Spacecraft Autonomy Needs Analysis
for Planetary Exploration Missions

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Abstract

There is a general realization within NASA that “onboard autonomy” is needed. Exact specifications of what that means are often vague at the onset of the mission design process. Moreover, autonomy technology is generally not well understood by the spacecraft design community, which complicates matters considerably. The work described in this paper is an effort to better define the autonomy needs for future planetary exploration missions based on the current mission designs for the roadmap set of solar system exploration missions. This is part of an ongoing NASA exercise to define technology requirements in order to better establish funding priorities. Autonomy technology needs are classified as either algorithms or system software. The algorithms have heritage in AI research domains, such as planning and scheduling, monitoring & diagnosis, and machine learning. System software is intended to meet mission objectives, such as low-cost routine operations, landing and hazard avoidance, or opportunistic science data collection.

1 Introduction

The challenges of future planetary exploration missions coupled with the desire to lower operations cost have resulted in a cultural and technological shift favoring more aggressive use of software technology onboard the space platform [1]. One objective is to migrate mission operations functions traditionally performed on the ground to the spacecraft to lower mission operations cost. There are also circumstances where onboard capabilities are needed to actually enable the mission because of the delays associated with round-trip light time between the spacecraft and the Earth. Decreasing the amount of communication (frequency of contact and data volume) to decrease the loading on NASA’s over-constrained Deep Space Network antennas is also an advantage of doing more processing onboard the spacecraft.

Typically, new software technology is classified as mission “enabling” or “enhancing.” Performing joystick control, for example, is not possible when light-time delays are significant. The solution, therefore, is to provide “mission enabling” software technology to close control loops onboard in order to achieve the primary mission objectives. Enhancing technology tends to be software for lowering total mission cost, DSN loading, or for enhancing science data return. Enhancing technology enters the mission design process as a candidate solution but may be ruled-out as mission design trade-studies occur. Enabling technology, on the other hand, is likely essential for mission success.

Another way to think of autonomy for NASA is that the term represents the current body of information technology (IT) research applied to space missions and that there will be, in fact, a continuum of software solutions for future missions. On the other hand, one could also argue that NASA missions, especially the unmanned ones, have long been autonomous. Providing capabilities onboard to enable the spacecraft to move to a “safe-hold” state or to switch to a back-up unit in the event of a failure are examples of current state of the art behavior that one could define as being autonomous. Onboard autonomy today, however, suggests more comprehensive capabilities that can replace major mission operations functions, suggest new paradigms for mission operations, or enable new classes of missions.

Two significant autonomy technologies were flight demonstrated on the Deep Space Mission in 1998 and 1999. These were the Remote Agent Experiment and the Beacon Monitor Experiment.[2] Remote Agent consisted of onboard planning and scheduling technology, an autonomous executive, and mode identification and recovery. The purpose of the experiment was to verify that substantial onboard capability could be deployed on a real spacecraft in a space environment. Beacon monitor technology is an approach for operating a spacecraft in a way that enables
the spacecraft to determine when ground intervention is required. The beacon technology consists of both telecommunications components and software. The flight software evaluates spacecraft health and determines one of four possible tone states to indicate the urgency of ground intervention. The flight software also employs AI-based techniques to summarize spacecraft engineering data for downlink to Earth when a telemetry link is indeed necessary. Otherwise, monitoring of the spacecraft only occurs via the simple modulated sub-carrier tone. This can result in less tracking time (and thus more efficient use of the antenna network) and lower cost operations due to decreased ground-based routine data analysis. [3]

2  Planetary Mission Science Goals and Strategic Missions

The exploration of the solar system is driven by the desire to understand the planets and the environment in which they exist. The current set of strategic missions consists of the eight highest priority science investigations in the field of planetary exploration.[4] These missions have ambitious scientific goals and as a result, push the limits of technology capability.[5] The following paragraphs describe the current concept for each mission.

2.1  Comet Nucleus Sample Return

The Comet Nucleus Sample Return (CNSR) mission will encounter and land on a comet, collect and store a sample of the comet nucleus material, and return it to Earth for study. The mission has several key technical challenges requiring autonomous operations; a long cruise period which requires adaptive sequencing and fault monitoring and recovery; complex operations near the comet and on the surface requiring autonomous decision making and hazard avoidance; and science operations in a relatively unknown environment. Each of these elements requires the spacecraft to operate essentially independent of the ground controllers for some period of the operation and local decision making enables the mission to deal with unanticipated conditions and collect high priority science data.

2.2  Europa Missions

The Jovian moon Europa is one of the most scientifically interesting objects in the Solar System because of the strong possibility that a liquid water ocean exists underneath its ice-covered surface. If a subsurface ocean exists on Europa, it can be assumed to contain both organic molecules and heat sources from tidal effects, the decay of radioactive elements, and geophysical mechanisms. Europa’s subsurface ocean environment may be similar to that of the deep ocean hydrothermal vents on Earth where remarkable life forms have been detected. The possibility of finding traces of biotic or pre-biotic materials has led to a high science interest in a Europa Lander mission.[6] This mission is technologically challenging in several areas and requires autonomous capability to complete essential elements of the mission. Most critical are the entry, descent and landing phases, which must be accomplished under local control. In addition, the long cruise period requires onboard health maintenance and fault monitoring to insure the successful completion of the mission. Prior to the Europa Lander mission, NASA plans to send an orbiter to assist in determining presence of Europa subsurface water, measure ice thickness and interior properties, and image surface features. This mission will add to the collection of scientific data gathered by the Galileo mission, which currently is conducting periodic flybys of the Jovian moon. Autonomy technology needs requirements for this mission are presented as an example in Section 4.

2.3  Neptune Orbiter

The Neptune orbiter mission is a continuation of the detailed exploration of the outer planets in the same manner as the Galileo mission to Jupiter and the Cassini mission to Saturn. The overall science goals of the Neptune Orbiter Mission are; to study the rings, ring arcs, and shepherd satellites; map Triton’s surface features and examine its geologic history; examine the composition, structure and dynamics of Neptune’s atmosphere; and image and determine the densities of the satellites Larissa, Proteus and Nereid. To accomplish these activities at the great distances requires autonomous health maintenance for the long cruise and orbital operations.

2.4  Mission to Pluto

Pluto is the only planet in the solar system that has not yet been explored. A flyby of the Pluto-Charon system has been formulated along with a continuing mission to one or more of the asteroid-sized Kuiper objects. The major objectives are to characterize surface geology and morphology of Pluto and Charon, map the surface composition, and characterize the neutral atmosphere of Pluto and its escape rate.

2.5  Titan Organics Explorer
The Titan Organics Explorer mission is a follow on to the Cassini/Huygens Probe, and provides a detailed in-situ exploration of the Saturnian moon Titan. To meet the objectives, several mission concepts have been studied, including both aerobot and rover missions. Autonomous operations for the critical atmospheric entry and descent phase is required, as well as autonomous operations for the surface or atmospheric vehicle.

2.6 Saturn Ring Observer

The Saturn Ring Observer (SRO) mission is designed to place an observing spacecraft in a unique orbit around Saturn to observe the rings. This orbit places the spacecraft above the rings in synchronous rotation with the ring particles, and the spacecraft observes the interaction and dynamics of the particles. The overarching goal is to understand ring processes and evolution as a model for the origin of planetary systems. This will involve measurement of ring particle physical properties, dynamics & spatial distribution. To do this, a non-Keplerian orbit has been developed which requires periodic orbit maintenance activities to maintain its position relative to the rings. This operation must be controlled locally in response to the dynamic environmental conditions.

2.7 Venus Surface Sample Return

The Venus Surface Sample Return (VSSR) mission is a very challenging mission. The principal science objective is to return samples of atmospheric and surface material to Earth for detailed chemical analysis. Knowledge of the surface chemistry of Venus is based on limited observations done by the Venera landers. Understanding the surface material will help in calibrating models of the evolution of the atmosphere and the interior. In the same manner as other sample return missions, autonomous capabilities are required for atmospheric entry, descent and landing, and for surface operations. Venus places an additional constraint on the surface operations due to the extremely hot environment (~760 K at the surface). The total surface operation is limited to approximately 1.5 hours, and must include autonomous decision-making ability to meet the science goals.

3 Mission Capability Needs

An intermediate step in identifying autonomy technology for a given mission or across the entire set of missions is to understand the characteristics of the mission and how the mission may stand to benefit if more substantial software technology is deployed. Figure 1 summarizes the mission characteristics for six of the eight candidate missions. From this, it is possible to begin understanding what autonomy functions are required and candidate technology solutions. The first line in Figure 1, “Long Cruise Period,” is often sited as a justification to implement flight software capabilities that reduce the need for ground contact. Dynamic landing environments require closing the control loop onboard in order to land with acceptable risk. Similarly, surface operations and autonomous sample handling suggest the need for onboard autonomy.

Only detailed trade-studies involving many mission design variables can yield the final software design solution for a given mission. In the end, if significant onboard processing is required, it is likely because the detailed trade studies have determined that enhanced onboard software can deliver the solution that best meshes with cost, risk, and schedule constraints.

Another part of the NASA activity is to roll-up the technology needs across the entire mission set. It may be the case that one mission has the need that will drive autonomy performance requirements in that area. Or perhaps several missions can benefit in much the same manner by having a certain software capability. Regardless, the mission capability needs at the roll-up level fall into three basic categories. One is the need to migrate ground functions to the spacecraft to lower mission operations cost and/or enhance the mission in some way (such as improving data quality). The other basic need is to contend with round-trip light delays associated with planetary exploration missions in order to achieve essential mission requirements. The third reason why autonomy may be valuable to NASA involves utilization of the oversubscribed Deep Space Network (DSN) antennas. This is ultimately a cost issue (the DSN could always build more antennas), but it also involves providing capabilities to enable most effective use of this scarce resource. While a valid concern, DSN loading is usually left out of individual mission design processes because agency-wide infrastructure planning and utilization issues are not tightly coupled with NASA mission design activities.
4 Required Autonomy Technologies

In actuality, an autonomous system in the space mission context consists of both hardware and software. For purposes of this discussion, we limit autonomy to be software only but realize that hardware provides many underlying enabling capabilities. It is also assumed that at the mission design level, the appropriate trade studies have been performed to determine the autonomy need. For the purposes of developing software needs requirements, it is most convenient to divide software into algorithms and system software. The algorithms map well to research thrusts within the artificial intelligence community. Autonomy system software maps well into mission needs and consists of combinations of autonomy algorithms (and other software modules) as appropriate for a given mission design and desired functionality. In defining technology needs, it is imperative to specify requirements at both the algorithm and the system level. The requirements breakdown structure shown in Figure 2 was created to classify the relevant autonomy technology needs.

Autonomy algorithms are typically mission functions that are to be migrated to the spacecraft. The functional disciplines are planning, scheduling & execution, monitoring & diagnosis, and machine learning. Guidance, navigation & control is also a valid area but is not within the scope of this paper because it is handled by a separate element in this NASA exercise. Algorithms were specified in the breakdown structure primarily because they match well to the currently funded technology tasks in the NASA technology inventory.

Figure 1: Summary of Mission Autonomy Drivers

**4.0 Onboard Autonomy Software**

**4.1 Autonomy Algorithms**

4.1.1 Planning & Execution

4.1.2 Monitoring & Diagnosis

4.1.3 Instrument Data Processing

**4.2 Architectures & Systems**

4.2.1 Spacecraft Bus Autonomy

4.2.2 Onboard Science Processing

4.2.3 Safe Landing Software

4.2.4 In-Situ Hazard Avoidance

4.2.5 Rendezvous & Docking

Figure 2: Autonomy Breakdown Structure
Today, spacecraft are typically commanded through intricate, pre-planned sequences. Generating these sequences is an expensive, human-intensive endeavor. Current research activities are laying the foundation for performing commanding at a much higher, goal-oriented level. In order to do this, onboard software must be able to plan the exact sequence of events based on its own observation of the environment, resource constraints, and the stated priorities of the mission.[7] With onboard planning and scheduling, the spacecraft can be less costly to operate because the need to carefully construct highly detailed sequences on the ground can be drastically reduced. There is also potential for increased science return if the spacecraft can react autonomously to unanticipated science opportunities. Similarly, a reduction in mission risk can be achieved since an onboard planner can react faster to unexpected problems in cases where round-trip light time delays are significant. Smart executives replace traditional sequencing engines with a more closed-loop software engine capable of resolving higher level goals into executable commands. In order to do this, the smart executive must be able to react to unexpected events, resource constraints, and errors or inconsistencies in the commands that have been generated. The executive acts as the overall coordinator of spacecraft activities and manager of spacecraft resources.[8]

Monitoring & diagnosis technology provides yet another requisite piece for closing the control loop onboard the spacecraft. There are aspects of automated monitoring that relate to both nominal and off-nominal system behavior. For the anomalous case, NASA has traditionally viewed monitoring in terms of fault detection, isolation, and recovery. This approach gives rise to threshold-based anomaly detection systems. If there is a problem, an alarm limit typically moves out of nominal limits and a fault response algorithm is initiated to attempt recovery or place the spacecraft in a safe-hold condition. Next generation monitoring extends fault protection capabilities but also emphasizes monitoring of nominal conditions for the purposes of generating reports to assure ground personnel that the mission is proceeding as planned. Examples of new capabilities in autonomous monitoring are neural networks, adaptive alarm limits, model-based reasoning, onboard empirical and/or model-based summarization, and onboard data archiving.[9]

Onboard instrument data processing encompasses a wide range of algorithms designed to either enable the spacecraft to be more survivable or to increase the science data return to earth. Techniques that leverage instrument data tend to involve use of data mining technologies, such as pattern recognition, machine learning, and knowledge discovery. Also applicable are methods that provide for more adaptive and event-driven science data compression. Onboard image processing algorithms can autonomously identify features of known interest, edit the science data to contain only the important features, and prioritize science data for downlink to Earth. This class of algorithms also enables the space system to be capable of reacting to unexpected science events and can signal the spacecraft to perform follow-up observations without ground contact. Data mining technologies can also be used to identify hazards, either for rovers or during descent and landing operations.[10]

The term autonomy system software, for purposes of this exercise, implies the creation of a system-level software product in order to achieve certain mission objectives.[11] Although each autonomy algorithm provides a necessary function, it is likely for a given deployment that many algorithms would work together to carry out mission objectives. For example, an onboard science algorithm may detect an event and would signal for a follow-up observation. The onboard planning and execution environment would receive that goal and resolve it based on mission priorities and constraints at that time. Another reason why making the distinction between system software and algorithms is important has to do with the various implementation options available for incorporating the autonomy components. The boundary between onboard executives and planners, for instance, can be quite fuzzy. This is because both disciplines involve resource management, command generation, and other shared functionality. Since the component autonomy algorithms have heritage in AI research disciplines, understanding the relevance of each of these disciplines to the higher-level architectures is important. That leads to the third reason to call-out system software as requirements, which is to show mission relevance. The final deployed software system for a space mission may actually combine the system software as identified in the requirements breakdown structure. For example, a mission software system may support both “low cost operations” and “adaptive science.” This form of overlap, for the purposes of this NASA exercise, has not been assessed. Using the breakdown structure to tie autonomy algorithms and research disciplines to mission system software needs is the more important distinction to make in the current NASA planning exercise. The result is an autonomy requirements breakdown structure that is useful to both the mission design community and the technology development community.

There is also a third category of autonomy, which is ground-only software. The ground software can then be divided into either design-time or mission operations software. Examples of design-time autonomy could include autonomous design
environments or mission simulations that are substantially more complex than the current state-of-the-art. For mission operations, planning & scheduling technology can be used to assist ground operators or to automate the deep space network scheduling operations. Ground autonomy, although completely valid, has not been included in the current the JPL planning activities for now.

As an example, Figure 3 summarizes the autonomy technology needs for the Saturn Ring Observer mission. Mission attributes are the features of the mission that provide justification for considering autonomy software. Capability needs are the specific performance objectives for the autonomous system.

5 Gap Analysis

An assessment of the technology gaps associated with each technology area was performed as part of the ground-work in setting future NASA funding priorities.

<table>
<thead>
<tr>
<th>Autonomy Element</th>
<th>Mission Attributes</th>
<th>Capability Needs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Automated Planning &amp; Execution</td>
<td>Long cruise period, long round-trip light delays</td>
<td>Technology for enabling spacecraft commanding to be accomplished from high-level goals to result in: 1) Increased quality/quantity of bonus science due to adaptive planning &amp; scheduling without ground intervention (due to long round-trip light time delays). 2) Reductions in operations cost by migrating routine planning, scheduling, and execution to the spacecraft.</td>
</tr>
<tr>
<td>Onboard instrument data processing</td>
<td>Long round-trip light delays and limited communications bandwidth</td>
<td>Autonomously perform aerocapture cleanup and maintenance of the hover orbit. Instrument data processing for the purpose of collecting event-driven science data is potentially enhancing.</td>
</tr>
<tr>
<td>Monitoring &amp; Diagnosis</td>
<td>Long cruise period, long round-trip light delays</td>
<td>Continuous monitoring during cruise to determine the urgency of ground contact. Adaptive onboard engineering data summarization to enable all relevant telemetry to be downlinked in a single telemetry pass after it has been determined by flight software that a pass is required. Adaptive onboard engineering data archive, onboard trending and automated fault detection and isolation. Two week safe-hold capability.</td>
</tr>
<tr>
<td>Software system for low-cost operations</td>
<td>Long cruise period, long round-trip light delays, limited communications bandwidth</td>
<td>Reduction in operations staffing, frequency of contact, and improved reliability through migration of planning &amp; scheduling, execution, and monitoring functions to the space platform.</td>
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Figure 3: Saturn Ring Observer Mission

5.1 Planning & Execution

An automated planner/scheduler was flight demonstrated as part of the Deep Space One remote agent experiment, but was only applied to a small set of spacecraft conditions in a controlled experiment. More comprehensive automated planning & scheduling systems are intended for flight demo on university-class spacecraft within the next three years. Full-up deployment for ESS roadmap missions requires still more new technology development and end-to-end software system engineering. Assuming that robust planning & scheduling systems are developed for MDS or similar efforts over the next 3-5 years, no gaps exist in this area. Currently funded research in the NASA Technology Inventory adequately addresses the funding need to mature the technology to TRL6 by 2005. There could, however, be significant shortfalls in specialized applications, such as Entry, Descent, and Landing operations and in-situ hazard avoidance. Research and technology development.
in either flight demonstration or technology developments that bridge the gap between the AI-research community and the flight project world. JPL Mission Data System fills this role. There is not a significant gap assuming that MDS or a similar project continues to evolve event-driven and goal-based execution technology to the point that can be infused into flight systems.

5.2 Onboard Instrument Data Processing

A wide-range of technology development tasks are funded by NASA to address various aspects of onboard instrument data processing. These include feature recognition, data compression techniques specially suited for space mission needs, buffer management, and feature tracking. Analysis of funded work suggests there is no major technology gap in this research discipline. Two gaps were identified having to do with evolving the more basic elements of this area of research into mission-relevant technology products. One is to fund technology work more at the system level to help tie together the work in this field. The other gap, identified in a recent NMP workshop targeting future flight opportunities, is to fund a flight demonstration of this technology.

5.3 Monitoring & Diagnosis

Relevant monitoring & diagnosis technology development is currently funded by several significant efforts at several NASA centers. For ESS missions, the most relevant work exists at NASA-ARC and NASA-JPL. Four gaps have been identified:

1. A gap exists because the infusion path for these technology developments is largely uncertain. The current process for coupling of technology products in this area to missions is largely ad-hoc. Currently funded work needs to be better aligned to ESS mission capability needs and an infusion path for these technologies needs to be established.

2. A gap exists in the area of onboard autonomous built-in test. It isn't clear that ongoing monitoring & diagnosis research is sufficiently tailored to meet this stated need of Neptune Orbiter. Autonomous built-in test is also enhancing to any of the missions in the ESS mission set.

3. A gap was identified in development of long-term onboard archiving and summarization to meet the stated capability needs of the Pluto and Europa missions.

4. Technology may be needed to identify, capture, and queue for transmission the most important sensor data during EDL operations. The main purpose of this technology is to capture the data that would show anomalies causing mission failure and provide information (via a black box devise) that could influence the next mission design. Software technology for the explicit purpose of adaptively selecting the appropriate data for EDL problem reporting purposes has not been funded to date and is a significant gap if it is indeed required.

5.4 Software Systems for Low-Cost Operations

Systems are needed to reduce the frequency of ground contact and monitoring requirements for long-duration missions. A subset of what the JPL Mission Data System (MDS) project is developing is directly addressing this gap, provided that the project continues between now and 2006. MDS creates an end-to-end mission system product to integrate goal-based commanding, autonomous monitoring, and onboard planning & scheduling. If MDS or a similar effort continues, there is no significant gap.

5.5 Safe Landing Systems

Onboard systems for completely closing the monitor/control loop are needed for highly adaptive landing environments. There are many applicable component technologies, including machine learning, image processing, event-driven execution, onboard planning/re-planning, and adaptive navigation. There are some onboard autonomous landing tasks that are addressing parts of this problem. Significant system-level tasks, leveraging several of the aforementioned areas, are not currently funded (per the FY00 NASA Technology Inventory). This gap has likely been at least partially filled by the FY01 Mars Technology Program.

5.6 Intelligent Sensing

No funded work was identified in this area and it is considered a significant technology gap. Two missions in the ESS non-Mars mission set identified capability needs in this area. If an aerobot is used on Titan Explorer, light-time delays prevent sample selection from occurring via ground control from...
Earth. Intelligent software systems enable more robust and opportunistic sample selection, controlling the timing of sample collection and local processing to establish sample quality, resampling if necessary. For VSSR, more advanced software can decrease the risk associated with sampling operations by providing more robust recovery to unexpected events. For these likely requirements, and possibly other similar requirements for similar missions, the solution technology will likely draw on elements of onboard execution, planning & scheduling, and instrument data processing technologies. System-level, focused research in the area of intelligent sensing is not being done to meet this need.

5.7 Rendezvous & Docking

Funding is required to fly an active sensor package on a maneuverable host vehicle to characterize sensor performance, provide the host vehicle with target information, validate several types of control algorithms, and assess mission support requirements.

6 Conclusion

Development of mission technology needs requirements is an ongoing process. It is expected that these requirements will be developed at a higher level of fidelity through the continuing discussions with potential mission users and technology developers. The next steps are to 1) update the potential solution technologies to reflect the FY01 NASA Technology Inventory, and 2) identify higher fidelity metrics for each capability need by coordinating with both technologists and mission personnel. The capability needs and associated technologies described in this paper, though specific to a candidate mission set, should be at least partially relevant to many other missions. It is hoped that this work will clarify the role of technology in future missions and focus technology development activities.

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References


