ONBOARD PLANNING FOR THE MARS 2020 PERSEVERANCE ROVER

Dan Gaines, Steve Chien, Gregg Rabideau, Stephen Kuhn, Vincent Wong, Amruta Yelamanchili, Shannon Towey, Jagriti Agrawal, Wayne Chi, Andrea Connell, Evan Davis, and Colette Lohr

Jet Propulsion Laboratory[*]
California Institute for Technology
4800 Oak Grove Drive
Pasadena, CA 91109-8099 USA

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+14, GAD+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+16] found that submaster 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+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,

---

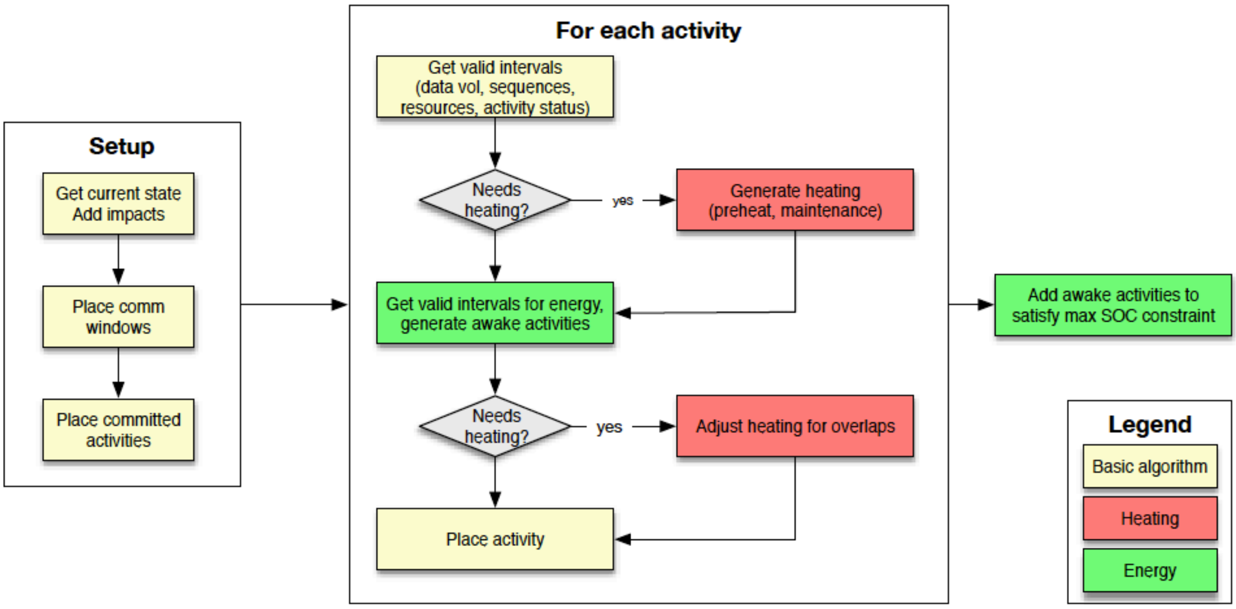

Figure 1. Onboard scheduler algorithm.

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+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+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+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 ONBOARD 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+19] has been developed. This estimation technique can also be used to set the schedulers 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+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+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 Cocpit and generates the wake/sleep schedule and thermal management (preheat 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 [1]. 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+12] for a description of some of these systems as well as more recent use on LADEE [Bre16], Rosetta [CRT+21], ECOSTRESS [YCCNF21], and OCO-3 [YWC+21]).

In 1999, the Remote Agent Experiment flew onboard the Deep Space One Mission for two periods totalling about 48 hours [MNPW98, JMM+00]. This planner worked in concert with an executive [PGK+97, PGG+98] and performed batch planning of engineering activities such as optical navigation.

The Autonomous Sciencecraft (ASE) [CST+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+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+16] was a cubesat flight demonstration of high throughput onboard product generation for the intelligent payload module of the proposed HyspIRI 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.

---

[1] In actuality the grounded plan is analyzed to extract a primary ”graph” which does allow modest parallelism.

REFERENCES

[ACC$^+$21a] J. Agrawal, W. Chi, S. A. Chien, G. Rabideau, D. Gaines, and S. Kuhn. Analyzing the effectiveness of rescheduling and flexible execution methods to address uncertainty in execution duration for a planetary rover. *Robotics and Autonomous Systems*, 140 (2021) 103758, 2021.

[ACC$^+$21b] J. Agrawal, W. Chi, S. A. Chien, G. Rabideau, S. Kuhn, D. Gaines, T. Vaquero, and S. Bhaskaran. Enabling limited resource-bounded disjunction in scheduling. *Journal of Aerospace Information Systems*, 18:6:322–332, 2021.

[AYC20] J. Agrawal, A. Yelamanchili, and S. Chien. Using explainable scheduling for the mars 2020 rover mission. In *Workshop on Explainable AI Planning (XAIP), International Conference on Automated Planning and Scheduling (ICAPS XAIP)*, October 2020.

[Bre16] John L Bresina. Activity planning for a lunar orbital mission. *AI Magazine*, 37(2):7–18, 2016.

[BWCZ21] Connor Basich, Daniel Wang, Steve Chien, and Shlomo Zilberstein. A sampling-based optimization approach to handling environmental uncertainty for a planetary lander. In *International Workshop on Planning Scheduling for Space (IWPSS)*, July 2021. Also presented at Also appears at the International Conference on Automated Planning and Scheduling (ICAPS) Workshop on Planning and Robotics (PlanRob).

[CAC$^+$19] W. Chi, J. Agrawal, S. Chien, E. Fosse, and U. Guduri. Optimizing parameters for uncertain execution and rescheduling robustness. In *International Conference on Automated Planning and Scheduling (ICAPS 2019)*, Berkeley, California, USA, July 2019.

[CCA20] W. Chi, S. Chien, and J. Agrawal. Scheduling with complex consumptive resources for a planetary rover. In *International Conference on Automated Planning and Scheduling (ICAPS 2020)*, Nancy, France, October 2020.

[CDT$^+$16] S. Chien, J. Doubleday, D. R. Thompson, K. Wagstaff, J. Bellardo, C. Francis, E. Baumgarten, A. Williams, E. Yee, E. Stanton, and J. Piug-Suari. Onboard autonomy on the intelligent payload experiment (ipex) cubesat mission. *Journal of Aerospace Information Systems (JAIS)*, April 2016.

[Chi21] S. Chien. Why explain? or why didn't i get my observation? challenges for explanation in space mission scheduling. In *Invited Talk, Workshop on Explainable AI Planing, International Conference on Automated Planning and Scheduling*, July 2021.

[CJP$^+$12] S. Chien, M. Johnston, N. Policella, J. Frank, C. Lenzen, M. Giuliano, and A. Kavelaars. A generalized timeline representation, services, and interface for automating space mission operations. In *International Conference On Space Operations (SpaceOps 2012)*, Stockholm, Sweden, June 2012.

[CKS$^+$00] Steve A Chien, Russell Knight, Andre Stechert, Rob Sherwood, and Gregg Rabideau. Using iterative repair to improve the responsiveness of planning and scheduling. In *AIPS*, pages 300–307, 2000.

[CMA$^+$14] Debarati Chattopadhyay, Andrew Mishkin, Alicia Allbaugh, Zainab N Cox, Steven W Lee, Grace Tan-Wang, and Guy Pyrzak. The mars science laboratory supratactical process. In *SpaceOps 2014 Conference*, page 1940, 2014.

[CRT$^+$21] S. A. Chien, G. Rabideau, D. Q. Tran, M. Troesch, F. Nespoli, M. Perez-Ayucar, M. Costa-Sitja, C. Vallat, B. Geiger, F. Vallejo, R. Andres, N. Altobelli, and M. Kueppers. Activity-based scheduling of science campaigns for the rosetta orbiter. *Journal of Aerospace Information Systems*, 18:10:711–727, 2021.

[CSDM09] Steve Chien, Dorothy Silverman, Ashley Gerard Davies, and Daniel Mandl. Onboard science processing concepts for the hyspiri mission. *IEEE Intelligent Systems*, 24(6):12–19, 2009.

[CST$^+$05] S. Chien, R. Sherwood, D. Tran, B. Cichy, G. Rabideau, R. Castano, A. Davies, D. Mandl, S. Frye, B. Trout, S. Shulman, and D. Boyer. Using autonomy flight software to improve science return on earth observing one. *Journal of Aerospace Computing, Information, and Communication (JACIC)*, pages 196–216, April 2005.

[CVR$^+$22] Rebecca Castano, Tiago Vaquero, Federico Rossi, Vandi Verma, Ellen Van Wyk, Dan Allard, Bennett Huffman, Erin Murphy, Nihal Dhamani, Robert Hewitt, Scott Davidoff, Rashied Amini, Anthony Barrett, Julie Castillo-Rogez, Mathieu Choukroun, Alain Dadaian, Raymond Francis, Ben Gorr, Mark Hofstadter, Mitch Ingham, Cristina Sorice, and Iain Tierney. Operations for autonomous spacecraft. In *IEEE Aerospace Conference*, March 2022.

[GAD$^+$16] Daniel Gaines, Robert Anderson, Gary Doran, William Huffman, Heather Justice, Ryan Mackey, Gregg Rabideau, Ashwin Vasavada, Vandana Verma, Tara Estlin, Lorraine Fesq, Michel Ingham, Mark Maimone, and Issa Nesnas. Productivity challenges for mars rover operations. In *Workshop on Planning and Robotics, International Conference on Automated Planning and Scheduling (PlanRob, ICAPS 2016)*, London, UK, June 2016.

[GDJ+16] D. Gaines, G. Doran, H. Justice, G. Rabideau, S. Schaffer, V. Verma, K. Wagstaff, V. Vasavada, W. Huffman, R. Anderson, R. Mackey, and T. Estlin. Productivity challenges for mars rover operations: A case study of mars science laboratory operations. *Technical Report D-97908, Jet Propulsion Laboratory*, January 2016.

[GRW+22] D. Gaines, G. Rabideau, V. Wong, S. Kuhn, E. Fosse, and S. Chien. The mars 2020 onboard planner: Balancing performance and computational constraints. In *Flight Software Workshop*, February 2022.

[Han17] Kevin P Hand. *Report of the Europa Lander science definition team.* National Aeronautics and Space Administration, 2017.

[JMM+00] A. Jónsson, P. Morris, N. Muscettola, K. Rajan, and B. Smith. Planning in interplanetary space: Theory and practice. In *AIPS*, pages 177–186, 2000.

[MNPW98] N. Muscettola, P. Nayak, B. Pell, and B. Williams. Remote agent: To boldly go where no ai system has gone before. *Artificial intelligence*, 103(1-2):5–47, 1998.

[PGG+98] Barney Pell, Edward B Gamble, Erann Gat, Ron Keesing, James Kurien, William Millar, P Pandurang Nayak, Christian Plaunt, and Brian C Williams. A hybrid procedural/deductive executive for autonomous spacecraft. In *Proceedings of the second international conference on autonomous agents*, pages 369–376, 1998.

[PGK+97] Barney Pell, Erann Gat, Ron Keesing, Nicola Muscettola, and Ben Smith. Robust periodic planning and execution for autonomous spacecraft. In *IJCAI*, pages 1234–1239, 1997.

[RAC+19] Basak Alper Ramaswamy, Jagriti Agrawal, Wayne Chi, So Young Kim, Scott Davidoff, and Steve Chien. Supporting automation in spacecraft activity planning with simulation and visualization. In *Proceedings of Science and Technology Forum and Exposition*. AIAA, 2019.

[RB17] G. Rabideau and E. Benowitz. Prototyping an onboard scheduler for the mars 2020 rover. In *International Workshop on Planning and Scheduling for Space (IWPSS 2017)*, Pittsburgh, PA, June 2017.

[RWG+20] G. Rabideau, V. Wong, D. Gaines, J. Agrawal, S. Chien, S. Kuhn, E. Fosse, and J. Biehl. Onboard automated scheduling for the mars 2020 rover. In *Proceedings of the International Symposium on Artificial Intelligence, Robotics and Automation for Space*, i-SAIRAS'2020, Noordwijk, NL, 2020. European Space Agency.

[TCRC04] D. Tran, S. Chien, G. Rabideau, and B. Cichy. Flight software issues in onboard automated planning: Lessons learned on eo-1. In *International Workshop on Planning and Scheduling for Space (IWPSS 2004)*, Darmstadt, Germany, June 2004.

[TCRC05] D. Tran, S. Chien, G. Rabideau, and B. Cichy. Safe agents in space: Preventing and responding to anomalies in the autonomous sciencecraft experiment. In *Autonomous Agents and Multi-Agent Systems Conference (AAMAS 2005)*, Utrecht, Netherlands, July 2005.

[WRBC22] D. Wang, J. A. Russino, C. Basich, and S. Chien. Analyzing the efficacy of flexible execution, replanning, and plan optimization for a planetary lander. In *International Conference on Automated Planning and Scheduling*, June 2022.

[YCCNF21] A. Yelamanchili, S. Chien, K. Cawse-Nicholson, and D. Freeborn. Scheduling and operations of the ecostress mission. In *Proceedings Space Operations 2021*, May 2021.

[YWC+21] A. Yelamanchili, C. Wells, S. Chien, A. Eldering, R. Pavlick, C. Cheng, R. Schneider, and A. Moy. Scheduling and operations of the orbiting carbon observatory-3 mission. In *Proceedings Space Operations 2021*, May 2021.