The Emergence of Spacecraft Autonomy

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Abstract

The challenge of space flight in NASA's future is to enable more frequent and more intensive space exploration missions at lower cost. Nowhere is this challenge more acute than among the planetary exploration missions which JPL conducts for NASA. The launching of a new era of solar system exploration -- beyond reconnaissance -- is being designed for the first time around the concept of sustained intelligent presence on the space platforms themselves. Artificial intelligence, spacecraft engineering, mission design, software engineering and systems engineering all have a role to play in this vision, and all are being integrated i n new work on spacecraft autonomy.

The Strategic Importance of Spacecraft Autonomy

The development of autonomy technologies is the key to three vastly important strategic technical challenges facing JPL: the reduction of mission costs, the continuing return of quality science products through limited communications bandwidth, and the launching of a new era of solar system exploration -- beyond reconnaissance - characterized by sustained presence and in-depth scientific studies.

Autonomy can reduce mission costs in multiple ways: 1) by migrating routine, traditionally ground-based functions to the spacecraft (e.g., resource management engineering data analysis, navigation), 2) by directly supporting the decoupling of space platforms from the ground through new operations concepts, 3) by supporting direct links between scientists and the space platforms carrying their instruments of investigation, and 4), via the closing of planning and control loops onboard, enabling the space platform to directly address uncertainty in the real-time mission context and obviating the need for many intense, indirect and inefficient interactions with the ground which occur in today 's missions by default. Recent estimates for expected cost savings in the operation of future JPL missions using autonomy capabilities run as high as 60%. The same study concluded uplink (commanding) savings alone could be as great as $ 14M/year for orbiter-type mapping missions (e.g., Magellan), and $30M/year for multiple-flyby tour-type missions (e.g., Galileo). (Ridenoure 1995).

Autonomy technology for onboard science data processing, along with advances in telecommunications technology, can address the challenge of limited communications bandwidth, which may worsen if NASA's vision of flying more space platforms at once is realized. Through onboard decision-making, scientist-trained recognizers, and judicious use of knowledge discovery methods, a portion of the scientist's awareness can be projected to the space platform, providing the basis for scientist-directed downlink prioritization and the processing of raw instrument data into science information products. This software-based partnership between scientist and space platform can evolve during the mission as the scientist becomes increasingly comfortable with the direct relationship with the space platform, intermediate scientific results emerge, and scientist-directed software updates arc uploaded.

Finally, autonomy is the central capability for enabling long-term scientific studies of a decade or more, currently prohibited by cost and self-reliance of space platforms, and for enabling new classes of missions which inherently must be executed without the benefit of ground support, either due to control challenges, e.g., small body rendezvous and landing missions, or due to planning challenges which arise from of the impossibility of communication for long periods, e.g., a Europan under-ice explorer, or a Titan aerobot.

The need for autonomy technology is nowhere greater than in the set of deep space planetary missions which JPL conducts for NASA. The extreme remoteness of the targets, the impossibility of hands-on troubleshooting or maintenance, and the difficulties of light-time delayed communication (four hours and greater round-trip in the outer solar system) all contribute to make JPL science missions the focus for the development and application of autonomy technology.

A Vision for the Development and Deployment of Autonomy Technology

Intelligent, highly autonomous space platforms will evolve and deploy in phases to support both low-cost mission goals and more excitingly, a new era of exploration characterized by in-depth scientific studies and sustained presence. The first phase involves automation of the basic engineering functions of the space platform. The relevant capabilities include mission planning and resource management, health management and fault protection, and guidance, navigation and control. Stated differently, these autonomous capabilities will make the space platform *self-commanding*, ***self-preserving*** and ***self-*** *mobilizing.* Some of the relevant AI and other technologies include planning & scheduling, operations research, decision theory, model-bawd reasoning, intelligent agents, spatial reasoning and neural and other specialized technologies. By 2000, we expect that NASA spacecraft will have demonstrated onboard automated closed loop control at a basic level among: planning activities to achieve mission goals, maneuvering and pointing to execute those activities, and detecting and resolving faults to continue the mission without requiring ground support. At this point, basic mission accomplishment can begin to become largely autonomous, and dramatic cost savings can be achieved in the form of reduced, shared ground staffing which responds on demand to spacecraft-based requests for interaction. Also in this phase, the first elements of onboard science autonomy will be deployed, based on techniques like trainable object recognition. In addition, some science-relevant decisions can begin to be made onboard. e.g., planning and executing additional observations when an object of stated *a priori* interest is detected and is observable only for a brief time, for example a natural satellite. However, the decision-making capacity to determine how mission priorities should change and what new mission goals should be added in the light of intermediate results, discoveries and other events would still reside largely with scientists and other analysts *on* the ground.

Work on automating the spacecraft will continue into challenging areas like greater onboard adaptability in responding to events, closed-loop control for small body rendezvous and landing missions, and operation of the multiple free-flying elements of space-based telescopes and interferometers. In addition, in the next phase of autonomy development and insertion, a portion of the scientist's awareness, i.e., an observing and discovery presence, will begin to move onboard. In other words, knowledge for discriminating and determining what information is scientifically important would start to migrate to the space platform. Relevant capabilities include feature detection and tracking, object recognition, and change detection. Some of the relevant AI and machine learning technologies are pattern recognition, classification, and data mining and knowledge discovery. There do not appear to be strong reasons why the interests and priorities of multiple scientists could not be encoded on a single space platform, given expected advances in flight computers and onboard memory capacity. At this point, the space platform begins to become ***self-directing***, and can respond to uncertainty within the mission context, a prerequisite for graduating beyond reconnaissance to interactive, *in situ* exploration. By 2005, we expect that a significant portion of the information routinely returned from platforms would not simply and strictly be raw data or match features of stated prior interest, but would be deemed by the onboard software to be "interesting" and worthy of further examination by scientists and other appropriate experts on the ground. At this point, limited communications bandwidth could then be utilized in an extremely efficient fashion, and alerts from various and far-flung platforms would be anticipated with great interest.

The Context for the Emergence of Spacecraft Autonomy

There is no question that the single greatest driver which has led to the emergence of spacecraft autonomy as a legitimate, perhaps critical application of AI technologies within NASA is the need to reduce the lifecycle costs of space missions. Autonomy technology is seen as on target towards the reduction of mission operations costs, through the automation of spacecraft functions, and the closing of loops onboard and decoupling of spacecraft from ground, with a collateral reduction in the ground workforce required to support missions. In fact, the development of autonomy technology is only one of several parallel technology development efforts which are required to collectively address the reduction of costs across the entire mission lifecycle. That lifecycle spans mission and spacecraft design, spacecraft and ground systems (hardware and software) development, launch, and operations. Although a full description of the technical and other challenges associated with all the phases of a mission lifecycle are outside the scope of this discussion, it is important to place the challenges for autonomy development in this full context. For example, cost savings achieved via autonomy in the operations phase of a mission will impress no one if those savings are offset or overwhelmed by increases in software development costs. More to the point, it is only when such development costs can be amortized across several missions that the benefit of autonomy technology for controlling the costs of NASA missions can be realized or claimed.

The full potential for autonomy technology to contribute to mission lifecycle and cross-mission cost reduction can be achieved only by understanding the relationships among autonomy development, design, and software engineering. First consider autonomy and design. Autonomy technology developers understand intimately the importance of encoding knowledge to be utilized by reasoning engines in the form of models, e.g., models of activities, resources and constraints for planners and schedulers, models of nominal and fault behaviors for a fault diagnosis system. If modeling languages and tools can be developed which are usable directly by spacecraft engineers and mission designers, then a major source of development costs within a single mission is avoided and an important source of leverage for amortizing costs across multiple missions through the reuse of models (and knowledge) becomes available. The model-based approach, in its general sense, is key to impacting mission costs at JPL and NASA.

Now consider autonomy and software engineering. Autonomy software certainly presents special challenges for validation. Autonomy software typically involves closing loops at the goal level, rather than at the level of deterministic sequences, by which spacecraft are traditionally commanded. AI practitioners understand that autonomy actually provides a form of robustness not found in the traditional approach because the spacecraft has the ability to reason about how to achieve goals in the possibly uncertain real-time context of the spacecraft. predictability at the level of specific low-level spacecraft activities is unavailable but predictability at the level of achieving goals (or high-level commands) is actually enhanced. The traditional sequencing approach can be brittle because of the difficulty of predicting precise details of the real-time context of the spacecraft. Although traditional spacecraft are robustly programmed to enter a "safe hold" if the context for executing commands is not as expected, when this happens the mission itself goes on hold as well. Autonomous spacecraft will have the means to reason about how to continue a mission in the face of such uncertainty without immediately entering a safe hold or falling back to the ground for assistance.

This digression must now return to the question of how to validate such robust behavior in autonomous systems. Certainly modern software engineering practices are a minimal starting point: spiral development with enough flexibility to accommodate development tracks proceeding at different paces; a balance between requirements- and scenario-based testing; continuing roles for developers as integrators and testers; development and use of specialized languages with automatic code generation (Rouquette and Dvorak 1997) and ideally, automatic test generation; novel use of techniques like plan recognition to identify and track different threads of behavior in a single test scenario; multiple-form and variable-fidelity simulation environments (Jain, Biesiadecki and James 1997). The challenge at JPL is exacerbated because modem software engineering practices are not always used uniformly in flight software development. At least in the early stages of autonomy technology development, these practices must be utilized and their value demonstrated by the autonomy technologists themselves. Quite possibly, new autonomy-specific software engineering practices may be required and developed as well. Ultimately, these software engineering practices, along with the autonomy technology itself, must be transferred for use within and across the lifecycles of future missions.

Current Work in Spacecraft Autonomy

The showcase item in spacecraft autonomy development at NASA is the Remote Agent, a joint AI technology project between JPL and NASA Ames Research Center (Bernard and Pen 1997; Muscettola, Smith et al 1997; Pen, Gat et al 1997; Williams and Nayak 1996a). Current plans call for a scaleable subset of the Remote Agent functionality to be demonstrated on the New Millennium DeepSpace 1 mission as an in-flight technology experiment in 1998. Additional functionality is to be demonstrated on the New Millennium Deep-Space 3 mission in 2000 or through other future flight experiment opportunities. Such opportunities fill an important, historically missing piece of the technology development and insertion cycle: the availability of space missions whose primary purpose is the validation of new technologies. NASA's New Millennium Program fills exactly this gap (Fesq et al 1996).

The Remote Agent consists of a Smart Executive, a Planning and Scheduling module, and a Mode Identification and Reconfiguration (MIR) module. The system receives mission goals as input and the executive provides robust, event-driven plan execution and runtime decision making. Planning and scheduling performs resource and constraint management by determining ordered activities free of constraint violations. MIR continuously monitors qualitative representations of sensor data, identifying current spacecraft modes or states, and when these are fault modes, selects recovery actions. Other functions such as guidance, navigation and control, power management, and science data processing are domain-specific functions that can be layered on top of this basic autonomy architecture, and are developed or modified for each new mission. The Remote Agent has been designed to be a core architecture for autonomous spacecraft.

Although initial work on autonomy is naturally emphasizing automation of the engineering functions of the spacecraft, additional payoff of autonomy technology will be realized in the area of onboard science. This year, in collaboration with scientists at the Southwest Research Institute, a software prototype was completed at JPL for an autonomous natural satellite search capability for use onboard a spacecraft (Stolorz, Doyle et al 1997). The automated process detects satellites in the presence of similar-appearing features such as background stars, detector defects, and cosmic ray hits. The algorithms were tested on images of the asteroid Ida and its companion Dactyl which were returned by the Galileo spacecraft. The tests were blind in that the location of Dactyl was not known to the software developers. The software achieved perfect performance, with Dactyl being successfully detected in all cases, with zero false alarms. In general, there is insufficient time in a flyby mission to transmit images to Earth, search for satellites, and send commands for retargeting. Autonomous natural satellite search, in concert with the capabilities represent by the Remote Agent, can close the loop on detection, replanning and retargeting and allow this kind of transient science opportunity to be fully captured.

In another early example of a project in onboard science, we have shown how intermediate results in onboard ultraviolet spectra analysis, specifically the confirmation or disconfirmation of the presence of molecular species, can be used inform decisions onboard on what to image next and whether to target greater spatial or spectral resolution. Such well-defined criteria for onboard decision making can help maximize science return in a flyby mission with a brief encounter.

In a related project, we are applying a change detection technique which utilizes a subpixel correlative registration technique (Stolorz and Dean 1996) to search for ice crust movement in multiple images of Europa recently returned by the Galileo spacecraft.

This form of autonomy technology aimed directly at the goal of scientific discovery applies generally to NASA's future deep-space missions and its potential in the service of science is only beginning to be articulated.

An important demonstration of autonomous guidance, navigation and control is being developed for the TOPEX/Poseidon follow-on mission, called JASON-I. The TOPEX Autonomy Maneuver Experiment will demonstrate the ability to plan and execute orbital maneuvers to maintain desired ground track for an earth-orbiting mission (Kia, Mellstrom et al 1996). This is a first step towards autonomous capabilities enabling exciting future missions such as comet and asteroid landers and interferometry constellations to resolve planetary bodies at nearby stars. This flight experiment takes place in June 1997.

In the area of new operations concepts enabled by autonomy, the showcase item is the development of "beacon" operations technology for cruise-dominated missions such as Pluto Express, also to be demonstrated on New Millennium Deep Space 1 (Wyatt, Sherwood and Miles 1997). The beacon mode of operations is a new paradigm where the spacecraft takes responsibility for determining when interaction with the ground is desirable, usually to resolve a fault, but possibly also to communicate a science alert. A single ground support staff covers an entire fleet of spacecraft, providing direct support for only a small number at any one time. Beacon operations requires an end-to-end infrastructure which must also include telecommunications technology. Beacon operations software includes onboard logic, interfaced to the fault protection system, for selecting the appropriate high-level beacon signal, capabilities for summarizing engineering data and reporting on anomalies, and automated Deep Space Network antenna scheduling on the ground after an emergency beacon signal is received. Beacon operations can involve long periods between high-bandwidth communications opportunities with the ground. Under such an operations approach, it is imperative that adaptive monitoring techniques be used onboard which can detect and track the inevitable nominal behavior drift which occurs on any space platform after launch (DeCoste 1997). Without such a capability, increasing false alarms would completely cripple beacon operations. onboard monitoring also supports engineering summarization and anomaly reporting, essential to provide context for ground experts when their assistance is sought by the autonomous spacecraft.

In a final example of current work in autonomy technology development, an integrated autonomy concept for a comet rendezvous mission was recently completed. Known as ASPIRE (Autonomous Small Planet In-situ Reaction to Events), this task demonstrates technologies which are good candidates for flight experiments in 2-5 years. Specifically, ASPIRE shows how onboard navigation, planning, maneuvering, tracking and science event detection can work together to achieve both science and engineering goals of a plausible comet rendezvous mission. The mission scenario includes 1) the detection of cracks in the cometary nucleus resulting in a planned and executed maneuver for close observation, 2) the detection and tracking of ejected cometary particles, and 3) a safety maneuver in the context of cometary breakup. The work is now being extended to address the problem of landing on small bodies autonomously (Matthies, Tharp and Olson 1997).

The examples cited here all build on a long and successful legacy of AI research and technology development at JPL, NASA Ames Research Center and elsewhere (Chien, DeCoste et al 1997, Williams and Nayak 1996b).

The Future Missions

The ultimate payoff for NASA of the development of autonomy technology will not be the reduction of mission costs, although this imperative is fully acknowledged. Rather it is in the enabling of whole new mission classes, especially those leading to new kinds of indepth scientific studies supported by sustained presence throughout the solar system (and eventually beyond). The future NASA mission set is extremely exciting, and the role for autonomy technology as enabling in many cases, is readily apparent. There is a mission to explore Pluto in little more than a day after a cruise period lasting more than a decade. There is a mission to rendezvous, land on, even return samples from a comet. There are a series of Mars missions utilizing increasingly sophisticated rovers interacting with the planetary surface. There are deep-space telescopes and interferometers composed of multiple elements which must be coordinated with unprecedented precision to achieve the lofty goal of imaging planets around other stars. There are aerobots which will only partly plan their random courses through Venus' or Titan's atmosphere, and thereby achieve an efficient sampling of those worlds. There is a cryobot which will penetrate Europa's ice crust and determine once and for all if Europa has underground oceans and what may exist there.

All of these missions, and others equally exciting, will require some capability not available before: closing planning and control loops onboard to even achieve the target, coping with the continuous uncertainty entailed by traversing a planetary surface, recognizing well the expected and important and recognizing increasingly well the unexpected and important, coordinating multiple spacecraft as the agents of a distributed system with common goals, or simply having enough self-reliance to exist without direct assistance for long periods.

AI researched and technologists at JPL and NASA are finding themselves, for the first time, working side by side with spacecraft engineers, mission designers, software engineers, and systems engineers to support such missions. We are delighted, in some ways we're surprised it came this early, but for many of us, it's what we were always after: the chance to contribute directly to what has always been NASA's most noble endeavor: exploration of the universe.

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