1 Abstract

In order to better account for competing requirements of safety, science, and engineering concerns, space missions must reason about the risks and rewards of plans with uncertain system variables (such as probabilistically varying activity duration, power consumption, and terrain irregularity) in a principled fashion. We propose to extend an existing, deployed automated planning and scheduling system to (1) generate and replan sequences based on this information to balance risks and rewards (i.e. improve expected utility), (2) project uncertain, continuous and discrete states, resources, effects of activities, start times and durations of activities, temporal constraints between activities, and utility, and (3) generate contingency plans for robust execution in the presence of uncertain outcomes. While the system will be applicable to many space missions for both ground and onboard mission planning, we will demonstrate planning with uncertainty for scenarios involving a simulated, autonomous Mars Science Laboratory (MSL) rover while working towards infusion into mission ground planning systems (including MSL extended operations).

We will do this in three ways: (1) by using local search to refine and modify plans in order to improve robustness and expected utility. This requires reasoning about the uncertainties associated with different activities and the values or utilities of the different objectives. The local search process can use this information to replace and/or reorder activities, thereby improving plan robustness and utility. (2) by approximating projections of arbitrary probability distributions of system variables representing with a Monte Carlo simulation. This provides "anytime" approximation results, the precision of which a planner can balance with available computation. We will also vary resolution of approximations for different variables over different time periods to focus computation on needs of the planning system. (3) and by adding contingency branches to the plan, so that different courses of action can be pursued depending on the actual outcome of actions and actual availability of resources. This also improves plan robustness and utility, because it allows the plan to react differently to different circumstances.

The expected result is a system that can generate sequences of hundreds of activities while handling uncertain information, including tens of uncertain state/resource variables, necessary for a day of a spacecraft's operations. We propose to demonstrate replanning for unexpected events with computational and memory performance acceptable for flight hardware. This capability is an order of magnitude larger both in number of plan steps and state variables than exhibited by existing approaches, which also suffer from representational limitations (e.g. no continuous resources) and memory explosion (as with MDP approaches).

The resulting planning and scheduling system will enable scientists, operations staff, and autonomous spacecraft to model uncertain, discrete and continuous system variables and metrics, reason about alternative scenarios, and automatically balance risk and reward (maximize expected utility) for short and long-term plan horizons. Almost all (if not all) missions must plan based on uncertainty and can benefit from using an automated planning system that handles uncertainty in a principled fashion.

This proposal addresses the Planning and Execution focus of the Automated Reasoning area of the call by providing "large-scale concurrent planning under uncertainty involving continuous quantities such as time and resources." The team is highly qualified to perform this work because of our research background in planning under uncertainty, experience in deploying automated planning systems (e.g. CASPER for EO-1, Mission Data Systems for MSL), and over 20 years of experience on deep space exploration projects.

2 NASA Relevance

2.1 Proposed Capability

At the end of this three-year project, the proposed automated planning and scheduling system will be able to reason about probabilistic models of spacecraft operation in order to generate sequences that balance risks (related to safety and goal attainment) with expected rewards (e.g. science value). More specifically, the proposed capabilities include the following.

C1) Projection of uncertain, discrete and continuous state, resource, and time values
The current and future uncertainty of system variables must be calculated to accurately predict the potential risks and rewards of an operations plan. These projected values depend on the timing of system commands, which can also vary probabilistically. Dependencies among these variables must also be enforced. For instance, energy is a function of power and time.

C2) Automated generation of sequences that balance risk and reward
In order to maximize the expected utility of an operations plan, goals must be refined into activities that can have conditional, probabilistic effects potentially leading to goal failure or safety violations. The objective is to choose and schedule the goals and activities in a way that increases the expected reward while avoiding risk to the spacecraft/rover. The planner should handle at least a day of typical spacecraft operations.

C3) Automated generation of contingency plans
Uncertainty (variance) of system variables (which can grow larger over time) can be great enough that no activities can be scheduled to guarantee safe operation, as described in Section 3.3.1, Figure 3. However, multiple alternative schedules (contingencies) can be generated to address different ranges of future energy levels.

2.2 NASA Enterprise and Mission Needs

The Automated Reasoning area requests technology for "managing the complexity inherent in the design, development and validation of complex autonomous systems." Sequence generation and validation rely on the accuracy of models of the spacecraft and its environment. However, uncertainty is traditionally handled by using conservative values, e.g. for resource consumption, and specialized software for determining these values and the consequent operational restrictions and scenarios are largely rewritten for each mission. No automated planning tools are available to reason in a principled fashion about uncertain and unknown information for spacecraft operations. The current process qualitatively limits the capabilities of spacecraft and rovers by improperly evaluating alternative courses of action and restricting the time horizon of operations between command uplinks, resulting in loss of productivity. Missions need general, automated planning tools to reason about uncertainty in order to fully exploit the capabilities of a spacecraft and enable greater autonomous operation, necessary for future deep space exploration missions to outer planets where frequent contact with Earth is impossible.

How are alternative sequences and scenarios improperly evaluated? By using conservative operational limits, planning ignores probable goals. For example, if an autonomous rover encounters a group of rocks with probabilistically varying science values and path difficulty, using conservative estimates, only rocks with the greatest minimum value and known simplest paths minimizing energy or mechanical wear will be investigated. While operations staff may recognize that additional goals can be scheduled safely, the decision process is manual and cannot be automated or validated without reasoning about the uncertainty and risks in a

principled fashion. Only by evaluating optional sequences according to expected overall science value and probability of risk to the vehicle can planning efficiently capitalize on the capabilities of the spacecraft.

How are operations limited to short horizons between uplinks? Investigating a rock by grinding, drilling, extracting a sample, and analyzing can take up to nine days because of the uncertainties of each activity in the sequence, requiring repeated replanning from ground. By reasoning about the likelihood of potential outcomes in advance, alternative sequences (contingencies) can be planned in advance and resources can be strategically managed. This can reduce the time for rock analysis by an order of magnitude. A rover investigating a rock field will halt and wait for Earth contact if the conservative projections of vehicle wear or energy go out of acceptable ranges. If autonomous, the rover might replan instead, but this could take hours of computation while it remains idle. If upon approaching the site, it had planned contingencies in advance, it could continue executing instead of stopping to replan.

Thus, software for generating sequences that balance expected risks and rewards is needed. This requires methods for efficiently projecting uncertain system variables that the planner can use in making scheduling decisions. Finally contingency planning is needed in conjunction with these in order to provide robust sequences for the most likely outcomes.

2.3 Expected NASA Impact of the Proposed Work

Using the developed planning system (onboard or on the ground) to make principled planning decisions will enable more efficient and missions while ensuring spacecraft health. As missions into deep space encounter greater uncertainty in partially known environments, future spacecraft/rovers that execute sequences planned based on hard estimates instead of probabilistic outcomes may function poorly or even dangerously when “safe modes” cannot be reached without properly sequenced actions. Our system will be able to generate day plans involving hundreds of activities with uncertain outcomes based on tens of uncertain state/resource variables. Preliminary investigations suggest that an autonomous spacecraft/rover using our system will be able to replan for unexpected events and goal changes within minutes [SC03].

Planning with uncertainty is not just an issue for remote rover missions. Orbiters and probes face similar uncertainties in timing, resources, and science value of alternative measurement targets. Spacecraft must individually and collectively schedule communications with the Deep Space Network (DSN) in weekly and yearly timeframes. These future communications needs are uncertain, and the transmissions can have uncertain bandwidth and data loss.

This technology will provide several benefits to NASA space missions. Our software will serve as a general tool to aid ground operations in evaluating alternative scenarios and generating efficient, safe sequences. The planning system can also be used to reduce effort in the design of missions, spacecraft, and their operations. Moreover, an autonomous spacecraft can automatically make principled decisions when evaluating optional courses of action in an uncertain or partially known environment.

There are many infusion possibilities for this technology. The planning system that we propose to leverage (CASPER, [CK00]) will soon autonomously command EO-1 and 3CS. The Modified Antarctic Mapping Mission used CASPER on the ground to reduce operation efforts by an order of magnitude [SE01]. It has commanded the Rocky 7 and 8 rovers and operated a 34m DSN antenna. By providing CASPER the capability of handling uncertainty, we expect current and future customers of the planning system to be open to support deployment. We plan milestones for ground planning infusion, and our support letters recognize value of our proposed technology for Mars missions, including an MSL extended mission.