Driving Rovers on Mars: Challenges and Opportunities associated with Robotic Planetary Explorers

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MER Instrument Positioning System Test and Ops Lead
MER Rover Driver

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Mars Science Strategy: Follow the Water!

Common Thread

LIFE

Determine if Life Ever Arose on Mars

CLIMATE

Characterize the Climate

GEOLOGY

Characterize the Geology

HUMAN

Prepare for Human Exploration

When? Where? Form? Amount?

WATER

W

A

T

E

R

Follow the Water!
Mars Exploration Rover (MER) Science Objectives

To determine the water, climate, and geologic history of two sites on Mars where evidence has been preserved for past and persistent liquid water activity that may have supported biotic or pre-biotic processes.
The history of Mars and its water is recorded in the rocks.
Robotic Field Geologists!

Chemical analyzer, iron-bearing mineral analyzer, microscopic imager, rock abrasion tool

Panorama stereo camera and viewport for infrared spectrometer

Mobility
Mast-Mounted Science

Mini-TES
infrared spectrometer
viewing port

Pancam color stereo panorama cameras
17° FOV
Engineering Cameras

- **Navcam**
  - Stereo cameras
  - 45° FOV

- **Front and Rear Hazcam**
  - Stereo cameras
  - 120° FOV
Instrument Deployment Device (IDD)

- The IDD is a 5 degree-of-freedom robotic manipulator that controls the 3D position (X, Y, Z) and 2D orientation (azimuth and elevation) of the in-situ instruments mounted to the IDD turret with respect to rock and soil targets.
In-Situ Science Payload

Microscopic Imager Image

APXS Spectrum

Counts MPF
Counts corrected 256 chn Athena

Energy [keV]

Counts/ 10000 sec

RAT Abraded Surface

Mössbauer Spectrum

Banded Iron (rock 3; Cornell target) 2 hours 10 min; 108 mCi Co-57

counts

Velocity [ mm/s ]

Counts

Hematite
Telecommunication: From Mars to Earth and Back Again

- UHF Antenna
- Low Gain Antenna
- High Gain Antenna
- Mars Orbiters
- Deep Space Network
Inside the Rover

- Li-Ion Batteries (with RHUs)
- UHF Radio
- IMU
- Rover’s “Brain” Rover Electronics Module (REM)
- X-Band SDST
- X-Band SSPA
- Li-Ion Batteries (with RHUs)
- X-Band SDST
Major Spacecraft Elements

- Flight System
  - Cruise Stage
  - Backshell
  - Heat Shield
  - Lander
  - Rover

Dimensions:
- Flight System: 2.65 m
- Rover: 1.7 m
Landing Site Selection Criteria

• Both landing sites must be safe (maximum elevation, dust, rock abundance, slopes, winds)
• Selected sites must permit a successful surface mission (e.g. thermal environment, solar energy, terrain characteristics for mobility)
• Selected sites should permit a scientifically successful mission, in which the rovers are capable of addressing the mission science objectives
• Part of the rationale for two rovers is to provide science redundancy by targeting two scientifically different sites (e.g. mineralogical and morphological)
Landing Sites

Meridiani Planum
- Water-formed hematite?

Gusev Crater
- Ancient lake sediments?
Meridiani Planum

Gray hematite: Precipitate from large standing body of water? Precipitate from warm percolating water? Cold ground water? Surface weathering coatings on rocks? High-temperature oxidation of volcanic rock?

119 km x 17 km landing ellipse (75 miles x 11 miles)
Gusev Crater

- Compelling evidence that water ponded in the crater
- Lakebed deposits can preserve substantial evidence of past water-related processes, environmental conditions, and habitability
- Ice-covered lake? Short-lived playa lakes? Muddy debris flows? Ancient highland rocks deposited in the crater?
Challenges for Robotic Planetary Explorers

- Robots operate in a completely unstructured and unknown terrain environments
- Orbital imagery does not yet provide fine scale details required for in-situ exploration (don’t know what is just around the corner)
- Rovers are autonomous receiving daily instructions in the Martian morning and tell us what happened in the Martian afternoon
  - Rovers are not “joy-sticked” or “teleoperated”
  - Two way light time precludes this type of operation
- Heavy use of on-board sensor feedback (vision, inertial, etc) for autonomous EDL, rover driving, manipulation
Robotic Functions

• Remote Sensing
  – Terrain classification and remote spectroscopy in the visible and near-infrared

• Mobility and Navigation
  – Rover localization using sensor fusion (wheel odometry, inertial measurements, vision, etc)
  – Autonomous sensor-based rover navigation including hazard detection and hazard avoidance

• In-situ Instrument Placement
  – Target selection via stereo range maps (3D position and surface normals)
  – Proximity sensing
  – Collision detection and fault protection
The Instrument Positioning System (IPS)
IPS Functions

• Place the APXS, MB and MI on rock and soil targets
• Place and hold the RAT on rock targets during rock grinding activities
• Place the APXS and MB on rover-mounted targets (magnet experiment and MB calibration target)
IPS Requirements Summary

- Initially place the in-situ instruments (MI, APXS, MB, RAT) to within 10 mm in position and 10 degrees in orientation relative to rock and soil target surfaces including appropriate actuation of each instrument’s contact sensors
  - Achieved 4.2 mm mean (9 mm $3\sigma$), 0.5 deg mean (1.5 deg $3\sigma$)
- Repeatable placement of the in-situ instruments to within 4 mm in position and 3 degrees in orientation relative to rock and soil target surfaces
  - Achieved 0.3 mm mean (1.3 mm $3\sigma$), 0.3 deg mean (1.2 deg $3\sigma$)
- Incrementally position the MI by the minimal controllable motion of 2 mm ± 1 mm
  - Achieved with sub-mm minimum motion
- Place the in-situ instruments any time during the Martian diurnal cycle
Proximity Sensing

- All instrument contact sensors are dual redundant with the exception of the APXS dust doors and contact sensor.
Instrument Placement Ops

- At end of rover drive, penultimate and final front Hazcam images are acquired
- From these stereo images, range maps of the terrain within the IDD workspace are computed
  - Range and surface normals \((x, y, z, n_x, n_y, n_z)\) are calculated for every image pixel
  - Every range point is tested to see if the point is reachable by each of the instruments
  - The reachable points are then tested in terms of detecting collisions between the IDD, rover, instruments and the environment
  - The resulting map is the so-called Reachability Map
  - 3D terrain meshes are also generated based on the stereo range maps
• Science-driven instrument placement targets are then selected from the locations within the reachability map.
Instrument Placement Ops

- Detailed IDD motion planning and sequence development is accomplished within a high fidelity simulation environment
  - 3D modeling of the IDD, rover, instruments and terrain
  - Simulations of IDD motion and sequence execution are driven flight software including terrain collision detection
IDD Software Functions

- High-level commanding for operations such as unstowing and stowing the IDD
- Commanding within Cartesian-space and/or joint-space
- Deflection (droop) compensation
- Collision detection between IDD, rover and instruments (no on-board terrain collision detection)
- IDD inverse kinematics computed based on current pose (no automatic pose configuration changes are allowed, e.g., elbow up to elbow down)
- Motor current limiting based on effects such as temperature and IDD pose
- Four motion modes based on the context of the instrument placement activity (e.g., free-space motion, guarded motion, pre-load motion, retraction motion)
Testing, Testing, Testing

- Testing occurred at sub-system, system and operations level for both flight and Engineering Model (EM) units.
Testing, Testing, Testing

• Operational Readiness Tests
Building the Rovers
Spirit Driving Tests
Stowed Rover and Lander
Stowing the Lander

Next stop, MARS!!!!
Integrated Lander
Lander in Backshell
Launch/Cruise Configuration
On the Third Stage
In the Launch Fairing
The Mission
The Three Challenging Mission Phases

Launch & Cruise

Entry, Descent & Landing

Egress & Surface Operations

Images From Mission Animation by Dan Maas
The Cruise Trajectory

- Earth at Arrival
- Mars at Arrival
- Earth at Launch
- Mars at Launch

Spacecraft Trajectory

- MER - A
- MER - B
Entry, Descent and Landing

Any steeper and you get to the ground too fast!

Any shallower and you “skip out” back into space!
Entry, Descent and Landing

- Entry Turn & HRS Freon Venting: Entry (E) – 70 min
- Cruise Stage Separation: E – 15 min
  - Entry: E – 0 s, 125 km, 5,700 m/s
  - Parachute Deployment: E + 295 s, 11.8 km, 430 m/s
  - Heatshield Separation: E + 315 s, L – 105 s
  - Lander Separation: E + 325 s, L – 95 s
  - Bridle Deployed: E + 335 s, L – 85 s
  - Radar Ground Acquisition: L – 18 s
  - Airbag Inflation: 355 m, L – 10.1 s
  - Rocket Firing: L – 7 s, ~150 m, 90 m/s
  - Bridle Cut: L – 3 s, ~20 m
  - Bounces
  - Roll-Stop: L+2 min
- Deflation: L+20 min
- Petals & SA Opened: L+90 min
- Airbags Retracted: L+74 min
The Landing Ellipse

Only 100 X 20 Kilometers
Heatshield takes out 90% of the energy
Parachutes open at Mach 1.3 and slow the lander to 200 mph
Rockets and airbags do the rest
Once safe on the surface, it’s time to:

Open up the lander,
Unfold the rover,
Call home,
Look around, and
Get moving!
MER Animation

Mars Exploration Rover
Opportunity Landing Day
Egress and on with Surface Ops
Investigating Stone Mountain
Grinding into El Capitan

Sol 29B Pre-RAT

Sol 31B Post-RAT

APXS Rock and Soil X-ray Spectra at Meridiani
Searching for Signs of Water

Last Chance: 4.5 m back

7 cm

Last Chance  MI Mosaic
Searching for Signs of Water

Upper Dells MI Mosaic
Searching for Signs of Water

Upper Dells MI Mosaic
Foraging for Blueberries

Blueberry Bowl
Foraging for Blueberries

- Eye-in-hand technique used to target specific blueberry cluster for targeting MB placement from MI image
- The targeted pixel is approximately 26 pixels from the center pixel in the MI image which corresponds to a targeting error of 0.8 mm (all from 200 million miles away)
Foraging for Blueberries

- MB spectrum shows giant hematite lines on berry cluster
Moving On

Eagle Crater Traverse

Sol 56: Black Forest
Sol 55: Meringue
Sol 54: Mudpie
Sol 53: Neopolitan
Sol 52: "Goal5"

Attempted Exit
Exit
Leaving Eagle Crater
Investigating Bounce Rock
From here to Endurance Crater

Anatolia Fracture Zones

Endurance Crater

Fram Crater

Endurance Crater
90 Sols on Mars!
The Future
Multi-Agent Systems

Anchorbot
Cliffbot
RECON bot
Anchorbot
Robotic Construction
Aerial and Subsurface Exploration
Join the Adventure!

http://mars.rovers.jpl.nasa.gov