Robust and Opportunistic Planning for Planetary Exploration

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Objective

• Use onboard planning, scheduling and execution techniques to...
  - Enable a rover to take advantage of new science opportunities
  - Enable a rover to respond appropriately to unexpected problems (e.g., traverse takes longer than expected)
  - Improve overall utilization of rover resources (e.g., power, memory)

• Current mission ops is to generate command sequences on ground
  - Time consuming and largely manual process
  - Not easy to build flexibility into sequence
  - Problems typically require Earth intervention
  - No onboard way to respond to new science opportunities
Challenges for onboard planning and execution

- Onboard system needs to reason about a rich model of resource and temporal constraints
  - Generate valid command sequences
  - Make science/resource trade-offs
  - Dynamically handle new science opportunities
- Must interact with spatial-reasoning capabilities
  - Dominating characteristic of rover ops is traverse to waypoints
  - Must coordinate with several levels of navigation software (path planning, obstacle avoidance, position estimation)
- Must handle high degree of uncertainty since exploring unknown terrain
  - Large amount of uncertainty in estimations for
    - Activity durations
    - Activity resource usage (e.g., power)
    - Current state (e.g., rover pose)
System Architecture

Science Analysis
- Science goals
- Science alerts
- Rocks, Features

CASPER Planner
- Commands
- Command status, state/resource updates

TDL Executive

Global Pathplanner
- Path queries

CLARAty Functional Layer capabilities

Navigation
Vision
Science Instruments

Rover hardware and simulation
Science Alerts
- System can respond to new science opportunities that are triggered by data analysis
- Different levels of reaction
  - Stop and call home
  - Collect additional data from current position
  - Alter rover’s path to be closer to object
- System will only add science alerts if required resources are available (i.e., will not delete other science targets or required activities)

Plan Optimization
- System can reason about goal priorities and other soft constraints
- User-defined preferences are used to compute plan quality
- Uses iterative process to generate higher quality plans
- Can be used to take advantage of unexpected resource availability by scheduling additional science operations
High-Level Planning Algorithm

- **Input:** prioritized science goals (oversubscribed) time and resource constraints
- **Initial plan generation:** DFBB
- **Repeat:**
  - Process updates from Executive
  - Commit and/or rescind activities
  - Optimize:
    - Resolve conflicts
    - Attempt to satisfy science alerts
    - Attempt to satisfy additional science goals
  - If idle, attempt to move up future activities
System Testing

- Performed series of tests in simulation and using rover hardware in JPL Mars Yard

- Have used several different hardware platforms for testing through CLARAty

- Recent tests have primarily used the FIDO rover, which was used in MER field tests
Demonstration overview

- **Initial plan generation**
  - Three prioritized, science targets will be given to system
  - Initial plan will contain only two targets due to time constraints

- **Plan execution**
  - Plan will be autonomously executed onboard rover
  - Relevant states and resources are continuously tracked (e.g., position, energy)

- **Science alerts**
  - During rover drives, several science alerts will be identified and handled by taking extra images

- **Additional re-planning**
  - Rover will complete first traverse earlier than expected
  - After traverse completes, third science target will be added to plan since more time is now available
Three prioritized science targets, representing ground-specified goals, are given to the system.

• Note, Target 2 is lower priority than Targets 1 and 3.
The planning system generates an initial plan to gather requested science data.

This plan only contains two of the three science targets due to time and power constraints.
During rover traverses, images are taken by hazard cameras for obstacle avoidance.

Using these images rocks are automatically identified by our Rock Finder software.
Data analysis software is then used to identify rocks of interest. Here, we are looking for rocks that match a pre-specified "target signature" of a light albedo (i.e., white rocks). If any such rocks are found, a science alert is triggered.
During the first traverse, several science alerts occur. The planner checks current resource and state information and if possible, schedules additional images of the rocks of interest. To take images, the rover is turned to face the target rock and then returns to its original traverse.
Sample image taken in response to a science alert
Replan to achieve additional science targets

- The first ground-specified science target is reached in less time than expected.
- The extra time enables the planning software to dynamically add Target 2 to the plan.

Now able to include lower priority target in plan
Other tested scenarios

- Other science alert responses
  - Stop and call home (wait for response from ground before taking further action)
  - Drive closer to rock to take additional science measurements

- Re-planning in response to problems
  - Handle resource oversubscription (by reducing rover activities)
  - Handle unexpected obstacles (by re-ordering or deleting hard to reach targets)
Science Alert Video
Related Work

- **Contingent Rover Language (CRL) (Bresina, et al., 1999)**
  - Allows contingency branches in rover plans
  - Produced by CPS (Contingent Planner/Scheduler) and then interpreted by Exec
  - Planner is ground-based; exec is onboard
  - Can only handle contingencies that are pre-planned

- **ASE (Chien, 2001)**
  - CASPER and SCL exec flying onboard

- **Remote Agent Experiment (RAX) (Jonsson, 2000)**
  - Flown on NASA Deep Space One (DS1) mission
  - Used batch planner and executive

- **Other three layer approaches (Bonasso, 1997; Alami, 1998; Gat, 1998)**
Future Work

- Increase levels of autonomy for science alert response
  - Driving closer to target
  - Using additional instruments
  - Close-contact measurements
- Apply system to handle add’l faults and exceptions
Extra Slides
System framework

Data Analysis
- Novelty
- Target Signature
- Rock Sampling

Planning / Scheduling / Execution
- Optimize
- Repair
- Execution

Science Goals

Science Alerts

Rock Features

Albedo - Shape - Visual Texture

Feature Extraction
- Rock Detection

Commands
- State/Resource Updates

Data

Control / Functional Layer
- Path Planning
- Navigation
- Estimation
- Vision
- Locomotion
...
Developed to closely coordinate goal-driven and event-driven behavior
Integration of CASPER planning system and TDL executive
  - CASPER (Chien, 2001)
    - Continuous planning and scheduling system
    - Handles temporal, resource and state constraints
    - Continual modification of plan based on changing operating context
  - TDL (Simmons, 1998)
    - Expansion of tasks based on current state information
    - Execution, monitoring and exception handling
Part of CLARAty robotic architecture (Nesnas, 2003)
Differences with typical three-layer architecture
  - Planning is continuous (secs) vs. batch (mins)
  - Only small window of activities is sent to exec (which allows re-planning to occur on parts of plan that are only 20-30 seconds in future)
  - Closes loop with data analysis (as part of OASIS system)