The Role of Information Technology in Human Space Exploration

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Abstract

Information Technology (IT) has a unique role in the Human Exploration of Space because it is an infrastructure technology which enables other technology and capabilities. This means that the application of IT must be considered from a system viewpoint, rather than in isolation. As an infrastructure technology, IT is cross-cutting and affects many areas, such as Lifecycle Design, Ground Operations, Transportation, and Surface operations. In addition to impacting many application areas, IT affects different aspects of the problem, such as: increasing safety, increasing efficiency, increasing performance, and decreasing cost. Some of these aspects are interrelated, such as decreasing cost and increasing safety, and are often in conflict. In assessing the potential impact of IT on Human Space Exploration, there are two prime areas of consideration: increasing safety and decreasing cost. In each of these areas, there are IT applications areas that stand out as having the greatest impact. For increasing safety, the IT application with the greatest impact is in Vehicle Health Management. For decreasing cost, the IT applications with the greatest impact are in Automated Assembly and in Automated Operations.

Background

Information Technology (IT) is a very broad discipline which is not easy to capture under a single label. The disipline encompasses smart control systems able to adapt to changing environments and capabilities, intelligent agents capable of making human-level decisions, systems capable of perusing very large databases and extracting knowledge from them, and human-machine teams able to accomplish much more than either could accomplish alone. IT has general applications to such areas as robotics, flight control, data mining, human-centered computing, instrument/industrial control, and many others.

Information Technology has a unique role in the Human Exploration of Space because it is an infrastructure technology which enables other technology and capabilities. Unlike propulsion, communications, power, life-support, or navigation, IT underlies these areas and gives them new or better capabilities. With a few exceptions, it is possible to accomplish many objectives of the Exploration Program without any IT contribution at all. This was proved during the Apollo missions, which relied on a very primitive IT infrastructure yet was able to accomplish an ambitious exploration goal. Where IT can make a dramatic difference is in the cost, efficiency, performance, or safety of a mission. We are long past the days when we can take a brute force, high risk, "money-is-no-object" approach to exploration. We have to rely on IT benefits to not only improve a mission, but actually enable it to happen.

Application Areas

Although the range of IT application areas which support Human Space Exploration is large, we can group them into five major areas and sub-areas:

- Automated Assembly
    - On-orbit assembly of transit vehicles
    - On-orbit assembly of observatories
    - Human surface habitat assembly
- Autonomous Science
    - Rover-based science mapping
    - Human exploration extensions
- Automated Operations
    - Automated life-support
    - Unattended ISR production
- Human Amplification
    - Spacecraft design automation
    - Flight control automation
    - Astronaut "cyber-suits"
- Vehicle Health Management
    - Launch Vehicles
    - Transit Vehicles
    - Safe landing/hazard avoidance

Automated Assembly

Automated or Robotic Assembly involves the construction of large structures either in Zero-G or on Planetary Surfaces without direct human manipulation capabilities. This can be accomplished either with human-in-the-loop teleoperation of robotic manipulators or with autonomous robotic systems commanded at a relatively high-level. The objective of robotic assembly is to enable the construction of vehicles, instruments, or habitats in location either too hazardous for humans or too costly for humans.

Application areas include:

- On-orbit construction of interplanetary vehicles or space stations
- On-orbit construction of large science platforms such as observatories
- Planetary surface construction of human habitats and bases

Autonomous Science

Autonomous Science means the ability to conduct scientific investigations with systems in "collaboration" with humans rather than "remotely-operated" by humans. The distinction is in the level of interaction required by the human scientist. A remote instrument must typically be told step-by-step what to do, and has relatively little decision-making capability. An autonomous science platform is able to accept a high-level science goal, such as "characterize the geology of this site", and then generate and execute a plan to accomplish this goal. In the extreme case, the platform is able to generate and test simple scientific hypotheses.

Application areas include:

- Rover-based science mapping
- Human exploration extensions

Automated Operations

Automated Operations involves control systems capable of operating complex systems without direct human control. This is very similar to advanced industrial automation, in which a physical plant or process is supervised by a human operator, but not directly controlled at a low-level by the operator. In the NASA application, the automated system must be able to operate for longer periods of time under harsher conditions, and make more complicated decisions with very limited human support due to communications time-delays.

Application areas include:

- Automated life-support
- Unattended ISR production

Human Amplification

Human Amplification is an umbrella label which encompasses the use of information or physical systems to augment a single human or a team of humans, enabling them to accomplish a task better than they could alone. At one end of the spectrum we have collaborative design tools which amplify a human designer's ability to quickly construct, model, and test spacecraft designs. At the other end of the spectrum are physical amplification systems which enable a weakened or disabled astronaut to perform tasks otherwise impossible.

Application areas include:

- Spacecraft design automation (collaborative design tools)
- Flight control automation (advanced pilot controls)
- Astronaut "cyber-suits" (exoskeletal amplifiers to overcome the effects of extended zero-g)

Vehicle Health Management

Vehicle Health Management (VHM) encompasses all areas involving the health and safety of a vehicle, including flight control, thermal management, system monitoring and diagnostics, fault isolation and recovery, and hazard identification and avoidance. Some VHM applications involve passive techniques such as thermal tiles, while others involve active techniques requiring high levels of system intelligence. It is the latter which are targets of Information Technology.

Application areas include:

- Earth-to-Orbit Vehicles
- Interplanetary Vehicles
- Entry, Descent, and Landing hazard avoidance

IT Components

Until now, we have made reference to "smart" or "intelligent" systems. These terms are relatively vague, and actually encompass a range of component technologies under the broader label of Information Technology. These component technologies range from advanced nonlinear control systems for low-level control all the way to autonomous reasoning systems capable of human-level decision making.

In order to accomplish the next generation of challenging missions, NASA must develop highly autonomous systems capable of making critical decisions independently of human operators, as well as mixed-initiative ground-based systems, that work in collaboration with humans to support missions. Current missions are accomplished using a combination of direct human control and preprogrammed "canned" responses. This approach sets a strong boundary on what we may accomplish in the future due to communications delays, light speed constraints, mission complexity, and cost. Future missions need to operate under circumstances in which direct human control is often impossible, impractical, or too expensive. Examples of such missions include the robotic colonization of Mars, Sensorweb, a Europa submarine and, ultimately, an interstellar probe. Autonomous systems capable of independent decision making will enable these missions by maintaining vehicle health and safety, accomplishing complex science and mission goals, and adapting to changing circumstances or opportunities.

Autonomy

Autonomy focuses on techniques that allow a spacecraft or system to react to uncertainties within the environment in a robust fashion while attempting to achieve a set of high-level goals or objectives. Millions of years of evolution have developed the prototypical example of just such a system — the human body. Just as in the body, the task of controlling such a complex device while making critical decisions is performed through a variety of techniques that operate at multiple levels of abstraction and respond at varying time-scales. From NASA's perspective, the problem of autonomy can be subdivided into the following levels of control and interaction: low-level adaptive control techniques, real-time execution and health management, high-level planning and scheduling, and distributed decision making.

In all of these areas, a variety of techniques and approaches are currently being explored within the larger research and industrial communities. NASA's mission challenges, however, are often quite different from those encountered in other contexts. First, NASA requires extremely high-levels of autonomy within unknown environments. Second, the devices being developed often cannot be fully tested until they are deployed at which point they must already be fully operational. Finally, NASA is often developing one-of-a-kind devices that have unique mission goals and objectives. Because of these requirements, it is critical to develop techniques that facilitate the rapid development of customized autonomy software that leverages the knowledge of the designers and the domain experts whenever possible. In addition, the software must be able to adapt to changes within the environment and to the performance of individual components. The ability of the system to adapt is particularly important for long duration missions in which component degradation is inevitable. Finally, this element must also respond to the need to demonstrate and validate the technology in a manner that addresses the reliability concerns of the enterprises to ensure that the technology is eventually adopted. This can be done through both advanced ground demonstrations of the technology as well as sophisticated simulation techniques that facilitate the evaluation of an autonomous controller under a wide range of operating conditions and failures.

Low-level adaptive control and reflexive response provides the ability to respond to external stimuli that might threaten the device and to adapt to changes both within the environment and the device itself. Just as in a biological organism, often these responses occur at very fast time-scales and below the awareness of the higher-level cognitive processing components. A simple example of this level of control occurs as we walk. We regularly adjust our gait to the variations and irregularities of the surface upon which we are walking while maintaining our balance. Furthermore, we can adapt to other perturbations such as an object being thrown at us. These tasks are performed in a reactive manner without requiring any conscious thought. Research advances in low-level adaptive control will enable NASA to field a variety autonomous systems, such as, robots that can navigate the harsh Martian terrain, space transportation vehicles that can adapt to catastrophic failures of the control surfaces, and regulatory systems that can optimally control the environment of a Mars or Lunar base. Research within this area includes biologically inspired soft-computing techniques such as neural networks and genetic algorithms, reinforcement learning for adaptive control, balance and coordination reflexes, and distributed control techniques that integrate multiple lower-level control loops.

Execution and health management is responsible for executing a sequence of commands in a robust fashion while monitoring and responding to failures within the system. Given some specification of the sequence of tasks to be performed, an executive is responsible for reactively selecting the next action to be taken based upon the sensory inputs available at that time. The key challenge to be addressed is the development of techniques that provide guaranteed real-time response given a flexible sequence of tasks while still reasoning about the myriad of system wide interactions and the future ramifications of an action. Research goals in execution include coordinating concurrent activity, achieving and maintaining goals, resolving run-time resource conflicts, opportunistically changing behavior, reasoning explicitly about uncertainty, and handling contingencies when executing a sequence.

Health management complements the execution activity since it is responsible for determining the current state of the device that is often critical in the selection of the next action to be taken. Currently, health status information is often obtained through limit thresholds and simple algorithms that reason locally about an individual component. In the future, health management systems will be able to integrate lower-level precise models with system-level representations to assess the overall state of the device based upon an assessment of the system-wide interactions and to provide automated fault localization in complex systems. This capability will limit the need for redundant sensors and will increase the overall robustness of the vehicle. Furthermore, the system will be able to perform these tasks within the real-time control loop, thus permitting the system to respond to failures based on a true identification of the source of the anomaly as opposed to limited local information.

Planning and scheduling focuses on the process of reasoning about a set of high-level goals and objectives and determining a sequence of actions that satisfy these goals. Traditionally, this task is performed by a myriad of ground resources that generate a relatively inflexible sequence of commands that is uplinked to the spacecraft. Often, this sequence must be highly conservative to ensure that the plan can be executed. While planning and scheduling systems exist throughout the agency, seldom have these systems been used in a closed-loop fashion to control an autonomous system. Furthermore, the existing technology is limited in its ability to generate a flexible sequence that allows for a variety of execution paths based upon an evaluation of the current state of the environment at the time of execution. Furthermore, existing systems are limited in their ability to handle larger problems. Research within this area includes: the generation of plans and schedules that allow flexibility at the time of execution; integration of a planning and scheduling system as part of an on-board, closed-loop controller; mixed-initiative techniques that allow the system to interact with a user when generating the plan; and the ability to scale up existing techniques to larger problem sizes.

Distributed decision-making addresses the need for cooperation between independent autonomous agents when they must collaborate to achieve a common goal. Effective cooperation requires resources to be shared across systems and the assignment of roles and responsibilities to minimize the coupling between agents while still ensuring coordination in the attempt to satisfy the higher-level mission goals. Distributed decision making is critical for missions such as a robotic colony on Mars, deployment of a fleet of sensing devices orbiting Earth or within an armada of cooperating deep space probes.

In addition to these different levels of control a variety of other critical issues must be addressed within this element to support the missions current being considered. Of critical importance is the ability of the autonomy software to interact seamlessly with the humans that will be interacting with the system. In the end, few if any missions will be fully autonomous. Invariably, humans will be interacting with the autonomous system at some level. Autonomy techniques must facilitate this interaction and ensure varying levels of autonomy depending upon the mission phase and the needs of the humans with which the system is interacting. This work is closely tied to the Human-Centered Computing element.

Automation

High-levels of autonomy are critical to our exploration of the solar systems in a cost-effective manner. Humans, however, will still be required to perform a variety of complex tasks on the ground in support of future missions. From mission control to maintenance and ground processing of a reusable launch vehicle, many of these tasks will require higher levels of automation to streamline the process and reduce costs. Often, the core technology required is very similar to the capabilities required under autonomy. For example, ground processing of a reusable launch vehicle requires sophisticated planning and scheduling capabilities that can provide a flexible schedule that can be dynamically adapted as maintenance actions are performed and additional information about the vehicle is discovered. As the maintenance process becomes conditioned upon the performance of the vehicle in-flight, the ability to dynamically adapt the maintenance schedule becomes particularly important. Similarly, for missions that are controlled by more traditional means, the ground support team often has to perform a variety of tasks when attempting to identify the current state of the vehicle. Many of these tasks can be automated thus allowing the ground operators to support a larger number of more diverse missions, alerting them when a problem occurs in the device, and recommending an appropriate recovery response following a catastrophic failure.

Analysis

Since Information Technology is a cross-cutting technology which can potentially impact many areas, it is important to identify the areas in which the application of IT has the greatest impact. For the purposes of this discussion, we can analyze the impact of IT on Human Exploration in four areas:

- *increasing safety*, which means lowering the risk that the mission will fail or the human crew will be harmed.
- *increasing efficiency*, which means increasing the amount of value returned from a mission when compared to other metrics such as total cost.
- *increasing performance*, which means increasing the total amount of a metric.
- *decreasing cost,* which means decreasing the total life-cycle cost of a mission or program.

It is clear from these definitions that *increasing efficiency* is mission enhancing rather than enabling. In some cases increasing performance can be mission enabling, such as when you increase the total amount of mass you can lift to LEO, but in most cases it is mission enhancing instead. The two areas above which are most likely to be mission enabling are *increasing safety* and *decreasing cost.* Cost and Safety are the most often quoted reasons why NASA is unable to propose ambitious missions in the current political climate. As far as IT Applications are concerned, addressing these two areas will have the greatest impact on Human Exploration.

Given the five IT Application Areas proposed earlier, we can rate the potential impact of IT on these areas as follows:

Impact of IT Applications

IT Application	**Safety**	**Efficiency**	**Performance**	**Cost**
Automated Assembly	Medium	Medium	Low	High
Autonomous Science	Low	High	Medium	Medium
Automated Operations	Medium	High	Low	High
Human Amplification	Medium	Medium	Low	Low
Vehicle Health Management	High	Low	Medium	Low

As far as Safety is concerned, the highest impact application for Information Technology is Vehicle Health Management (VHM). Although three of the other four application areas can impact Safety in a secondary manner, VHM impacts Safety directly. For the second mission enabling categories, Cost, there are two high impact IT applications: Automated Assembly and Automated Operations. Automated Assembly impacts cost because the use of On-Orbit construction allows larger vehicles to be used for Mars mission architectures than can be launched with conventional mass and shroud-size limitations of current. Eliminating the requirement of a Heavy Lift Launch Vehicle development program is a major cost savings. Automated Assembly also impacts cost because the robotic construction of human habitats and In-Situ Resource (ISR) production facilities *prior* to human arrival means that the human-crewed vehicles do not need to transport sufficient quantities of consumables for the entire mission, but only for the time needed to rendezvous with the pre-constructed base. Since robotic missions have a much less stringent reliability requirement than the man-rated missions, this impacts cost directly (independent of the savings due to ISRU fuel production). Automated Operations is another high Cost impact application area for IT. The cost savings here comes from using IT to reduce the requirements for a "standing army" of ground controllers during the life of the mission (or even the program). This cost saving can be quite large over the life of a mission, although probably not as large as can be obtained through the use of Automated Assembly.

Recommendations

In assessing the potential impact of IT on Human Space Exploration, there are two prime areas of consideration: increasing safety and decreasing cost. In each of these areas, there are IT applications areas that stand out as having the greatest impact. For increasing safety, the IT application with the greatest impact is in Vehicle Health Management. For decreasing cost, the IT applications with the greatest impact are in Automated Assembly and in Automated Operations.

Within the agency, there are low-TRL programs underway which address VHM and to some extent Automated Operations. There are also a couple of mid-to-high TRL projects in VHM. There are currently no active mid-to-high TRL projects in NASA dealing with Automated Assembly, the LaRC program having been shut down in the mid-1990's.

Since these three areas have the potential to be enablers for Human Exploration, an obvious recommendation is ensure that there are healthy high-TRL projects in VHM and Automated Operations, and that NASA restart focused work in Robotic On-Orbit Assembly and Robotic Planetary Surface Assembly.

Appendices

Robotic Construction

The following documents are good representations of the state-of-the-art in Robotic Assembly. The 1994 report from LaRC [1] represents the latest NASA work in Robotic On-Orbit Construction of Large Truss Structures. That program is no longer active. The best work to date on Robotic Construction Tools suitable for planetary habitat construction is represented by the NIST document [2] on their Robocrane system. Finally, the CMU Whitepaper [3] summarizing their NASA-related research interests and capabilities contains a section on their SkyWalker system, which is representative of another approach to On-Orbit Construction.

(1) Baseline Test of an Autonomous Telerobotic System for Assembly of Space Truss Structures, M.D. Rhodes and R.W. Will (LaRC) and C. Quach (Lockheed Engineering & Sciences Co.), NASA Technical Paper 3448, July 1994.
Hyperlink: LaRC_Robotic_Assy.pdf

(2) The NIST Robocrane: An Integration Testbed for Large Scale Manufacturing and Construction Automation, R. Bostelman (NIST), October 1998.
Hyperlink: RoboCrane98.pdf

(3) Robotic Research at NASA and CMU, CMU Whitepaper, May 2000.
Hyperlink: CMU-Ames-wp.pdf

Vehicle Health Management

The following documents contain good summaries of Vehicle Health Management technology, and represents the state-of-the-art in this area.

(4) Reusable Rocket Engine Advanced Health Management System: Architecture and Technology Evaluation Summary, C.D. Pettit, S. Barkhoudarian, A. G. Daumann, Jr. (Rocketdyne Propulsion & Power), G. M. Provan and Y. M. El Fattah (Rockwell Science Center), and D. E. Glover (Intelligent Systems Consulting), AIAA 99-2527, 1999.
Hyperlink: ahms-AIAA paper-4-14.pdf

(5) Merope: An IVHM Experiment for Reusable Launch Testbeds, B. Glass (ARC), J. Zakrajsek (LeRC), and J. Fox (KSC), Future-X Pathfinder Flight Demonstrators Proposal, October 1998.
Hyperlink: Final-Future-X-X34-proposal.pdf