Mobile Robotic Explorers: Roving Throughout the Solar System

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UTC Institute for Advanced Systems Engineering
Seminar Series

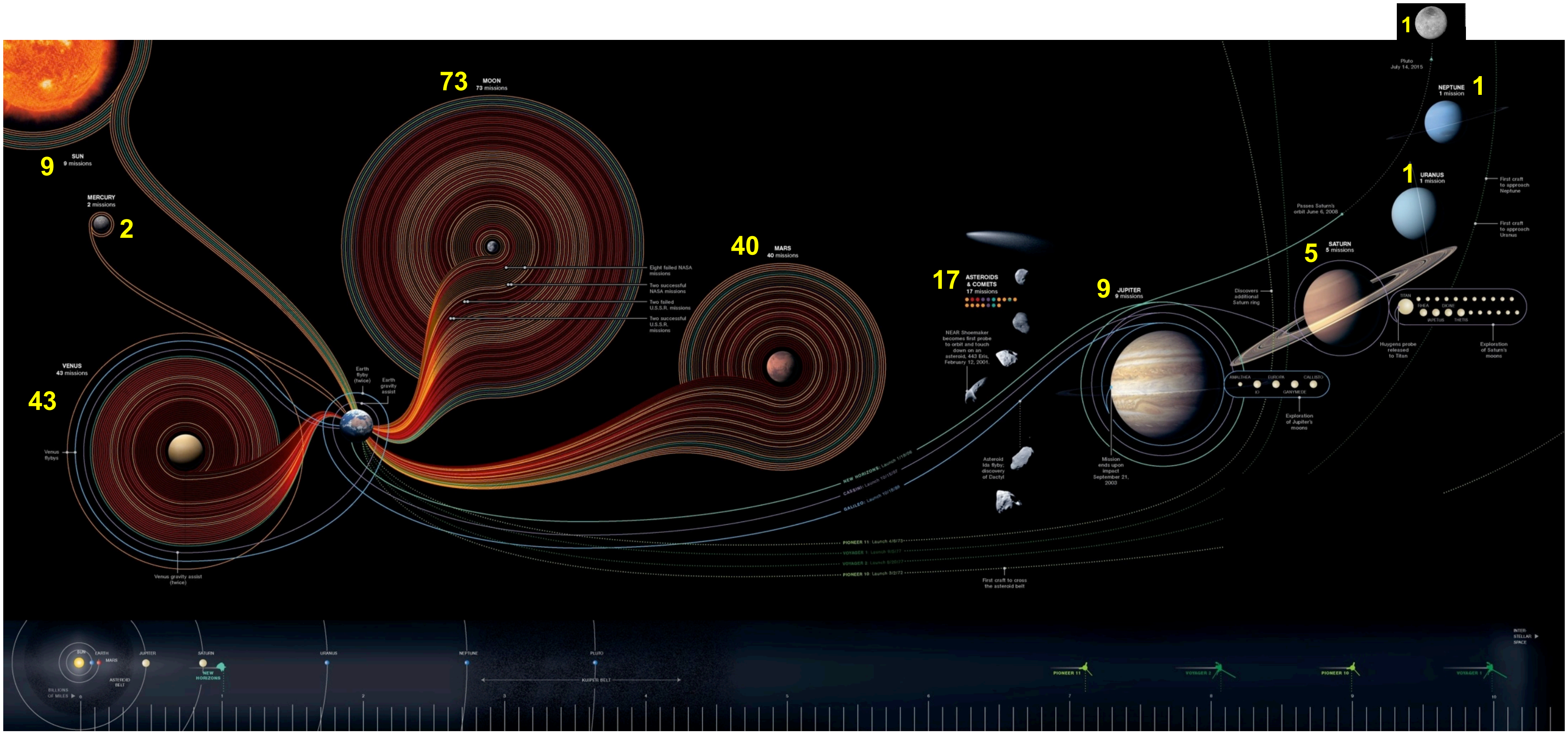
University of Connecticut
School of Engineering

23 April 2018

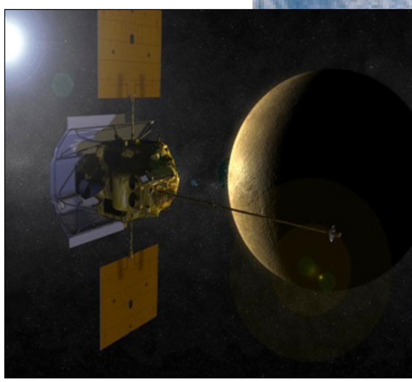
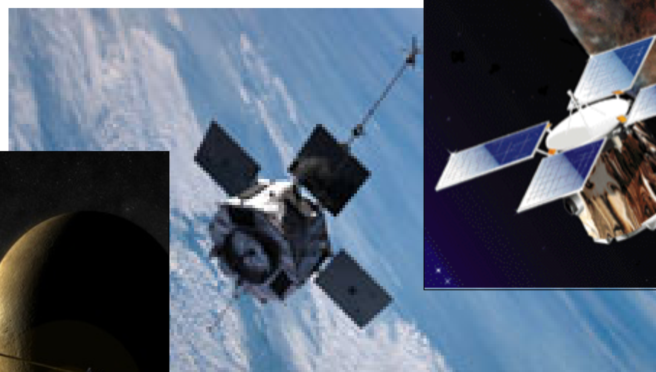
Outline

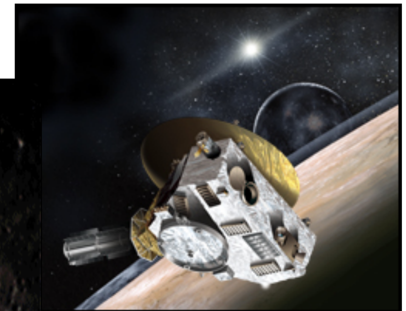
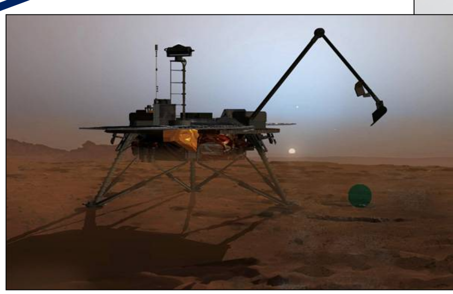
- Current technology / state of the art
- Challenges & technologies for Mars, moon, asteroids, Mercury & Venus
- Technology & capability needs
- Q & A

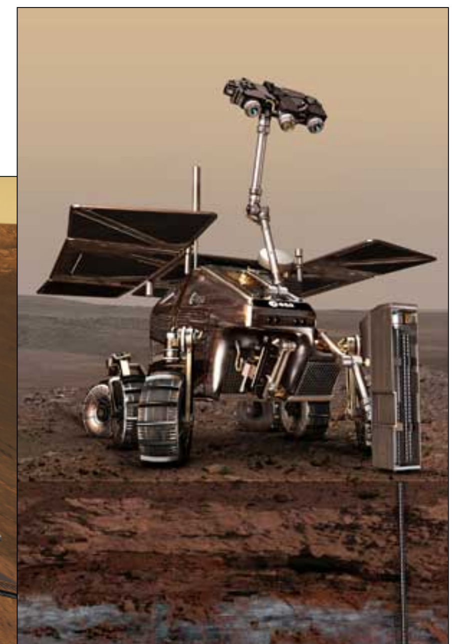
Deep Space Mission Flight Paths



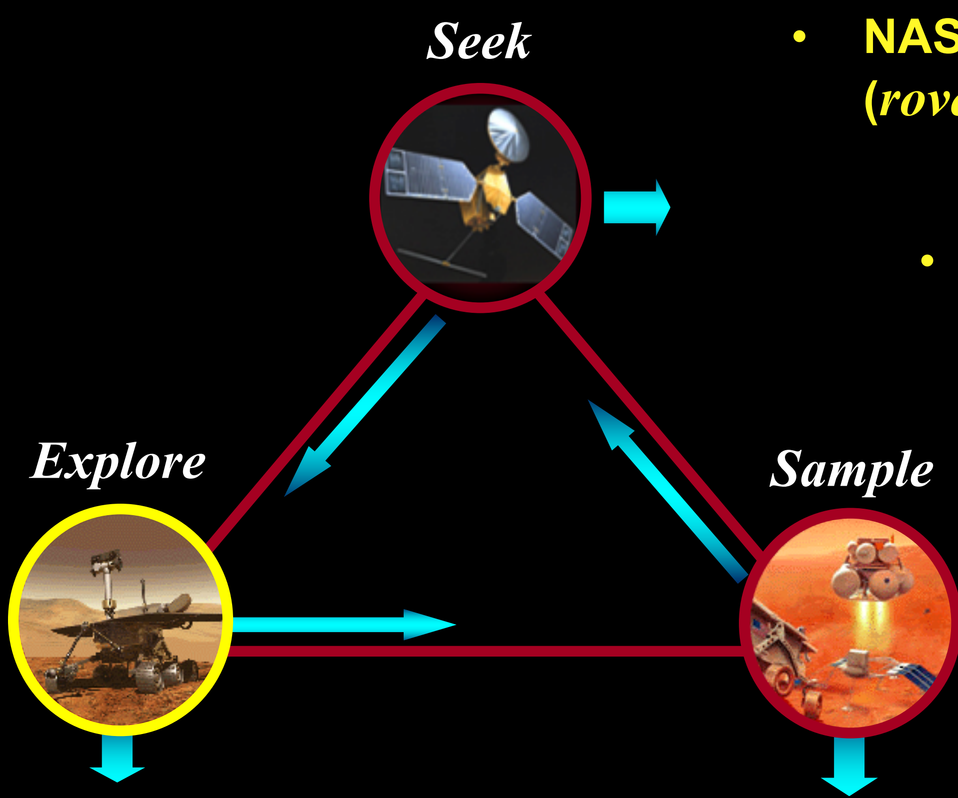
Robotic Spacecraft & Planetary Surface Robots
(Unmanned)

Planetary Surface Exploration



- NASA sends mobile robotic explorers (*rovers*) to explore the surface of Mars
    - Computerized rovers are effective tools for getting "up close and personal" with the Martian surface
        - Autonomous driving and operation of onboard science instruments enables rovers to act as ***robotic geologists***.

Planetary Surface Robotics

- Development of robots capable of performing tasks in extreme planetary surface environments
- Example Tasks: exploration, inspection, servicing/maintenance, astronaut assistance, assembly/construction, etc
- Example Mission Capabilities
  - Science instrument delivery to multiple, disparate surface locations
  - Large area coverage over benign to extreme/hard-to-access terrain
  - Physical sample acquisition, dexterous handling/processing, return
  - Utility work supporting human exploration or habitat preparation
- Controlled directly via teleoperation or remotely across substantial distance and communications time-delay via semi-autonomous control

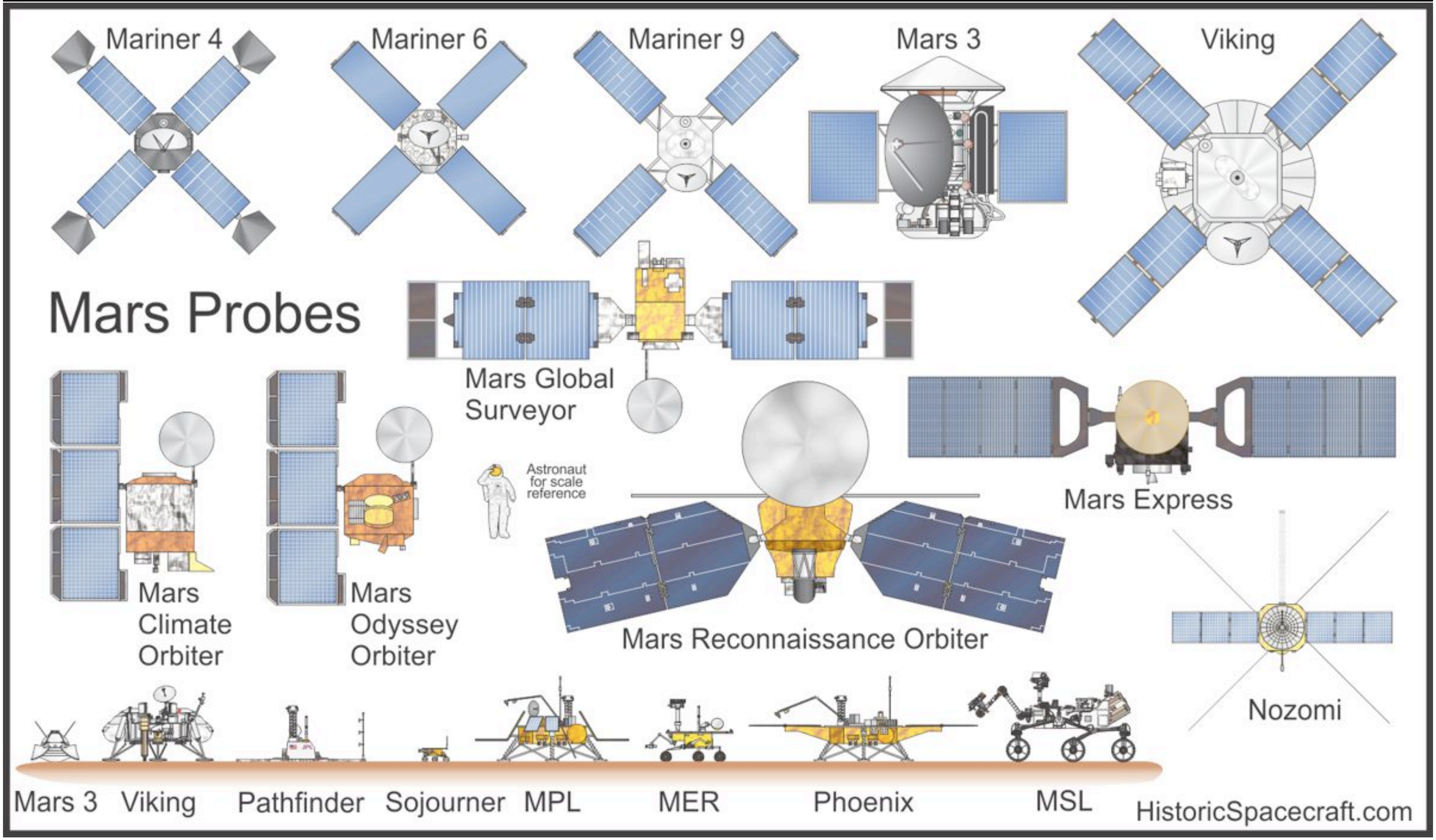
Key Capabilities

- **Mobility**
- **Manipulation**
- **Environment survivability**
- **Time-delay accommodation**

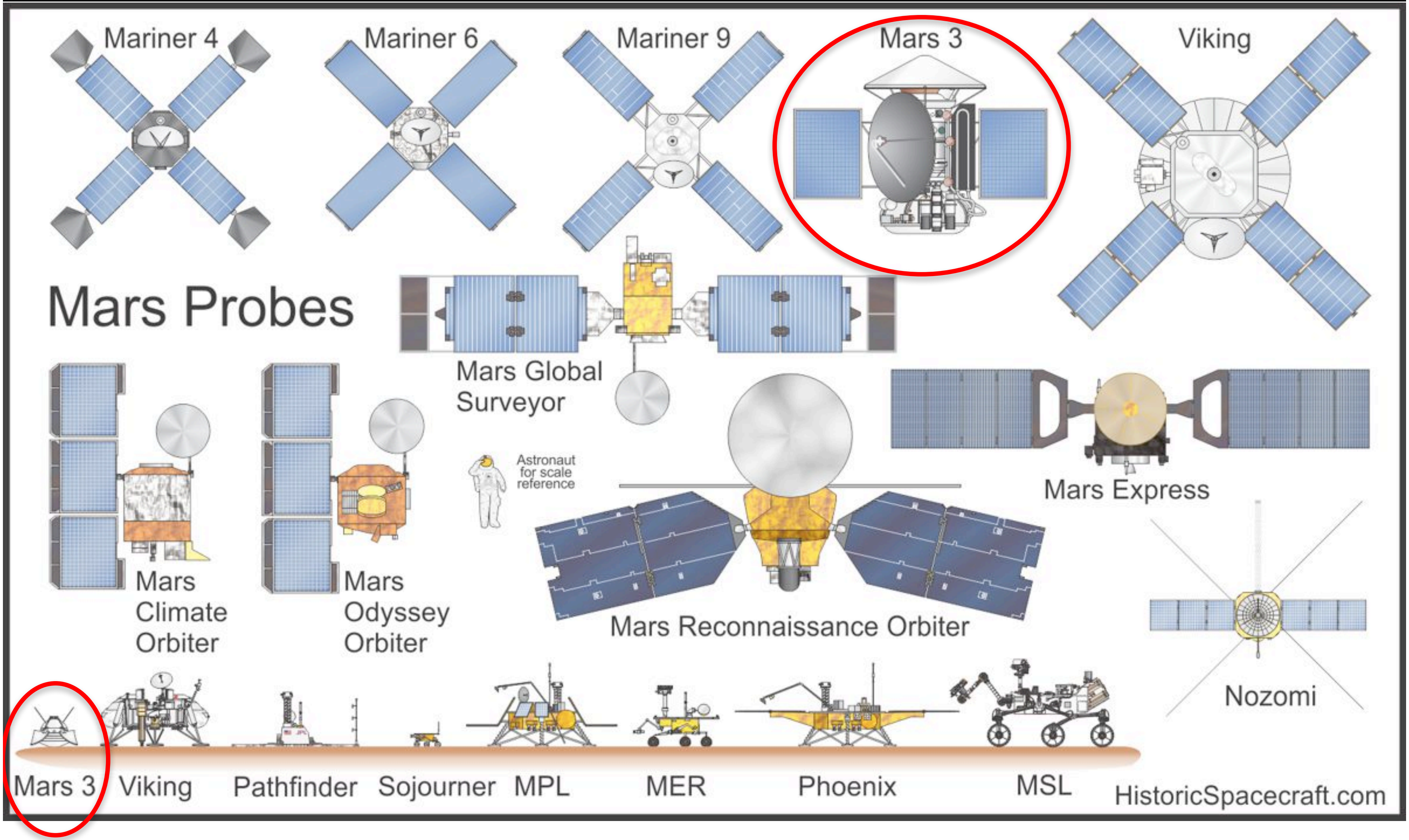
(*with many supporting technologies*)

- **Mission-driven desired capabilities**
  - **Science instrument delivery to multiple, disparate surface locations**
  - **Large area coverage over benign to extreme/hard-to-access terrain**
  - **Physical sample acquisition, dexterous handling/processing, return**
  - **Maximum capability or functionality as systems degrade over the course of long duration missions**

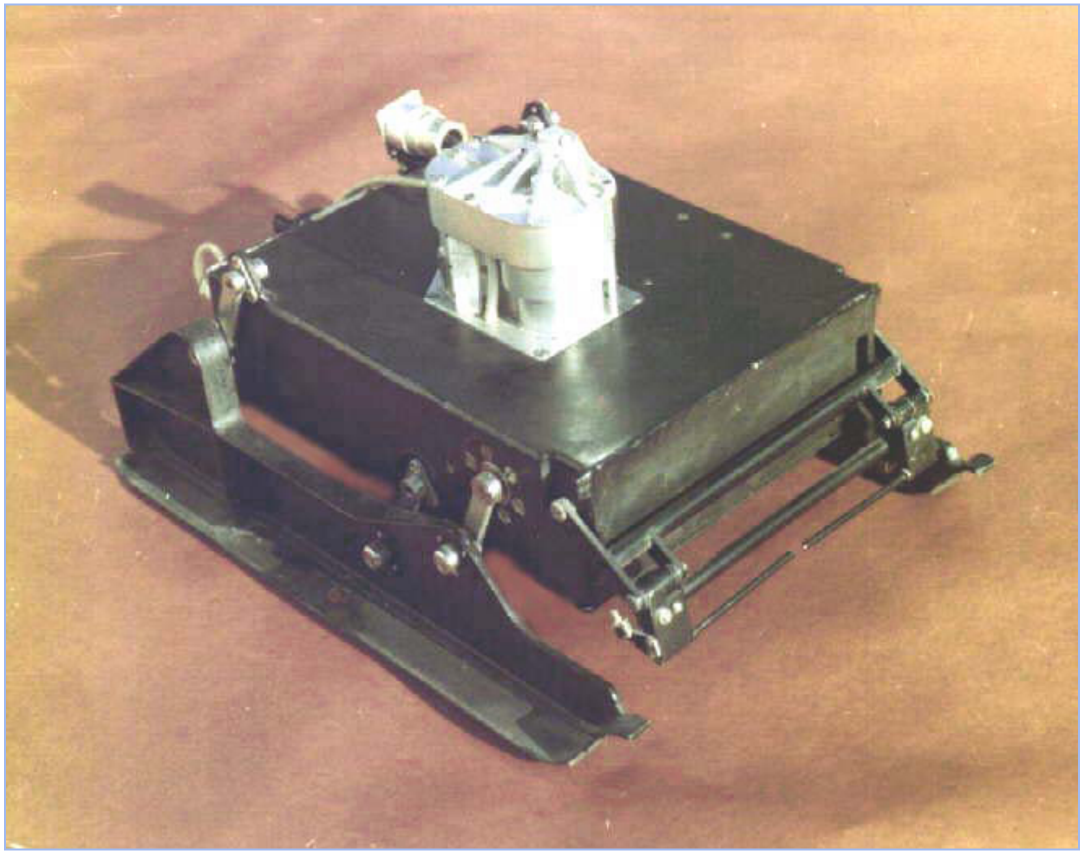
Mars probes: transition to surface



Mars probes: transition to surface

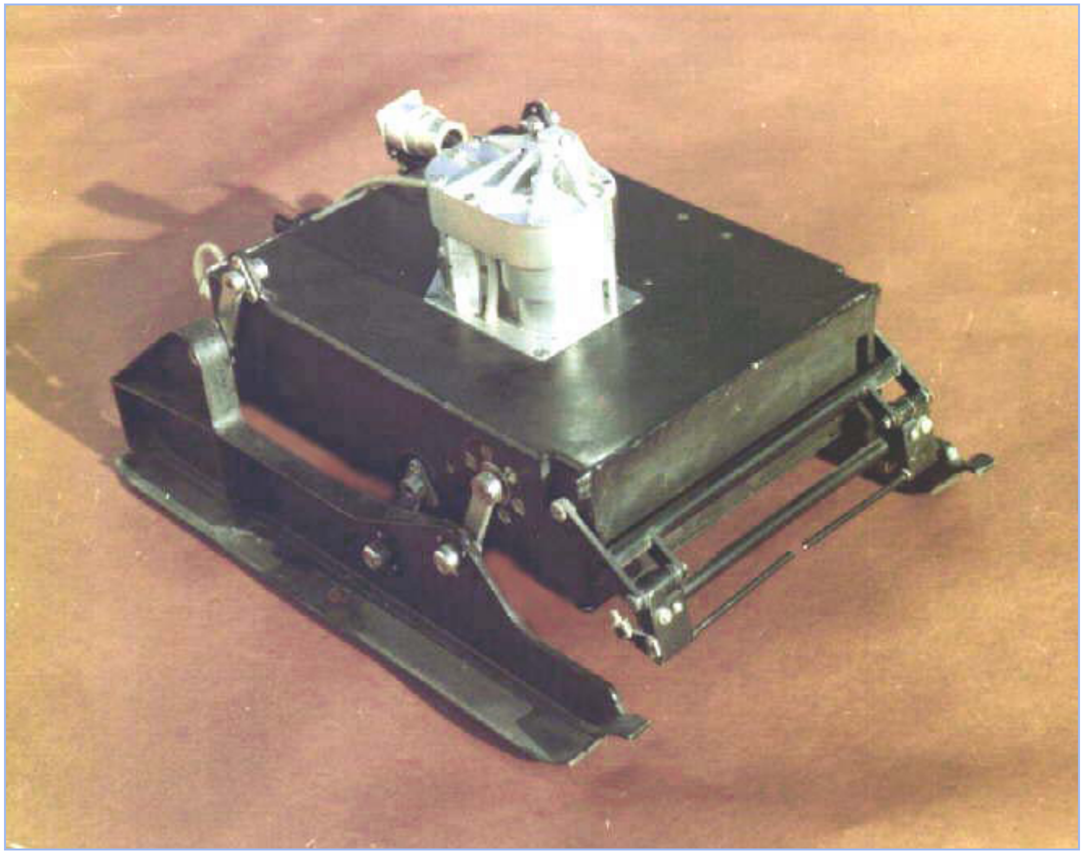


Recognize this?



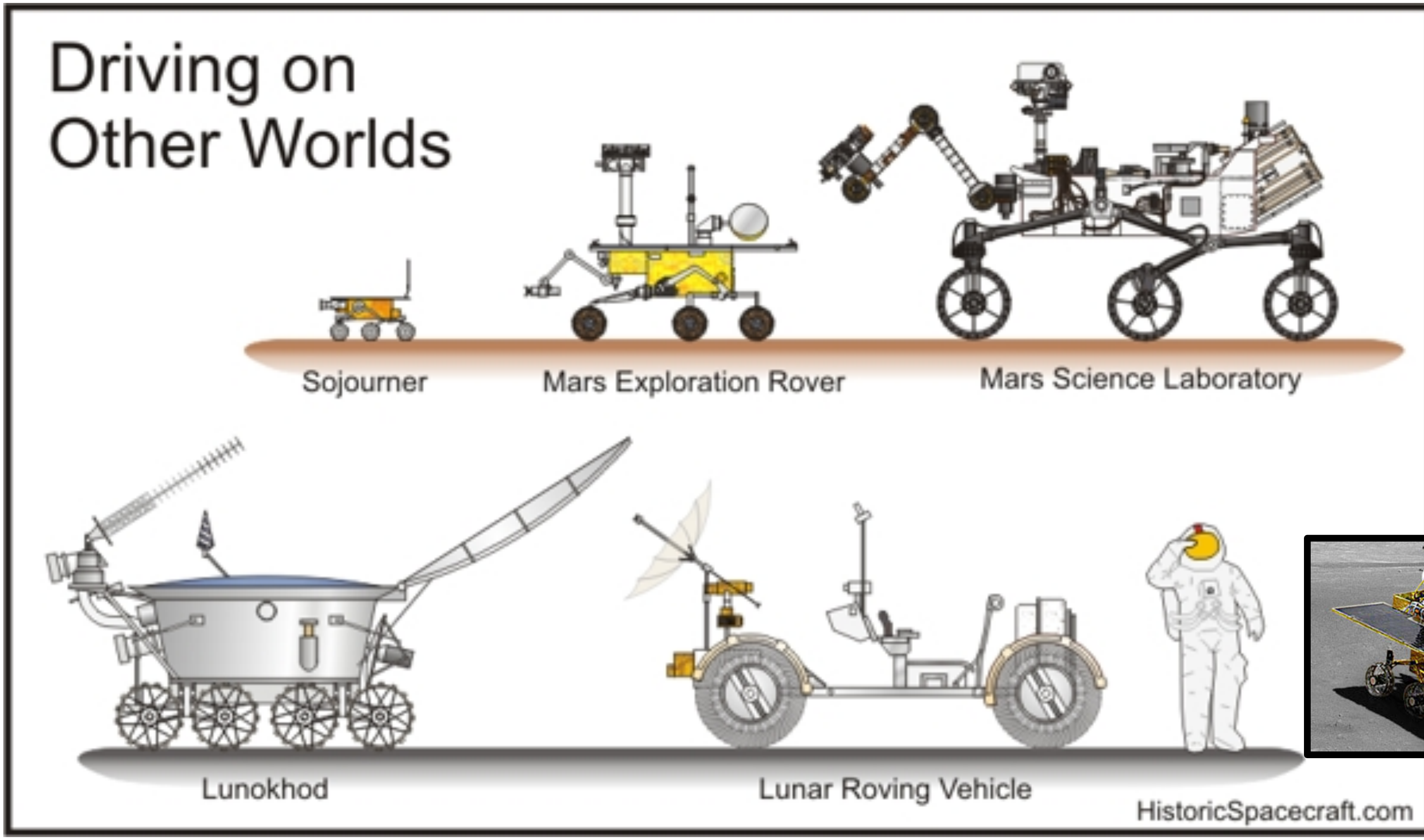
PrOP-M Rover (early 1970s)

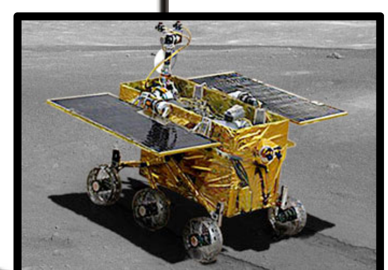
Soviet Russia's rover on ill-fated Mars 2 and Mars 3 landers



- **15-meter umbilical tether**
- **tactile obstacle avoidance bumpers**
- **soil densitometer and penetrometer**

All rovers operated on planetary surfaces to date





Mars surface exploration

NASA Mars Exploration Rover (Spirit)

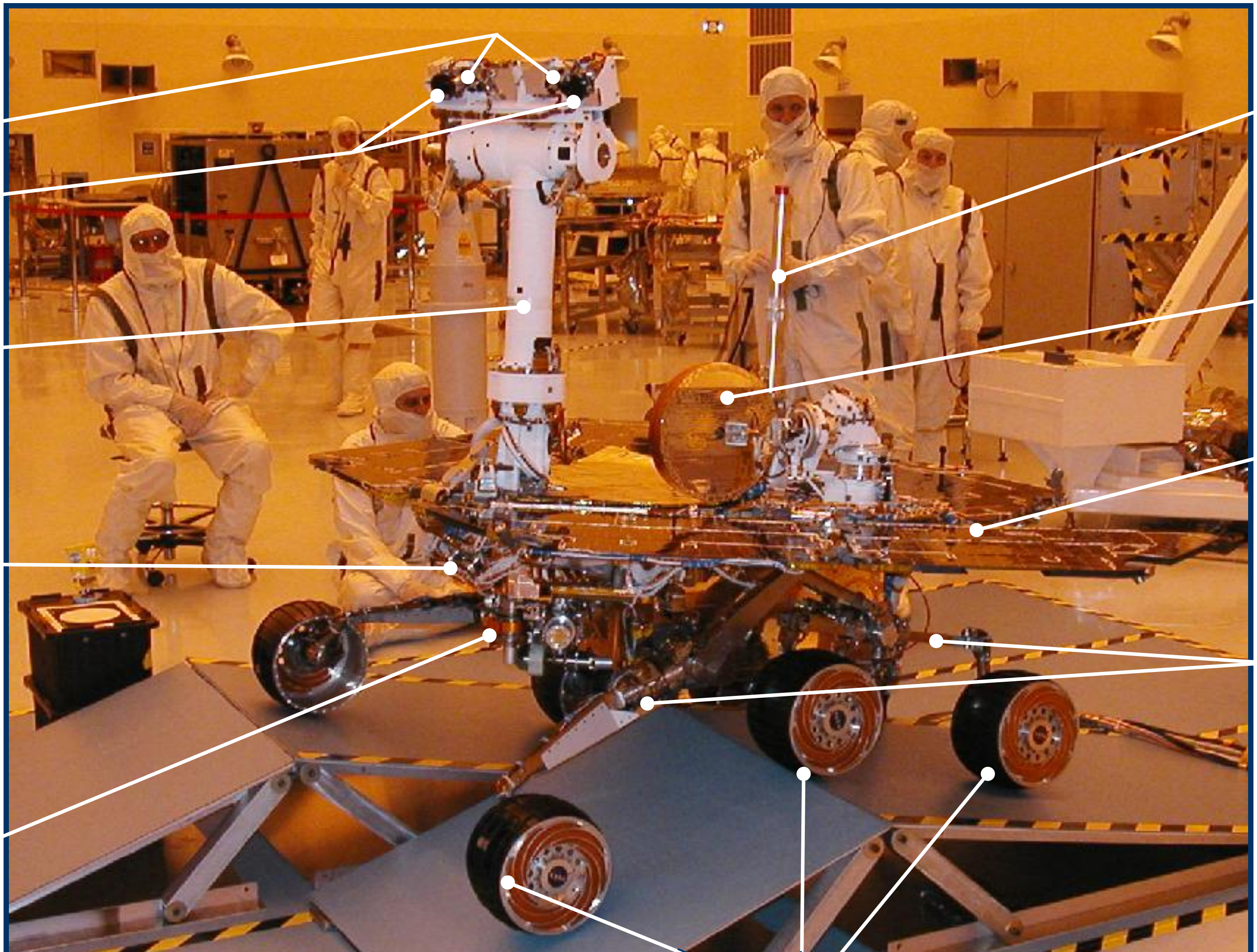
Navigation Cameras

Panoramic Cameras

Mast

Front Hazard Cameras

Robotic Arm (stowed)



Low gain Antenna

High Gain Antenna

Solar Arrays

Rocker-Bogie Mobility Suspension

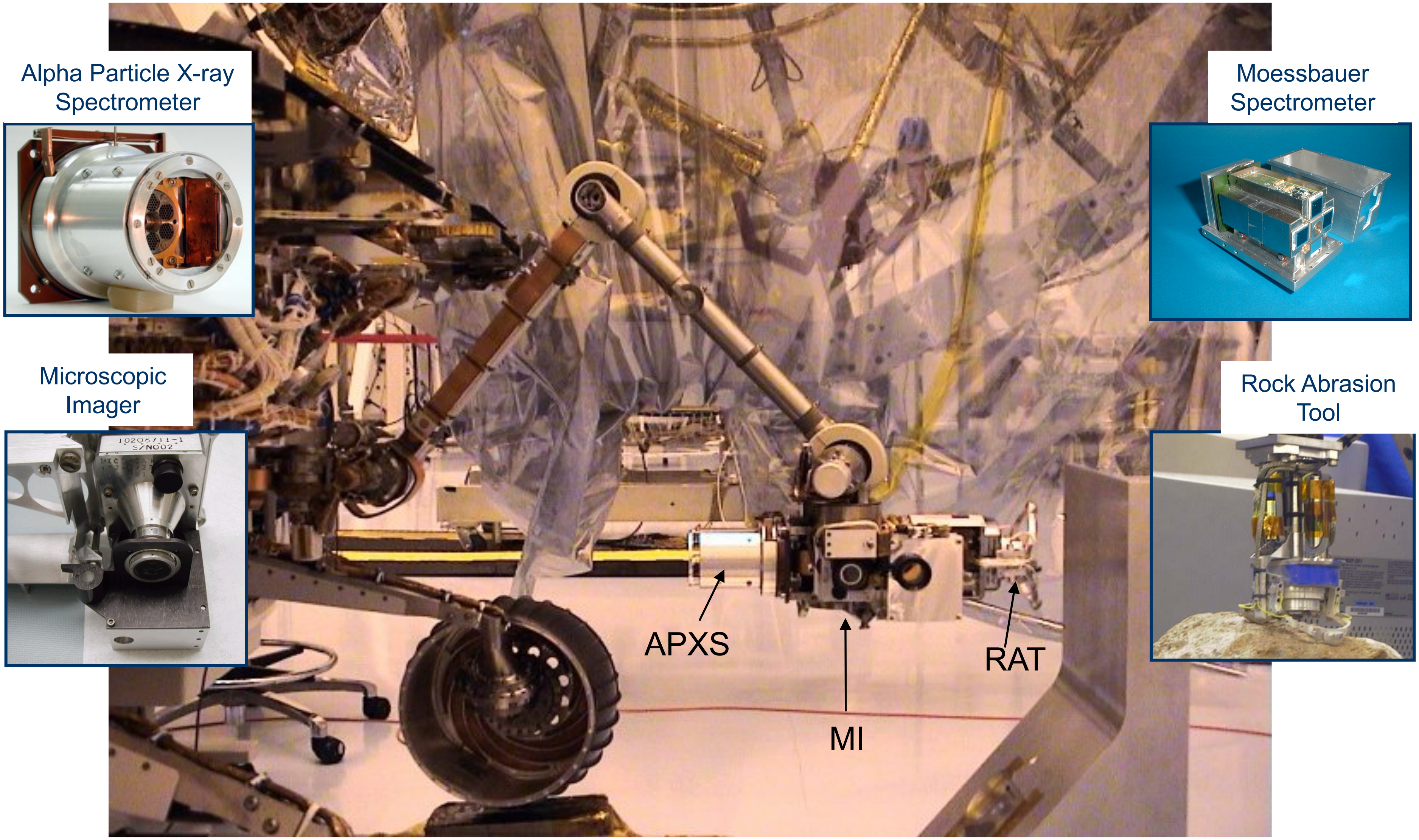
6 *Wheels*

- Weight = 179 kg (~ 395 pounds) [on Earth]
- Height = 1.54 m (~ 5 feet) from ground to “eye” level on top of mast

Arm-mounted Science (geology) Instruments

Alpha Particle X-ray Spectrometer

Microscopic Imager

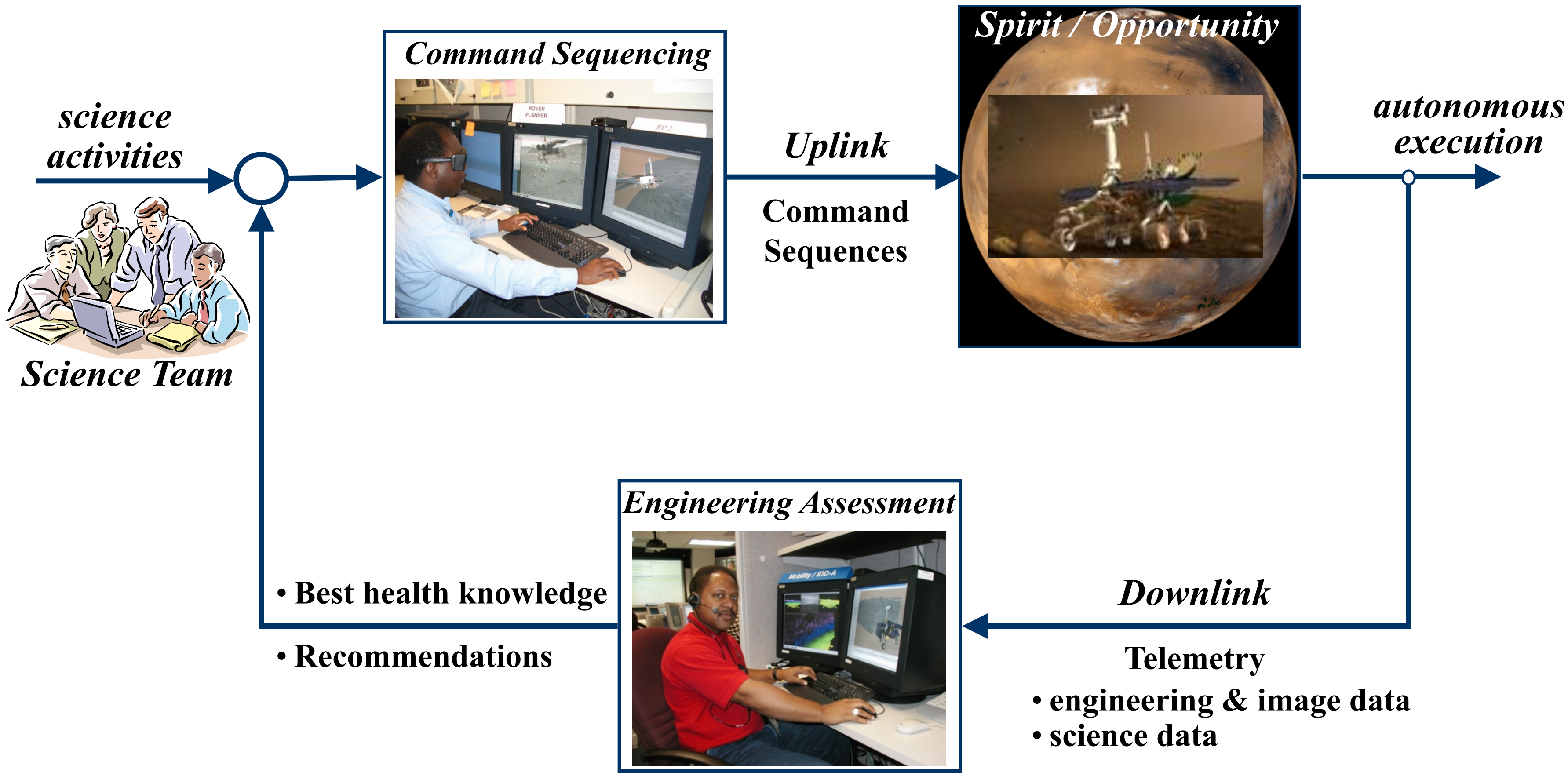


Moessbauer Spectrometer

Rock Abrasion Tool

Video available at: https://www.youtube.com/watch?v=-_9BYSDtwRc

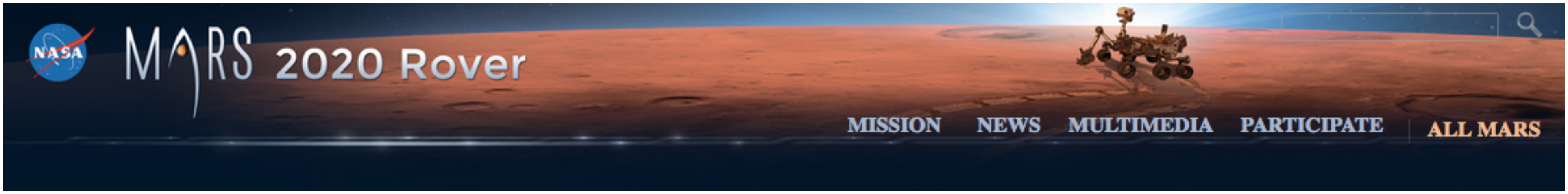
Semi-autonomous operations from Earth



<u>Intelligence and Autonomy</u>

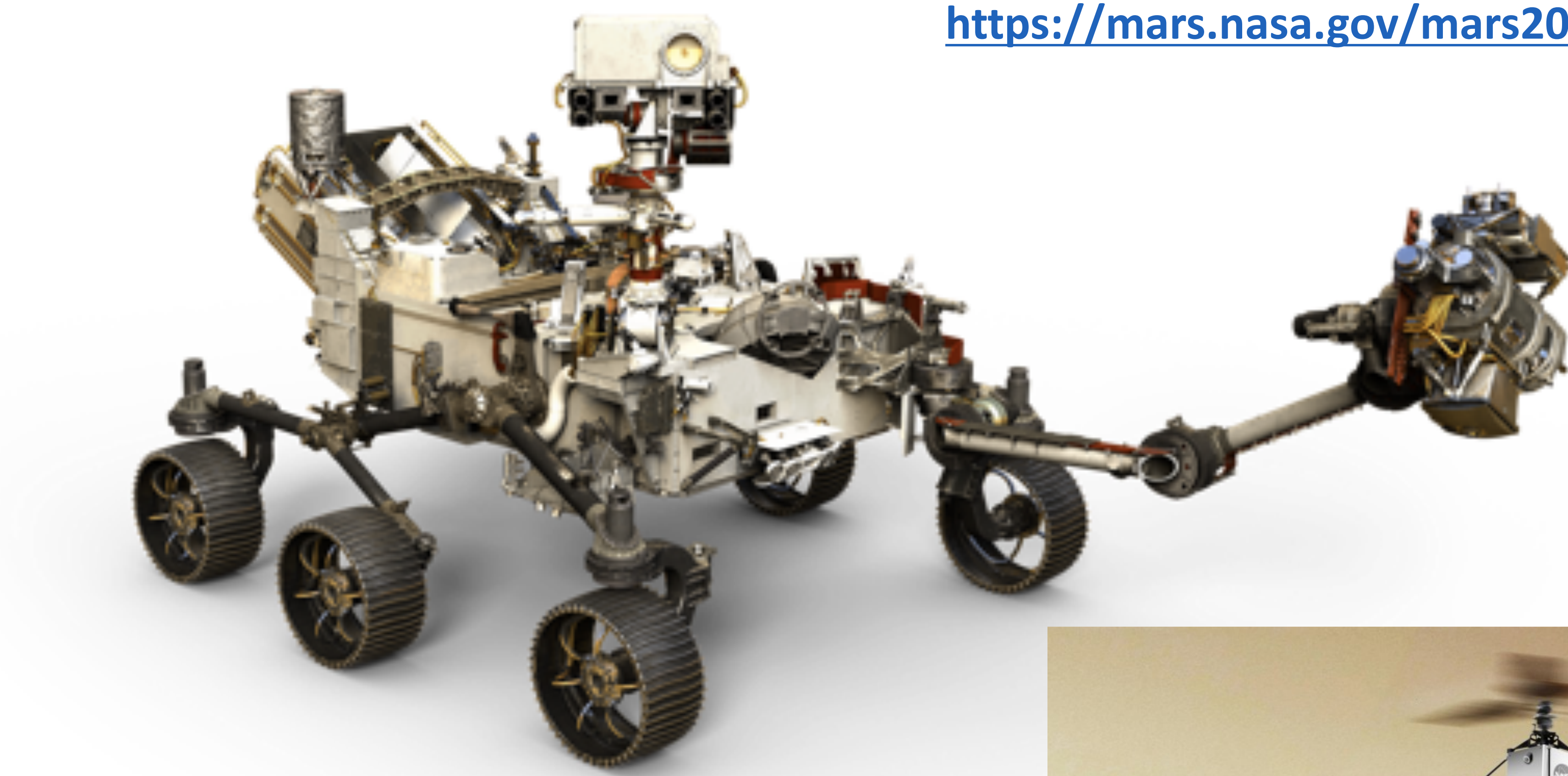
- *Mission intelligence (science/exploration) is largely human while remote autonomy is necessarily robotic*
- *Sequencing and analysis teams plan and assess robotic activities using their perception of the rover surroundings and knowledge of rover state and behavior*

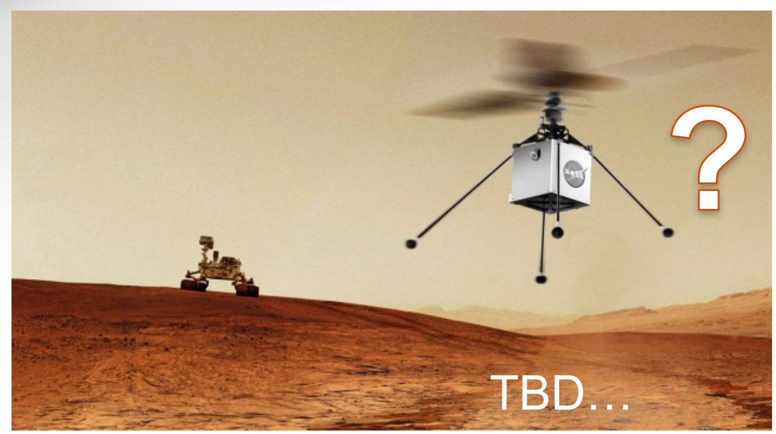
- Less frequent commanding
- Sample acquisition & onboard processing
- Already found evidence of ancient environmental conditions favorable for microbial life.



Next up…

https://mars.nasa.gov/mars2020/



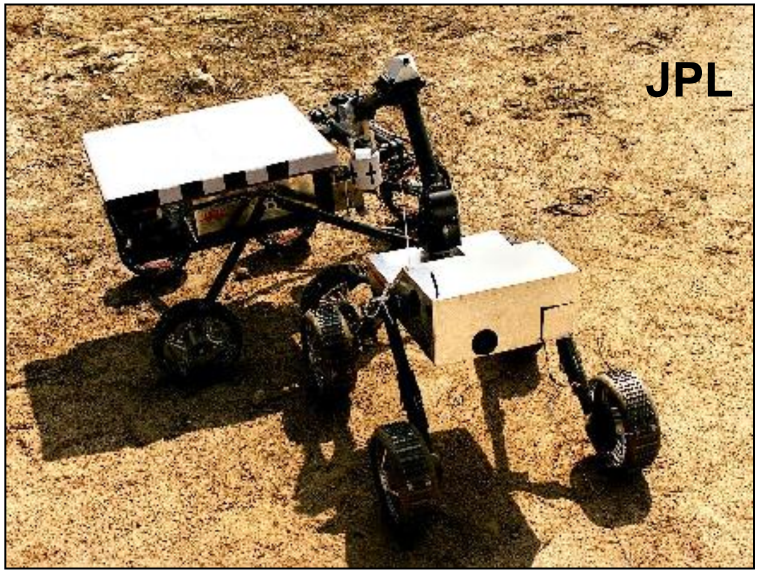


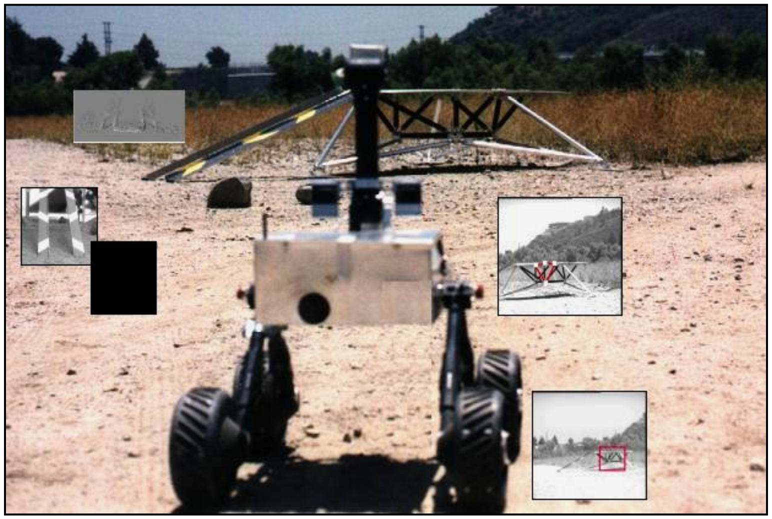
Mars Sample Return

- **Surface robotics capabilities**
  - Sample acquisition & handling
  - Sample fetch & retrieval
  - Lander detection & rendezvous

- **Mobility & manipulation capability mature for *sample caching* and *fetch rovers***
  - Prototype systems demonstrated in field as recently as a decade ago *

- **Mars 2020 rover is representative of the sample-caching rover in Mars sample return mission concepts**





* Schenker, Huntsberger, Pirjanian, Baumgartner and Tunstel, "Planetary Rover Developments Supporting Mars Exploration, Sample Return and Future Human-Robotic Colonization," *Autonomous Robots*, Vol. 14, 2003.

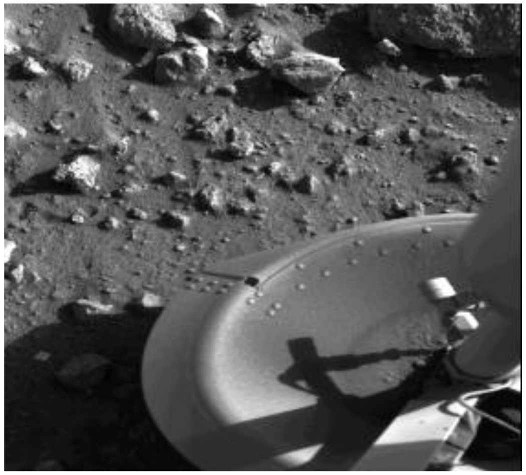
Lunar surface exploration

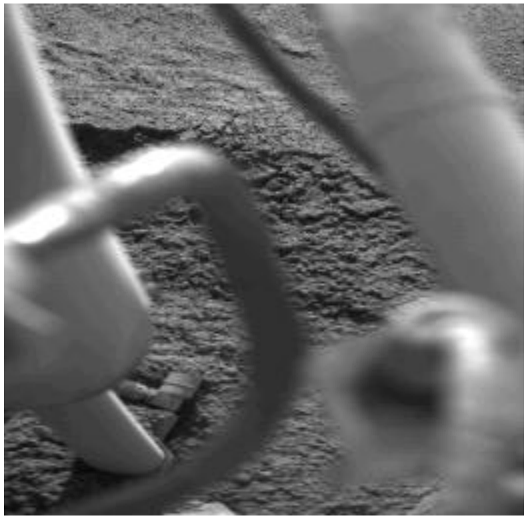
Perception for "Night" Driving

- *Sojourner*, used laser stripe projection – in principle could operate in darkness
- *Spirit* & *Opportunity* and *Curiosity* use passive stereo vision perception presuming sunlight
- Night driving using flash and other LIDARs has been studied for Lunar polar navigation and for Mars – key issues are:
  - flash illumination synchronized with camera shutters
  - overexposed near field, underexposed far field
  - small or zero phase-angle between illumination source and camera (no shadows, poor contrast, little shape-from-shading)
- Suitable compact LIDARs are under development

Sinkage/Slippage Terrain Hazards

- Mars Viking Lander 1 (1970's) found dune-fields, and one of its footpads sunk 17 cm into drift material.
- First image from Mars showed footpad #1 on firm surface.
- Later mage taken of footpad #3 generated serious concern.
- The consistency of the drift material was such that it flowed almost like a fluid around the footpad.

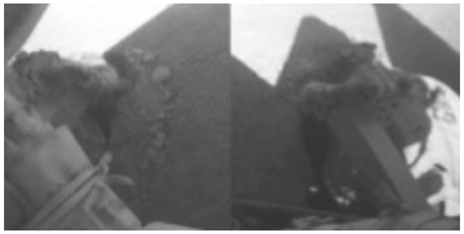




- Apollo Lunar Rover driving in dusty lunar terrain

- Mars Pathfinder rover, *Sojourner*, found similar dunes...

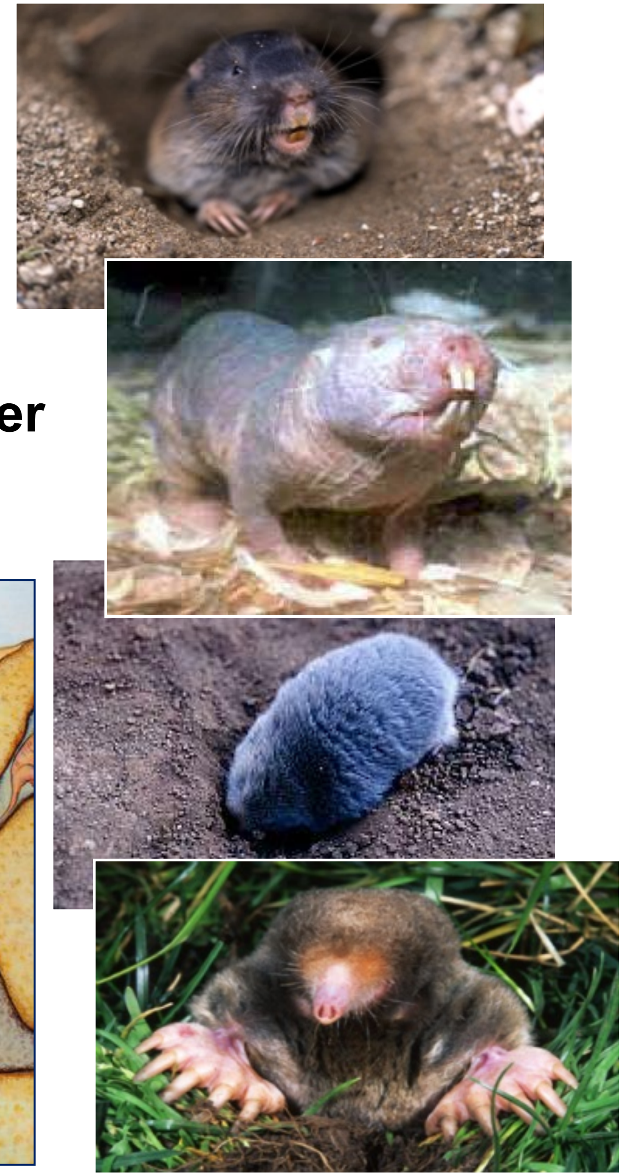
- MER rover, *Opportunity*, encountered similar...

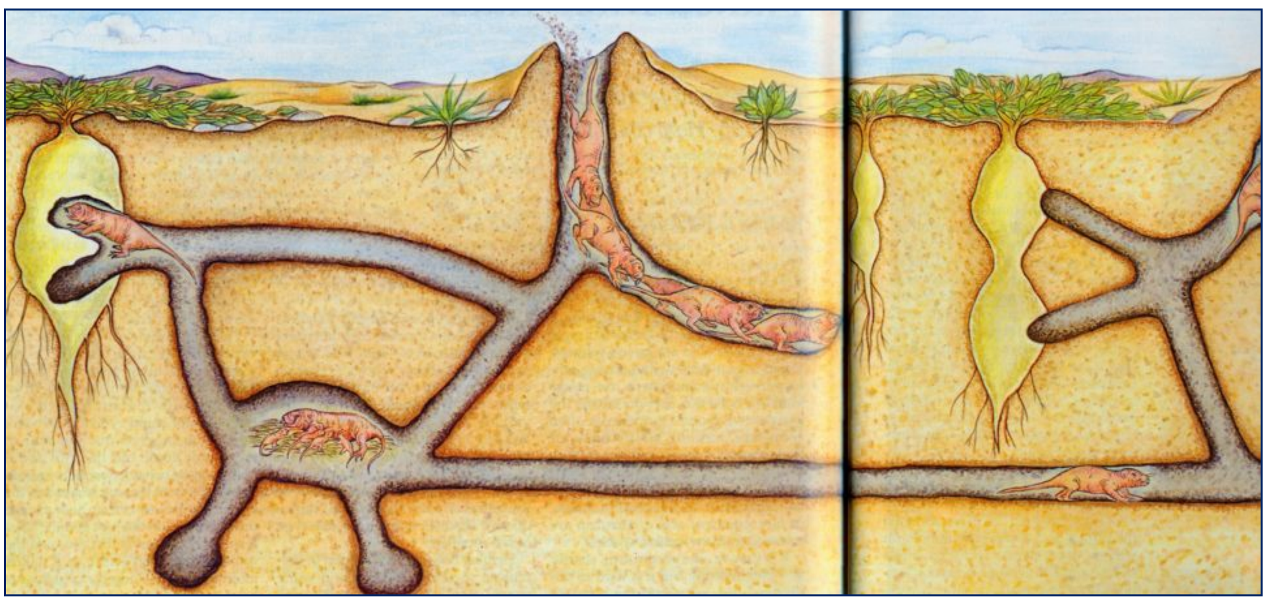


Moon and Mars

Planetary subsurface access

- **High priority science measurements and resources are likely found underground**
- **Nature offers examples of small animals that efficiently burrow underground and create tunnel networks.**
- **Can we mimic nature in this sense, to engineer burrowing robots that are more agile than traditional drilling concepts?**

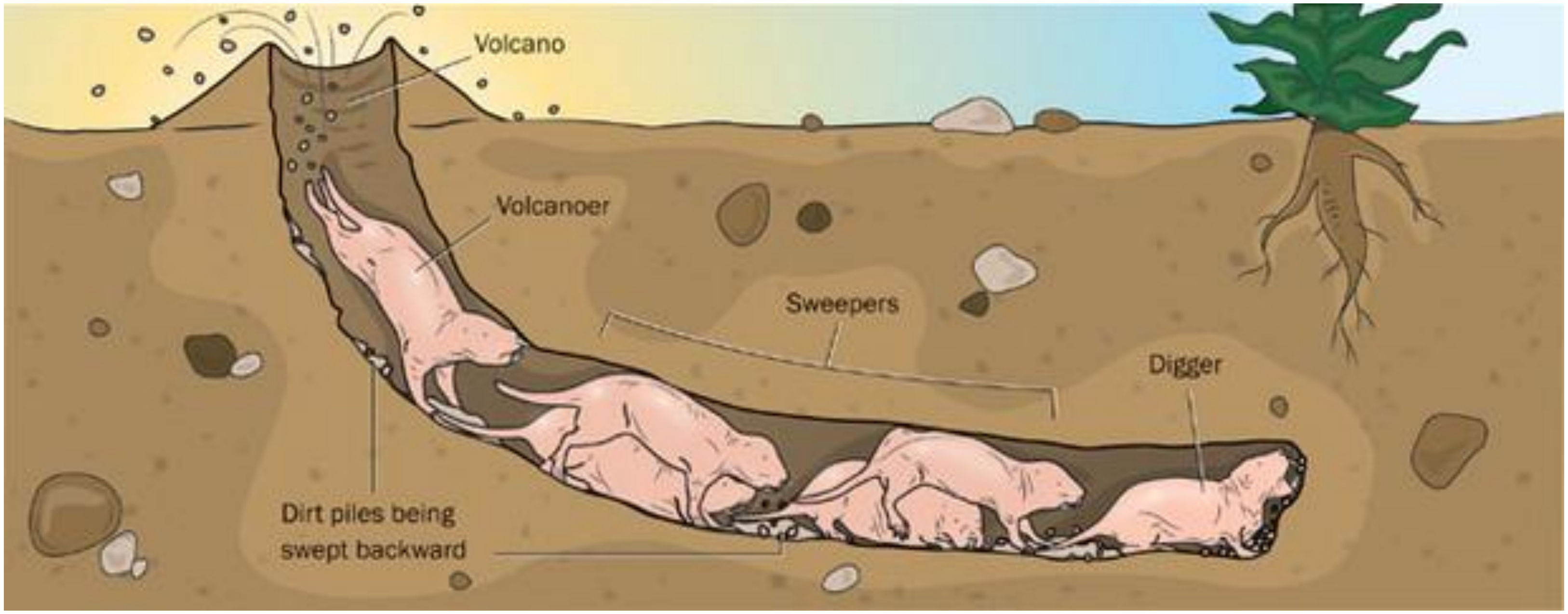




E. Tunstel

BurrowBot Concept

- **Goal: build an operational prototype capable of digging itself into and burrowing beneath soil.**
- **Challenged JHU engineering students to design a robotic device that can mechanically effect soil environments in a manner similar to burrowing animals … more work required.**



JHU ME Students 2010

D. Bagdorf

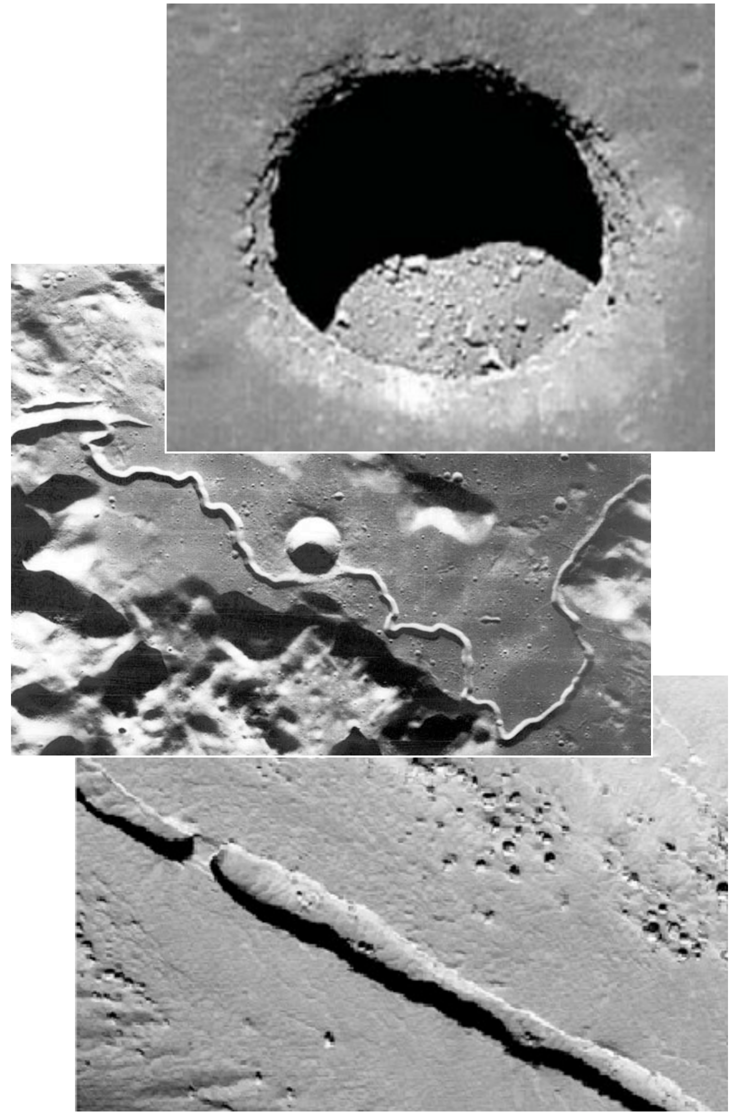
B. Hahn

R. Spatz

Sub-Planetary Access: Moon & Mars

- **Access to lava tubes via skylights**
- **Access to cave interior surfaces**
- **Candidate habitation for humans**
- **Harbors for life or water signatures**
- **Windows into a planet's history**
- **Major mobility, navigation, autonomy, and communications challenges**

(AMA Studios, for NASA GSFC, Dr. Steve Curtis, PI)



-G.E. Cushing, "Candidate cave entrances on Mars," *Journal of Cave and Karst Studies*, v. 74, no. 1, April 2012.
-W. Whittaker, Technologies Enabling Exploration of Skylights, Lava Tubes and Caves, NASA NIAC Phase I Final Report, 2012.

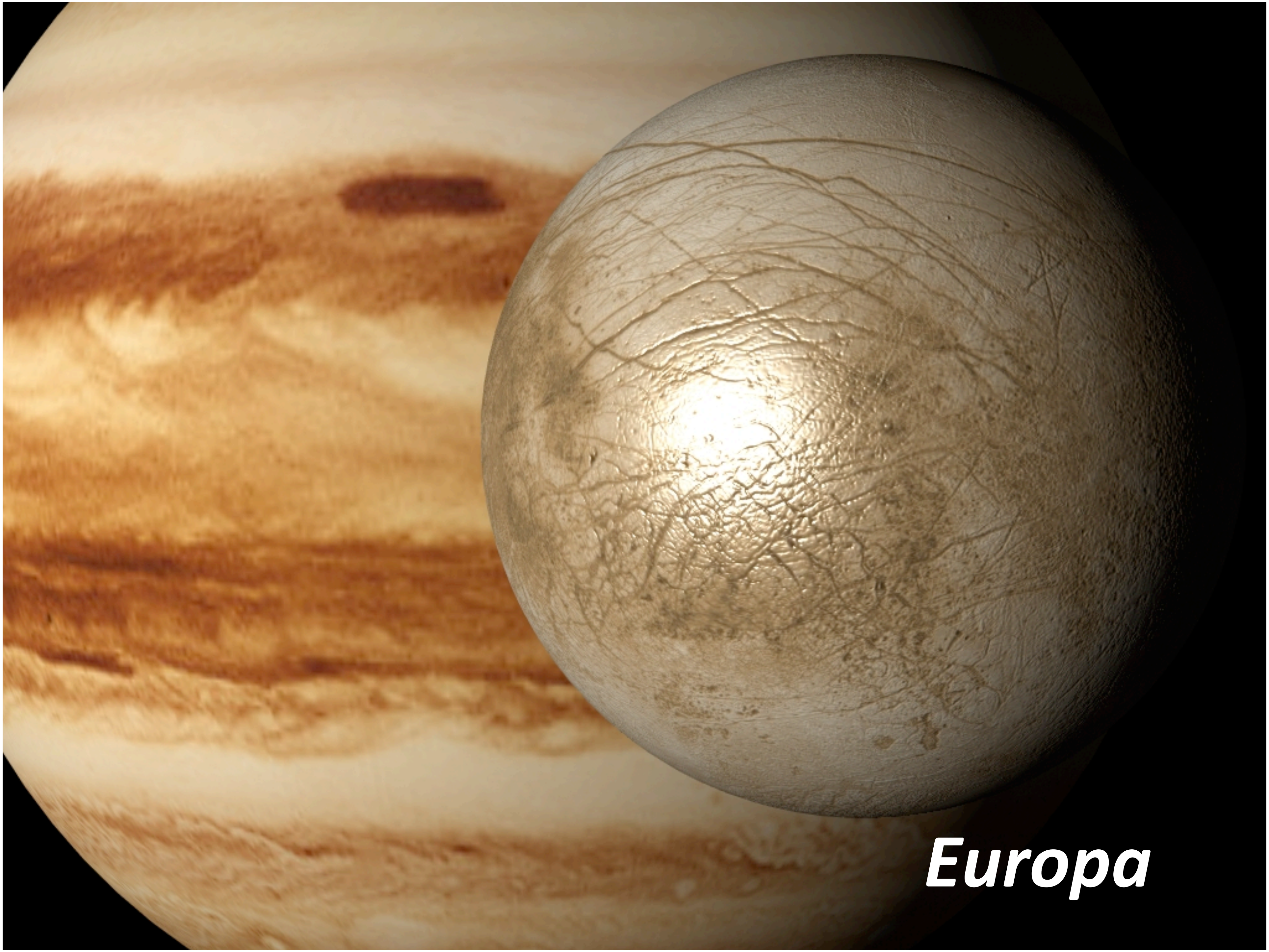
Telerobotics from planetary orbits

- **Dexterous manipulation by astronauts from afar**
- **Telepresence & haptics (sense of touch from robot to operator)**

Telerobotics from planetary orbits

Teleoperated surface sampling experiment over Delay-Tolerant Network (JHU/APL)

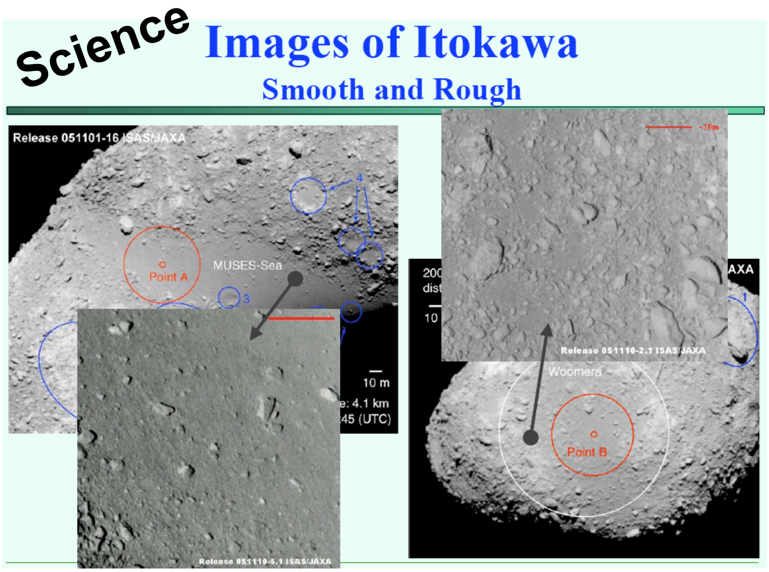
Video available at:
https://www.youtube.com/watch?v=pKwiBp5lmu0


Europa


Cryobot / Hydrobot
Concept
Challenges:
• Mobility
• Navigation
• Autonomy
• Communications

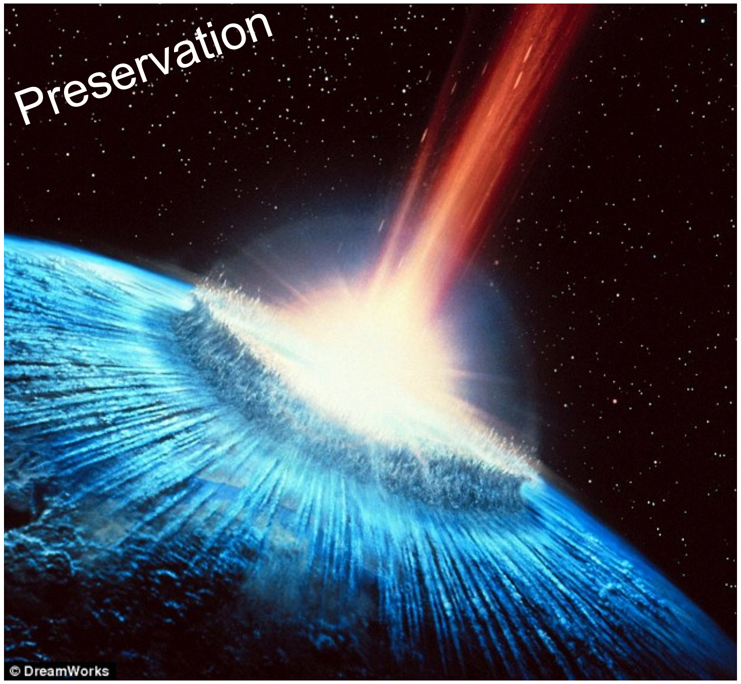
Asteroid & comet surface exploration

Asteroids


Science
Images of Itokawa
Smooth and Rough
Release 051101-16 ISAS/JAXA
Point A
MUSES-Sea
10 m
Release 051110-2.1 ISAS/JAXA
Woomera
Point B
Release 051110-5.1 ISAS/JAXA

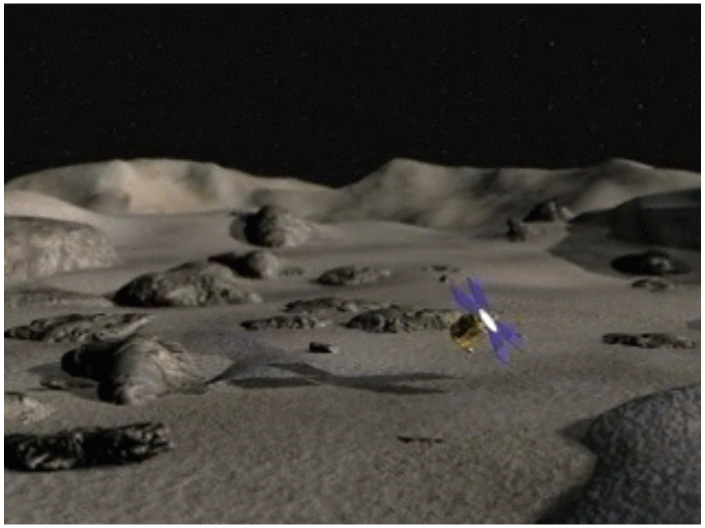

Exploration
Dan Durda
FIAAA

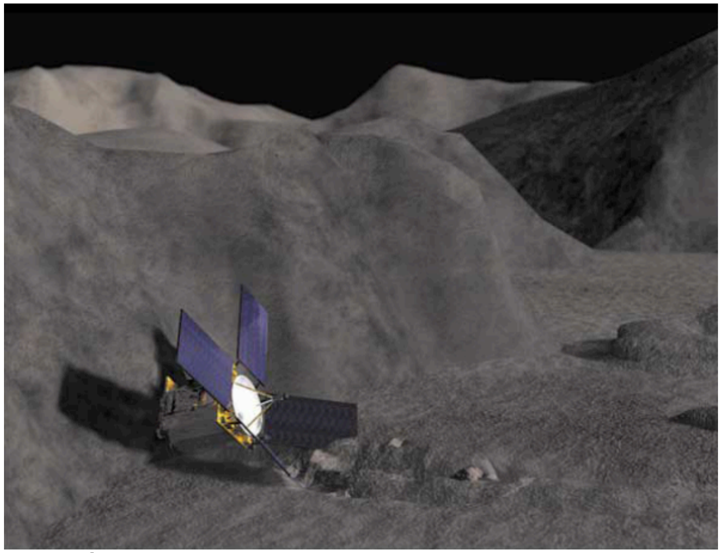

Resources


Preservation
© DreamWorks

Asteroid robotic systems

- Integral part of small body exploration campaign
  - Orbit/rendezvous → landing/ touch-and-go sampling → surface exploration (as precursor mission payloads and as astronaut leave-behinds)
- Opportunity to drive convergence of technology from different robotics application domains
- Focus is on local mobility in persistent contact with the surface in high priority science regions

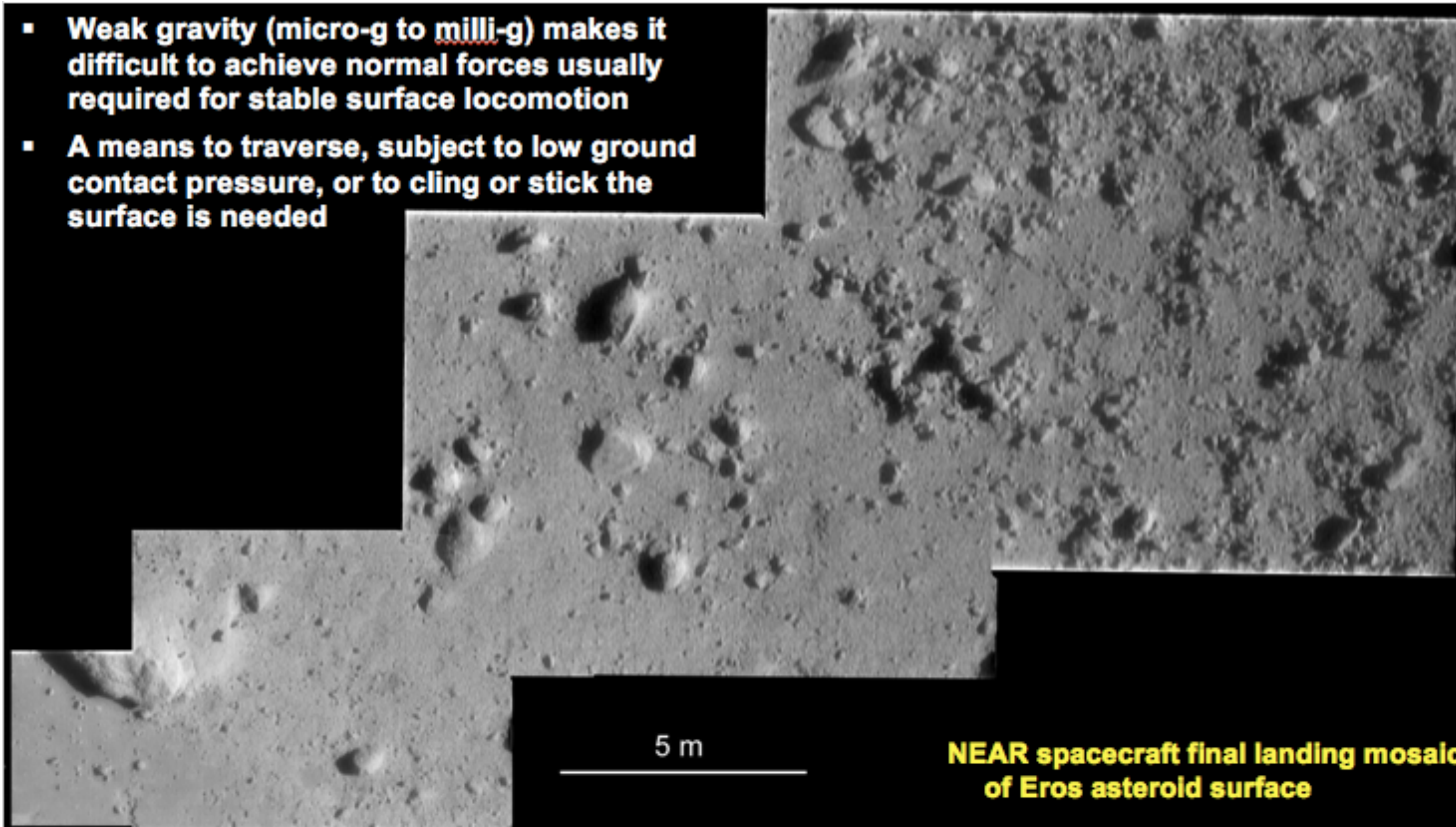




Artist's concept of NEAR Shoemaker on surface of Eros

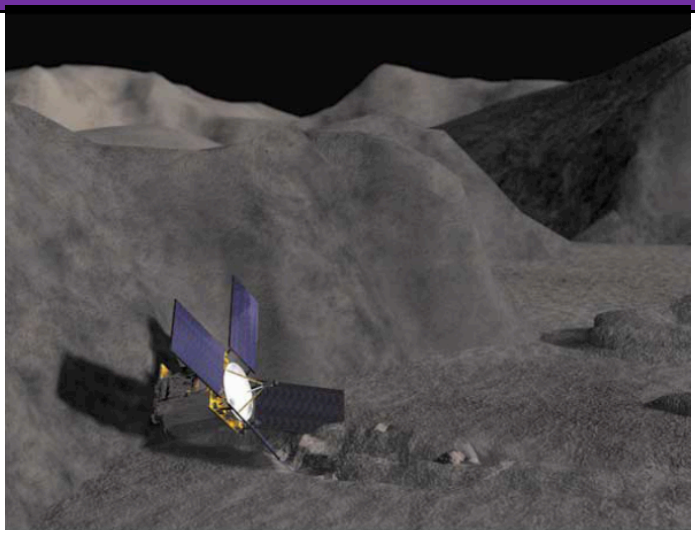
Surface characteristics

- Weak gravity (micro-g to milli-g) makes it difficult to achieve normal forces usually required for stable surface locomotion
- A means to traverse, subject to low ground contact pressure, or to cling or stick the surface is needed



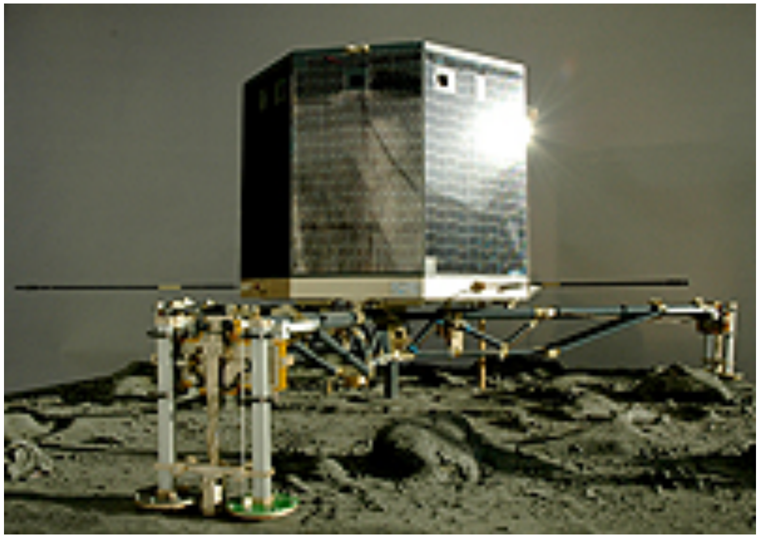
NEAR spacecraft final landing mosaic of Eros asteroid surface

Where are we now?



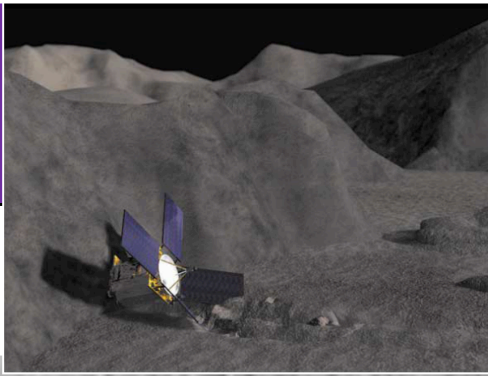
Artist' s concept of NASA's NEAR S/C on surface of asteroid Eros

Artist' s depiction of JAXA's Hayabusa S/C touching down to sample the surface of asteroid Itokawa



ESA's Rosetta spacecraft comet lander, Philae, designed to land on and anchor to a comet surface, 2014

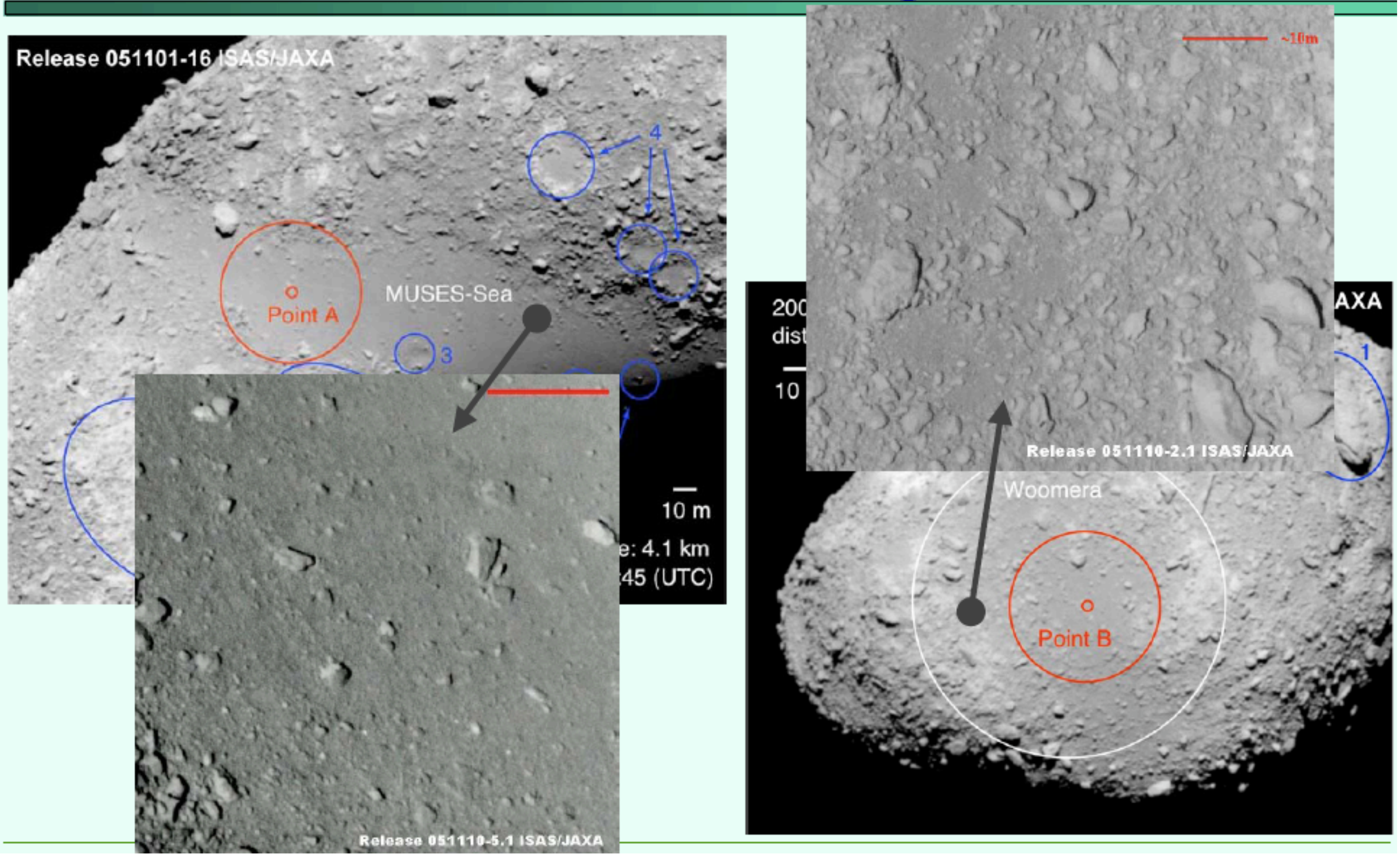
Surface characteristics



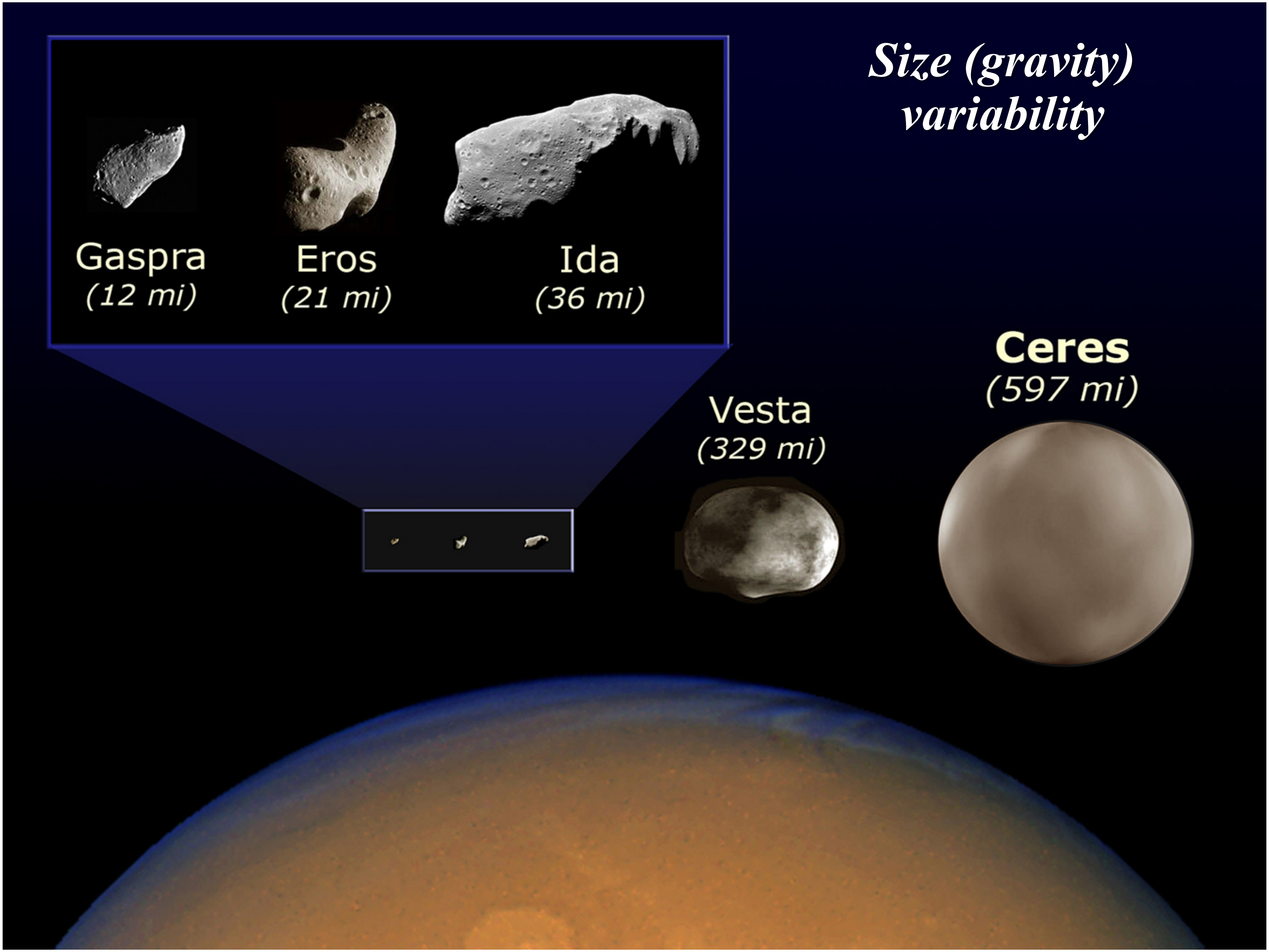
Final image from NASA NEAR spacecraft

Images of Itokawa

Smooth and Rough



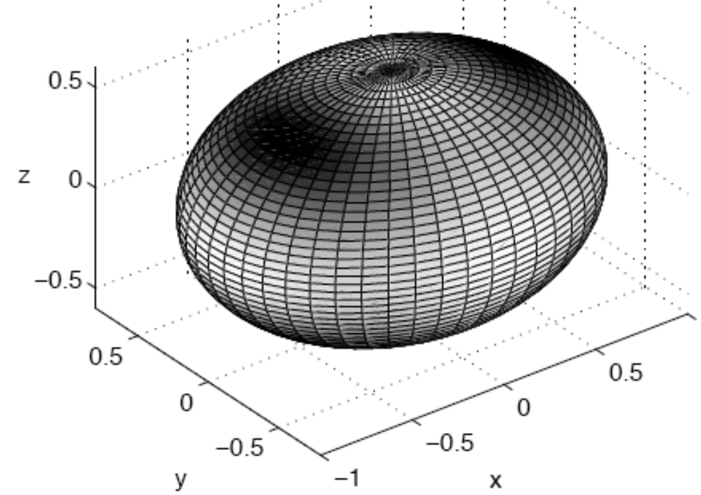
 M. Yoshikawa et al (JAXA) COSPAR Capacity Building Workshop on Planetary Science, Montevideo, Uruguay, July 2007

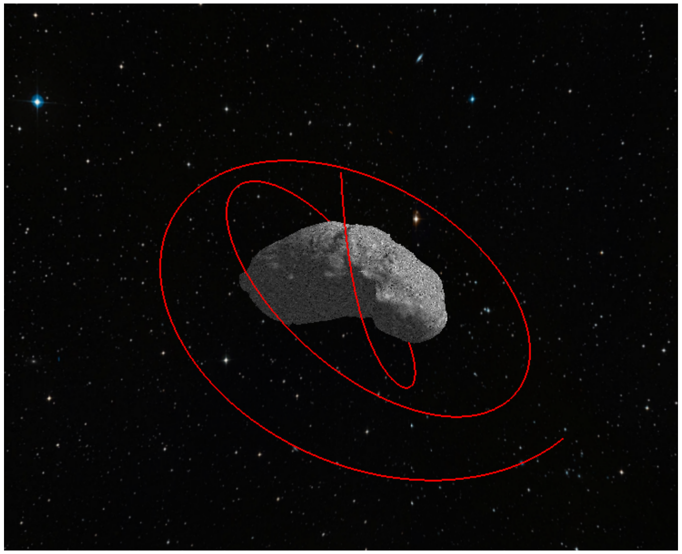

Size (gravity) variability
Gaspra
(12 mi)
Eros
(21 mi)
Ida
(36 mi)
Vesta
(329 mi)
Ceres
(597 mi)

CHALLENGES

- **Mechanics of controlled ballistic hopping on rotating asteroids in non-uniform gravity fields**
- **Landing after hopping in such a way as to avoid or minimize rebound**
- **Maintaining grip or temporary anchoring while controlling force, for closure and compliance**
- **Determining, updating & maintaining knowledge of where you are on the surface**
- **Testing! …and verification of gravity-independent locomotion systems**

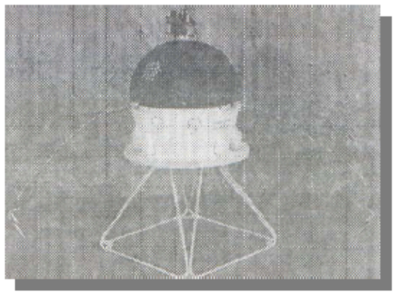
J. Bellerose & D. Sheeres
(U. Michigan, Ann Arbor)



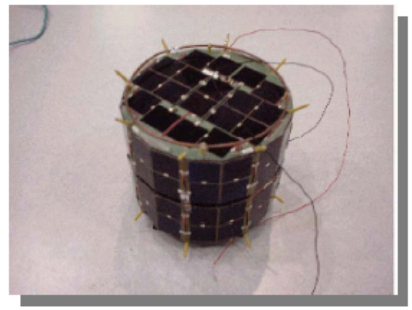


Rolling & Hopping

Proposed Hopping Robots



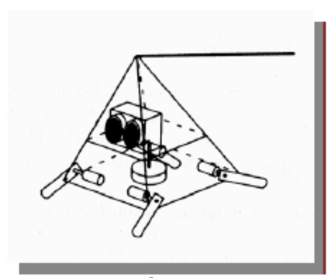
PROP-F
(Soviet Union)



MINERVA
(ISAS/JAXA)

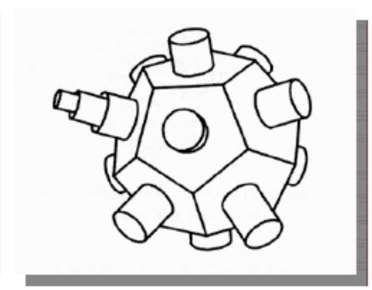
SSV
(NASA/JPL)

Frog type
(NASA/JPL)



Legged type
(Tohoku Univ.)

Iron-Ball type
(Univ. of Tokyo)

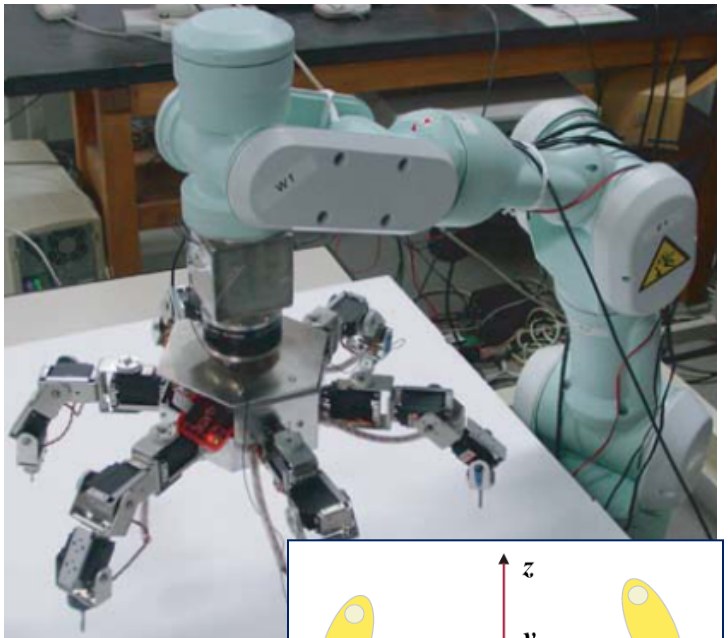


Legged type
(Kyushu Univ.)

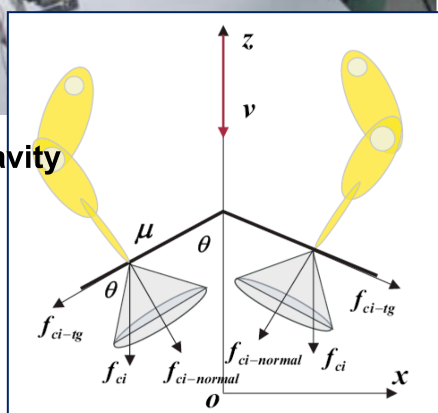
T. Kubota and T. Yoshimitsu (ISAS/JAXA) Asteroid Exploration Rover, IEEE ICRA 2005, Planetary Rover Workshop

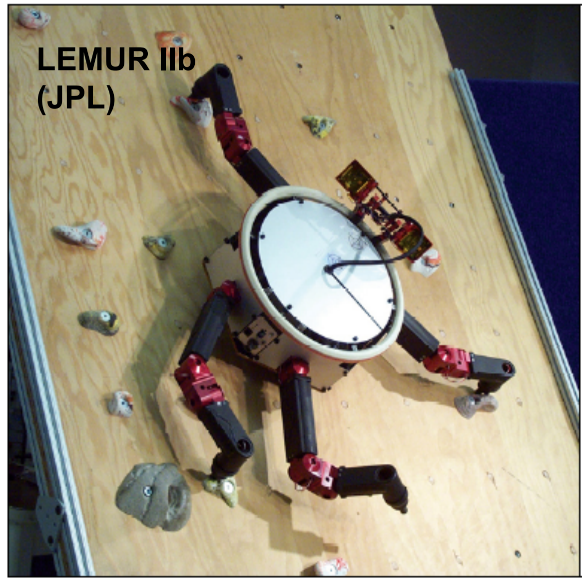
E. Tunstel and L. Palmer III, (APL, USF), “Gravity-Independent Locomotion: Potential approaches…,” IEEE ICRA 2010, Planetary Rover Workshop

Crawling & Climbing

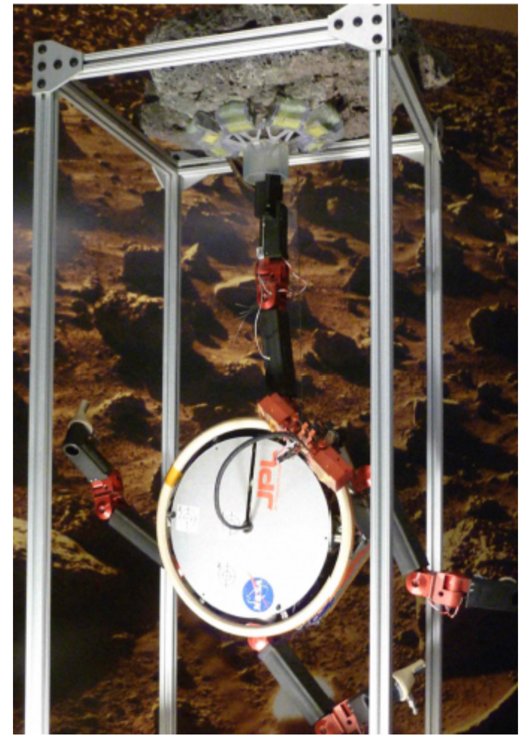


ASTRO on microgravity emulation testbed (Tohoku University)
M. Chacin & K. Yoshida
IEEE ICRA 2009





B. Kennedy CLAWAR 2005)



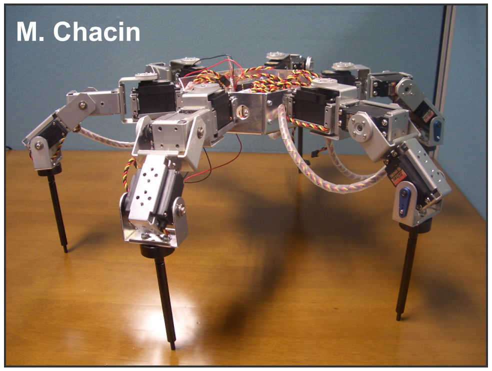
A. Parness (IEEE ICRA 2011)

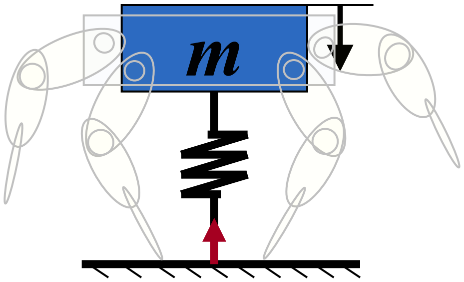
AWIMR (NGST, JPL, CMU)

R. Wagner (IEEE ICRA 2007
Planetary Rover Workshop)

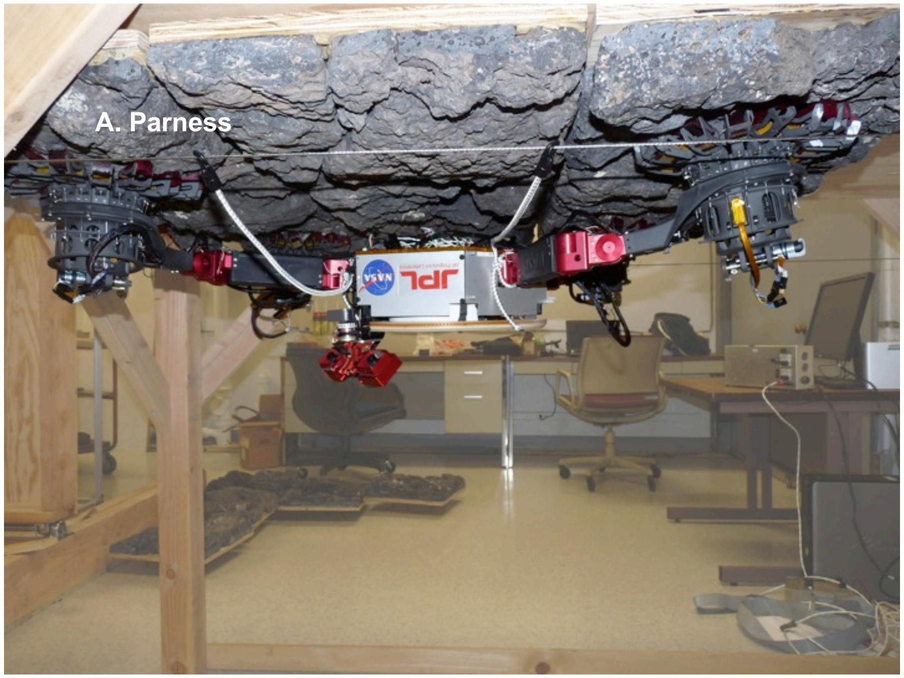
Gravity-Independent Locomotion

- ***GIL* systems**
  - ***Locomotion without strict dependence on the local gravity vector for traction or stability and local motion control***





- **Methods of gripping rocky surfaces to allow mobility without gravitational assistance**
- **Enables future exploration of asteroids (as well as vertical or inverted rock walls of lava tubes, caves, and cliff faces)**

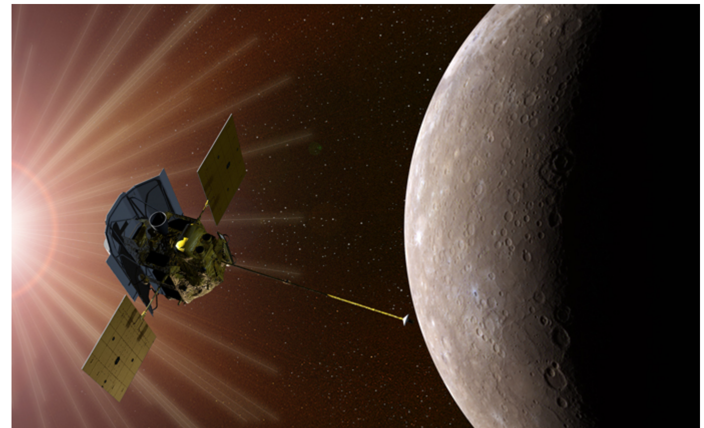


- A. Parness et al, "Gravity-Independent Mobility and Drilling on Natural Rock Using Microspines," IEEE ICRA 2012.
- M. Chacin & E. Tunstel, "Gravity-Independent Locomotion: Dynamics and Position-based Control of Robots on Asteroid Surfaces, *Robotic Systems – Applications, Control and Programming*, InTech, 2012.

Mercury/Venus surface exploration

MESSENGER

MErcury Surface, Space ENvironment, GEochemistry, and Ranging



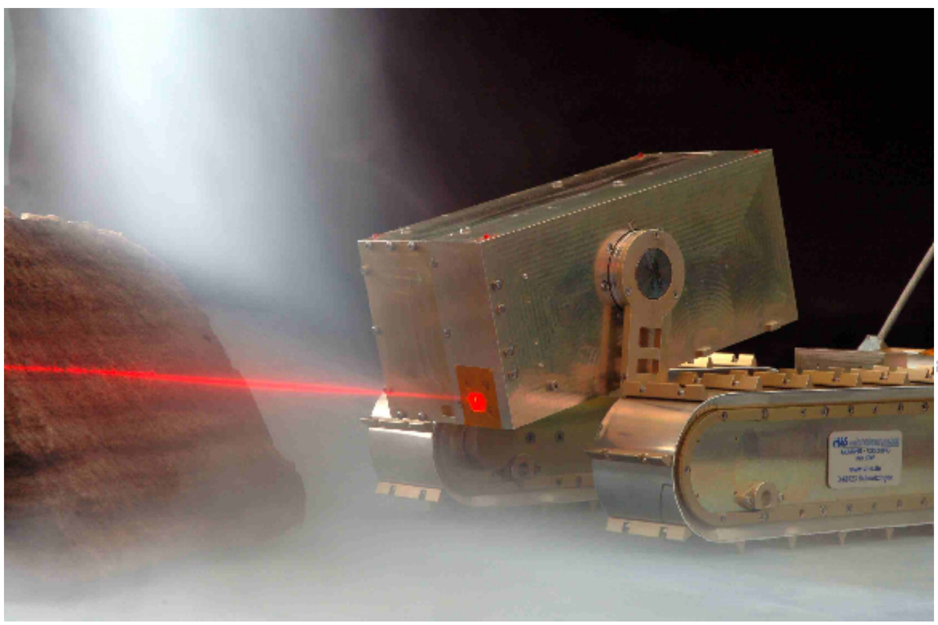
- NASA spacecraft, APL-built & operated
- 1st mission to orbit Mercury
- Entered orbit March 2011 to measure and map the surface for 1 Earth year (mission extended beyond)
- 1st images of key features on the surface of Mercury
- New evidence supporting 20-year hypothesis of abundant water ice at its poles
- Future surface missions being studied

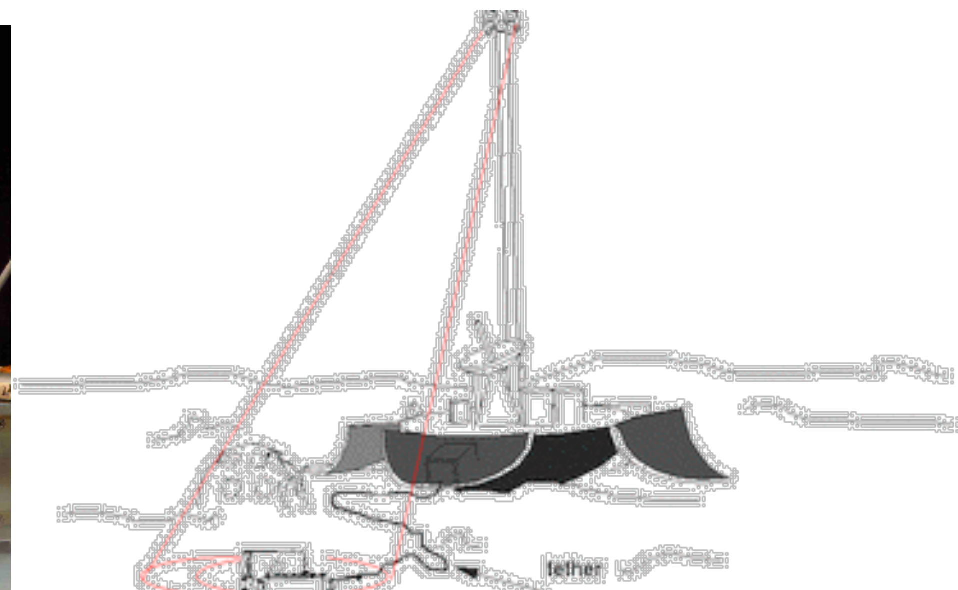
- Surface operations challenges:
  - power (3-month night)
  - thermal (600 C at equator)

http://messenger.jhuapl.edu

Mercury rover concept (ESA)

- **1-2 week mission on night side of the planet**
- **Tethered to lander allowing exploration within 10m**
- **Science instruments for surface geochemistry**
- **Near-autonomous operation with single lander–Earth comm. period once per day**

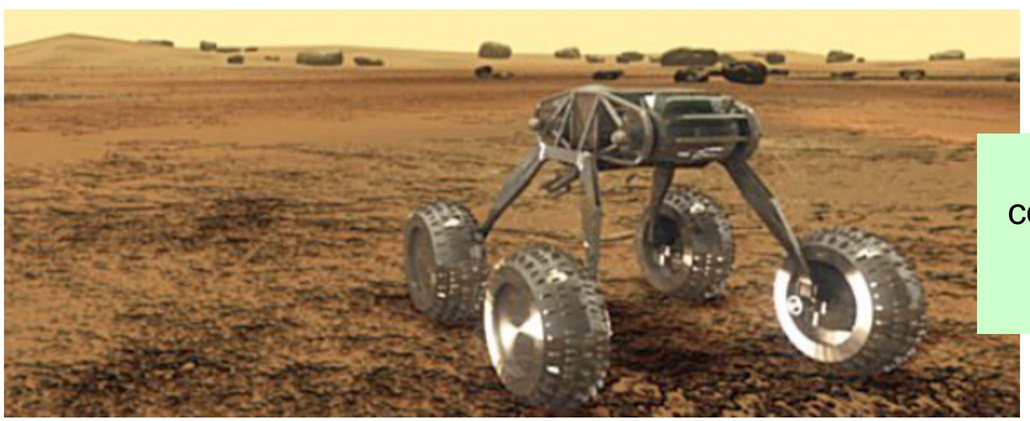


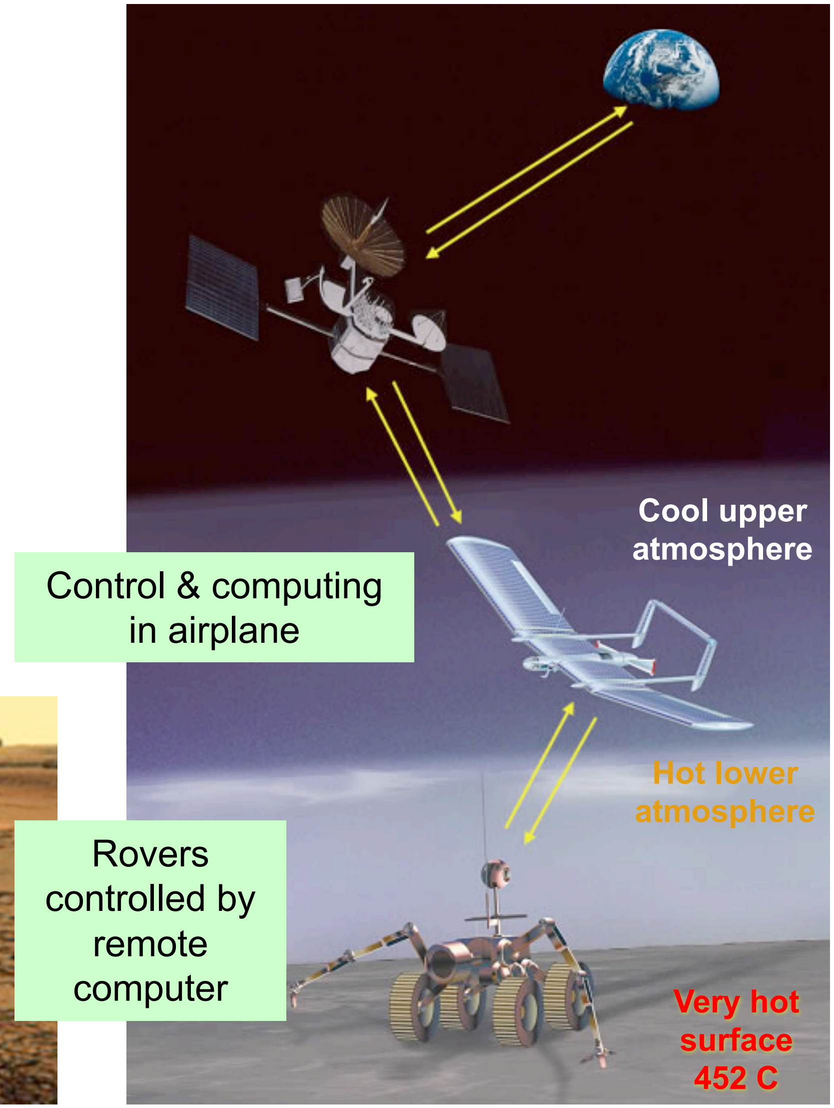


 Lee, C.G.-Y., et al. "Mercury Nanokhod Rover - Hardware Realisation and Testing, ASTRA 2006, Noordwijk, Nov. 2006.

Venus rover concept (NASA)

- **Science mission:**
  - **characterize the surface at geologically diverse locations**
  - **emplace seismometers to determine interior structure**
- **Very hot surface**
  - **High-temp. electronics on rover with science instruments and tools**
  - **Radioisotope power**
  - **Onboard cooling system**



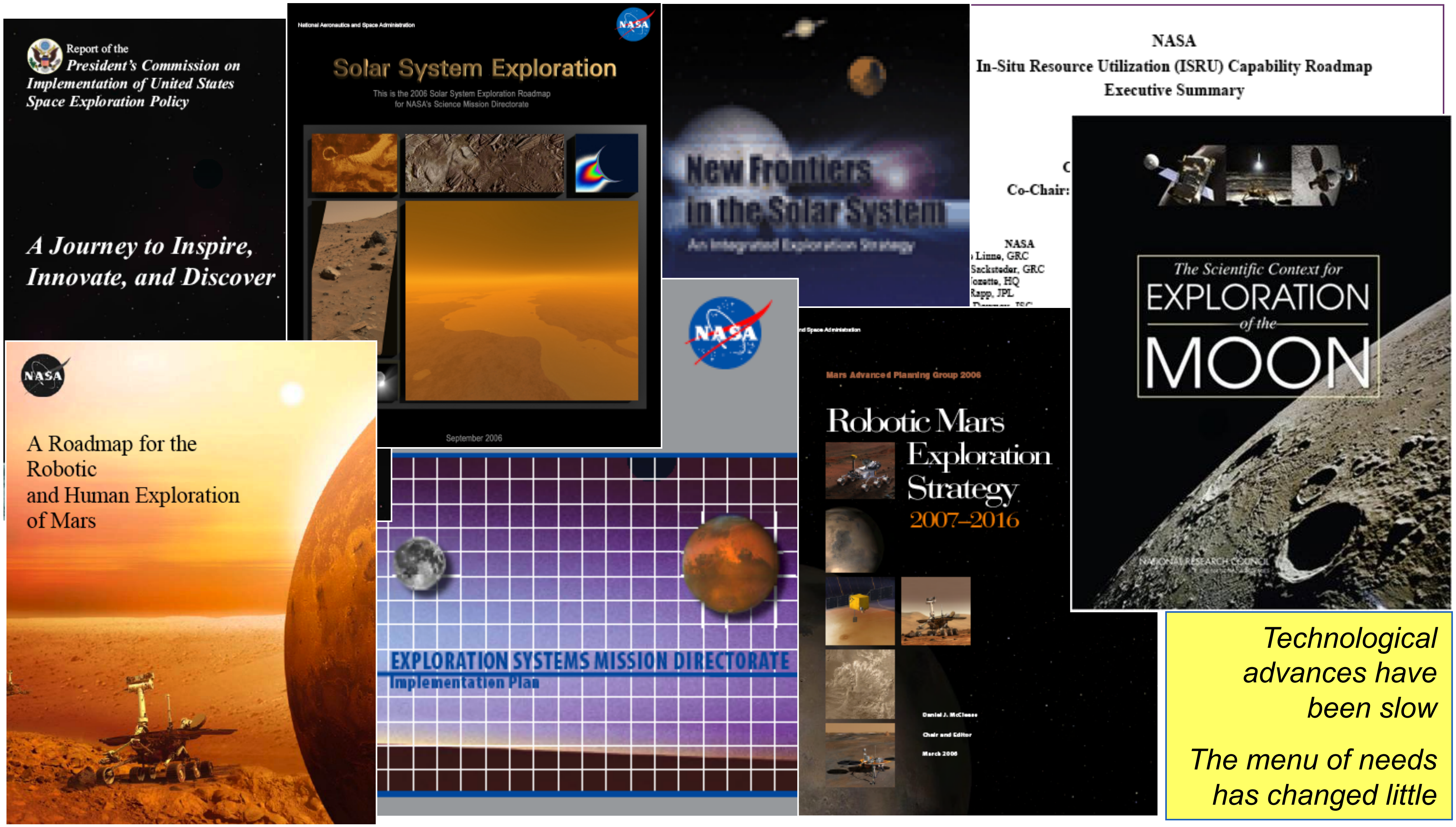


G. Landis, "Robotic Exploration of the Surface and Atmosphere of Venus," Acta Astronautica, Vol. 59, 7, 517-580, 2006.

VIDEO: https://rt.grc.nasa.gov/files/venus_mission.mp4 OR venus_mission.wmv

What else remains to be addressed?

Past NASA studies, roadmaps, & visions

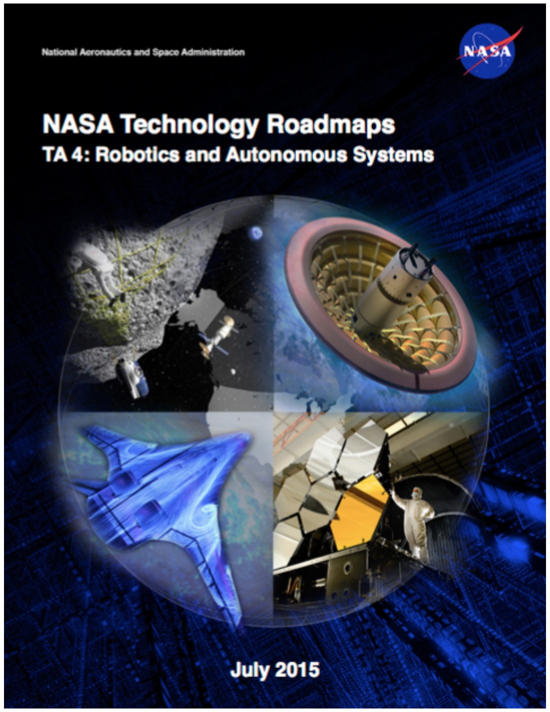


Technological advances have been slow

The menu of needs has changed little

Technology Needs

- Human-like vehicle piloting
- Extreme terrain access
- Highly dexterous manipulation
- Immersive telepresence
- Mobility & manipulation sensing
- Access to small body surfaces
- Access to planet subsurfaces
- …



- **Low-risk learning/adaptation**
  - Maximize functional capability or performance of degrading/failed hardware during long-duration missions (e.g., mobility w/faulty wheel(s) or leg(s))
- **Learning by demonstration for complex manipulation / sampling tasks**
  - human-like capability obviating formulation of complex yet inadequate models
  - improve performance over time

Lingering needs driving planetary surface robotics research

Advanced autonomous mobility
- steep slope mobility
- autonomous mobility in dark/ shadowed environments
- Subsurface access mobility and mechanisms
- reconfigurability
- in-space mobility

Autonomy and operations
- robotic autonomy software
- autonomous control
- "human equivalent" robotic operations
- human-robot and autonomous systems V&V
- advanced operations software
- remote robotic system supervision and teleoperation
- human-system interaction

ISRU and outpost tasks
- site/resource characterization
- regolith excavation
- regolith manipulation and transportation
- landing site preparation
- resource/cargo predeployment

Robotic systems
- robotic assistants
- construction robots
- environment/site survey rovers
- cooperative robotic networks
- autonomous monitoring and repair robots

Robotic capabilities
- precise instrument placement and manipulation
- end-effectors w/dust tolerant mechanisms
- sample gathering, handling, and analysis
- remote sensing for robotic surface systems
- automated rendezvous and docking

Parting Thoughts…

- **Beyond lunar rovers of the past and today's Mars rovers, there are many more tasks for robots on planetary surfaces**
- **Concepts have been studied or prototypes built for every rocky planet and for asteroids and comets**
  - **Much research and technology development lies ahead**
- **Despite differences in requirements or capabilities for Earth-based and planetary robotics technology, much of what we know how to do on Earth may apply (with skilled tailoring) for planetary mission use**
- **Breakthroughs areas include subsurface access and gravity independent locomotion (GIL)**

Thank You!

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QUESTIONS?

Sunset as imaged by the Spirit rover from a hilltop on the surface of Mars