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Paper Session I-C - Robotics for Interstellar Missions

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ROBOTICS FOR INTERSTELLAR MISSIONS

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Abstract

This paper discusses the requirements for robotics in future interstellar missions and describes the various robotic development activities at NASA KSC that are laying the basis for the robotics of the future. The first long-duration interstellar missions, which might occur at the end of the 21st century, would probably be preceded by trips to outer planets in the Solar System and by near-Solar interstellar probe missions. The time span, dangers, and uncertainties involved would almost certainly decree that the first missions be unmanned. If an interstellar mission involved a surface landing, all initial exploration would be performed by robots or other autonomous devices. These robots of the next century must possess true autonomy: onboard intelligence; sensor systems to provide information on the visual scene, temperature, radiation, task forces, and torques; stable locomotion; self-maintenance and repair capabilities; and so on. The varied sensor data must be integrated into an intelligent understanding of the environment to support decisions concerning that environment—for example, avoiding collisions or other dangers, or selecting areas of interest for exploration. The capability to store and transmit data, and to modify behavior based on experience, would also be required. Many of these capabilities are in their infancy today. However, NASA is expanding the state-of-the-art of robotics in directions which, while supporting near-term endeavors, will eventually lay the necessary foundation for the interstellar missions of the next century. For instance, the NASA KSC robotics program is making very meaningful contributions in areas of robot mobility, collision avoidance, vision systems, and special end-effectors. One example of this activity concerns the KSC Thermal Protection System robot, which provides an autonomous mobile platform and special end-effectors and vision systems for navigation, inspection, and positioning tasks. The robot can also store task data for downloading at a later date. Other developments at KSC include special mechanisms and controls for robotic space vehicle cleaning and component inspection, and the development of self-diagnostics for automated systems. In summary, while we are presently a long way from achieving the robotics capabilities to support interstellar missions, present-day robotics development activities at KSC and at other NASA centers are laying the groundwork for these exciting future endeavors.

1. Interstellar Missions

Interstellar space is defined as the area in space where local effects of physical bodies, such as the Sun or planets in the Solar System, can be neglected [Drysdale and Vick, 1991). More generally, interstellar space has come to be known as the area beyond the heliosphere (approximately 50-100 astronomical units from the Sun). A mission to any object outside the heliosphere will require travel through interstellar space, and therefore, the mission becomes an interstellar mission. Drysdale outlines several locations of interest in interstellar space. Selected (hypothetical) future near-Solar interstellar missions are outlined in Table 1. Short-distance missions into interstellar space are within reach, as exemplified by Pioneer 10 and 11, and the Voyager probes, on their journeys past the planets of the Solar System.

Table 1. Future Interstellar Mission Tasks

Mission	Duration (Years) (Conservative)
Precisely locate magnetopause	10^1
Characterize heliosphere	10^1
Examine heliosphere boundary phenomena	10^1
Look for effects of a possible Solar binary twin ("Nemesis")	10^1
Examine space/time effects without curvature due to Sun	$10^1 - 10^2$
Observe Universe from beyond heliosphere: TAU Observatory [Anderson, 1992]	$10^1 - 10^2$
Explore area between stars: interstellar medium, Oort Cloud	$10^2 - 10^3$

The time and distance, dangers, and uncertainties involved in interstellar missions place great costs on the use of manned spacecraft, at least for the foreseeable future. However, the need for spacecraft maintenance on long-duration missions will require some type of intervention capabilities. Just as advanced propulsion systems need to be developed for interstellar missions, advanced robotic systems must also be developed to fulfill these intervention needs. The Thousand Astronomical Unit (TAU) Probe Mission [Nock, 1987], for example, will be powered by nuclear energy and is expected to have a 50-year duration. Robots aboard this probe will be used (1) to assemble the spacecraft from its ground-launch configuration and (2) to maintain all spacecraft systems. Many of the onboard systems will require periodic maintenance during this long-duration mission. For general interstellar missions, robots will be used for spacecraft assembly, general spacecraft maintenance (including maintenance of nuclear power systems and communication systems), and the release of probes (similar to the manner in which satellites are released from the STS using the RMS). When planets or other physical bodies are encountered, surface probes with robotic capabilities will be utilized for exploration and sampling. Robotics will play a key role on any interstellar mission.

Before a robot-assisted interstellar mission is initiated, there are likely to be precursor missions to the outer Solar System. A successful robotic-assisted mission within the Solar System could validate the utility of robotics for longer missions. Technologies and needs for interstellar mission robots can be explored and tested on missions closer to home; there will be many opportunities for missions within the Solar System before any interstellar missions will be fully developed. Technologies that will require further development for interstellar missions can be identified under less critical conditions.

A typical near-future mission to the outer Solar System is described below, with emphasis placed on the robotic technology necessary for its success. The purpose of this mission is to explore several large asteroids in the asteroid belt. The Asteroid Prospector mission [Walters et. al., 1989] provides basic feasibility of such a mission, although robotic capabilities are not highlighted in this study. A similar mission could explore the moons of Neptune, a group of interstellar asteroids, or even the planets orbiting a distant star.

The mission plan presented here (modified from the Asteroid Prospector) involves exploration of five asteroids, including deployment of surface probes and maintenance of communication between each surface probe and Earth. The scenario is outlined in Table 2. Each phase of the mission will require some level of robotic intervention. Telerobotics will be used for assembly of the Large Space Vehicle (LSV) in Earth orbit (Task 1), minimizing the EVA needed. This level of robotic capability will likely be implemented as basic space station technology. Task 2 will require autonomous, preprogrammed deployment of the Asteroid

Table 2. Asteroid Exploration Mission Scenario

Task 1: Assemble Large Space Vehicle (LSV) in Earth orbit. LSV is launched toward asteroid belt

Task 2: Orbit asteroid, deploy Asteroid Exploration Satellite (AES). LSV continues to next asteroid

Task 3: AES deploys surface probe, then acts as communication satellite (direct communication to Earth)

Task 4: Surface probe explores asteroid surface:
  Subtask 4.1: Assemble antenna for communications with AES
  Subtask 4.2: Autonomously explore asteroid surface
  Subtask 4.3: Launch samples back to Earth (includes construction of a launch site by surface probe, further construction, and relay to Earth by AES)

Exploration Satellite (AES) from the LSV. The robotic technology needed is similar to STS satellite deployment currently in use, but requires autonomy instead of teleoperation. Task 3 requires self-guided deployment of surface probe from AES. This will require autonomous path generation by the deploying arm to guide the probe into an entry trajectory calculated autonomously. A surface probe will require many autonomous robotic capabilities (Task 4). Surface mapping, sensing, data gathering, and navigation will all be accomplished autonomously. Further, the probe must have stable locomotion over rugged surfaces; must be able to mine, gather, and analyze samples; and must be able to perform basic construction needs, such as building a communications antenna and a launch site for returning data and samples to the orbiting AES for relay to Earth. All tasks require that all of the systems on the mission (robotic and others) must be self-diagnosing. Further, all systems must be maintainable during the mission; the onboard robots should be able to accomplish all scheduled maintenance and most unscheduled maintenance (including self-maintenance of the robotic systems themselves). This is important on long-duration missions to extend the life of component systems. Further, the success of the mission does not have to depend on 100-percent reliability of all component systems, because there is the ability for on-mission repairs.

2. Robotics Requirements

The generic capabilities needed for space robots generally increase as the distance from human intervention increases. The further away from Earth, the more intelligent robots must be. Telerobots in Earth orbit can be relatively unintelligent, mainly controlled manually by human operators with low levels of robotic assistance. But a surface probe on a distant asteroid must be fully autonomous. Robot systems for interstellar missions similarly must be fully autonomous. Such intelligence may be obtained using artificial intelligence techniques, including neural nets and knowledge-based (expert) systems, and using advanced control techniques for uncertain situations (adaptive control, fuzzy logic control, etc.). Artificial intelligence can be used to modify behavior based on experience, and to select areas that require further exploration or sensing. Robust sensing is extremely important for distant robotic missions. Force/torque, vision, and other sensors for specific needs (temperature and radiation for monitoring power plants, for example) may be adequate for space vehicle-based robots; much more sensing is required for surface probes, including material characterization abilities and mapping, vision, and sensor-guided motion. A high level of dexterity/manipulability is also required for the robots aboard space missions: robot arms must reach all parts of space vehicles/surface probes, including the robot arms themselves, for maintenance and repair. This will require more articulation than most of today's robots, which will generally lead to more degrees of freedom in manipulators, and therefore, to more complex control algorithms. Because it is almost impossible to characterize all failure modes (and then design a robot which can repair all failures), a form of robotic self-replication may be necessary. This would involve one robot, using generic robotic subassemblies, to assemble another robot with the articulation or dynamic characteristics necessary for a specific task. As mentioned previously, the robots must have self-diagnostics, to determine when and where troubles have occurred. The robot systems cannot be expected to be 100-percent reliable. However, provisions must be made for self-maintenance and self-repair when problems have been detected. The farther away the mission takes the robots from Earth, the longer they must survive. With self-diagnostics, self-maintenance, and self-repair, system life can be increased. The capabilities described above are baseline characteristics necessary for robotics for interstellar missions.

3. Present-Day Capabilities Being Developed by NASA

The robotics program at KSC focuses on the implementation of robotics in Space Shuttle reprocessing. For example, capabilities in autonomous navigation, special end-effectors, vision systems, and self-diagnostics are being developed. While these activities have the obvious near-term goal of more efficient space vehicle reprocessing, they also contribute to the foundations of robotics for the advanced missions of the next century. Table 3 relates the needed future capabilities to present-day robotics projects at KSC. These projects are discussed below.

Table 3. Basic Capabilities for Robots for Interstellar Missions

Need Capability	Applicable KSC Projects
Mobility/articulation	HFCR, ARID, TPS
Sensors	HFCR, ARID, TPS
Diagnostics	TPS
Intelligence	TPS
Self-replication	HFCR

HFCR System

The high-efficiency particle accumulator (HEPA) filter certification robot (HFCR) will be used to maintain the "clean" environment of the payload changeout rooms (PCRs) at KSC [Spencer et. al., 1992]. The inspection system utilizes robotic motion and sensors to complete the certification task during one shift, rather than the 1-week downtime currently required. Further, the robot is better able to follow the desired sensor trajectory for proper filter inspection than are the human workers. The HFCR has the mobility to reach the majority of the ceiling filters, utilizing a 4-degree-of-freedom (DOF) manipulator that travels on existing ceiling-mounted overhead crane tracks (Figure 1). As well as using specialized sensors to detect leaks in the filters, the robot will be able to modify its motion based on sensors that monitor obstacles, which will greatly increase system safety. The modular design of the HFCR greatly enhances its maintainability and usefulness. Component parts can be removed and replaced easily when components fail, and it would be possible to replace certain components with other parts that have superior performance for specific tasks. The ease of integration of the components into the system (the robot can

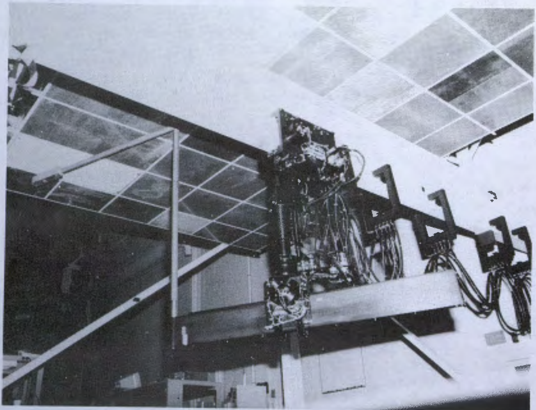

Figure 1. The HFCR Inspecting HEPA Filters

be assembled from its six major parts in 30 minutes or less) indicates that such a process could be accomplished with another robot—a form of self-replication which will become quite important in future-generation robots.

ARID Robot

The orbiter radiators are currently inspected twice in the Orbiter Processing Facility (OPF) for any damage that may have been sustained. This task is a time-consuming, laborious process, and under certain circumstances, it is difficult for workers to quantify damaged radiators. To alleviate these problems, the Automated Radiator Inspection Device (ARID) was conceived. The ARID will automatically inspect the Space Shuttle orbiter radiators, located on the underside of the payload bay doors, for defects. It will inspect the radiators twice during each OPF flow—a postflight inspection and a close-out inspection prior to rollout, as in the manual process. The system will measure the defects in 2-D and 3-D, and automatically generate the problem paper for an engineer to disposition. It will allow reliable, repeatable inspection of the radiators; end quantification ambiguities; and shorten Shuttle flow time.

The ARID trolley moves on a 65-foot beam (rack) along each side of the payload bay in order to access the entire surface of the bay doors (Figure 2). An articulated arm is attached to the trolley and holds a visual inspection system. It moves along each radiator panel, moves forward in increments of 4 inches, and moves back. Repeating this pattern, it completes a sweep of each side in about 3 hours. The arm utilizes complete redundancy in computers, drive motors, and software; it may be the world's first robot with total redundancy.

TPS Robot

The Thermal Protection System (TPS) robot will be used to inspect and reprocess the orbiter tiles after each flight [Dowling et. al., 1992; Manouchehri et. al., 1992]. It is the first KSC robot that utilizes a fully mobile base to achieve the mobility necessary to reach all orbiter tiles (Figure 3). This requires more advanced intelligence for navigation; the TPS compares internal mapping with vision system input to align itself to the orbiter and area targets. Vision sensors are also used for automated inspection

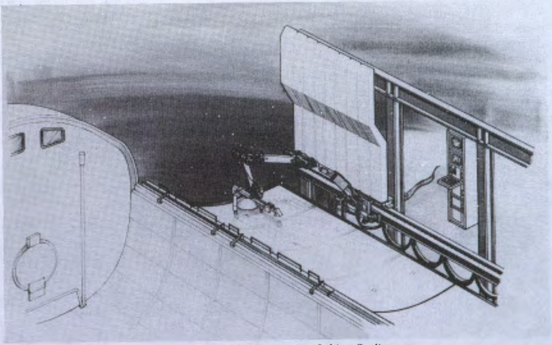

Figure 2. The ARID Inspecting Orbiter Radiators

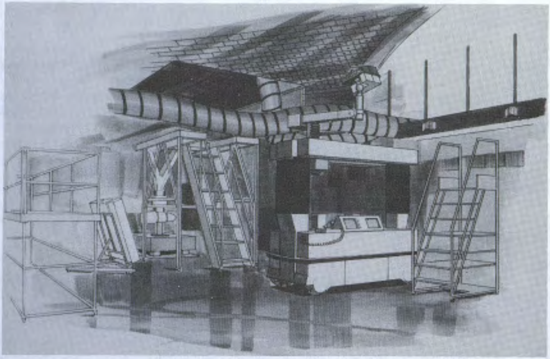

Figure 3. The TPS Robot Servicing Orbiter Tiles

and precise positioning of the manipulator with respect to target tiles. Specialized end-effectors could then be used for various tasks, including injection of a rewaterproofing compound into the tiles and inspection of tile integrity. The protection of the orbiter during these operations is extremely important, because the robot system makes physical contact with the tiles. Intelligent control algorithms, including fuzzy logic and adaptive control, for example, are being developed for one of the active end-effectors to ensure that the force against the tile is maintained within the proper limits. The system must also have diagnostic and failure detection capabilities; failure of the system to inject the rewaterproofing compound into a tile must be detected and documented. Additionally, a system monitors various sensor signals from component hardware and functions as a smart fuse when it detects problems, and corrective action can be taken utilizing this sensor-based diagnostic feature.

4. Conclusion

The development of robotics systems to fulfill current implementational needs at KSC is also an important step toward the future of robotics in the next century. The contributions toward key robotic characteristics today will lead to development of robotics for space missions of the future, and will eventually result in robotic system technology that will enable interstellar missions.

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