Challenges in Mobility and Robotics for In-situ Science

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Abstract

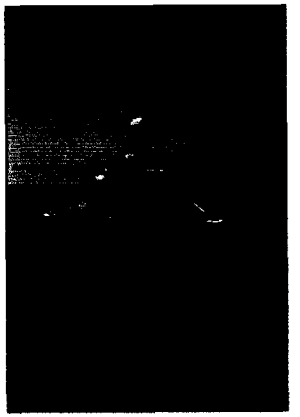
- In-situ science on planetary surfaces such as Mars, Venus, Mercury and Titan pose extreme challenges for mobile robots. Mobility is needed to avoid the kind of situation which occurred with the two Viking landers in 1976: despite the rich array of rocks visible all around the landers, no rocks could be reached by either of the robotic arms, and thus no real "hard rock" science could be done. Future missions will involve surface, subsurface, and atmospheric mobility which focuses the need for technology development in sensing, autonomy, and mobile robot architectures for solar system exploration.

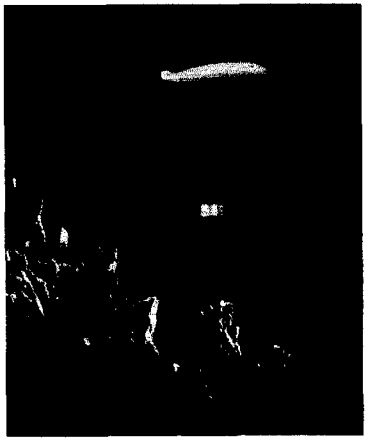
Outline

- Mission Drivers
- Need for Mobility
- Challenges in Surface Mobility
- Challenges in Subsurface Mobility
- Challenges in Aerial Mobility
- Challenges in Sample Handling and Manipulation
- Challenges in In-Situ system architectures

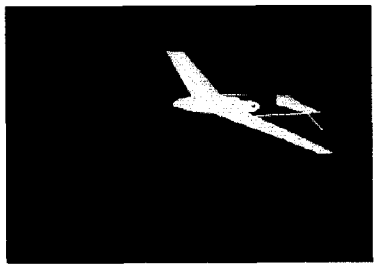
Mission Drivers

On the Surface





Beneath the Surface



Through the Atmosphere

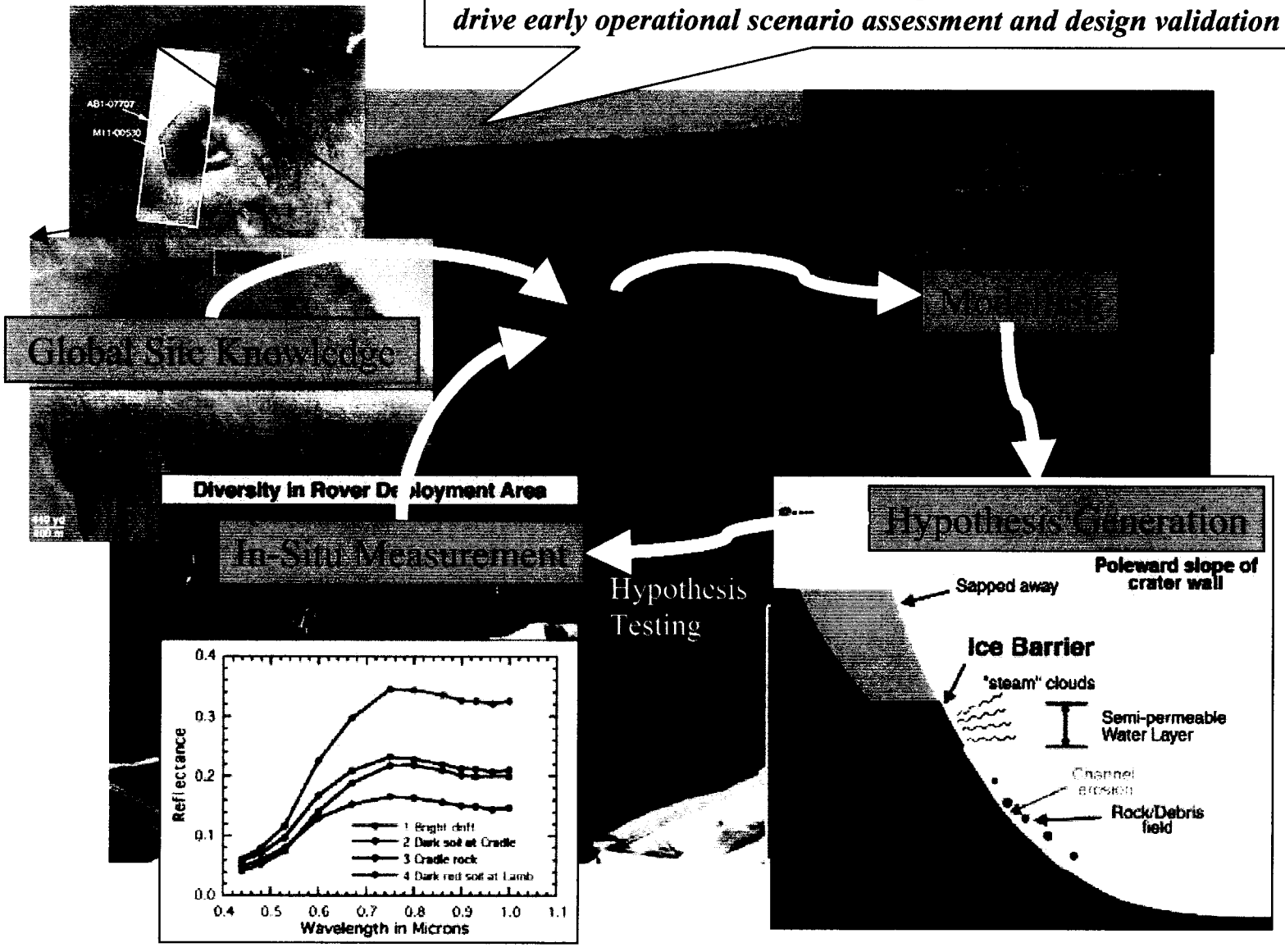
- Rovers - rock and regolith (Mars, Venus (enabled by Nuclear Initiative), Mercury, Lunar); ice (Mars polar, Lunar polar, Mercury polar, Jovian Moons)
- Aerobots (airships or aircraft) (Titan, Venus, Mars); anchoring/sampling
- Subsurface Exploration - rock and regolith (Mars equatorial, Venus, Mercury, Lunar); ice (Mars polar, Lunar polar, Mercury polar, Jovian Moons)
- Small Bodies (Comets and Asteroids); mobility in microgravity environment, anchoring, sampling
- Safe Landing (Mars, Mercury, Lunar, Jovian Moons)

Need for Mobility

- A Scientist on Earth would never try to understand geology or biology by staying in one place
- Unequivocal evidence of past processes is rare
- A mental model:
  - a graduate student in the field with jeep, map, cell phone, GPS, a digital camera/modem on surveyors tripod,
  - the 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



Challenges in Mobility

Mobility is required to reach key science sites for Solar System Exploration

- rovers
  - rock and regolith (Mars, Venus (enabled by Nuclear Initiative), Mercury, Lunar)
  - ice (Mars polar, Lunar polar, Mercury polar?, Jovian Moons)
- aerobots (airships or aircraft) (Titan, Venus, Mars)
- Subsurface Exploration
  - rock and regolith (Mars equatorial, Venus, Mercury, Lunar)
  - ice (Mars polar, Lunar polar, Mercury polar?, Jovian Moons)
- Small Bodies (Comets and Asteroids)
  - mobility in microgravity environment
  - anchoring, sampling

– mapping of missions to mobility technology areas

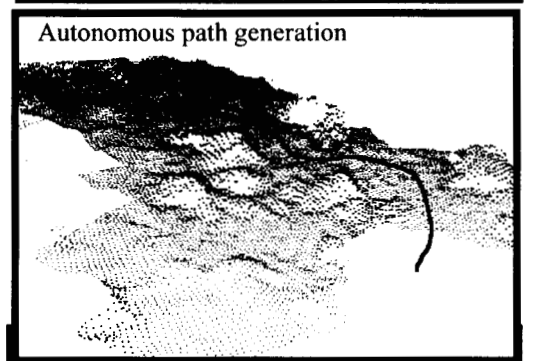
– need critical mass of capability in mobility technologies

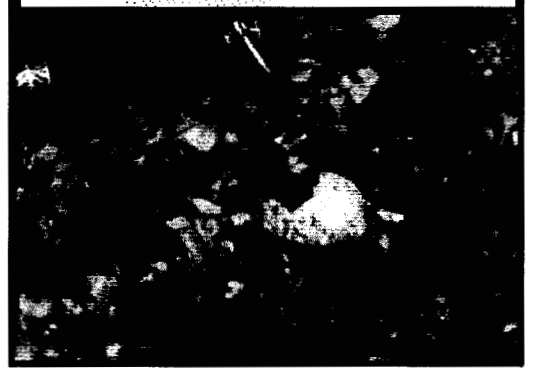
Challenges in Surface Mobility

- Autonomous precision science site
  - approach (from 10 m or more),
  - surface preparation,
  - instrument placement, and/or
  - sample extraction
- "Human Equivalent" long range driving
  - "positive obstacle" (e.g. rocks) detection and avoidance
  - "negative obstacle" (e.g. holes) detection and avoidance
  - "wheel traps" and other pathological terrains
  - sinkage and slippage estimation
  - safe path planning in extreme terrain
  - simulation of vehicle/terrain interactions

Challenges in Surface Mobility (Con't)

- steep slope driving
  - adaptive geometries, advanced perception
  - tethered (rappelling)
- resource planning
  - statistically valid estimation of time-to-complete, energy-to-complete, etc.
  - planning and dynamic replanning of task sequences
- "serendipitous science"
  - dynamic classification of instrument data; outlier detection
  - anomalous combination detection, machine learning

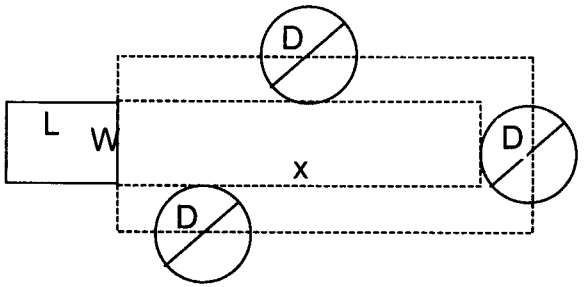


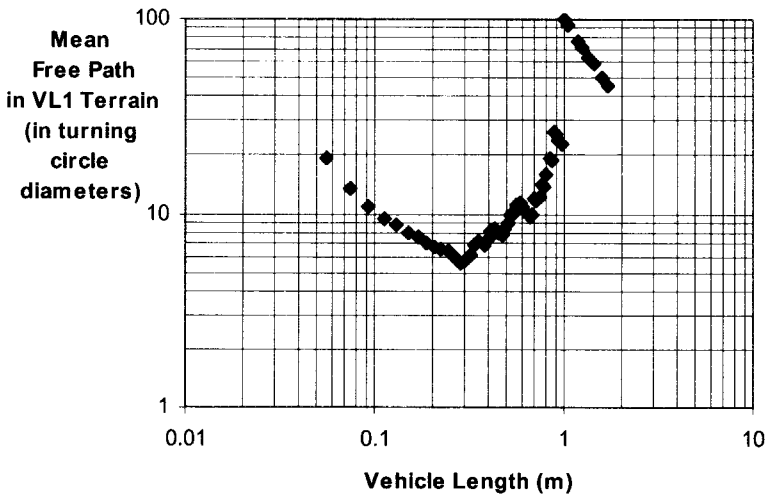


Hazard Detection and Avoidance

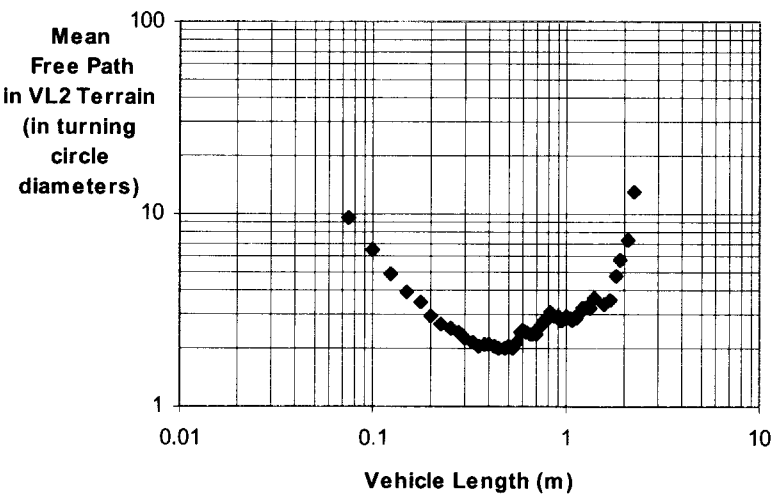
- Nominal strategy is to designate piecewise-linear hazard-free paths to targets using stereo imagery from lander or rover. Rover establishes that a full turn-in-place circle is free from hazards. Algorithm turns in place until it sees a clear circle, advances half a vehicle length, and starts an arc back toward the goal direction. This algorithm can run mazes, extract itself from box canyons, etc.
- 5 Laser stripes, each imaged at 4 points to give 5x4 array of elevation measurements.
- Nearest neighbor differences, and overall highest to lowest determine hazards.
- Relatively coarse sampling of terrain led to setting of maximum nearest neighbor differences to 7 cm, despite the overall capability of the vehicle to cross hazards up to 13 cm tall.
- Internal pitch, roll, and contact sensors also used to define hazards
- A "thread-the-needle" algorithm was included after project decided not to land in VL1-class terrain, allowing the vehicle to move between two hazards less than a turn-in-place circle diameter apart.

Robotic Vehicle Hazard Avoidance - Mean Free Path

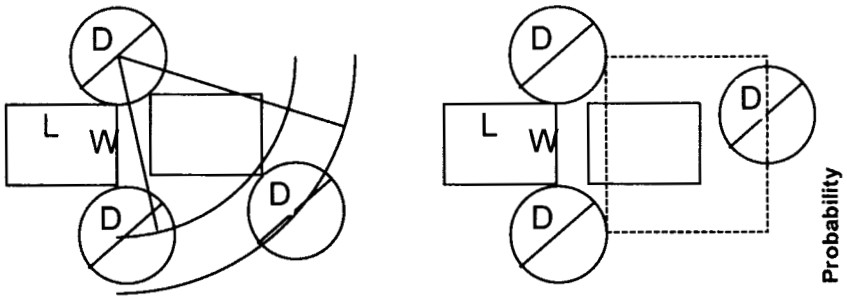


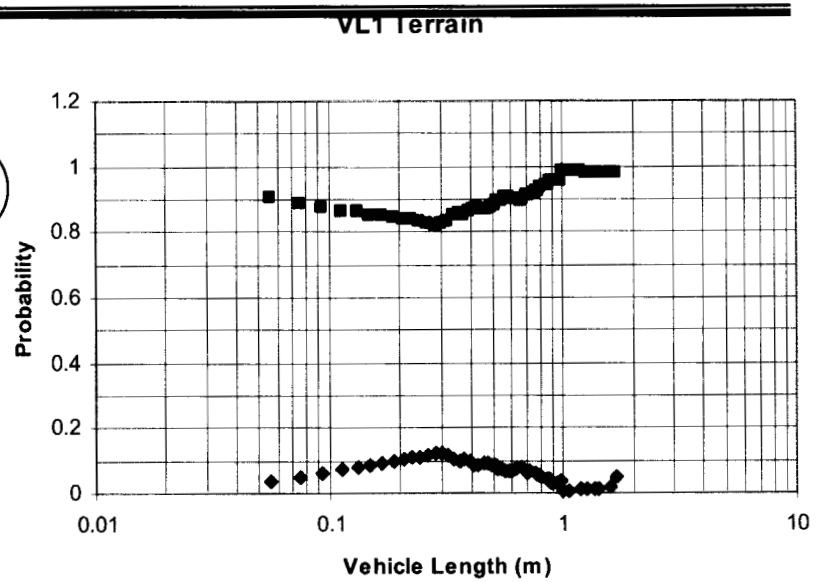


- Used Viking rock size/frequency data and estimated mean free path (in units of vehicle turn-in-place circle diameter)
- Plot mean free path versus vehicle scale

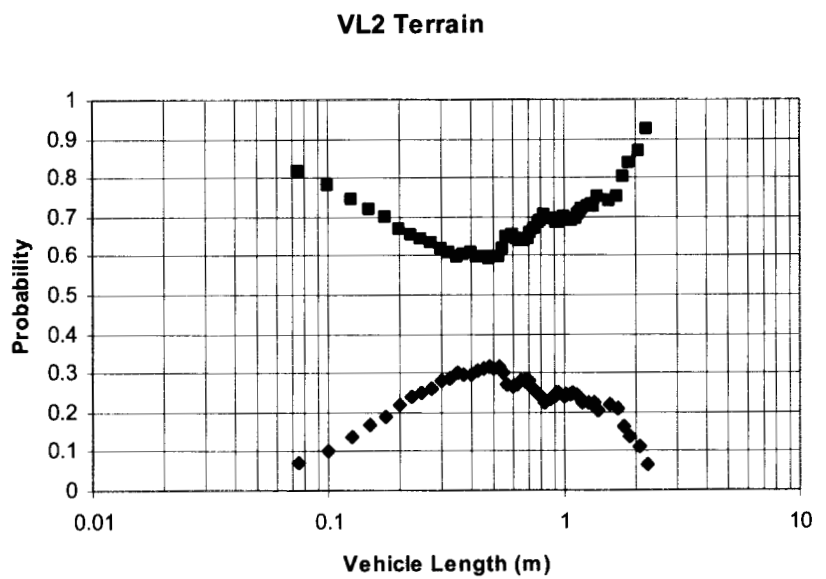


Dense Obstacle Fields - Thread-the-Needle





- When Pathfinder Science Working Group decided on a landing site as rocky as VL2 (based on thermal inertia), we added "thread-the-needle" to the repertoire of behaviors.
- Plot of likelihood of any given hazard invoking thread-the-needle (lower curve), and probability of success (upper curve) for VL1 and VL2 terrain.

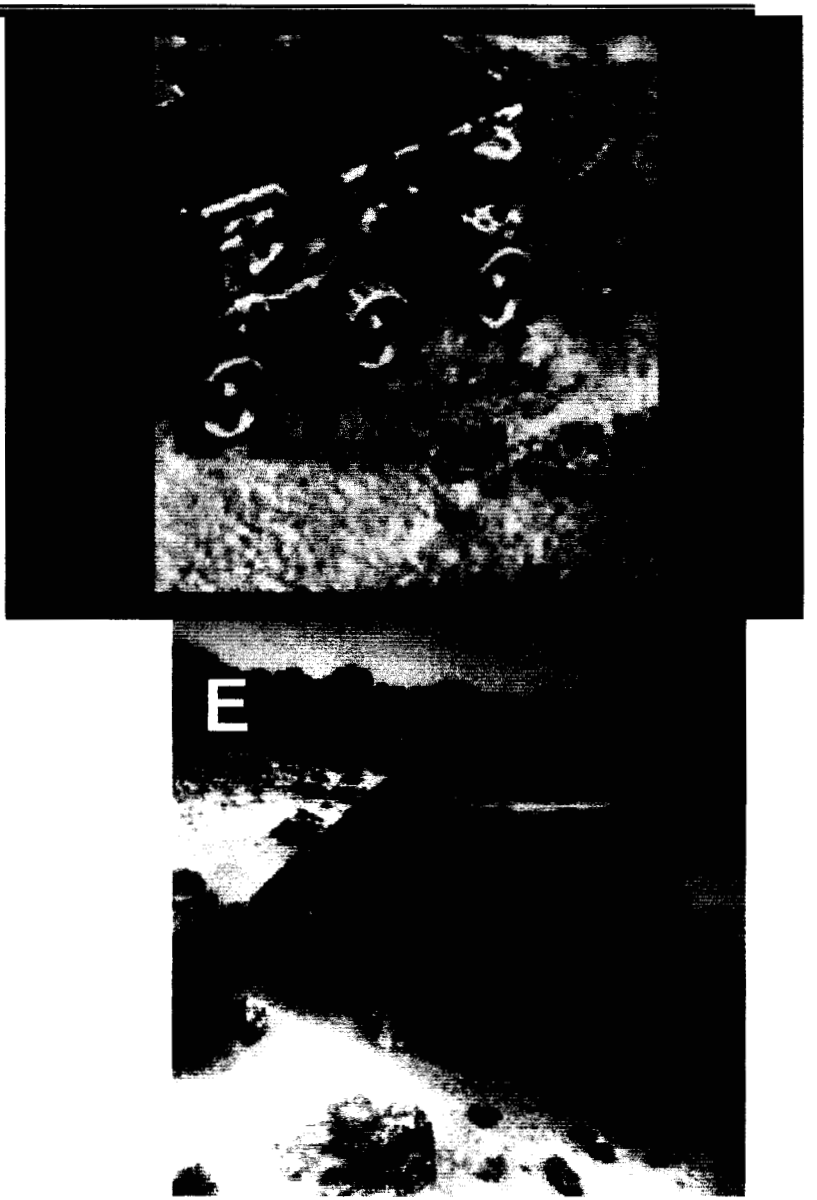


Human Control is Not Safe!

- This situation occurred when humans, overriding the autonomous naviation system, went into a very rocky area.
- "Blind" moves and turns were used, compounded by noise on rate gyro.

"Find Rock" Autonomy

- Operator designates last waypoint as a rock to find
- Hazard avoidance sensors are used to detect rock and center vehicle in front of rock
- If rock not found at designated point, a search pattern is executed to find nearest rock
- Vehicle "hunts" back and forth to center in front of rock



Sojourner Log Data Reconstruction

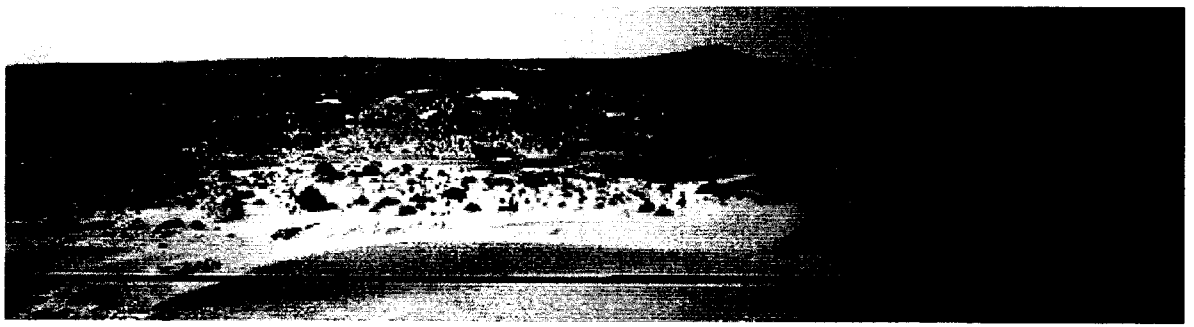
Movie of Find Rock and Hazard Avoidance Log Data Reconstruction

- Rover uses laser hazard avoidance system to move through 2 waypoints and execute find rock at "soufflé".
- Rover executes long traverse and avoids one rock during traverse.
- Key points:
  - Relatively coarse sampling of terrain
  - Dead reckoning errors make objects show up in unexpected places

Fault Detection and Recovery

- Where rover has redundant sensing, it can recover from failures.
- Example: wheel drive failure
  - Encoder and motor current sensing.
  - If encoder counting but current anomolous, then increment failure flag on current sensor.
  - If current normal but encoder not counting, then increment failure flag on encoder.
  - If HW works later, decrement failure flag.
  - If failure flag increments up to 5, then HW flagged as permanently broken.
- Backup algorithms implemented for cases of HW failure
  - (e.g. differential wheel motion to estimate turn angle if gyro broken, use Z accel to estimate tilt if roll or pitch broken)

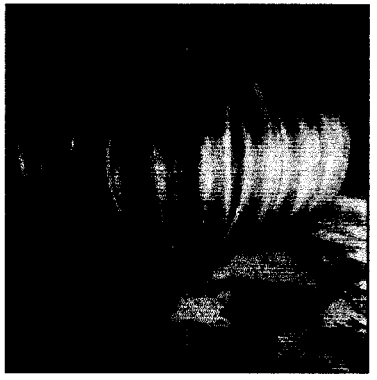
Sinkage and Slippage on Mars

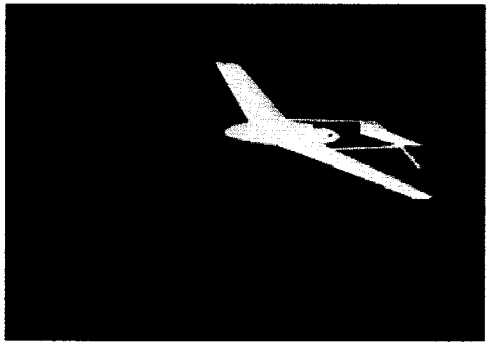


- Viking Lander 1 found dunefields (top left), and one of the footpads sunk 17 cm into drift material. Sojourner found similar dunes (lower left).
- First image from Mars (bottom right) showed footpad 1 on firm surface. Image of footpad 3 taken later (top right) gave serious concern.
- The consistency of the drift material was such that it flowed almost like a fluid around the footpad.

Challenges in Aerial Mobility

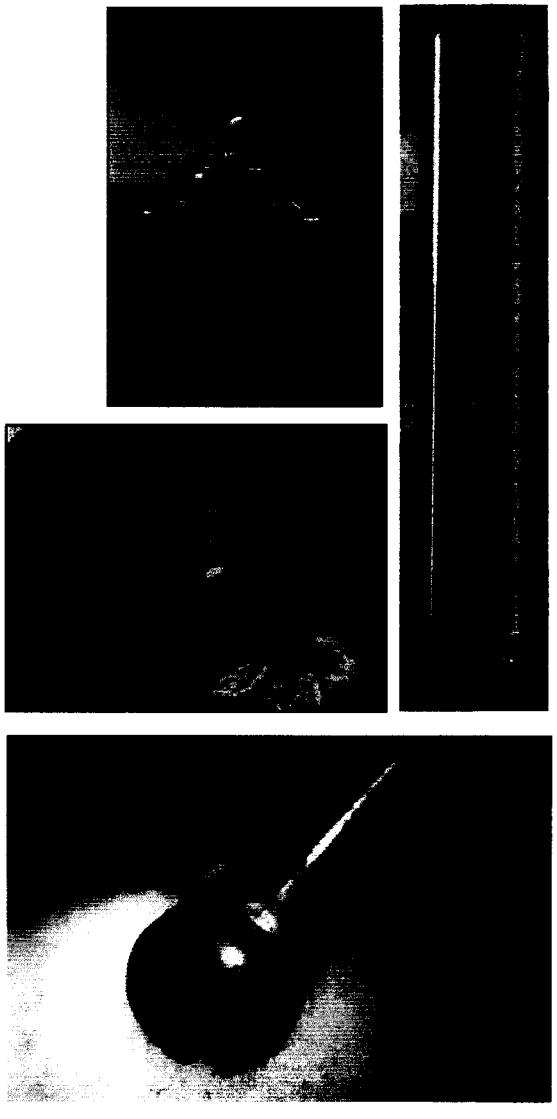
- Safe navigation of airships in a turbulent lower atmosphere
  - reaching and stationkeeping over specific targets
  - lowering of payloads to surface without damage or risk
  - interaction of payload with surface, sampling, etc.
  - modeling and simulation (CFD)
  - control stability, disturbance rejection, etc.
  - test and validation
- Long range precision navigation of Aerobots
  - position estimation
  - atmospheric modeling and trajectory propagation
- Balloon materials (Mars, Venus, Titan)





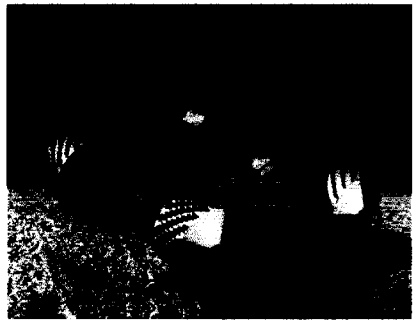
Challenges in Subsurface Mobility

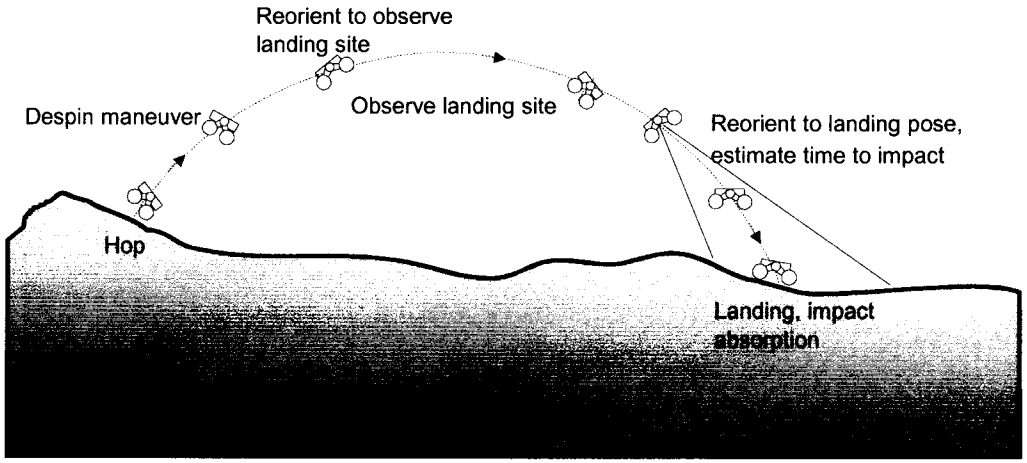
- Rock/Regolith
  - rock destruction (diamond drills, ultrasound, lasers)
  - cuttings transport
  - hole lining
  - power and communications
  - downhole instruments and sampling
- Ice
  - melting or vaporization of ice
  - dealing with sediment buildup
  - maintaining power and communications despite ice shear
  - downhole instruments and sampling

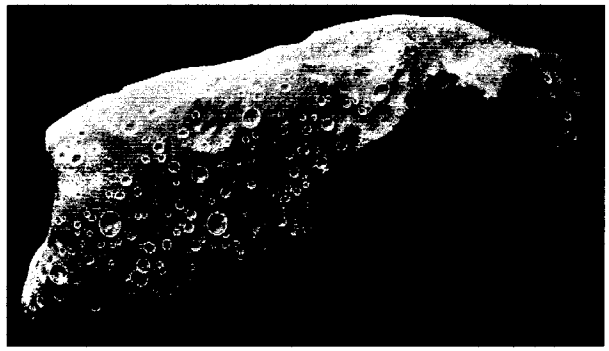


Challenges for Small Body Mobility

- Mobility in a Microgravity Environment
  - trajectory propagation, gravity and dynamics modeling
  - vehicle 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







Challenges in Sample Handling and Manipulation

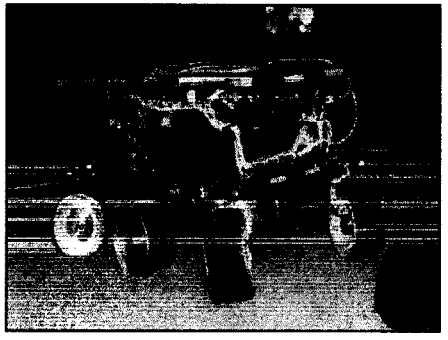
- Taking and handling samples is key to science return
- Ideally, samples would be uniform in shape/size (e.g. core drills)
- These uniform samples can be handled and processed by automated system
- An exciting possibility is the prospect of a micro-fluidic sample handling system:
    - Sample device (e.g. deep drill) generates samples in powdered form (e.g. 100 μ particles).
    - Samples blown out of hole with fluid (e.g. liquid or gaseous CO_2)
    - Samples routed through sample handling system by microfluidic switching network

Challenges for Mobile System architectures

- Architectures for mobility
  - distributed computing in extreme environments (electronics needs to be at extremities, e.g. on mast)
  - use of redundant high performance commercial processors to enable sufficient throughput
  - survivable, low mass, low power I/O electronics for
    - brushless motor control
    - camera interfacing
    - analog signal chains for all analog engineering and science sensors
    - power and communications management
- Sensors and sensor processing (vision, inertial, etc.)
- Test and Validation

Vision/Strategic Goal

Develop the ability to move around within a planetary environment in order to make breakthrough scientific measurements.



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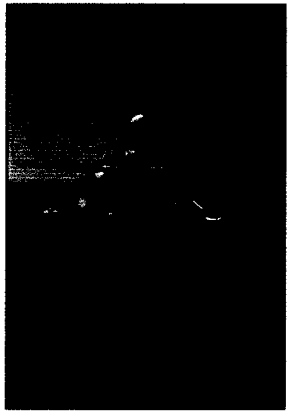

Beneath the Surface

Through the Atmosphere