CS-417 INTRODUCTION TO ROBOTICS AND INTELLIGENT SYSTEMS

Planetary Exploration: Autonomous Over-the-Horizon Navigation
Outline

• Mars Exploration
• Background
• Main Blocks are: Terrain Modeling, Path Planning, Motion
• Control Tests from 2006 and 2007
Exploring Mars

Sojourner

Spirit

Phoenix

Beagle II
View from Sojourner
Missions - Pathfinder 1997
Missions – Spirit: Day 155
More Current Data

• As of Sol 2055 (Oct. 14, 2009), Spirit's total odometry remains at 7,729.93 meters (4.80 miles).
• As of Sol 2049 (Oct. 29, 2009), Opportunity's total odometry is 18,622.44 meters (11.57 miles).
• 2,022nd sol, (Oct. 1, 2009) Opportunity found another meteorite.
• Spirit is trapped in a sand pit.
A Panorama from Spirit
Phoenix in action
For more information visit:

- http://marsrovers.jpl.nasa.gov/home/
- http://phoenix.lpl.arizona.edu/index.php
- http://www.google.com/mars/
Long-Term Goal: Autonomous Robotic Exploration
Current Research Objectives

• Over-the-horizon Navigation in a Single Command Cycle

• Assumptions:
  – Rough A Priori Knowledge:
    • Localization
    • Terrain
  – Terrain Sensing Using LIDAR
Global Localization → Global Path Plan → Acquire Scan → Process Scan → Localize → Segment Global Path → Localize → Follow Path → Local Path Plan → Local Path Plan → Global Path Plan → Global Localization
Experimental Testbed 2006

- CSA Mars Terrain
  - 60m x 30m
- Pioneer P2-AT Robot
- ILRIS-3D LIDAR
  - 3D point cloud
  - 1.5km-range (trimmed down to ~30m)
  - 40 degree FOV
Mars Emulation Terrain

A
B
C

30m
60m
Terrain Modeling

- Raw Data: 3D Point Cloud
  - Variable resolution
  - Long shadows

- Terrain Model based on Irregular Triangular Mesh (ITM)
  - Variable Resolution (Dense where required)
  - Memory-Efficient
  - Preserves Topography and Useful for Navigation
Terrain Modeling: Irregular Triangular Mesh (ITM)

- Delaunay triangulation,
- Cartesian coordinates
- Decimated mesh
- Raw data
- Delaunay triangulation,
  polar coordinates
2006, Scans Collected: 96
• Successful Traverses
• A Sequence of Local Traverses
• Operator Intervention Necessary at Every Step (Semi-Autonomous)

• Achieved Traverse on the order of 150m
2006, Over-The-Horizon Traverses
Lessons Learned from 2006 Testing Period

- Extensive Field Testing EXTREMELY useful!
- Validate Navigation Software
- Active Vision Great under Poor Lighting
- Identify Issues Requiring further Development
Lessons Learned

• Top level issues:
  – Environment Sensor Unwieldy
    • FOV Too Narrow
    • Logistics a Nightmare
Lessons Learned

• Top level issues:
  – Environment Sensor Unwieldy
    • FOV Too Narrow
    • Logistics a Nightmare
  – Horizon Sometimes Much Closer than Expected
  – Environment Scans Need to be Interpreted (Shadows)
2007 Test Campaign
Updates in the Testbed 2007

A 360° LIDAR scanner
• A SICK LRF
• Mounted on a pan-unit
Scan Processing

- Raw data
- Delaunay triangulation, Cartesian coordinates
- Delaunay triangulation, polar coordinates
- Decimated mesh
2007, Scans Collected: 93
Comparison between the two LIDARs

**SICK on Pan Unit**
- 360° coverage
- Portable
- Easy Interface
- Limited Range
- Lower resolution
- Lower accuracy
- Low cost ~12K

**ILRIS 3D**
- Highly accurate
- Long range
- High resolution
- Limited field of View
- Restrictive Interface
- Unwieldy
- Not Portable
- High cost ~250K
## Irregular Triangular Mesh Decimation

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Acceptable error 1.5cm

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CS-417 Introduction to Robotics and Intelligent Systems
2007, Over-the-Horizon Navigation

- Global Localization
  - Global Path Plan
    - Acquire Scan
      - Process Scan
    - Follow Path
      - Local Path Plan
        - Segment Global Path
          - Localize
            - Global Path Plan
Global Path Plan and Segmentation

- Produce a rough global path using the low-resolution model
- Find the portion of the global path that is inside the local scan
- Select the largest acceptable triangle closest to the furthest accessible point
Path Planning

- Convert ITM into Connected Graph
Path Planning

• Convert ITM into Connected Graph
• Path Planning using Graph Search Algorithms:
  – Dijkstra, A*
Planning

• Convert ITM into Connected Graph
• Path Planning using Graph Search Algorithms:
  – Dijkstra, A* search algorithms
• Different Cost Functions $Q$
  – Number of triangles $Q = 1$
Planning

• Convert ITM into Connected Graph
• Path Planning using Graph Search Algorithms:  
  – Dijkstra, A*
• Different Cost Functions $Q$
  – Number of triangles
  – Euclidean distance $Q = \| \bar{x}_i - \bar{x}_j \|$
Planning

• Convert ITM into Connected Graph
• Path Planning using Graph Search Algorithms:
  – Dijkstra, A*
• Different Cost Functions $Q$
  – Number of triangles
  – Euclidian distance
  – Slope of each triangle $v_j = \frac{p_{j}^{1} \times p_{i}^{2}}{\|p_{j}^{1}\| \|p_{j}^{2}\|}$
Planning

• Convert ITM into Connected Graph

• Path Planning using Graph Search Algorithms:
  – Dijkstra, A*

• Different Cost Functions $Q$
  – Number of triangles
  – Euclidian distance
  – Slope of each triangle
  – Cross triangle slope
Path Planning

• Convert ITM into Connected Graph
• Path Planning using Graph Search Algorithms:
  – Dijkstra, A*
• Cost function:
  – Distance travelled
  – Penalty for uphill slope
  – Infinite cost for moving into too-steep triangles
  – Roughness of the area under the footprint of the robot
  – A* is biasing the cost towards the destination
Path Simplification

- Path Simplification
  - Point-Robot

- Path Simplification
  - Safety Corridor
Local Path Plan
Motion Control

• Sensor Suite: Wheel Odometry, IMU, Heading sensor, No Visual Odometry

• 3D Pose Estimation:
  Filter combines IMU+Odometry
  No uncertainty estimation (currently)

• Path approximated with Catmull-Rom spline for smoothness

• Astolfi controller follows the spline trajectory
Closed Loop Tests
Closed Loop Tests
Closed Loop Tests
The Mars Terrain and Trajectories
Fully Autonomous Navigation from flat to canyon
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Fully Autonomous Navigation
from flat to canyon
Fully Autonomous Navigation
from crater to canyon
Fully Autonomous Navigation
from crater to canyon
Fully Autonomous Navigation from crater to canyon
Fully Autonomous Navigation from crater to canyon
Fully Autonomous Navigation from crater to canyon

Wheel odometry

Start

Goal

5 meters

Wheel odometry
Lessons Learned

• There is a need for Localization
• Limitations in the rover capabilities
• Several components require domain specific parameters
• Extensive testing extremely useful
Future Work

• Terrain analysis
  – What does the robot see?
    • Open area, cluttered environment, the side of a hill?

• Different mobility platforms

• State estimation:
  – Implement 6DOF KF or RBPF

• Localization

• SLAM
Conclusions

• Active vision is accurate and robust
• ITM representation is compact and accurate
• ITM useful for environmental modeling and also for path planning
• Successful Over-the-Horizon navigation an important step towards autonomy capabilities in planetary exploration
Mars Exploration Rover (NASA)