Opportunistic Planning and Execution for Planetary Exploration

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Introduction

The Mars Exploration Rovers have entered their second year of surface operations. During this time they have acquired vast amounts of scientific data and made new discoveries about the nature of the planet. While mission planning for rover operations has been made more efficient during the course of the mission it still remains a time consuming and largely manual process. The rovers have also demonstrated new levels of autonomous planetary exploration. These onboard capabilities enable the rovers to drive further and collect more science data than would otherwise be possible. However, when the plan does not go as expected, the onboard control does not always make the most effective use of available resources including taking advantage of new science opportunities and responding when activities take longer than expected.

We are developing technologies to increase the autonomous capabilities of future rover missions. Our objectives are to make rovers easier to command and to enable them to make more effective use of rover resources when problems arise or when things go better than expected. We will demonstrate OASIS (Onboard Analysis Science Investigation System) which combined planning and scheduling techniques with machine learning to enable rovers to perform robust and opportunistic science operations.

OASIS includes a continuous planning system to generate operations plans given prioritized science goals and mission constraints and to monitor and repair plans during execution. The system also includes a data analysis unit that uses machine learning algorithms to perform onboard processing of collected science data. When a science opportunity is detected, one or more requests are sent to the planning and execution system which attempts to accomplish these additional objectives while still achieving current mission goals.

We have demonstrated the OASIS system at the Jet Propulsion Mars Yard using prototype Mars rover hardware. For the purposes of this demonstration, we will use the Roams high-fidelity rover simulation (Jain *et al.* 2003). Roams simulates Martian terrain and rover hardware, including wheels, suspension system and cameras. From the perspective of our software, running with the Roams simulator is equivalent to running with actual hardware.

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OASIS

OASIS consists of the following components:

Planning and Scheduling: generates operations plans for mission goals and dynamically modifies plan in response to new science requests.

Execution: carries out the rover functional capabilities to perform the plan and collect data and monitors execution.

Feature Extraction: detects rocks in images and extracts rock properties (e.g. shape and texture).

Data Analysis: uses extracted features to assess the scientific value of the planetary scene and to generate new science objectives that will further contribute to this assessment.

The following sections provide a brief overview of OASIS. For more details, the reader is referred to (Estlin *et al.* 2005; Castano *et al.* 2005).

Planning and Scheduling

Planning and scheduling capabilities in OASIS are provided by CASPER (Chien *et al.* 2000), which employs a continuous planning technique where the planner continually evaluates the current plan and modifies it when necessary based on new state and resource information. At any time an incremental update to the goals or current state may update the current plan. This update may be an unexpected event (such as a new science opportunity) or a current reading for a particular resource level (such as power). The planner is then responsible for maintaining a plan consistent with the most current information.

A plan consists of a set of grounded (i.e., time-tagged) activities that represent different rover actions and behaviors. Rover state in CASPER is modeled by a set of plan timelines, which contain information on states, such as rover position, and resources, such as power. Timelines are calculated by reasoning about activity effects and represent the past, current and expected state of the rover over time. As time progresses, the actual state of the rover drifts from the state expected by the timelines, reflecting changes in the world. If an update results in a problem, such as an activity consuming more memory than expected and thereby over-subscribing RAM, CASPER re-plans, using iterative repair to address conflict.

Plan Execution CASPER monitors updates from the Executive as the plan is executed, checking for problems that must be resolved or opportunities that can be exploited. A problem can occur with an activity at any point during its lifetime. For examples, an update may indicate that there will be a problem with an activity scheduled to start at some time in the future. In this case, CASPER will use iterative repair as part of the optimization loop to try to resolve the conflict.

The Executive itself monitors problems with activities that are currently executing. If a problem is detected, it is the responsibility of the executive to abort the activity and send an update to CASPER to let CASPER know that the activity was aborted.

While the first priority of the planning and scheduling system is to ensure robust execution, it is also continually checking for opportunities to increase science return. An update from the Executive may indicate that an activity took less time or energy than predicted. In this case, it may be possible to achieve a goal that was not included in the initial plan. During the optimization loop, if all conflicts have been resolved, CASPER will select a high priority goal from the set of unsatisfied goals and add it to the schedule. This will most likely introduce new conflicts and CASPER will begin work attempting to repair the plan.

If an opportunistic science opportunity has been identified by Data Analysis, CASPER will try to add it to the plan. Again, this is likely to introduce conflicts and iterative repair will be used to try to fix them. It may be that the rover's schedule is too constrained to achieve the opportunistic goal. We set a timer for each opportunistic goal and if the timer expires before the goal is achieved, the goal is permanently deleted.

OASIS uses TDL (Simmons and Apfelbaum 1998) for its Executive and the CLARAty (Nesnas *et al.* 2003) functional layer for low-level robotic capabilities.

Feature Extraction

OASIS enables rovers to look for new science opportunities in data that is collected during plan execution. Currently, the system looks for interesting rocks in images that are collected for navigation. Each image is segmented using a rock identification algorithm based on edge detection and tracing. Next, a set of properties is extracted from each rock. Currently we extract information about the rocks albedo and shape.

Data Analysis

OASIS runs a set of data analysis algorithms on the collected features to look for interesting rocks. Two of these algorithms can result in the generation of science alerts: key target signature and novelty detection. Key Target signature enables scientists to efficiently and easily stipulate the value and importance of certain features. Rocks are then prioritized as a function of the weighted Euclidean distance of their extracted features from the target feature vector. Novelty Detection detects and prioritizes unusual rocks that are dissimilar to previous rocks encountered.

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