

# ONBOARD PLANNING FOR THE MARS 2020 PERSEVERANCE ROVER

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## ABSTRACT

The Mars 2020 Mission is developing a scheduler for use onboard the Mars 2020 Perseverance Rover. The purpose of this scheduler is to adjust the activities to account for variances in onboard resources (e.g. available energy) or execution (e.g. activity failures or activities taking shorter or longer than expected). The onboard scheduler is a priority-first non backtracking scheduler. The scheduling problem is challenged by: (1) limited onboard computing resources; (2) scheduler/execution interactions; (3) energy management including scheduling of wakeup and shutdown; (4) and thermal management (preheat and maintenance heating for mechanical actuation). We overview how these challenges are addressed in the scheduler design. We also discuss the ground software being developed to support operations with onboard autonomy. We also describe the current status and target deployment timeline.

Key words: rover autonomy; artificial intelligence; scheduling; flight software; operations.

## 1. INTRODUCTION

Efficiently operating a rover on the surface of Mars is challenging. Two factors combine to make this job particularly difficult: 1) communication opportunities are limited, 2) certain aspects of rover performance are difficult to predict. With limited communications, the rover must be given instructions on what to do for one or more Martian days (Sols) at a time. In addition, rover activities may fail. Or the duration of many rover activities can be hard to predict, which can also lead to unpredictable energy use.

Traditionally, rover activities are sequenced in a time based fashion (e.g. an activity is designated to start at a specific time) [CMA<sup>+</sup>14, GAD<sup>+</sup>16], and activities are

scheduled using conservative (e.g. long) durations. This approach has been used effectively for operations of Mars rovers, but it can result in a measurable loss in rover productivity. Specifically, a study of several Mars Science Laboratory science campaigns [GDJ<sup>+</sup>16] found that sub-master sequences (a reasonable proxy for activities) completed on average more than 20% early. This results in unused rover time as the rover waits until the next fixed time to start the following activity as well as wasted energy to keep the rover awake during these times. Reducing conservative durations can cause other challenges - if an activity runs long it can cause cancellation of the next activity and subsequent dependent activities. Conservative durations are set so that this occurs rarely (less than one out of every 100 plans). This type of failure also can effect subsequent planning cycles as the ground operations team must determine the failure point and appropriate action from that point.

To regain some of this productivity, the Mars 2020 mission is developing onboard scheduling software. The primary objective of this software is to identify and utilize opportunities that arise when actual rover performance is more efficient than the original, conservative prediction.

## 2. ONBOARD PLANNER

The Mars 2020 Onboard Planner is a priority-first non backtracking scheduler [RB17, RWG<sup>+</sup>20]. As shown in Figure 1, the scheduler considers each activity in turn. Specific complications relate to scheduling thermal management activities and energy management (eg rover wake and sleep periods [CCA20]). When considering an activity it first finds the valid temporal intervals satisfying the activity constraints, and then considers thermal (preheat, maintenance) and energy (wake/sleep) considerations. If required thermal activities can be accommodated and a valid wake/sleep schedule generated the activity is accepted. Once it places an activity it does not consider modifications (delete, move) to that activity.

The Mars 2020 Onboard Planner has to fit within Flight Computing and Flight Software constraints. Specifically,

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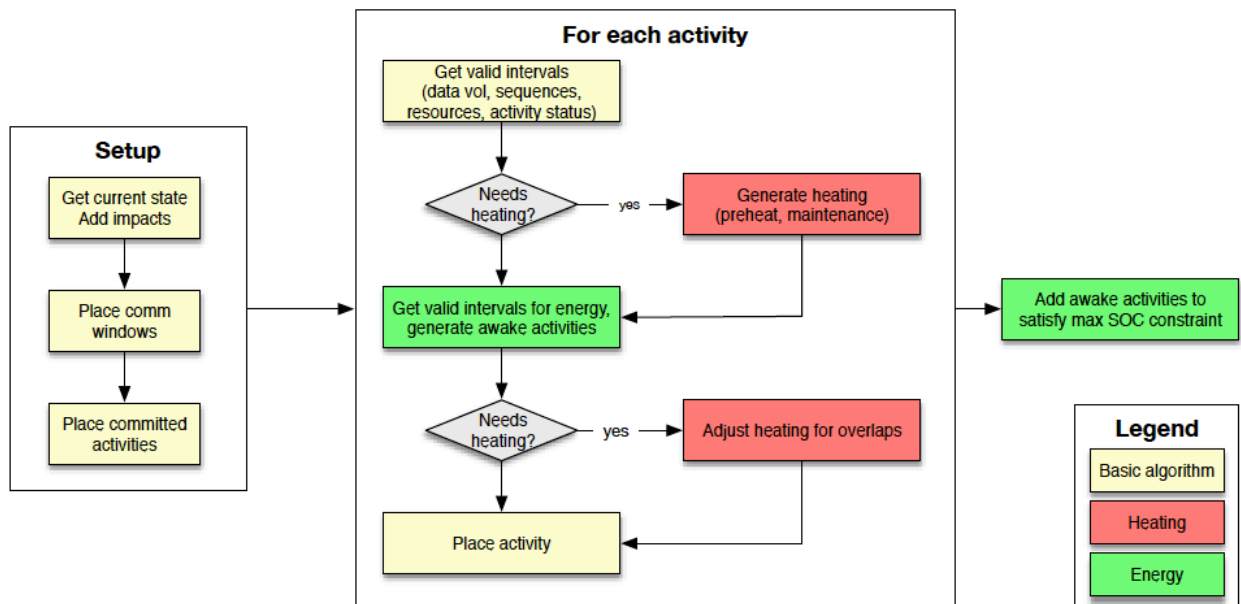


Figure 1. Onboard scheduler algorithm.

it had to be designed to be computationally lightweight and software priority was set to ensure non interference with the many other flight software tasks onboard the rover [GRW<sup>+</sup>22]. Additionally, the scheduler is designed to work with the execution element. This execution element uses flexible execution to enable adjustments to activity execution timing without requiring invocation of the scheduler [ACC<sup>+</sup>21a] and also uses event-driven scheduler invocation to minimize both time and computation expense from scheduler invocation.

In addition to optional activities that are scheduled when resources allow, the scheduler also handles "switch groups" which are a limited form of disjunction in plans where a small number of options of varying resource usage are considered [ACC<sup>+</sup>21b]. This enables the operations team another method of using resources freed up by fortuitous execution earlier in the Sol.

Another scheduler capability is handling expanding activities. In this mode activities can be specified to run until time or resources are expended (e.g. drive until a specified time and/or energy limit). This provides yet another method for the operations team to take advantage of available resources.

### 3. GROUND-BASED SUPPORT FOR THE ON-BOARD PLANNER

Use of onboard autonomy such as the M2020 scheduler also requires ground capabilities to enable the operations team to best utilize onboard autonomy. The operations team needs to understand how a ground developed plan may execute onboard. To this end a Monte Carlo estimation technique [CAC<sup>+</sup>19] has been developed. This estimation technique can also be used to set the scheduler's activity priorities (the order in which activities are considered for scheduling). Setting of these priorities can be quite challenging as there are many possible combinations of execution outcomes and activity durations and therefore the scheduler can be invoked in many different contexts. Because of the complexity of possible executions, a prototype graphical user interface has been developed to assist in understanding the range of possible execution outcomes [RAC<sup>+</sup>19]. However, the Monte Carlo approach and execution visualization are prototypes and the mission is still considering a range of possible operations tools. Note that operations concepts for missions with autonomy and operations team tooling for such missions is an area of active work [CVR<sup>+</sup>22].

One key part of any solution is explanation capability to assist the operations team in understanding the scheduler behavior. To this end, the Crosscheck explanation system was developed [AYC20] and has been in use to assist the ground operations team in understanding the current ground scheduler as well as operations constraints relevant to manually scheduled activities. This scheduler represents the growing importance of explainability in not only space mission operations [Chi21] but all of Artificial Intelligence and Autonomous Systems.

#### 4. CURRENT STATUS FOR THE ONBOARD AND GROUND PLANNERS

The initial infrastructure for automated planning on the ground has been in use since after landing (February 2021) and checkout. This limited planning capability takes a time grounded plan from Coptit and generates the wake/sleep schedule and thermal management (pre-heat and maintenance heating) activities.

As the time of this article (April 2022), the onboard planner effort is proceeding with planned phased deliveries into operations. The first phase focuses on "accordion" plans in which a primary thread of activities is extracted from a grounded plan and these activities are operated primarily serially within awake islands<sup>1</sup>. Within these mostly serial awake islands constraints are added such that the activities execute mostly in sequence. In this mode of operations, the primary utility of the onboard planner is to allow the rover to complete these "accordions" early when possible and sleep to conserve energy for future sols.

In future phase(s) the planner will be allowed to harvest saved resources (time, energy) within the same sol by scheduling and executing: expanding activities (e.g. drive until you run out of time or energy), switch groups (upgrading pre-specified activities to more resource intensive ones if possible), and optional activities (add these activities if available resources).

#### 5. RELATED AND FUTURE WORK

There have been relatively few flights of planner/schedulers on space missions. Use of such technologies on the ground has been more common (see [CJP<sup>+</sup>12] for a description of some of these systems as well as more recent use on LADEE [Bre16], Rosetta [CRT<sup>+</sup>21], ECOSTRESS [YCCNF21], and OCO-3 [YWC<sup>+</sup>21]).

In 1999, the Remote Agent Experiment flew onboard the Deep Space One Mission for two periods totalling about 48 hours [MNPW98, JMM<sup>+</sup>00]. This planner worked in

<sup>1</sup>In actuality the grounded plan is analyzed to extract a primary "graph" which does allow modest parallelism.

concert with an executive [PGK<sup>+</sup>97, PGG<sup>+</sup>98] and performed batch planning of engineering activities such as optical navigation.

The Autonomous Sciencecraft (ASE) [CST<sup>+</sup>05] flew onboard the Earth Observing One Mission first as a six month technology demonstration and later becoming the primary operations system for the mission flying for over a dozen years. ASE flew the CASPER continuous planner [CKS<sup>+</sup>00] and the SCL executive. ASE had to fit within modest computing and RAM resources [TCRC04] and demonstrated very high reliability operations (for a discussion of anomalies encountered see [TCRC05]).

The Intelligent Payload Experiment (IPEX) [CDT<sup>+</sup>16] was a cubesat flight demonstration of high throughput onboard product generation for the intelligent payload module of the proposed HypIRI mission concept [CSDM09]. IPEX used the CASPER onboard planner in concert with a linux shell-based task executive. IPEX flew for approximately fourteen months.

Future missions such as the Europa Lander Mission Concept [Han17] will make even greater demands on onboard scheduling. Such a lander is likely to land with uncertain, fixed energy (mission duration of approximately 30 Earth days) and operate with great uncertainty in action execution (failure, duration, energy consumption) and limited communications with the ground (over 42 out of every 84 hours out of earth communication). These constraints require onboard autonomy to consider utility (acquiring the best samples) and probability in order to best achieve mission objectives [WRBC22, BWCZ21].

#### 6. CONCLUSIONS

We have provided an overview of the onboard scheduler under development for the Mars 2020 Perseverance Rover. This onboard scheduler is intended to adjust planned activities in response to execution variations such as: activities failing, activities completing early or late, and/or activities consuming more or less resources than expected. The scheduler must fit within onboard computing and flight software constraints and handle complications such as thermal and energy management. We also provided an overview of supporting ground software under development to support the onboard scheduler. Finally, we discussed the implementation status and projected plans for deployment.

#### ACKNOWLEDGMENTS

This work was performed at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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