CS-765 SPATIAL REPRESENTATION AND MOBILE ROBOTICS

Space Robotics
On-Orbit Servicing of Satellites

Work done at the Canadian Space Agency
AUTONOMOUS CAPTURE OF A TUMBLING SATELLITE

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Space Technologies
Canadian Space Agency
Montréal, Canada

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Motivation

• More than 10K objects bigger than 10cm in orbit
• More than 280 satellites currently in GEO orbit
• The life span of a satellite is around 10 years
• The cost of sending even a small satellite is $10M

SOLUTION

• Use a servicing satellite to extend the life of a satellite or to de-orbit an object
On-Orbit Servicing Opportunities

- OOS missions with Canadian involvement

Shuttle Return to Flight  XSS-11  Orbital Express

Hubble servicing study  TECSAS  MBS, Canadarm2, Dextre
OOS Related Missions
(examples)

- Russian Progress Vehicle
- Japan ETS-7 Mission
- NASA DART Mission
- ESA ATV Mission
- CX-OLEV Mission
- DARPA NRL SUMO Mission
Autonomous Control

- Toolbox for Reactive Autonomy
- Hierarchical Finite State Machines
High-Level Scenario
Laboratory Setup

Laser Camera System (LCS), Cape S/W from Neptec

The SARAH hand from Laval University
Autonomous Capture
Trajectory Generation of the Target Satellite
A standard implementation of an extended Kalman Filter is used to track the pose of the target satellite
- Signal at 2Hz
- Delay of 1 step
- EKF prediction of 1 step
Tracking
Capture
Main Accomplishments

- Autonomous capture of a tumbling satellite
- Transatlantic monitoring and operation of the capture procedure
- Emulate the motion of a tumbling satellite using a 7-DOF manipulator
Conclusions

• Cortex greatly facilitated the creation of autonomy scenarios

• The LCS from Neptec provided robust pose estimation (varying illumination conditions, obstructions)

• First step of autonomous capture in a laboratory setting
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://phoenix.lpl.arizona.edu/index.php](http://phoenix.lpl.arizona.edu/index.php)
- [http://www.google.com/mars/](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
Local Path Planning

Robot Arrives At First Way Point

Robot is Localized

Operator Selects Destination

Global Path Planning

Local Scan

Second Local Scan
Over the Horizon Navigation

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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
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
- Polar coordinates
- Decimated mesh
Spatial Representation and Mobile Robotics
2006, Scans Collected: 96
2006, Over-the-Horizon Traverses
Semi-Autonomous

- Successful Traverses
- A Sequence of Local Traverses
- Operator Intervention Necessary at Every Step (Semi-Autonomous)

- Achieved Traverse on the order of 150m
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
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Acceptable error 1.5cm

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2007, Over-the-Horizon Navigation

Global Localization → Global Path Plan → Acquire Scan

Follow Path → Local Path Plan → Process Scan

Segment Global Path → Localize
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
  – Euclidian 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
  – Euclidean 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 crater to canyon
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from crater to canyon
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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 sees?
    - 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)