Robust and Opportunistic Planning for Planetary Exploration

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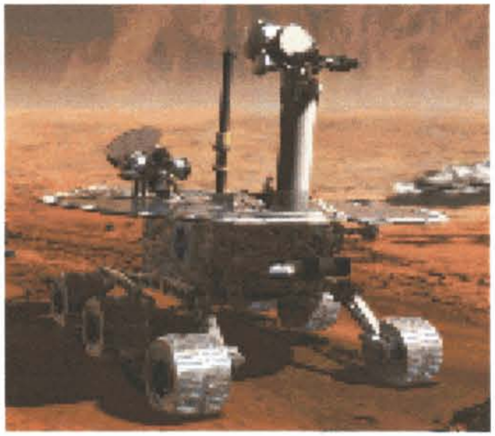
Objective

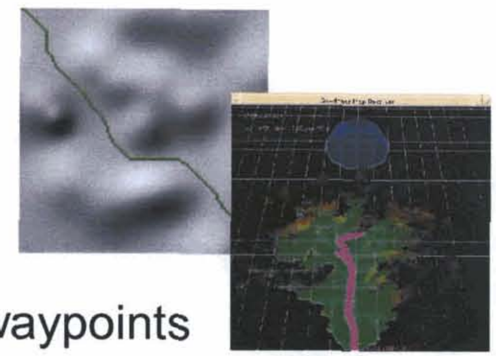
- Use onboard planning, scheduling and execution techniques to…
  - Enable a rover to take advantage of new science opportunities
  - Enable a rover to respond appropriately to unexpected problems (e.g., traverse takes longer than expected)
  - Improve overall utilization of rover resources (e.g., power,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

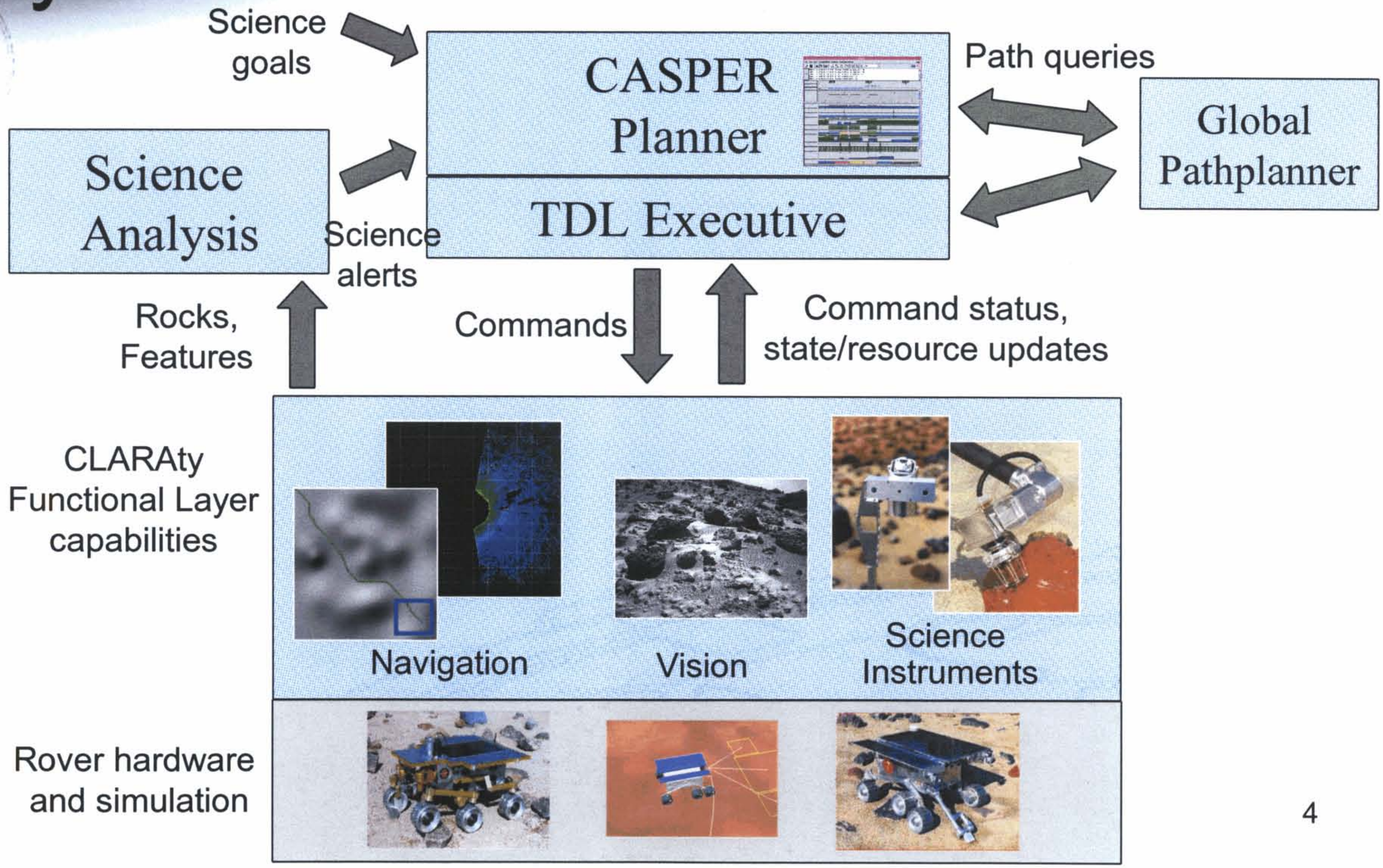
- Onboard system needs to reason about a rich model of resource and temporal constraints
  - Generate valid command sequences
  - Make science/resource trade-offs
  - Dynamically handle new science opportunities



- 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



Planning System Features

- 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

Rocky 8

FIDO

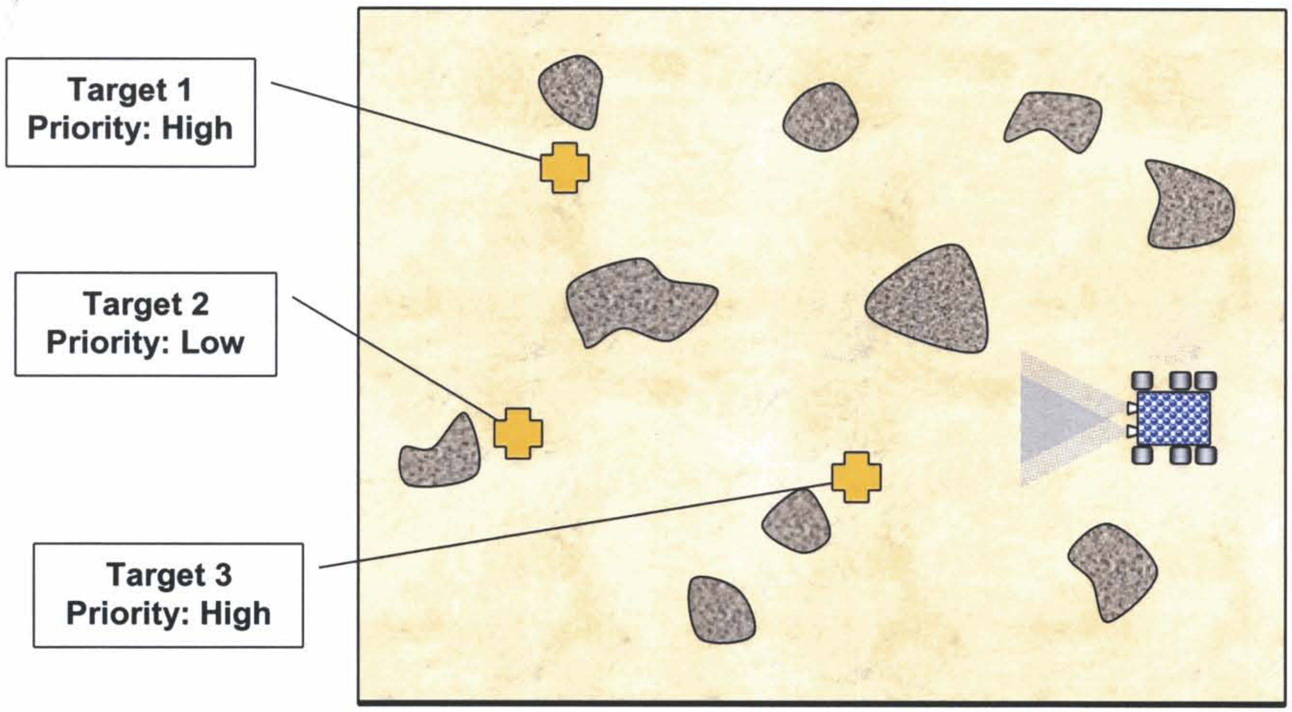
- Recent tests have primarily used the FIDO rover, which was used in MER field tests

Rocky 7

Demonstration overview

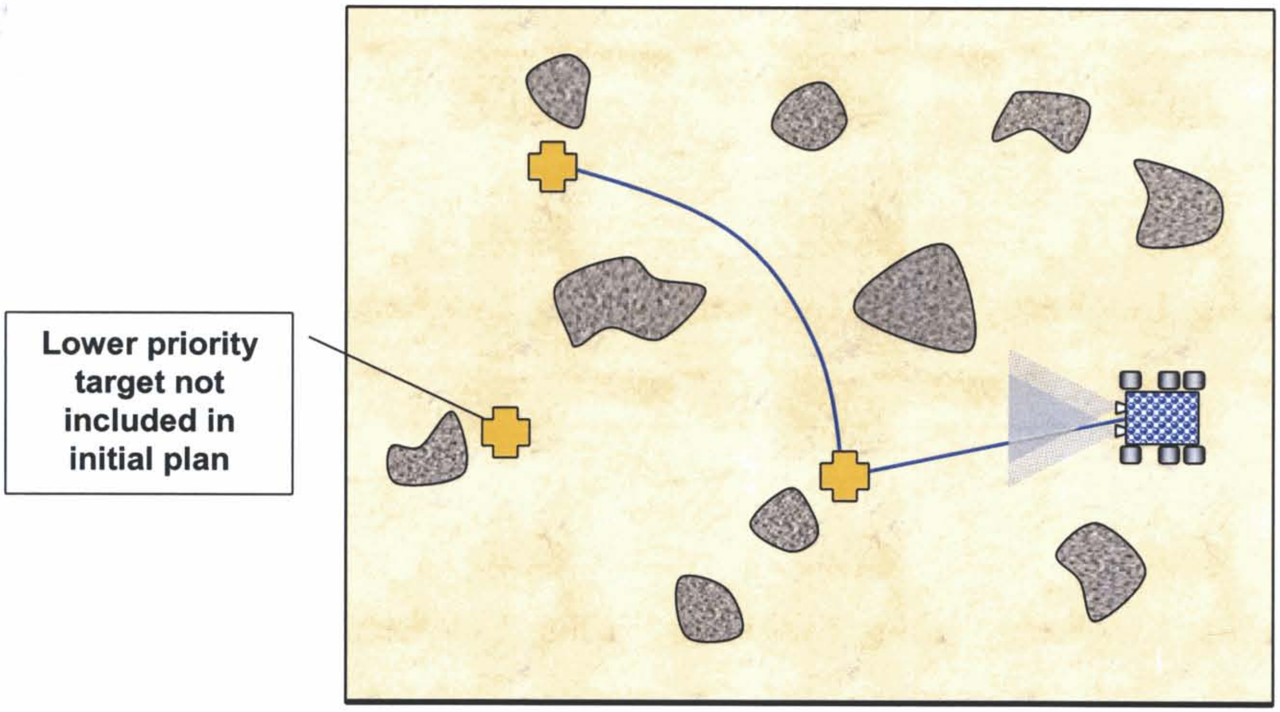
- Initial plan generation
  - Three prioritized, science targets will be given to system
  - Initial plan will contain only two targets due to time constraints
- Plan execution
  - Plan will be autonomously executed onboard rover
  - Relevant states and resources are continuously tracked (e.g., position, 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

Initial Science Targets



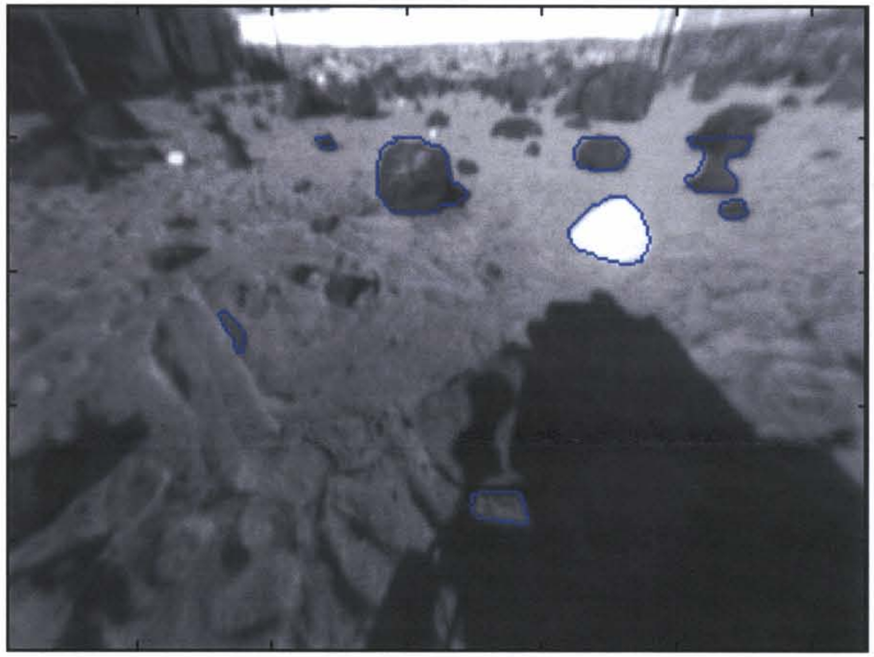
- Three prioritized science targets, representing ground-specified goals, are given to the system.
- Note, Target 2 is lower priority than Targets 1 and 3.

Plan Generation



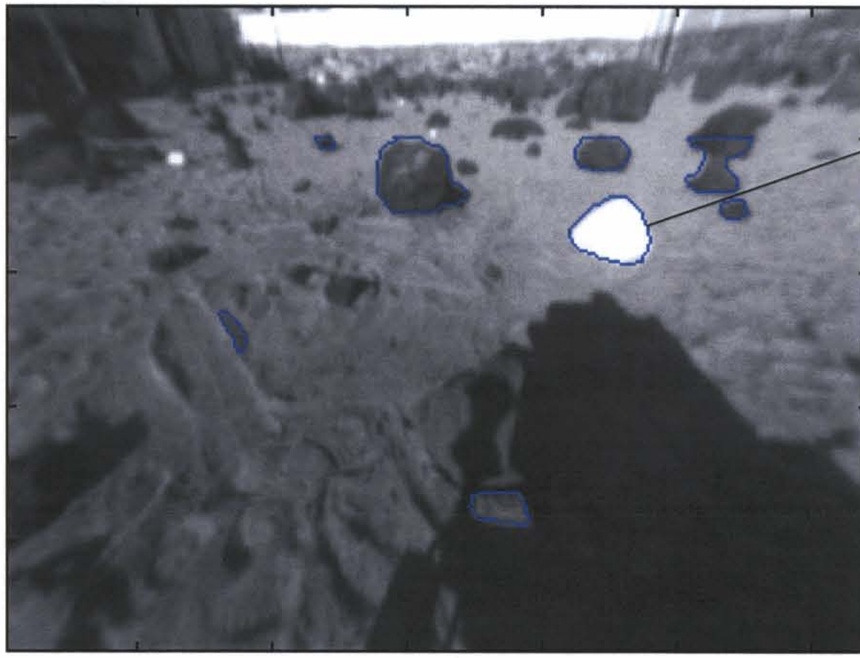
- The planning system generates an initial plan to gather requested science data.
- This plan only contains two of the three science targets due to time and power constraints.

Rockfinding
(provided through OASIS rockfinder)



- During rover traverses, images are taken by hazard cameras for obstacle avoidance.
- Using these images rocks are automatically identified by our Rock Finder software.

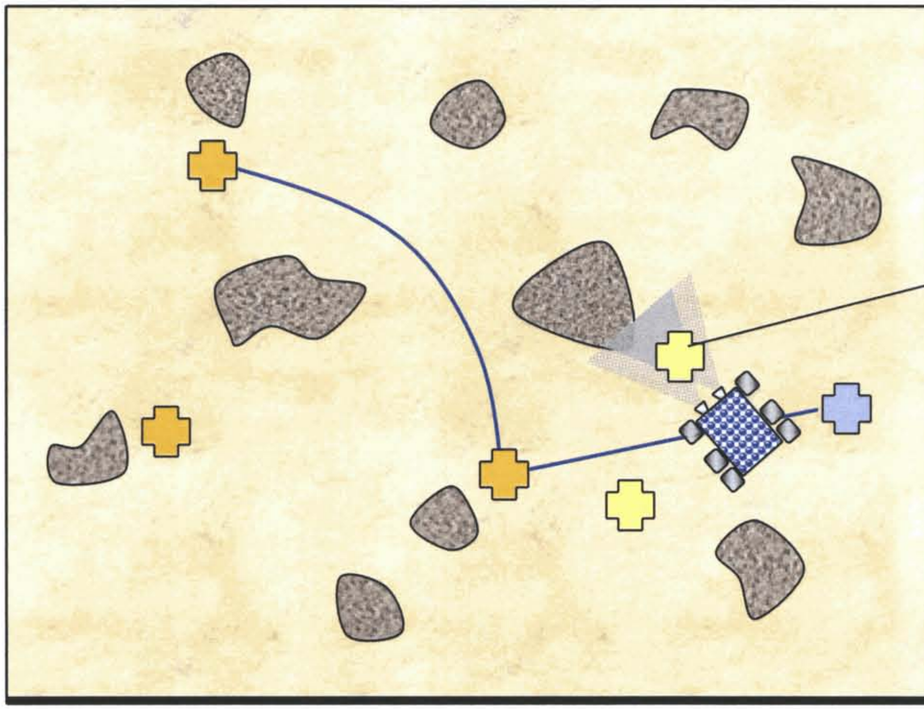
Identifying rocks of interest
(provided through OASIS data analysis)



White rock triggers science alert

- 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.

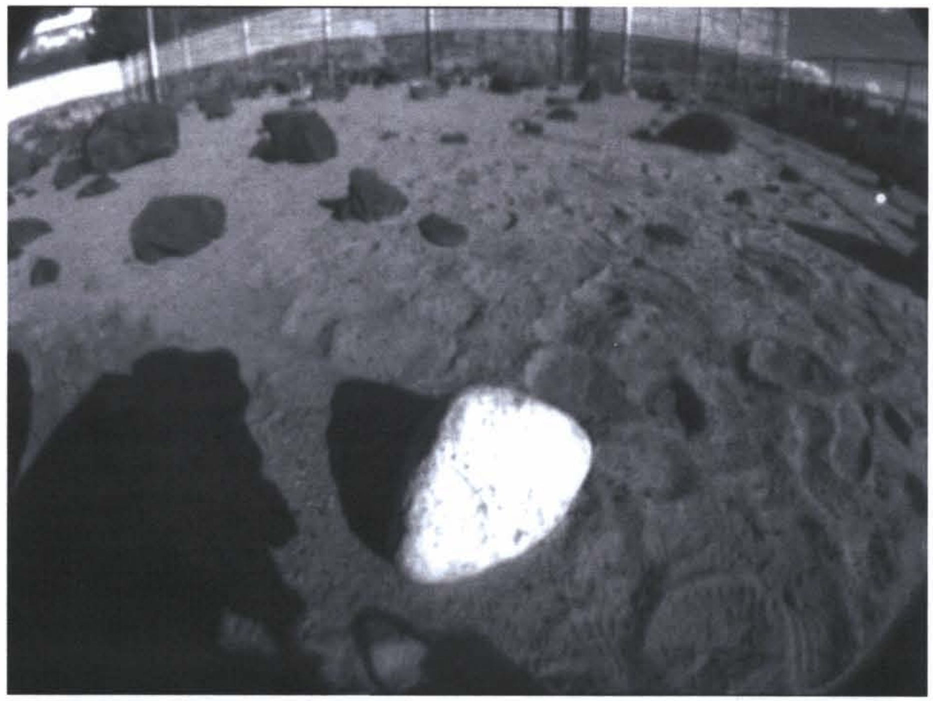
Science Alerts



New science observation

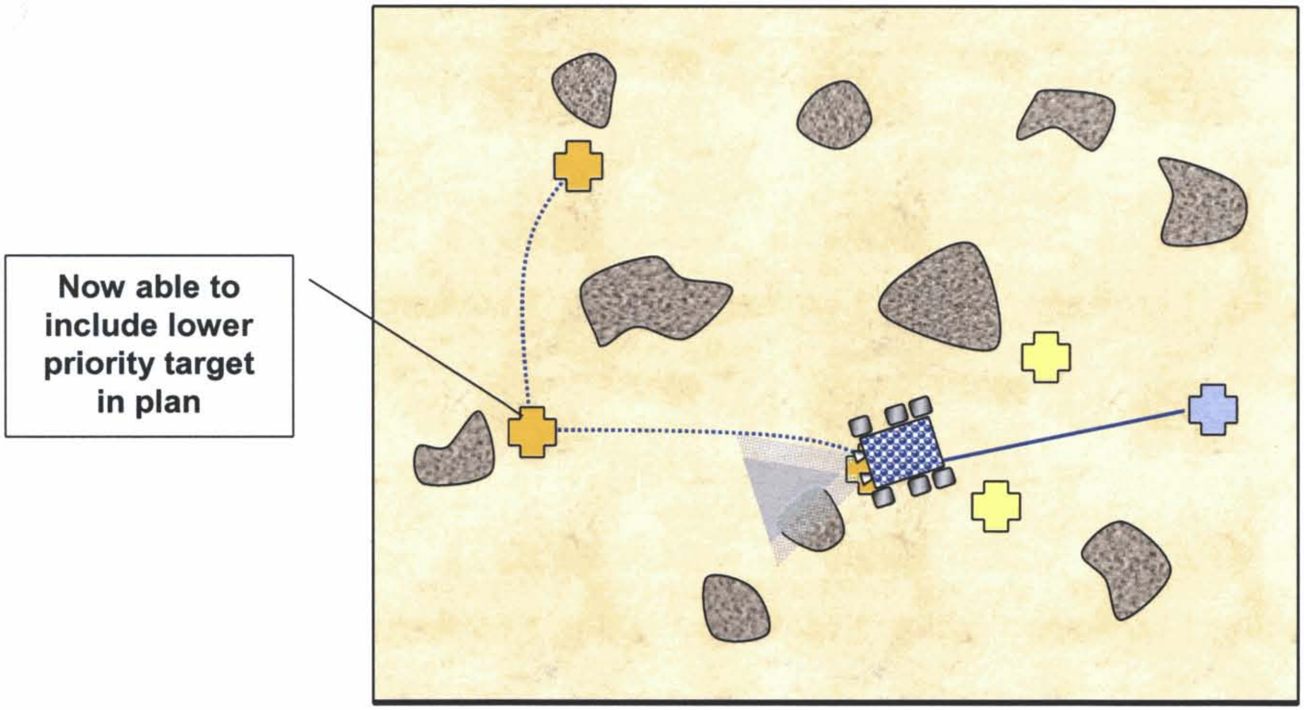
- During the first traverse, several science alerts occur.
- The planner checks current resource and state information and if possible, schedules additional images of the rocks of interest.
- To take images, the rover is turned to face the target rock and then returns to its original traverse.

Science Alert Image



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.

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

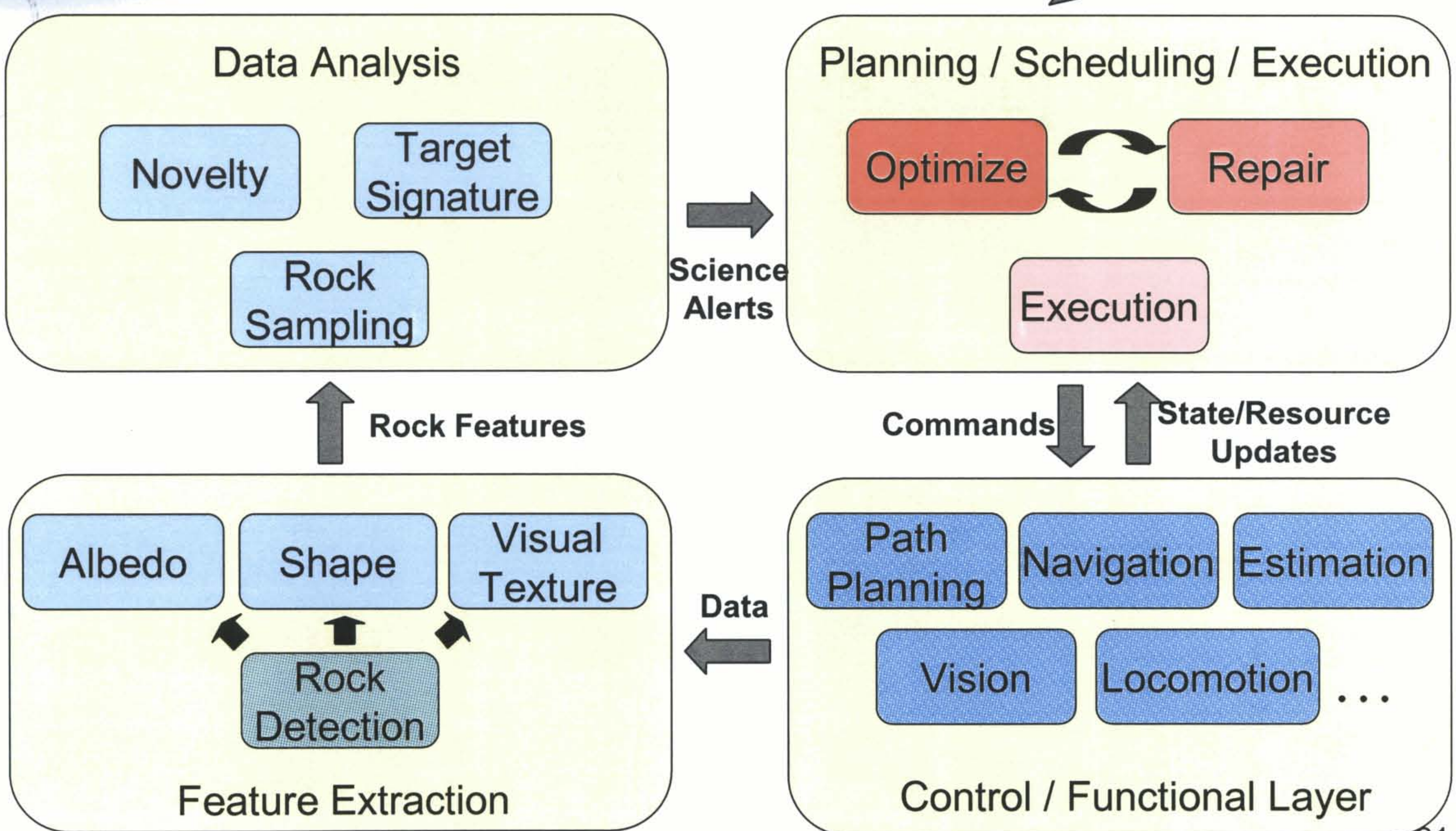
- Contingent Rover Language (CRL) (Bresina, et al., 1999)
  - Allows contingency branches in rover plans
  - Produced by CPS (Contingent Planner/Scheduler) and then interpreted by Exec
  - Planner is ground-based; exec is onboard
  - Can only handle contingencies that are pre-planned
- ASE (Chien, 2001)
  - 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



CLEaR System
(Closed-Loop Execution and Recovery)

- 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)