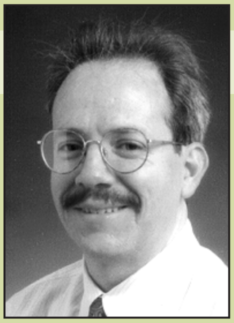


Editor: Richard Doyle
Jet Propulsion Lab
rdoyle@jpl.nasa.gov

A Day in an Astronaut's Life: Reflections on Advanced Planning and Scheduling Technology

David Kortenkamp, *Metrica Inc. and NASA Johnson Space Center*

The day in a Space Station astronaut's life starts a year before his or her mission (or *increment*, in NASA-ese), when the mission planning and scheduling begins. The mission controllers refine and review the mission plan until execution time, when they upload it to the Space Station as an *onboard short-term plan* (OSTP).

This installment of the AI in Space department looks at the process NASA uses to plan and execute an astronaut's "day in the life." As I do so, I will examine new planning and scheduling technologies recently presented at the Third International NASA Workshop on Planning and Scheduling for Space, held in Houston last October, and show how they might affect future Space Station astronauts.

Pre-increment planning phase

Starting a year before the Space Station crew arrives, the pre-increment mission-planning phase involves accepting input from a variety of sources, including the international partners, public affairs department, and scientists with experimental payloads, among others. A detailed schedule of the crew's activities results. At the heart of all plan development is a single relational database at NASA Johnson Space Center (see Figure 1). A planning and scheduling software application called the *consolidated planning system* provides resource and constraint checking of the database's data. The CPS tracks such resources as crew, power, communications bandwidth, and consumables. The construction of a pre-increment plan is still largely a manual process, consuming huge numbers of work hours.

Changing this process from a mostly manual to a more automated one will require significant advances in planning and scheduling software. Because humans will always be part of the planning process, especially to resolve political issues, any deployed system must exhibit mixed-initiative interaction, whereby automated software and human experts collaborate to create a plan.[1] During the recent NASA Workshop on Planning and Scheduling for Space, James Allen of the University of Rochester presented a paper on "Human-Machine Collaborative Planning" that discussed an explicit problem-solving level to mediate between the human-computer interaction and the underlying automated plan reasoners, bridging the gap between human and automated planning.[2] In his approach, mission planners would use natural language and graphical interfaces to input objectives they wish to achieve and constraints on possible solutions. Mission planners could build a plan incrementally, adding or subtracting constraints as necessary or suggesting potential solutions. The underlying plan reasoners would then decompose objectives into tasks, check constraints, and optimize resources, returning the incremental plan to the mission planners.

In "Passat: A User-Centric Planning Framework," Karen Myers from SRI International discussed a framework that provides a set of plan editing and manipulation capabilities to support novice users in creating and modifying plans.[3] The Passat system builds upon a library of predefined templates that encode task networks describing standard operating procedures and previous cases. Users can select from these templates during plan development,

Editor's Perspective

Previously in these pages I've made the observation that planning and scheduling technology often provides the core capability of a space system incorporating AI. Whether the fundamental approach is human-machine interaction or autonomy, what is sought is the ability to determine and adjust the set of actions that will accomplish mission objectives, their specific timings, and the management of system resources to successfully execute those actions. When the environment's operational uncertainty is high, mission planning might become a more continuous activity, engaged in near real time.

Here, Dave Kortenkamp provides a report from the user perspective on the Third International NASA Workshop on Planning and Scheduling. This recent event marks the currently longest-running workshop series on an AI subtopic within NASA, attesting to its known importance as an emerging and central technology contribution to space exploration.

—Richard Doyle

1094-7167/03/$17.00 © 2003 IEEE
Published by the IEEE Computer Society

The Columbia tragedy

The loss of the Columbia came as a complete shock, very early on Saturday, February 1st, as phone calls around the country quickly alerted the NASA family to the tragedy.

The emotions ran hard and fast, but it was not long before a strong feeling of affirmation of what we at NASA do and what we represent came through. Our hearts go out to the STS-107 astronauts' families and loved ones. We also know that these explorers embraced the risk and would want us to go on steadfastly with our business of exploration, becoming always smarter in both experience and knowledge. In that spirit, we offer this article which describes some of the activities of human spaceflight.

with the system providing various forms of automated assistance. In this approach, mission planners can reuse successful plans, changing them slightly to accommodate the specific situation. Both systems aim not to replace human planning expertise but to augment it with tools that will improve mission-planning efficiency.

Current planning methodology does not capture the interaction between multiple crew members in accomplishing tasks. These interactions can often be quite complex. Martin Sierhuis of the Research Institute for Advanced Computer Science at NASA Ames Research Center presented a paper on a multiagent approach to modeling crew activities. This modeling approach captures the interactions between crew members, procedures, and Space Station hardware to create more accurate and flexible plans for the crew.[4] Mission planners using such a tool could replan activities during a Space Station increment more quickly.

Executing the plan

A crew member's day starts by looking at the OSTP, using the OSTP viewer. The day's short-term plan was created during pre-increment planning. Then before execution, the crew reviews the next day's plan and provides comments and questions to ground controllers, who update and uplink the OSTP daily. In addition, the crew can access a "bigger picture" view of the plan for the entire month. As crew members execute the day's plan, they interact with the OSTP viewer to provide ongoing status of activity execution. To give crew members more flexibility and autonomy, the OSTP is augmented with a *job jar* concept; crew members can select and complete certain tasks whenever they have the time and desire (see Figure 2).

The job jar reflects NASA's commitment to increase crew autonomy and reduce ground control oversight (and thus cost), which will require moving many planning and plan-monitoring functions from ground control to the space vehicle. This shift will be even more important in missions beyond low Earth orbit as the time latency in communications becomes substantial. At the workshop, an invited talk by Tony Griffith of the NASA Johnson Space Center Mission Operations Directorate described new approaches to onboard crew autonomy for next-generation launch vehicles.

He introduced an architecture in which autonomous software onboard the vehicle performs most mission planning and monitoring. The architecture consists of an onboard mission planner that builds deliberative plans and schedules, a mission manager that executes and repairs deliberative plans, and a reactive planner that then executes the plans, either autonomously or through the crew. Reactive planning techniques have already proven to assist crew members in executing complex procedures.[5] Any approach to onboard planning and execution must use adjustable autonomy to allow for varying degrees of crew support.[6]

While the crew member is performing his or her daily activities, ground controllers are monitoring the vehicle's operation (see Figure 3). At the workshop, Marcello Balduccini of Texas Tech University presented a decision support system for Space Shuttle flight controllers. The system diagnoses failures in the Space Shuttle's reaction control system and plans workarounds. The RCS is modeled as a set of A-Prolog rules; action-set programming searches the rules and creates a plan for achieving mission objectives even in the face of failures.[7] Planning technologies such as these will be invaluable to maintaining an ongoing vehicle such as the Space Station.

Figure 1. The Mission Control Center at NASA Johnson Space Center in Houston.

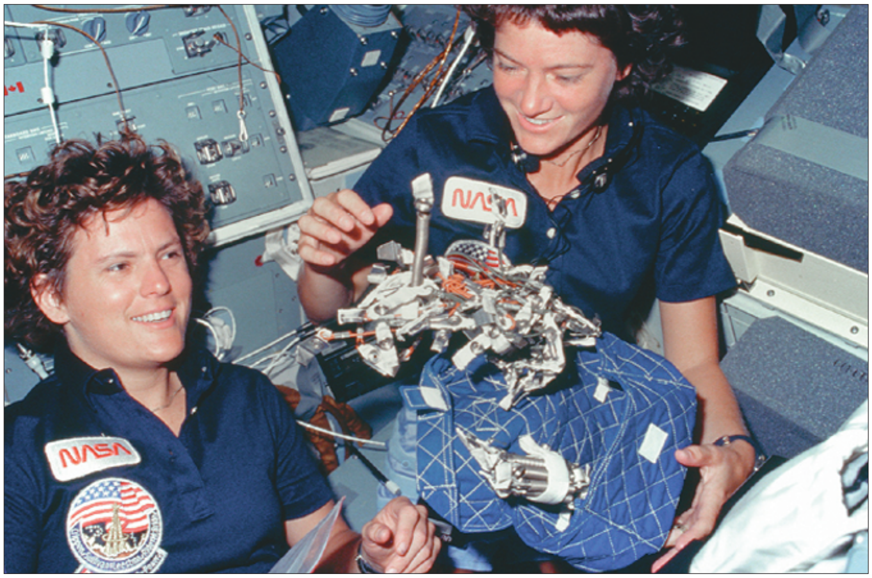


Figure 2. Two astronauts conduct experiments in space.

Uncrewed spacecraft and rovers

So far, I have concentrated on planning and scheduling for human spaceflight. However, planning and scheduling for uncrewed spacecraft and rovers also present many challenges. Surprisingly, the day in the life of an uncrewed spacecraft or rover is similar to the crew member's day in the life. Mission planning begins well before the actual mission and involves scheduling activities and resources with significant human participation (mostly scientists who have instruments on board and spacecraft engineers). Thus, the collaborative planning technologies I described earlier are relevant to uncrewed missions as well.

The day in the life does differ in the plan's execution phase. There is no human to execute or monitor execution. Instead, the plan must execute in software. Long time delays and limited communication mean that replanning in the face of problems or opportunities must often be done autonomously onboard the spacecraft. While previous uncrewed missions, such as Voyager, or rovers, such as Sojourner, used time-sequenced sets of activities with little autonomy or flexibility, a recent experiment demonstrated the effectiveness of sophisticated onboard planning and scheduling software. The Remote Agent control architecture flew on the Deep Space One spacecraft[8,9] and included a planner, an executive, and a model-based mode identification component that worked together with low-level control code to accomplish mission objectives.

The workshop had several presentations concerning new planning and scheduling approaches for spacecraft and rover control. Nicola Muscettola of NASA Ames presented the Intelligent Distributed Execution Architecture, which builds on the Remote Agent work by providing a unified representation and reasoning framework. IDEA has four main components: a domain model, a plan database, a plan runner, and a reactive planner. Together these components choose actions for the autonomous spacecraft and execute those actions.

JPL's Steve Chien presented two applications for planning technology: the 3 Corner Sat Mission and Tech-Sat 21. Both are multispacecraft experiments that feature onboard decision-making capabilities.[10] The onboard Continuous Activity Scheduling Planning Execution and Replanning software interacts with the Spacecraft Command Language to control the spacecraft. The Casper planner plans continuously to enable the spacecraft to respond to mission anomalies and opportunities.

A day in the life of a planetary rover is similar to that of a Space Station crew member. Just before evening (Mars' evening), the rover sends back a panoramic picture of its surroundings and then goes "to sleep." Planetary scientists on the ground examine those pictures and, while the rover is sleeping, debate what it should do the next day (see Figure 4). The plan then passes to rover engineers who translate it into a sequence of commands for the rover to execute. After testing and verification, the sequence goes to the rover, which then executes it. Often, approaching a particular rock takes two or three of these plan-execute cycles (each taking a day). The twin rovers going to Mars in 2003 create a need for more autonomy both to increase science return and to decrease ground control costs.

Two presentations at the workshop highlighted differences in autonomy philosophies. Rich Washington at RIACS argued for ground-based contingency planners owing to rovers' computational limitations. In contingency planning, each time an uncertain action is added to the plan, the planner establishes goals for the different possible outcomes—*just in case planning*. JPL's Tara Estlin argued

Figure 3. An astronaut conducts an extravehicular activity.

for onboard planning capabilities. Using the Casper planner, her system plans sequences of actions for the rover.[11] Casper's continuous nature allows for replanning actions based on the current situation.

Both approaches would increase a planetary rover's autonomy and capability. These surface-system needs, and the role that planning and scheduling capabilities can play to address them, are starting to come into focus in the context of the next rover mission to Mars, called Mars Science Laboratory. This mission, scheduled for a 2009 launch, would operate a rover on the Martian surface for up to 1,000 sols (Martian days), compared to 90 sols for the Mars Exploration Rover twins in 2003.

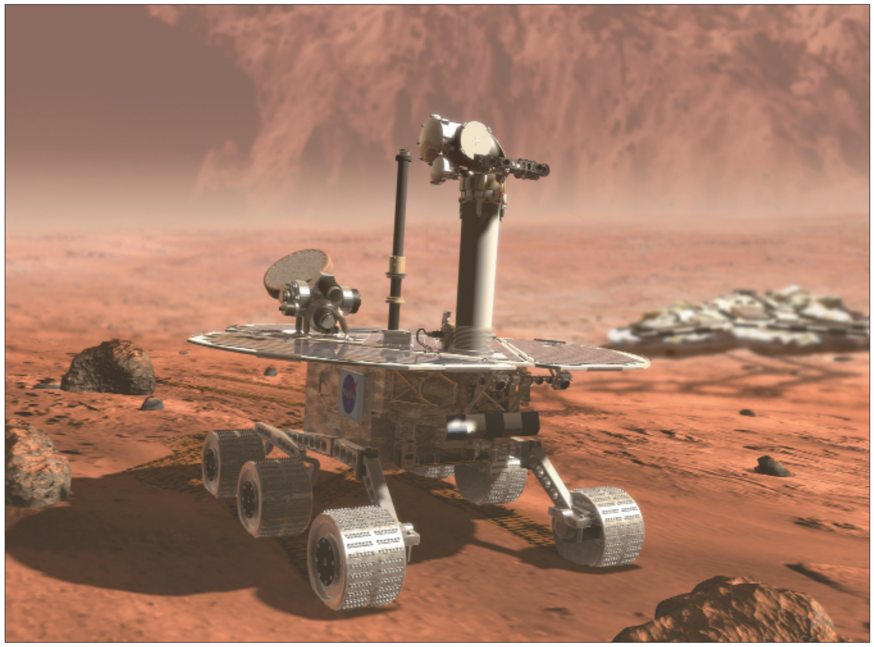


Figure 4. A drawing of the Mars Exploration Rover, two of which will launch in 2003.

Whether for crewed or uncrewed missions, planning and executing mission objectives is labor and time intensive. As a manual activity, mission planning consumes huge amounts of engineering resources. In past years, when seven or eight Space Shuttle missions lasted no more than two weeks each or when planetary rovers and spacecraft were relatively rare, this was acceptable. Now, with a permanent human presence in space and multiple planetary spacecraft, mission planning and execution will have to be more automated and flexible.

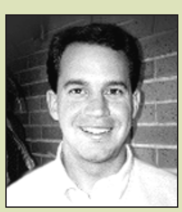
Acknowledgments

The Third International NASA Workshop on Planning and Scheduling for Space was held in Houston in October 2002. Workshop proceedings are available through the Institute for Advanced Interdisciplinary Research (www.systems.org). A grant from the Research Institute for Advanced Computer Science supported the workshop. David Korth and Troy LeBlanc of NASA's Johnson Space Center presented an overview of International Space Station mission planning called "International Space Station Alpha Operations Planning," which was a source of information for many parts of this article. David Smith, Jeremy Frank, and Ari Jonsson have created an excellent overview of challenges in planning and scheduling.[12]

References

1. M.H. Burstein and D.V. McDermott, "Issues in the Development of Human-Computer Mixed-Initiative Planning," *Cognitive Technology: In Search of a Humane Interface*, B. Gorayska and J.L. May, eds., Elsevier Science, 1996, pp. 285–303.
2. J. Allen, G. Ferguson, and N. Blaylock, "A Problem Solving Model for Collaborative Agents," *Proc. First Int'l Joint Conf. Autonomous Agents and Multiagent Systems,* ACM Press, 2002, pp. 774–781.
3. K. Meyers, P.A. Jarvis, T.J. Lee. "Active Coordination of Distributed Human Planners," *Proc. 6th Int'l Conf. AI Planning and Scheduling*, AAAI Press, 2002, pp. 63-71.
4. W.J. Clancey et al., "Brahms: Simulating Practice for Work Systems Design," *Int'l J. Human-Computer Studies*, vol. 49, 1998, pp. 831–865.
5. R.P. Bonasso, D. Kortenkamp, and T. Whitney, "Using a Robot Control Architecture to Automate Space Shuttle Operations," *Proc. Innovative Applications of Artificial Intelligence Conf.*, AAAI Press, 1997, pp. 949–956.
6. G. Dorais et al., "Adjustable Autonomy for Human-Centered Autonomous Systems on Mars," *Proc. 1st Int'l Conf. Mars Soc.*, Univelt, 1998.
7. M. Balduccini et al., "An A-Prolog Decision Support System for the Space Shuttle," Lecture Notes in Computer Science, no. 1990, *Proc. Practical Aspects of Declarative Languages '01*, Springer-Verlag, 2001, pp. 169–183.
8. S. Chien et al., "Automated Planning and Scheduling for Goal-Based Autonomous Spacecraft," *IEEE Intelligent Systems*, vol. 13, no. 5, Sept./Oct. 1998, pp. 50–55.
9. N. Muscettola et al., "Remote Agent: To Boldly Go Where No AI System Has Gone Before," *Artificial Intelligence*, vol. 103, no. 1, Aug. 1998, pp. 5–47.
10. S. Chien et al., "The Techsat-21 Autonomous Science Agent," *Proc. 1st Int'l Joint Conf. Autonomous Agents and Multiagent Systems,* ACM Press, 2002, pp. 570–577.
11. T. Estlin et al., "Decision Making in a Robotic Architecture for Assembly," *Proc. 6th Int'l Conf. AI, Robotics, and Automation for Space (i-SAIRAS 2001)*, Canadian Space Agency, 2001.
12. D. Smith et al., "Bridging the Gap between Planning and Scheduling," *Knowledge Eng. Rev.*, vol. 15, no. 1, Mar. 2000, pp. 47–83.

The Author



David Kortenkamp is a senior research scientist at Metrica Inc., supporting NASA's Johnson Space Center. His research interests include intelligent robotics, autonomous control of spacecraft, and human-automation interaction. He was the chair of the organizing committee of the Third NASA International Workshop on Planning and Scheduling for Space. He is coauthor of *Mobile Robots and Artificial Intelligence*. He received his PhD in computer science and engineering from the University of Michigan and his BS in computer science from the University of Minnesota. He is a member of the IEEE. Contact him at the NASA Johnson Space Center, Mail Code ER2, Houston TX 77058; kortenkamp@jsc.nasa.gov.