Motion Planning Technologies for Planetary Rovers and Manipulators

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Acknowledgments

• This paper summarizes the work of many people who contributed to both the on-board software, ground software and operational strategies used to command and control the Mars Exploration Rovers, Spirit and Opportunity

• They are:
  – Rover Navigation
    • Mark Maimone and Jeff Biesadecki
  – Robotic Arm
    • Eric Baumgartner, Robert Bonitz, and Chris Leger
  – Rover Sequencing and Visualization Planner (RSVP)
    • Brian Cooper, Frank Hartman, John Wright, Scott Maxwell, Jeng Yen

• References
Robotics for Planetary Exploration

- NASA/JPL flight missions utilizing robotic systems
  - Viking Landers (1976)
  - Pathfinder Lander and the Sojourner Rover (1997)
  - Phoenix (2007)
  - Mars Science Laboratory (2009)
Robotics for Planetary Exploration

- 2001: NASA Mars Odyssey, Japanese Nozomi Orbiter
- 2003: ESA Mars Express
- 2005: NASA Mars Reconnaissance Orbiter (Italian SHARAD)
- 2007: MARVEL
- 2009: NASA Telesat

Science pathways responsive to discovery
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

**WATER**
- When? Where? Form? Amount?
Mars Exploration Rover Landing Sites

- Water-formed hematite?
- Ancient lake sediments?
Robotic Field Geologists: Spirit & Opportunity

Panorama stereo camera and viewport for infrared spectrometer

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

Mobility
MER Payload and Cameras

- **Pancam**
  - high-resolution (16°x16°) color panchromatic stereo cameras
- **Mini-TES**
  - a mid-infrared point spectrometer
- **Microscopic Imager (MI)**
  - close-up imaging of rock and “soil”
- **Mössbauer Spectrometer (MB)**
  - analysis of iron in rocks
- **Alpha Particle X-Ray Spectrometer (APXS)**
  - detects elements in rocks and “soils”
- **Rock Abrasion Tool (RAT)**
  - used to remove outer surface of rocks for analysis of non-weathered rock material
- **Magnets and calibration targets**
  - to collect iron containing dust and for comparison to known sources
- **Engineering cameras**
  - **Navcam** – wide-angle stereo cameras (45°x45°) used for traverse planning
  - **Hazcam** – very wide-angle (120°x120°) stereo cameras used for identifying potential hazards to rover driving and arm movement
The Mobility/Navigation System

• Note: MER CPU is a single 12MHz radiation-hardened processor
Instrument Deployment Device (IDD)

Azimuth (J1)
Elevation (J2)
Elbow (J3)
Wrist (J4)
Turret (J5)
Front Hazcams
APXS
MI
RAT
MB (hidden)
Rover Motion Planning

Basic Mobility

- Arc (distance, delta-heading, mode, timeout)
- Prescribed Arc
- New Position ($x_1, y_1$)
- Initial Position ($x_0, y_0$)
- Move along circular arc or straight line path of commanded length - Open-loop relative to on-board position/heading estimate

Autonomous Navigation

- Turn_absolute (angle, timeout)
- Turn_relative (angle, timeout)
- Turn_to (x,y, offset, timeout)
- Goto_waypoint (x, y, tolerance, mode, timeout)
- Site Frame
- Autonomous traverse toward a commanded waypoint with on-board hazard detection using stereo vision - Closed-loop around position and heading estimate
Ground-Based Rover Motion Planning

- Terrain meshes are generated via Hazcam, Navcam and Pancam stereo image pairs
- Detailed rover motion planning accomplished using the Rover Sequencing and Visualization Planner (RSVP) which simulates the rover “settling” on the terrain
Ground-Based Rover Motion Planning

- Long range traverse planning consists of 20-40 meters of ground-directed driving followed by autonomous driving (typically restricted by energy and time-of-day constraints)
Ground-Based Rover Motion Planning

- Rover Motion Simulation – Spirit Sol 100
Ground-Based Rover Motion Planning

- Rover Motion Simulation – Spirit Sol 112
The MER vehicles employ sensors that can detect when the vehicle has already entered a potentially risky configuration, and stop it in its tracks (raising a *Motion Error*).

- Tilt check
- Motor fault (e.g., stall)
- Bogie/Differential Angle bounds

Additional sensing detects if the vehicle might enter an unsafe configuration if it were to start moving (raising a *Goal Error*).

- Activity Constraint Manager says the vehicle configuration is not appropriate for driving
- Guarded motion predicts a single path is not safe
- Autonomous navigation predicts *none* of its available paths is safe
- A driving command (autonomous or otherwise) timed out, thus failing to reach the specified goal
• MER vehicles also have the ability to predict (and therefore avoid) hazardous situations. The technologies that enable this are:
  – Stereo Vision Image Processing
    · Any stereo pair can be used: Hazcams, Navcam, and Pancam
  – Visual Odometry
    · The coarse position estimated by wheel odometry is refined by automatically tracking features in the environment
  – Traversability Analysis – Terrain data is fit to an appropriately-sized disc, and the resulting data is analyzed for:
    · Step Obstacles – Difference between extreme elevations within a patch
    · Tilt Obstacles – Terrain whose average slope exceeds some limit
    · Rough Terrain – Average elevation change over a patch exceeds some limit
Spirit Navcam Stereo Results
1. Take images
2. Accept only good data
3. Compute 3D Elevation
4. Save traversability information at each cell in a World Map
5. Choose a safe path that moves the rover closer to its goal

Autonomous Hazard Avoidance
Autonomous Hazard Avoidance Example

- Hazard avoidance has been used on Spirit many times to achieve long distance drives beyond the ground-directed drive distances.
- To date, Spirit has driven well over 4 km from the landing site to the Columbia Hills.
Guarded motion accepts a blind driving command only after verifying its safety using the existing World Map.

Only two possible outcomes: perform the commanded drive, or stay put and raise a Goal Error.

Most often to ensure a safe and pre-imaged approach into a target area for IDD activities at the end of a long drive.

Guarded motion used extensively on the Opportunity rover to increase rover traverse rate since terrain is relative obstacle free.
Ground-Based Manipulation Motion Planning

- 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 in-situ instruments using the ground version of the IDD flight software
  - The reachable points are then tested in terms of detecting collisions between the IDD, rover, instruments and the environment using the ground version of the IDD flight software
  - 3D terrain meshes are also generated based on the stereo range maps
Ground-Based Manipulation Motion Planning

- Science targets are selected within the Science Activity Planner (SAP) are imported into RSVP
- Detailed motion planning of the IDD to reach the selected science targets is accomplished within RSVP
  - High-fidelity 3D modeling of the IDD, rover, instruments and terrain
  - Detailed simulations of IDD motion are driven by the ground version of the IDD flight software including terrain collision detection

IDD Motion Simulation

Front Hazcam of APXS on Lion Stone
Ground-Based Manipulation Motion Planning

- IDD Motion Simulation – Spirit Sol 137
Manipulation Collision Detection

• Performed both on as part of the ground validation of the manipulator sequences and on-board the rover to verify safe manipulator motions
  – Ground validation also includes terrain collision detection
• Technique determines collisions between geometric models of the robotic arm, rover, and associated hardware
  – Geometric models consist of Oriented Bounding Boxes (OBBs) and Oriented Bounding Prisms (OBPs)
  – Geometric models are arranged hierarchically to reduce the total number object-to-object intersection tests to perform
  – OBBs and OBPs tightly and efficiently bound the manipulator/rover geometry in a small number of primitives
Manipulation Collision Detection

Example Hierarchy

Collision Bounding Volumes
• After exiting Endurance Crater, the Opportunity rover drove over to the heatshield that was utilized to protect the rover and lander during the Entry, Decent and Landing (EDL) phase of the mission.

• The IDD was then utilized to inspect the heat shield in high spatial resolution to determine engineering measurements such as the total material ablation, etc.
Manipulation Collision Detection
Manipulation Collision Detection

- IDD Motion Simulation – Opportunity Sol 334
Conclusions

- The Mars Exploration Rovers have utilized a combination of both ground-based (sequenced) and on-board (autonomous) motion planning techniques
  - Rover motion planning makes use of a virtual terrain environment coupled with estimated wheel/soil terrain interactions to sequence rover with respect to desired science targets
  - Long rover traverses are autonomous with on-board path planning around detected obstacles
  - Robotic arm motion planning is primarily ground directed with on-board collision detection
  - Manipulator sequences are validated through a high-fidelity simulation of the flight software that is used to control the robotic arm
- Future work includes including terrain collision detection on-board as part of the flight software and utilizing advanced motion planning techniques to perform automatic instrument placement activities
Join the Adventure!

http://marsrovers.jpl.nasa.gov