development)

Micro-sensors have very small power consumption (25 to 100mW)

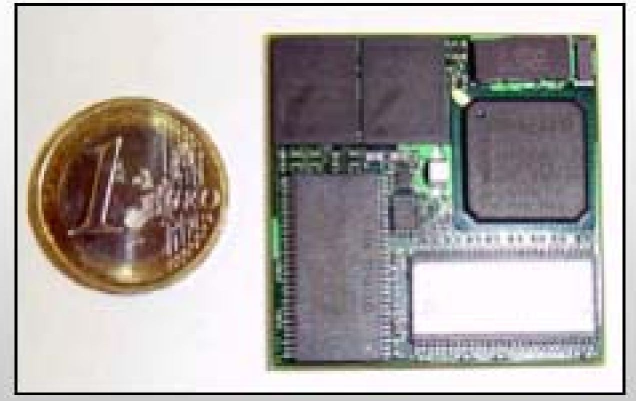
Proposed sensors suites include:

- Image sensors
- Environmental sensors
- Gas analysis sensors
- Spectrometers

On-board processing reduces data transmission requirements



4 Gig Disk Drive - 2004 (Toshiba)

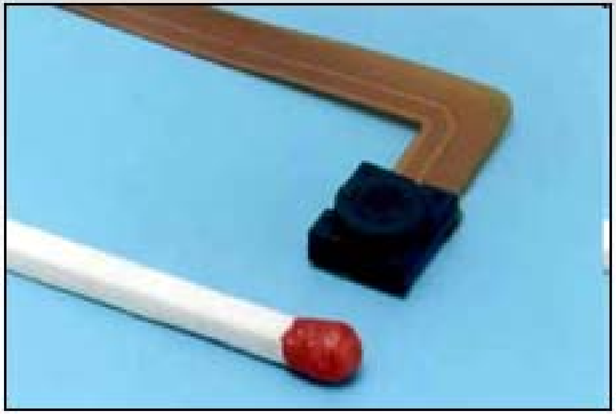


On-board-data processing Technical University of Braunschweig

Sensors

Image sensors

- Panoramic camera to identify science sites, localize and navigate microbot
- Microscopy for close up and high resolution analysis

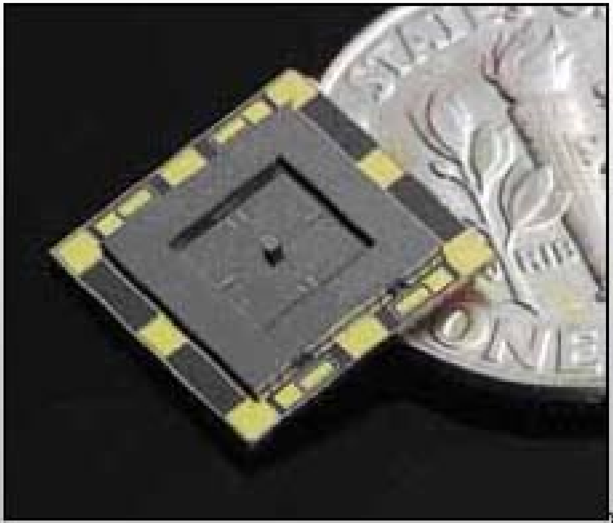


Fujitsu: CMOS Micro-Camera

Environmental sensors

- Pressure, temperature and dust sensors
- Accelerometers and gyroscopes system mobility
- Gaussmeters, Magnetoscops for field measurements

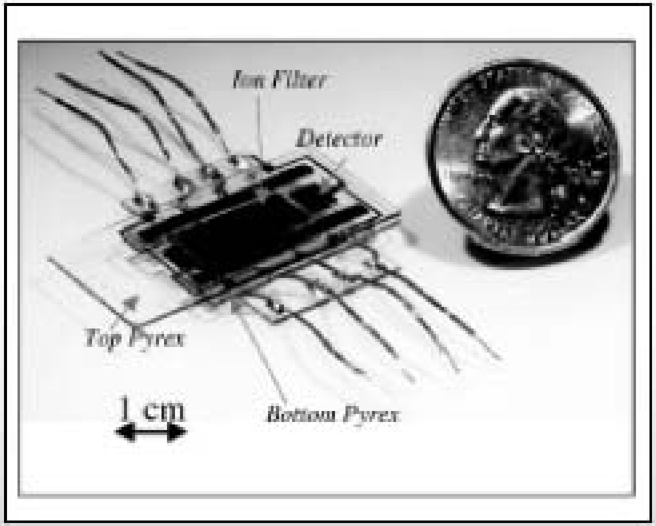
Micro-scale prototypes are underdevelopment.



Miniaturized gyro by JPL.

Sensors

- Gas analysis
  - Primarily for detection of carbon compounds
  - Detection of methane to study biological activity
  - Micro-scale *laboratory-on-chip* type sensors are under development
- X-Ray, Raman and Mössbauer spectrometers
  - Play key roles in planetary geo-chemical characterization
  - Greatest limitations for miniaturization and largest power consumption
    - “Spectrobots” to carry only spectrometers
    - Specific measurement and limited spectra resolution could be key for data reduction



Miniaturized mass spectrometer- Draper Laboratories

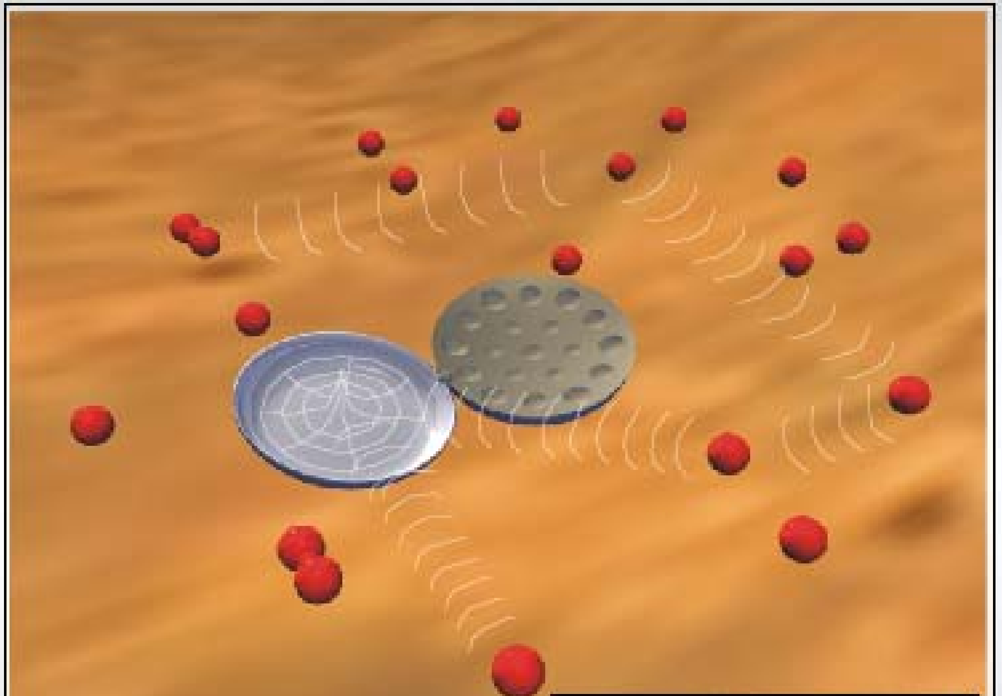
Communication-Surface

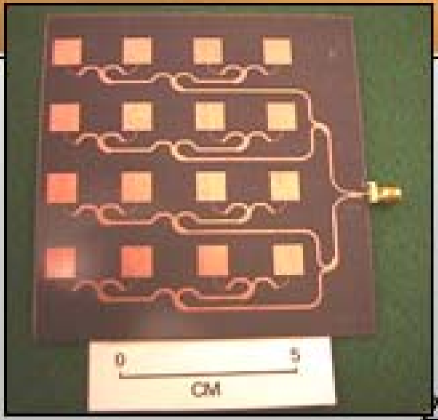
Surface exploration

Microbots communicate with a central unit (lander) and each other via LAN.

Maximum distance to cover in reference surface mission ≅ 6.5 km without LAN.

RF frequency between 1 and 25 GHz would meet the requirement (≅ 100mW)

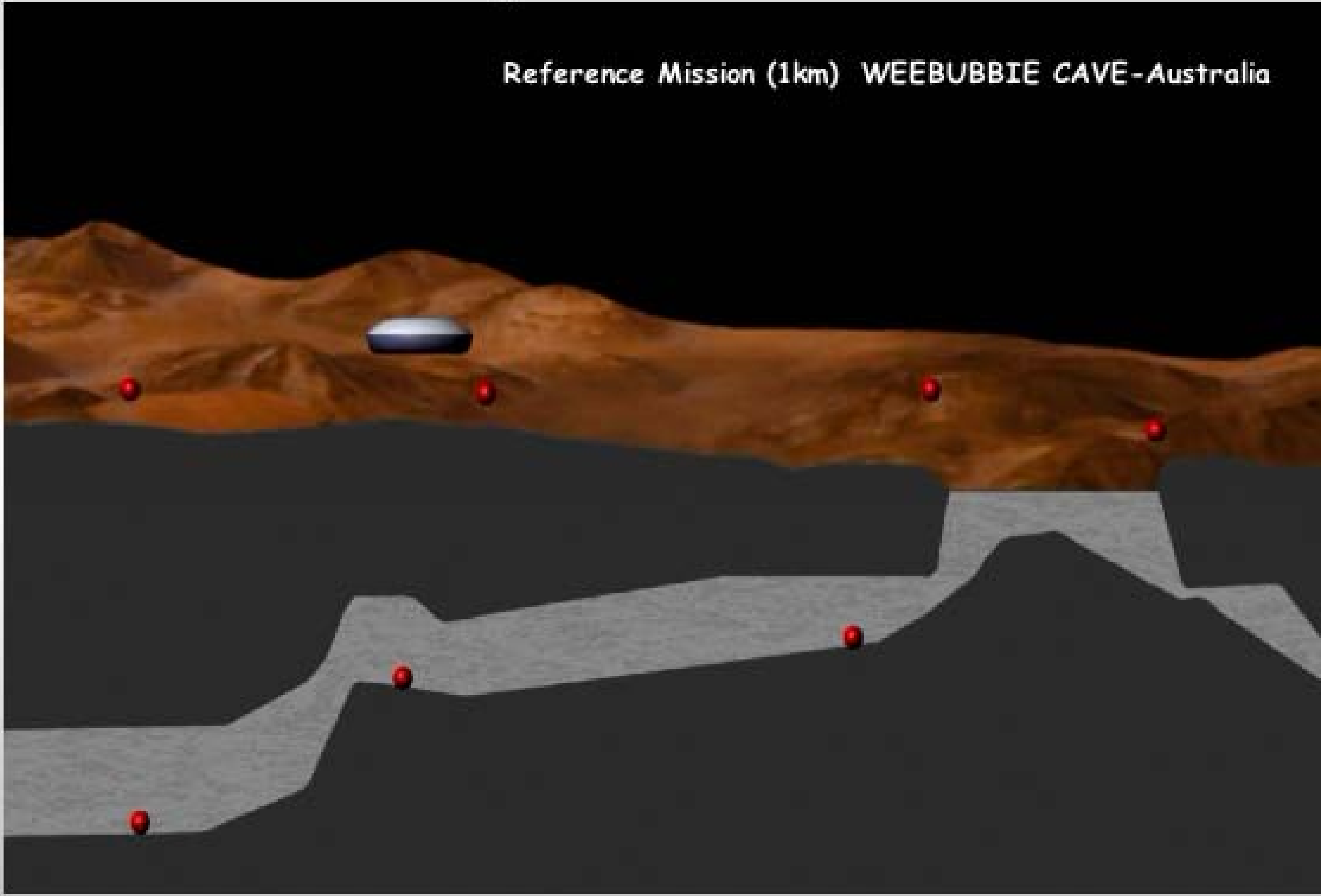




X-band antenna-Department of engineering science, Oxford, UK

Communications- Subsurface

Microbots communicate with lander by a "trail of breadcrumbs"



- -50 Microbots
- -Field Measurements show Range in caves at 25 GHz is greater than 20 meters- (non-line-of-sight)

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*Boston, P.J , et al , SL Extraterrestrial subsurface technology test bed- Human use and scientific value of Martian caves STAIF(Space Tech & Applic Forum 2003)Proc AIP #654 Amer Inst of Physics, College Park, MD .2004

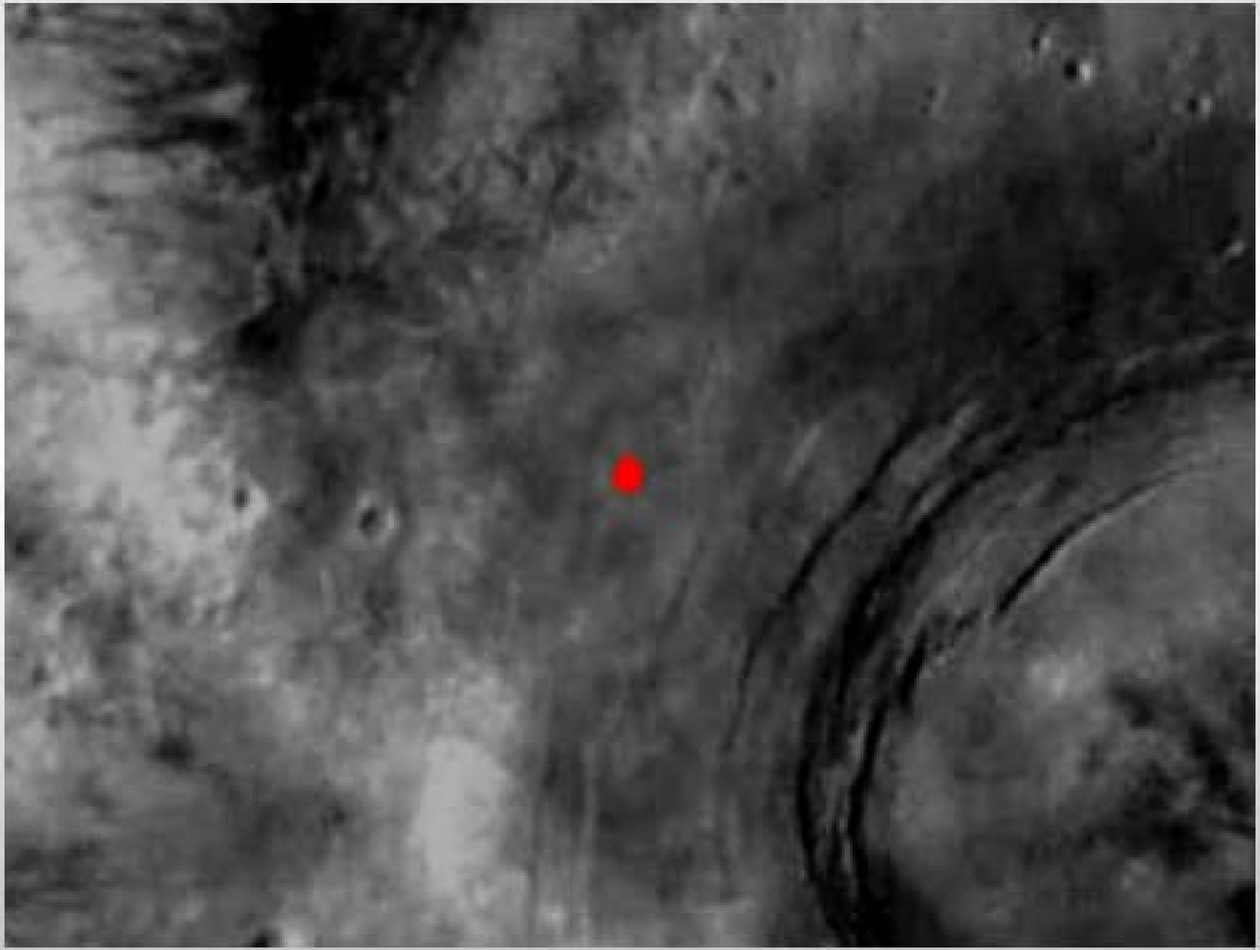
Surface Mobility--Simulations Study Results

Analysis of microbot surface mobility

- 100 Microbots
- 1.5 m per jump
- 4320 jumps
- 6 jumps / hour
- 30 days

133 square km or 50 square mi covered

- Result for one "team"
- Mission might have multiple teams with various starting on planet

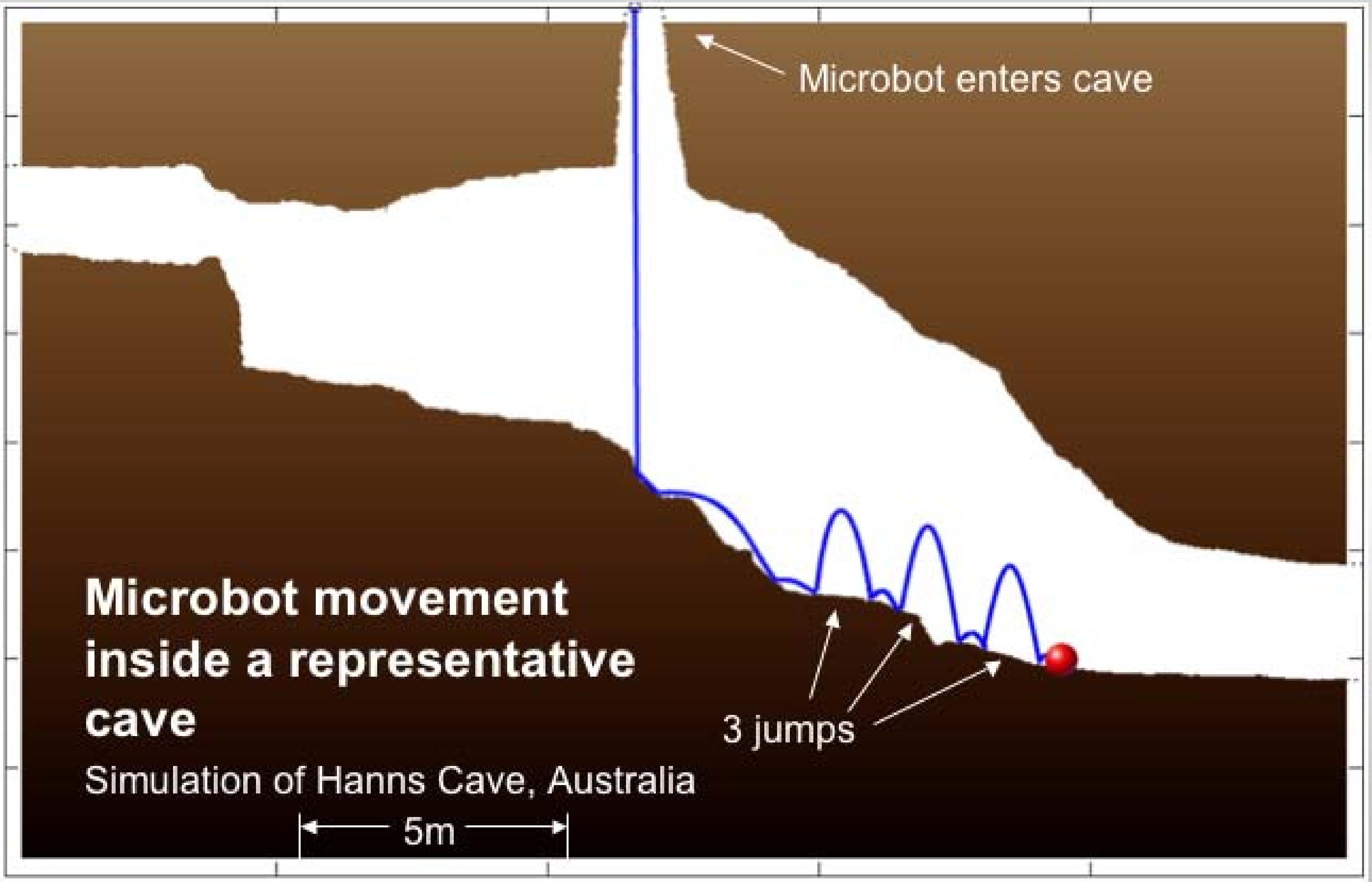


Cave Mobility

The Hibashi Cave, Saudi Arabia

Hibashi by candlelight: Show that the cave has a relatively uniform cross-section.

Cave Mobility -- Simulations Study Results



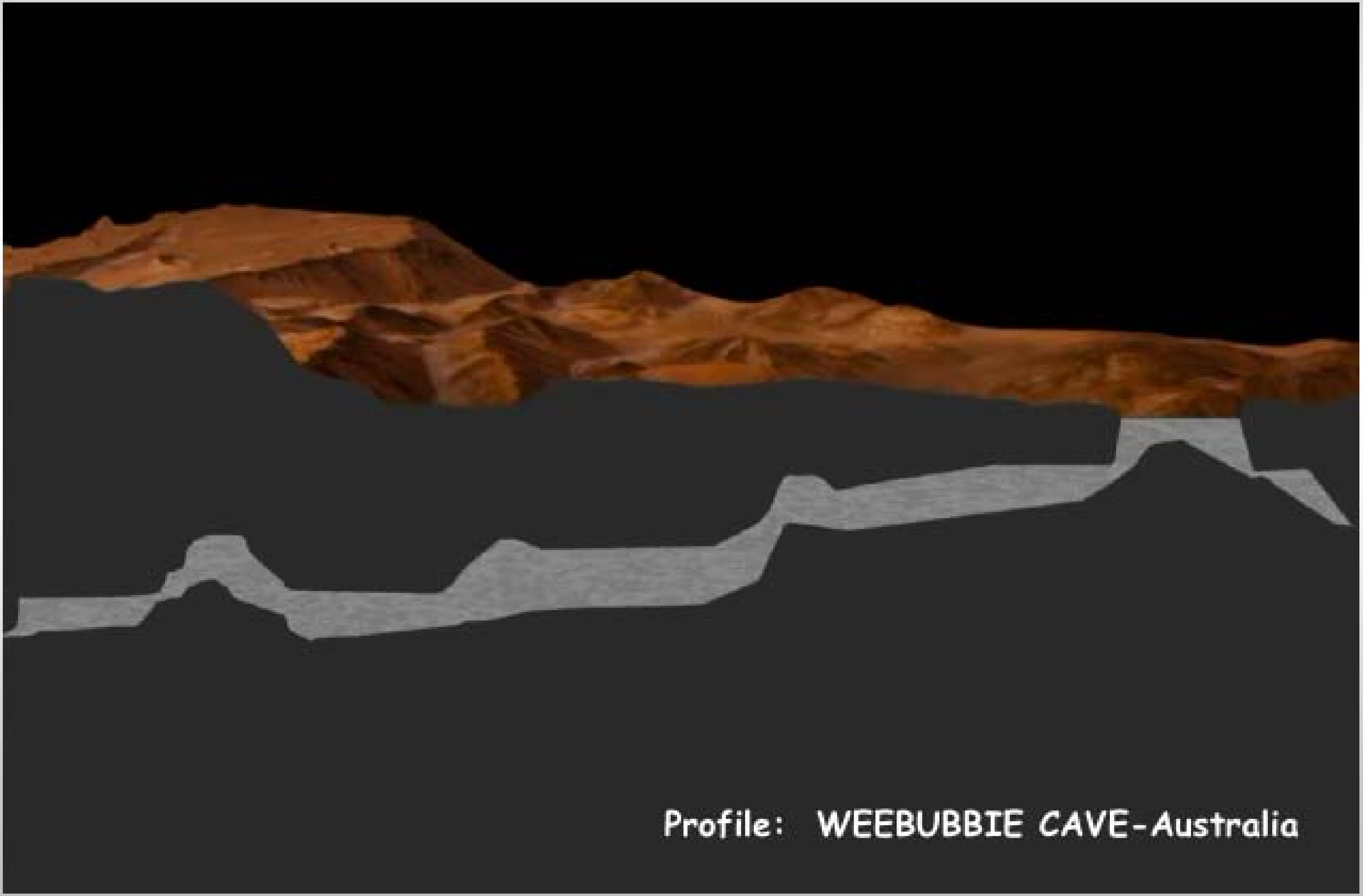
Microbot enters cave

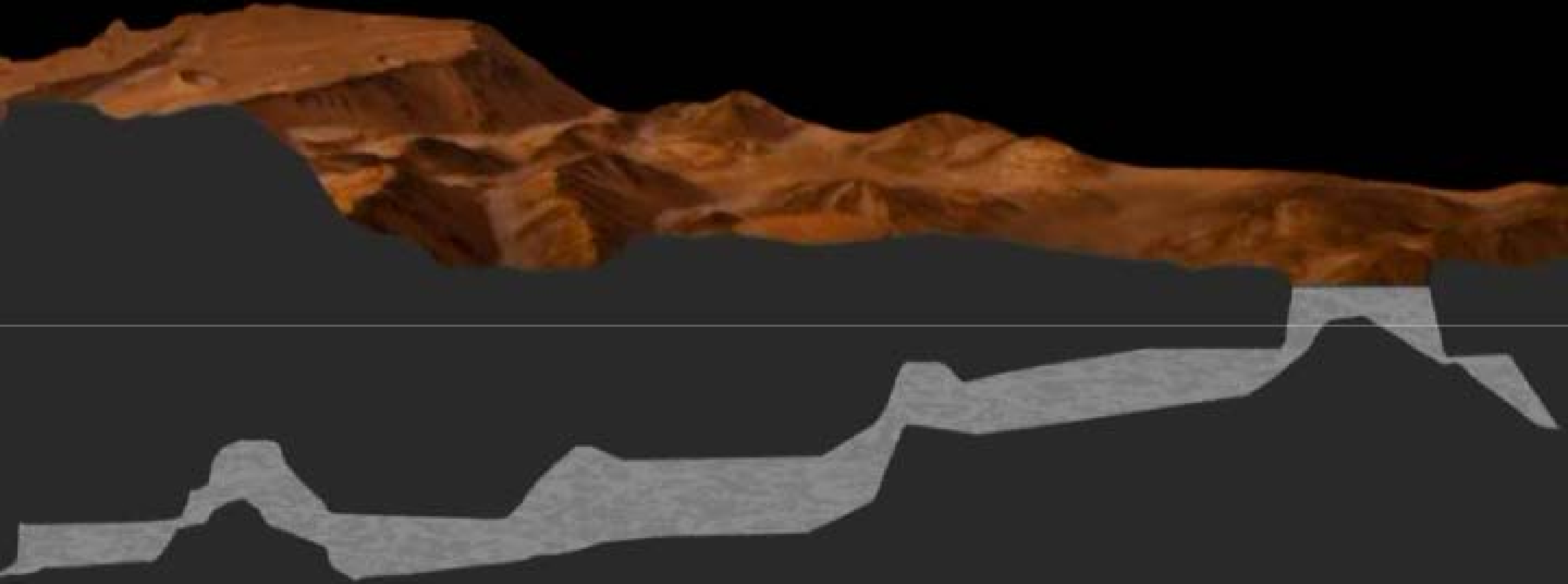
3 jumps

Microbot movement inside a representative cave

Simulation of Hanns Cave, Australia

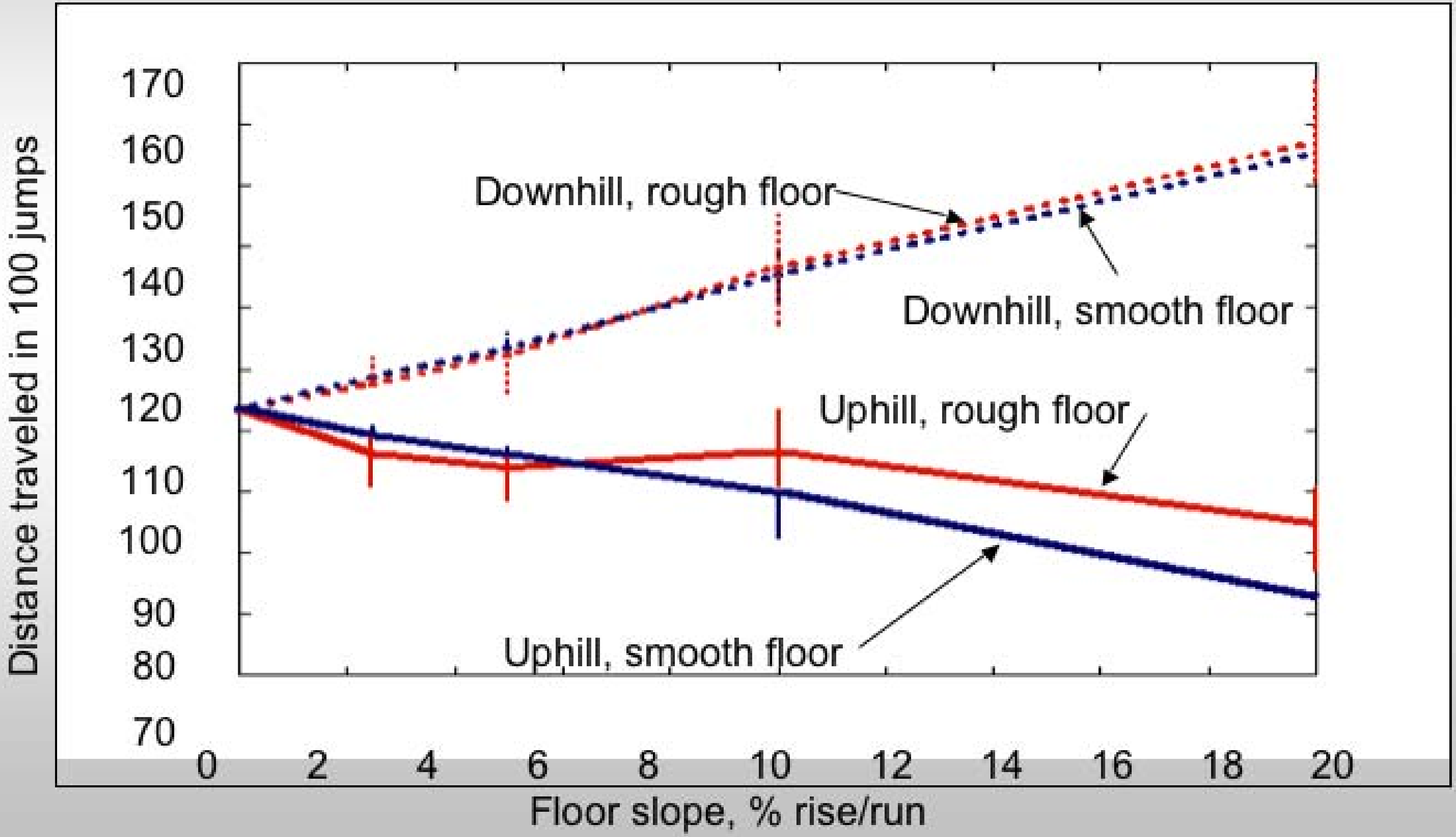
Cave Mobility





Cave Mobility Studies

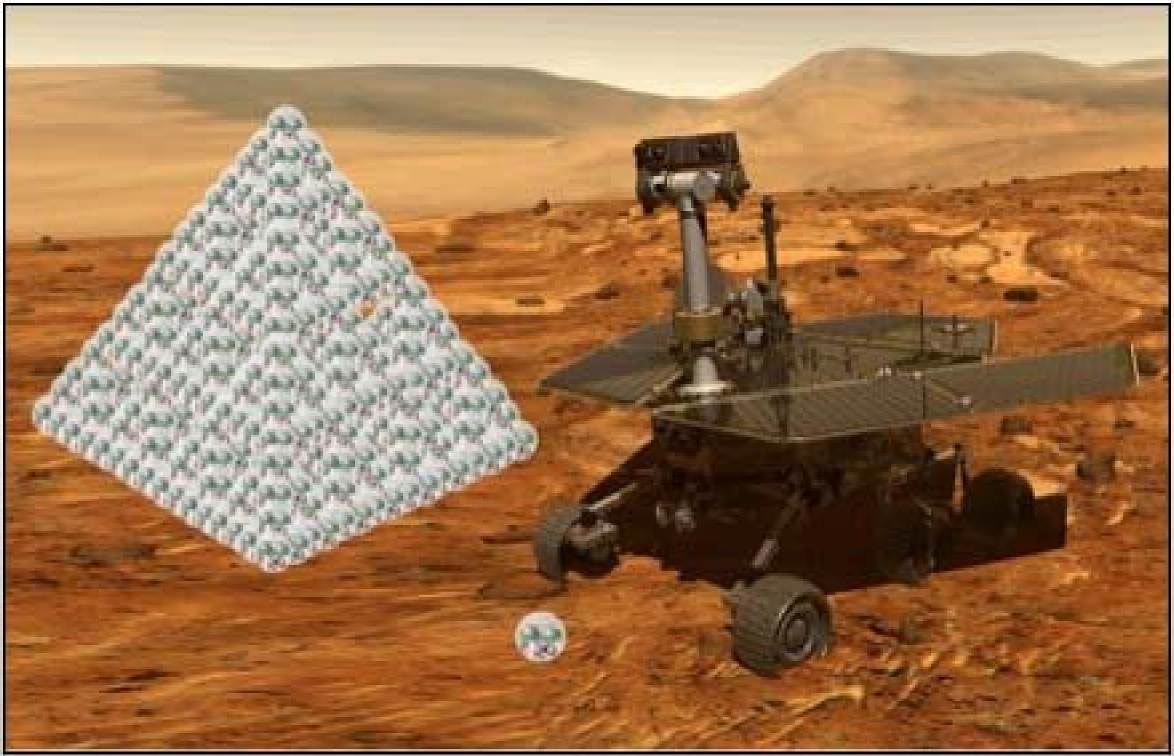
Effect of slope on microbot travel - Sandy cave floor



REMots - A New Paradigm for Exploration of the Bodies of the Solar System

ReMotes could provide the ability to:

- Explore Very Large Surface Areas
- Access complex subsurface topologies
- Traverse very rough terrain



…at comparable launch volume and mass to existing *linear single point* sampling strategies!

…and they could go where no robot has gone before.

Important Feasibility Questions Remain

Issues would be addressed in a Phase II Study

- The effects of extreme environments (Professor John Lienhard (MIT and Mr.. Burg (ETH)
- Design and control concepts for mobility in rough terrain -- resistance to entrapment.
- The investigation sensor suites for maximum science return.
- Command, control and communications concepts for microbot teams
- The fundamental limitations of microbot scaling - the performance of very small sensors, actuators, fuel cells, etc.
- Comparison projected performance of microbot mission to conventional rovers (MSL 2009 mission baseline)
- Laboratory and field demonstrations of key technologies
  - Oct 2006
  - Oct 2006

REMots: *A* new design paradigm for the exploration of the planets, the moons and other bodies of the Solar System.

Our Team

MEMBERS OF THE FSRL

Penny

Fritz