The Future of AI in Space

Steve Chien, Richard Doyle, and Ashley Gerard Davies, *Jet Propulsion Laboratory*
Ari Jónsson, *NASA Ames*
Ralph Lorenz, *University of Arizona*

Casual observers of NASA spacecraft, systems, and missions might assume that artificial intelligence—whether they know or would use the term itself—has long been integral to what NASA does. However, the reality of high-stakes space missions must balance bold concepts with careful engineering, especially risk management. New capabilities, whether based on AI or other technologies, are adopted only when they offer overwhelming benefits to a mission. Even then, a new capability's risks must be well understood and aggressively retired.

And yet, space exploration, whether by robotic spacecraft or astronauts, is not for the faint of heart or vision. Since 1998, when we initiated this department via a special issue (see the sidebar), AI has made steady progress in the space realm. In particular, two successful flight technology experiments—the Remote Agent Experiment (RAX) in 1999,[1] and the Autonomous Sciencecraft Experiment (ASE),[2] deployed in 2003 and still functioning on the Earth Observing One (EO-1) platform—validated appropriate uses of AI-based capabilities in future robotic missions. These capabilities will also support NASA's renewed emphasis on robotic and human exploration of the Moon, Mars, and beyond.

Recent AI history in space

Flight technology experiments are focused activities that support NASA's pursuit of the capabilities it needs to explore space frontiers. The experiments validate new spacecraft capabilities, exploring their potential and value, and mitigating the inherent risks. Generally, the experiments are conducted on separate spacecraft designated for the purpose, but they're also uploaded to spacecraft that have already accomplished their primary missions.

For example, the RAX remote agent was uploaded to Deep Space One and controlled the DS-1 mission for several days in 1999. RAX was the groundbreaker—actually, flightbreaker: for the first time, AI flight software controlled a spacecraft. It included an onboard planning system, execution engine, and model-based diagnosis and recovery capability. RAX accomplished all its experiment objectives and demonstrated the potential and utility of spacecraft autonomy.

This success led to MapGen (Mixed Initiative Activity Planning Generator), the tactical planning system for the Mars exploration rovers.[3] MapGen integrated a descendant of RAX's planning system with a JPL activity plan editing system. Other RAX legacies include the Livingstone model-based diagnosis engine,[4] which is currently part of discussions for system-health management onboard the Crew Exploration Vehicle (CEV) within NASA's new human space exploration program. RAX was co-winner of the 1999 NASA Software of the Year Award.

As a technology experiment, the ASE software demonstrated autonomous tracking of volcanic, flooding, and freeze-thaw phenomena on Earth.[5] The experiment was so successful that in November 2004, the EO-1 mission adopted the ASE's flight and ground software as an operational capability. This led to over US$1 million per year savings in operation costs—a key factor in EO-1's recent two-year mission extension. ASE was co-winner of the 2005 NASA Software of the Year Award. It features the Casper (Continuous Activity Scheduling Planning Execution and Replanning) software planner, a robust execution engine, and several examples of AI-based science event-detection software—for example, recognizers, change detectors, and classifiers. Version 2 of the Livingstone software flew onboard EO-1 in 2004–2005, demonstrating the diagnosis and tracking of simulated failures in the EO-1 science instruments.[6]

Other successful AI applications include the Descent Image Motion Estimation Subsystem.[7] Dimes is a machine-vision component of the Mars rovers' entry, descent, and landing system. It tracked features such as craters during the intense period of descent, while calculating horizontal wind velocities onboard and firing thrusters autonomously to compensate for shear winds.

Future AI applications in space science

These recent successes of AI-based capabilities have opened up thinking about their appropriate uses in future

1541-1672/06/$20.00 © 2006 IEEE
Published by the IEEE Computer Society

Retrospective on 1998 Special Issue: "Autonomy in Space"

Several themes ran through *IEEE Intelligent Systems*' Autonomy in Space issue,[1] and those themes remain largely relevant today. Successes and advances in the applications of component AI capabilities have varied since 1998, but certain cases are further along than we projected. Most of the space exploration mission concepts are still ahead of us—for example, the Titan Aerobot and the Europa Submersible—but others are accomplished, including the spectacularly successful Mars rovers. Another is Deep Impact, which featured autonomous guidance and control in the impactor spacecraft that penetrated Comet Tempel 1.

An overarching theme from 1998 was the importance of spacecraft control architectures to support autonomy. Both the Remote Agent Experiment (RAX) and the Autonomous Sciencecraft Experiment (ASE) featured such architectures. Others have been proposed and developed, such as the Mission Data System, but deployments are still limited. This might change with current interest across the aerospace community in *goal-based operations,* which imply autonomy—in particular, automated planning capability.

Planning and execution capabilities featured prominently in the special issue, and they're reflected in the planning and execution engines of both the RAX and ASE architectures. Much work has gone into extending and refining these systems. For example, ASE uses continuous planning to respond rapidly despite limited onboard computing.

Science-directed autonomy came into its own on ASE, and AI practitioners can rightly point to significant accomplishments in this area. ASE routinely detects and responds to dynamic science events. Most important, the science community has taken note, and many more applications are under way.

The special issue also looked at model-based software verification methods. At the time, such work was largely off the radar for most AI practitioners, but this is no longer the case. AI capabilities are, after all, embodied in software, and the techniques that verify flight software as its functional complexity increases must apply, in some form, to autonomy software as well. NASA has been emphasizing all aspects of software engineering; it remains an open question whether autonomy software's special needs—for example, in memory management—will require separate or extended verification and system validation techniques.

Reference

1. R.J. Doyle, "Spacecraft Autonomy and the Missions of Exploration," *IEEE Intelligent Systems* (Guest Editor's Introduction), Sept./Oct. 1998, pp. 36-44.

space exploration. By enabling onboard decision-making, AI technologies support spacecraft in detecting and tracking events of scientific interest. In the most aggressive use of these technologies, the spacecraft can respond to events by further investigating them. Onboard decision-making can also improve access to dynamic environments, such as comets.

Earth science applications

Onboard EO-1, ASE has enabled development of a sensorweb that networks autonomous decision-making nodes to study Earth science events.[8] EO-1 is networked with other spaceborne observing assets and with ground-based sensors such as seismometers, tiltmeters, and temperature sensors to track volcanic activity, flooding, lake and sea ice freeze-thaw, and snowfall.

AI has played several roles in the ASE and EO-1 sensorweb deployments, demonstrating onboard decision-making's potential to enhance Earth science:

- Machine learning develops event detectors that also track science events, interpreting noisy and incomplete data.
- Automated planning systems allocate scarce observational resources to the highest-priority targets.
- Task execution systems handle execution anomalies inherent in real-time systems.

The applications developed in Earth orbit will translate to future sensorwebs in other planetary orbits.

Mars applications

Recent explorations have shown Mars to be far more dynamic than expected. A flight software upload in July 2006 to the Spirit and Opportunity rovers will provide image-processing software to enable onboard tracking of dust devils and clouds.[9] The new software lets the rovers efficiently monitor these infrequent events, downlinking only the images or image portions containing the targets of interest. Such investigations will further our understanding of the Martian atmosphere.

Additional work for Themis (Thermal Emission Imaging System), an instrument onboard the Mars Odyssey Orbiter, will help detect and track phenomena such as thermal anomalies from volcanic activity, seasonal variations in polar frost caps, dust storms, and water ice clouds.[10] Other dynamic features of interest include wind-related features such as dust devil tracks and the dark slope streaks shown in figure 1.

Onboard decision-making could also enhance surface missions to study Mars geology. For example, a rover that could detect when it moves from an area formed

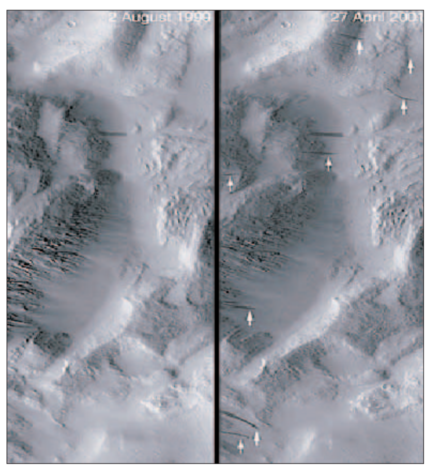


Figure 1. Images of (left) Mars surface and (right) same surface later showing new dark slope streaks. (photo courtesy of Malin Space Science Systems)

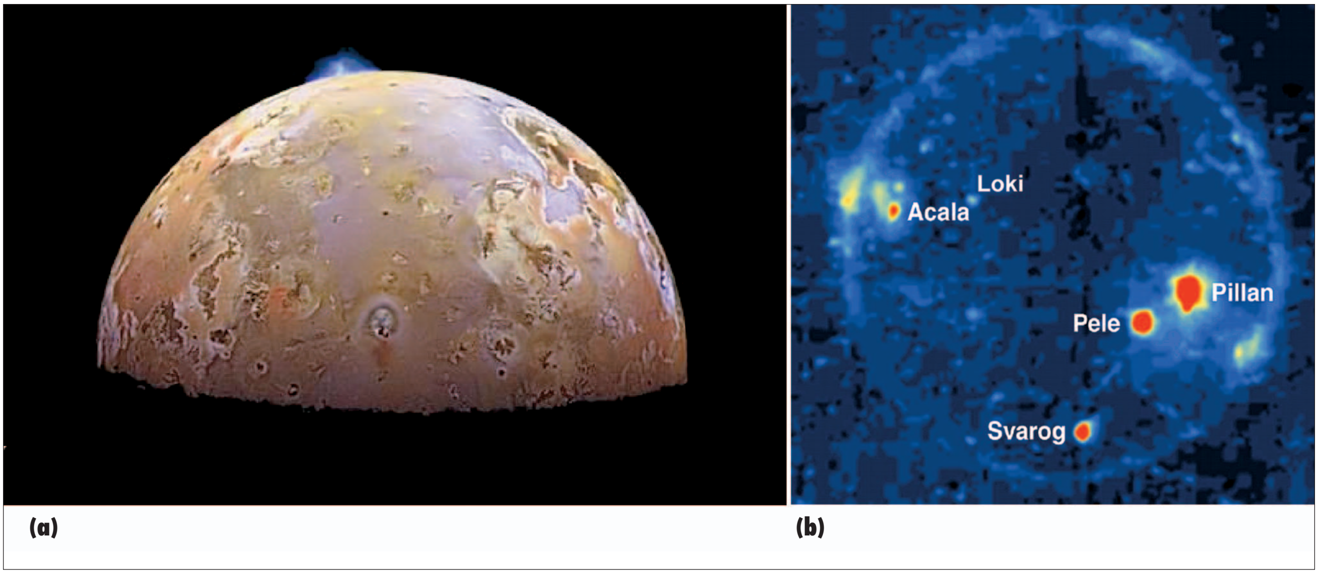


Figure 2. (a) Plume from the 1997 eruption of Io's Pillan volcano and (b) lava fountain at Pillan as seen by Galileo Solid State Imaging system. The intensity of thermal emissions saturated the detector, reducing the returned data's content and value (images courtesy of NASA)

by lava flows to one formed by water deposition would support more efficient exploration of the Martian surface.

Outer planet applications

The benefits of onboard AI and spacecraft autonomy can be highlighted further by considering a mission to study Io, a Jupiter moon that's the most volcanically active body in our solar system. Although the NASA Galileo spacecraft studied Io extensively, many questions remain as to the exact nature of its volcanic activity—for example, the composition of the lava erupting onto the surface. Lava eruption temperature constrains interior composition and evolution models for Io. Lava temperature is best studied during rare lava-fountain events that expose relatively large areas at or close to the liquid lava's eruption temperature (see figure 2).[11]

With onboard decision-making, a spacecraft could rapidly identify such an event, even from a great distance. It could then use this information, first, to obtain observations during a close encounter and, second, to reset instruments to avoid detector saturation by the thermal source.[12] Later exploration could bring additional instrumentation to observe the eruption site and obtain, for example, high-resolution infrared spectra for compositional analysis.

Europa. A proposed probe to investigate subsurface oceans on Europa, another of Jupiter's moons, would require considerable autonomy to survive, much less explore. Even getting to the subsurface ocean requires landing on Europa's icy surface, melting through or otherwise penetrating the ice cap, then releasing a submersible (or becoming one) to explore the subsurface ocean.

Such a probe would need to deal with a great many uncertainties, including the ice cap's thickness and composition, the energy required to penetrate the surface, and sensor effectiveness in the underground ocean. The capabilities to survive the journey, operate with limited communications to Earth, and accomplish science objectives represent an incredible challenge to onboard autonomy.

Titan. The Cassini mission has shown that the Saturnian moon Titan has a complex, diverse landscape. Its low gravity (one-seventh of Earth's) and dense atmosphere (four times Earth's) make it an attractive place to explore with an aerial platform. Balloons, airships, aircraft, and helicopters are all possible for a mission planned in the 2015–2020 time frame, although lighter-than-air vehicles have received most attention to date (see figure 3).

There are two key motivations for invoking autonomy in this exploration. First, the two-way light time is between two and two-and-a-half hours, which effectively rules out interactive operations. If a balloon is drifting at, say, 1 meter per second at an altitude of 5 kilometers and can image effectively out to 45 degrees from nadir, then by the time the aerobot could send a signal to Earth and receive a response, it would typically be out of sight of whatever object triggered the signal.

The second issue is downlink bandwidth. With a pointable antenna, an aerobot can send data direct to Earth (when the Earth is above the horizon) at a few kilobits per second. A mission at the summer pole (the north pole in the 2015–2020 time frame) would be in continuous view of the Earth; in general, a mission at low latitudes would be visible from Earth only a third to half the time. Most likely, an orbiter would support the aerobot via a low-gain antenna and a UHF link. However, orbital dynamics around Titan are such that this relay link would be available for windows of only some tens of minutes, perhaps once a day or more. This relay link permits hundreds of megabits per pass and calls for distinguishing between high-priority data to send immediately and lower-priority data to buffer and downlink at the next available relay opportunity.

A Titan aerobot would likely have several instruments:

- in situ state measurements such as temperature, pressure, and methane abundance;
- a subsurface radar sounder to measure the depth of organic deposits on the surface and look for subsurface layering, buried craters, and other phenomena; and

- an imager with a wide field of view, since it's close to the surface and can achieve a high resolution without ambitious optics.

With onboard decision-making, a Titan aerobot could potentially investigate dynamic phenomena such as methane thunderstorms. methane geysers, or cryovolcanic eruptions. Such events, while presenting some danger to investigate, would be of enormous scientific interest. Conceivably, an autonomous system could even sample such an event.

Other missions

AI and onboard decision-making would apply directly to missions to dynamic bodies such as comets. Approaching a comet requires orbiting a small body with a very hazardous environment. Plumes or geysers from the comet's surface represent interesting science events as well as hazards to the spacecraft. Imaging these events in detail, collecting samples from them, and landing and acquiring subsurface samples are all valuable mission capabilities. Landing and drilling for samples present unique challenges. For example, uncertain surface hardness makes it difficult to predict the time or power required to drill to specified depths.

Onboard decision-making will have applications to NASA astrophysics missions, including those designed to detect planets around other stars.

Space weather is another fertile area for AI applications. NASA and other agencies have several spacecraft monitoring the sun for various events, including coronal mass ejections. A space weather sensorweb of instruments could detect and track these events, which dramatically affect communications, power grids, and satellites at or near the Earth.

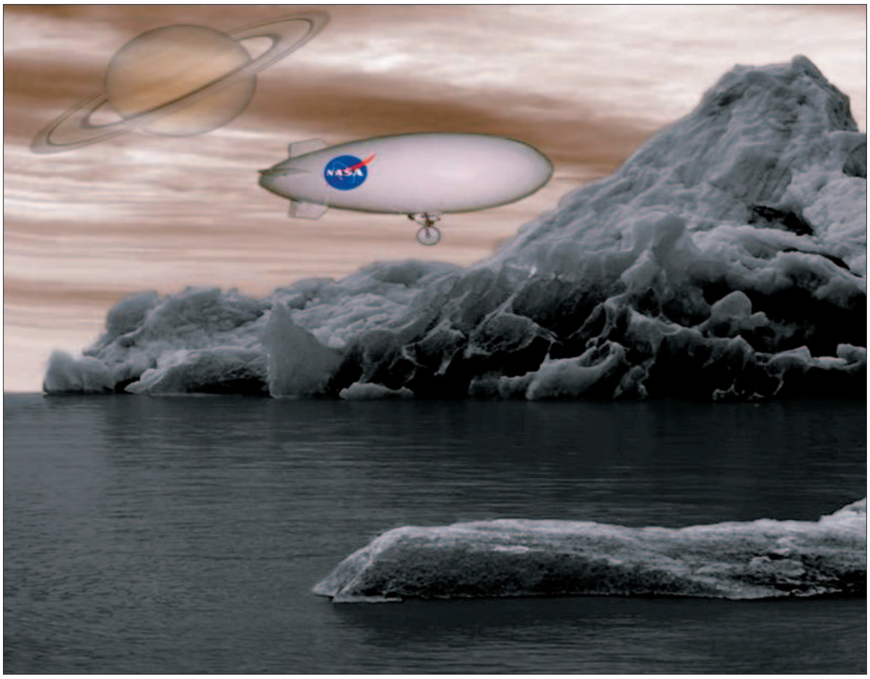


Figure 3. Artist rendering of NASA aerobot. (artwork courtesy of NASA)

Figure 4. The proposed Crew Exploration Vehicle visiting the International Space Station. (artwork courtesy of NASA)

Future AI applications in human space exploration

Today's NASA exploration vision calls for renewed emphasis on human exploration of space, and it has a new space flight vehicle on the drawing board to support this vision. The CEV (see figure 4) has an ambitious agenda: support continued low-Earth-orbit flights, transport astronauts back to the moon, support extended presence on the lunar surface, and—eventually—enable human travel to Mars.

At first, considering AI's future in the context of human exploration might seem counterintuitive. After all, a key motivation for more intelligent science spacecraft is to extend remote space operations beyond human involvement. However, as human spaceflight moves beyond low Earth orbit, a number of key changes will occur. Longer missions and increased complexity will require improved handling of operations plan management, crew scheduling, and other issues involving task coordination as well as operations of systems, vehicles, habitats, and robotics.

Intelligent crew and mission operations

Traditional mission operations planning, including crew scheduling, involves significant support from ground operations staff. Aside from cost and rigidity, the approach works against the very reason for human space travel, not to say human nature. In fact, during Skylab operations, crews rebelled against the carefully constructed, detailed schedules laid out for them. International Space Station operations today are much more flexible, letting the crew manage their own task schedules, within certain limits.

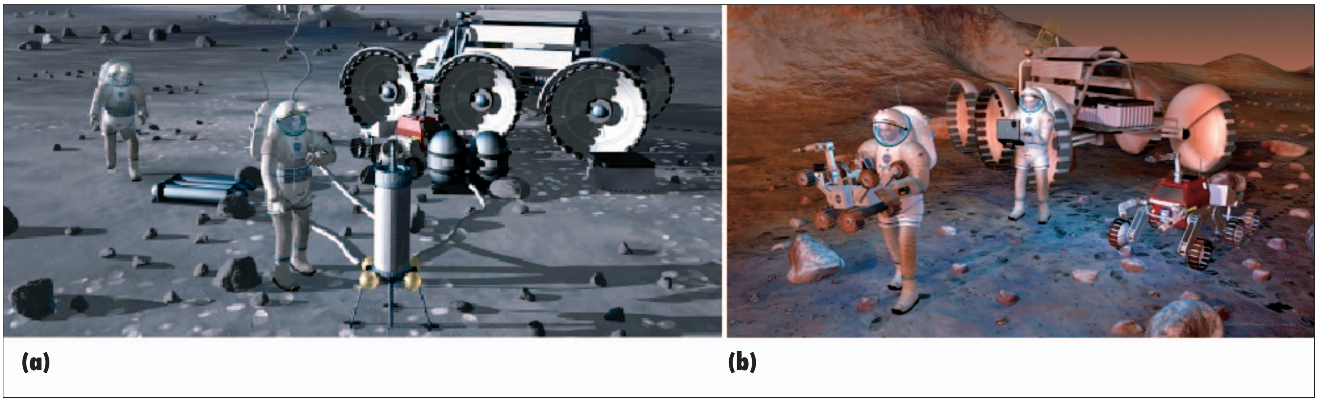


Figure 5. Astronauts (a) performing operations on the lunar surface with robotic assistance and (b) preparing for autonomous robotic sample collection on the Martian surface. (artwork courtesy of NASA)

At the same time, spaceflight operations are too complex and high-risk for arbitrary decisions to be safe. Interdependencies among systems, limited resources, complex tasks, and many other factors restrict operations plan flexibility. AI-based mission operations technology has already proven itself in the context of science operations planning. These technologies can play a key role in helping crews, ground operations staff, and others manage operations plans through interactive systems. Such systems let the crew safely manage their own schedules, in concert with mission operations plans and constraints from mission control on Earth.

Intelligent systems management

As human space exploration moves forward, the level of expert training and staffing needed to oversee and manage all systems from the ground isn't sustainable. Moreover, as humans venture further from low Earth orbit, light-speed time delays and contact interruptions will change how crew and ground staff work together. These factors will require spacecraft crews to manage their own systems. However, because the crew has other responsibilities and possibly limited in-depth expertise in system operations, AI-based techniques are an attractive means to assist them in systems management.

Intelligent systems management involves not only traditional aspects of AI-based control, such as state determination, decision-making, and execution, but also a significant human-in-the-loop component. AI software can provide situational awareness, explanations, and information summaries to accommodate crew needs and desires.

Consider a spacecraft's power system as an example. Power management involves production, such as through photovoltaic panels, storage in batteries, load management, protection of critical systems, distribution, and more. The crew can't and shouldn't perform this work; rather, automated control software should handle the details. In nominal operations, this involves operating the system according to a plan, tracking the system's state, projecting and making decisions about load management, and other actions. Clearly, the power system isn't managed in isolation; other systems, such as those using power, must be operated in concert with power management. In addition, spacecraft attitude will significantly impact power generation capabilities of solar panels. Finally, crew activities and needs strongly affect power management.

Intelligent state determination and failure response are crucial in this context: the automated software will have to respond to failures by isolating the cause and, if needed, providing initial and immediate response. The software might then involve the crew, which requires knowledge of crew activities as well as failure criticality, ground contact, and many other types of information. Working with the crew and possibly ground control, the software can respond to unexpected events, performing repair actions, reconfiguring systems, and evaluating impacts on future operations.

While current systems operations might work for near-term exploration activities in low Earth orbit, the sheer complexity of surface operations on the Moon, along with limited crew members and ground-control involvement, makes a compelling case for AI-based assistance in managing systems.

Human-robotic exploration

The ultimate objective of human presence in space is to explore and gain a permanent foothold on bodies in the solar system—first the Moon, then Mars and beyond. Achieving these objectives will involve significant exploration and development in space, on the Moon, and on Mars.

Although humans are very capable and flexible space explorers, they're limited in their physical capabilities and numbers. So, future explorations will rely on assistance from robotics, ranging from data-gathering scout rovers to robotic machinery for in-situ resource utilization and habitat construction (see figure 5).

Consider a future scenario on the lunar surface. A small crew of astronauts is working from a habitat near the lunar south pole. Their mission is to set up infrastructure that can support extended capabilities and to continue exploration of that area. Cosmic ray exposure and lunar dust severely limit how often and how long the crew can operate outside, so robotic systems perform activities that don't strictly require human involvement. These include scouting the polar region, gathering data for science and engineering activities, performing certain construction and setup tasks, and so forth. The crew might be directing many of these robotic operations, but from inside the habitat. When crew members go outside, they would still rely on robotics to facilitate their tasks. The robotics might be operated by humans or automated software, depending on needs and situations.

Joint human-robotic operations on planetary surfaces, such as on the Moon and Mars, will offer some of the most challenging problems for AI in space exploration. Managing robotic equipment such as rovers has long been part and parcel of AI applications. However, remote operations to support human crews bring new challenges, including human-robotic and human-automation interactions, situational awareness for both robotics and humans, and much more dynamic environments.

Sensorweb scenarios will become more common as NASA invests in space-based networking capabilities, catalyzed by the great success of using relays at Mars to return data from Spirit and Opportunity. Over 95 percent of the science data from these rovers was relayed, either via Mars Odyssey, Mars Global Surveyor, or the European Space Agency's Mars Express platforms. NASA has just placed the Mars Reconnaissance Orbiter in Mars orbit; it plans to use this platform as a relay for the next rover mission, the Mars Science Laboratory. A dedicated networking platform at Mars, the Mars Science Telecom Orbiter, is planned.

As space-based networking becomes the norm, more missions will exploit space platforms to accomplish their objectives. EO-1 is showing now what Earth-based sensorwebs can achieve, and it's not difficult to imagine scenarios on Mars where a detection event originates from an orbital platform while surface assets conduct appropriate follow-on activities.

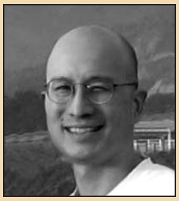
Such scenarios place an implicit survivability requirement on the platforms. The longer space assets survive, the greater the possibilities for them to participate flexibly in different coordinated configurations, supported by space networks. The longer-than-expected lifetimes of Spirit and Opportunity are encouraging in this regard.

Mission concepts involving coordinated space platforms will drive AI research in areas such as distributed planning and control and distributed fault management. If space platforms turn out to be really rugged, surviving a decade or more, they might be able to evolve their mission objectives over time, eventually performing missions well beyond those for which they were originally conceived. Such prospects inevitably rely on further research in reasoning, learning, evolutionary systems, and other AI technologies. ■

References

1. N. Muscettola et al., "To Boldly Go Where No AI System Has Gone Before," *Artificial Intelligence*, vol. 103, nos. 1–2, Aug. 1998, pp. 5–48.
2. S. Chien et al., "Using Autonomy Flight Software to Improve Science Return on Earth Observing One," *J. Aerospace Computing, Information, and Communication*, Apr. 2005, pp. 196–216.
3. J. Bresina et al., "Activity Planning for the Mars Exploration Rovers," *Proc. Int'l Conf. Automated Planning and Scheduling*, Am. Inst. Aeronautics and Astronautics, 2005.
4. A. Bajwa and A. Sweet, "The Livingstone Model of a Main Propulsion System," RIACS tech. report 03.04, Research Inst. for Advanced Computer Science, Dec. 2002.
5. A.G. Davies et al., "Monitoring Active Volcanism with the Autonomous Sciencecraft Experiment (ASE) on EO-1," *Remote Sensing of Environment*, vol. 101, no. 4, 2006, pp. 427–446.
6. S. Hayden, A. Sweet, and S. Shulman, "Lessons Learned in the Livingstone 2 on Earth Observing One Flight Experiment," *Proc. AIAA 1st Intelligent Systems Tech. Conf.*, Am. Inst. Aeronautics and Astronautics, 2004.
7. Y. Cheng et al., "The Mars Exploration Rovers Descent Image Motion Estimation System," *IEEE Intelligent Systems*, vol. 19., no. 3, 2004, pp. 13–21.
8. S. Chien et al., "An Autonomous Earth-Observing Sensorweb," *IEEE Intelligent Systems*, vol.20, no. 3, 2005, pp. 16–24.
9. A. Castano et al., "Autonomous Detection of Dust Devils and Clouds on Mars," to appear in *Proc. IEEE Int'l Conf. Image Processing* (ICIP 06), IEEE Press.
10. K. Wagstaff, "An Onboard Data Analysis Method to Track the Seasonal Polar Caps on Mars," *Proc. 8th Int'l Symp. Artificial Intelligence, Robotics, and Automation in Space* (i-SAIRAS 2005), European Space Agency, 2005.
11. A.S. McEwen et al., "High-Temperature Silicate Volcanism on Jupiter's Moon Io," *Science*, vol. 281, 3 July 1998, pp. 87–90.
12. A.G. Davies et al., "Improving Mission Survivability and Science Return with Onboard Autonomy," working paper, *Proc. Int'l Planetary Probe Workshop 4*, Jet Propulsion Laboratory, 2006.

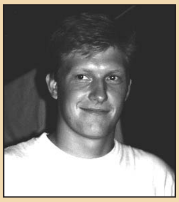
For more information on this or any other computing topic, please visit our Digital Library at www.computer.org/publications/dlib.



Steve Chien is a principal scientist at the Jet Propulsion Laboratory, where he leads efforts in autonomous space systems. Contact him at steve.chien@jpl.nasa.gov.

Richard Doyle is manager of the Mission Information Technology Program Office at JPL, where he leads the development and application of autonomy and related software and computing capabilities for JPL's missions. Contact him at richard.doyle@jpl.nasa.gov.

Ashley Gerard Davies is a volcanologist at JPL and the lead scientist for the Autonomous Sciencecraft Experiment. Contact him at ashley.davies@jpl.nasa.gov.



Ari Jónsson is a research scientist with NASA Ames' Research Institute for Advanced Computer Science. His research focuses on autonomous planning and scheduling for spacecraft operations. Contact him at jonsson@ptolemy.arc.nasa.gov.

Ralph Lorenz is a planetary scientist at the Lunar and Planetary Lab, University of Arizona, with interests in Titan and Mars exploration. Contact him at rlorenz@lpl.arizona.edu.