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SPACE STATION AS A VITAL FOCUS FOR ADVANCING THE TECHNOLOGIES OF AUTOMATION AND ROBOTICS[1]

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ABSTRACT

A major guideline for the design of the United States' Space Station is that the Space Station address a wide variety of functions. These functions include the servicing of unmanned assets in space, the support of commercial laboratories in space and the efficient management of the Space Station itself; the largest space asset. For the Space station to address successfully these and other functions, the operating costs must be minimized. Furthermore, crew time in space will be an exceedingly scarce and valuable commodity. The human operator should perform only those tasks that are unique in demanding the use of the human creative capability in coping with unanticipated events.

The technologies of Automation and Robotics (A&R) have the promise to help in reducing Space Station operating costs and to achieve a highly efficient use of the human in space. The use of advanced automation and artificial intelligence techniques, such as expert systems, in Space Station subsystems for activity planning and failure mode management will enable us to reduce dependency on a mission control center and could ultimately result in breaking the umbilical link from Earth to the Space Station. The application of robotic technologies with advanced perception capability and hierarchical intelligent control to servicing systems will enable us to service assets either at the Space Station or <u>in situ</u> with a high degree of human efficiency.

This paper presents the results of studies conducted by NASA and its contractors, at the urging of the Congress, leading toward the formulation of an automation and robotics plan for Space Station development.

KEYWORDS

Space Station; Automation; Robotics; Artificial Intelligence; Crew Productivity.

[1]It has become customary to refer to cognitive and manipulative tasks by the terms "automation" and "robotics," respectively. This convention will be used throughout this paper.

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INTRODUCTION

The United States' Space Station is a permanent multipurpose facility, with an initial crew of six to eight astronauts, that will serve as a research laboratory, a permanent observatory, a transportation node, a storage depot, and a base for staging missions to higher orbits, the planets and beyond. It is also a facility for assembling complex payloads and for servicing satellites and instruments. To fulfill this variety of functions, the Station is designed as a very complex system consisting of a modular manned base and several unmanned free flyers provided by several nations, Fig. 1.

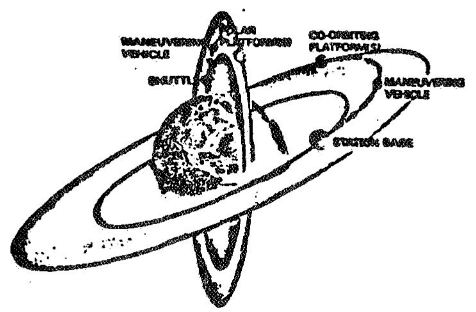

Fig. 1. Initial Space Station Complex

In the words of the National Commission on Space (NCOS, 1986), the Station is the first of 12 technological milestones in space toward a bridge between worlds and the beginning of the Earth Spaceport: for such a "port" we can easily envision a rich and always growing ferment of varied activities. Because of the size of the investment in the Space Station and the expected long life of this facility, versatility of architecture and capability to add new features must be provided from the beginning in the design of the system and its subsystems.

ROLE OF AUTOMATION AND ROBOTICS

Two resources that are critical for the construction and operation of the Station are: payload in orbit and crew time. Because of the legacy of the destruction of Challenger and the limitations of current technology, both are becoming more precious as we impose stricter limitations to enhance safety. While the payload limitations may be overcome in the not too distant future by the development of heavy-lift vehicles and performance improvements to the shuttle, the availability of crew time will always be at a premium.

The judicious application of the technologies of automation and robotics can overcome the limitation of this vital resource as shown in Fig. 2, which summarizes one result of a recent study (Boeing, 1986). The study indicates that, by implementing a series of A&R applications consistent with the advancement of technology and the scope of the station program, a given crew can increase the number of its members devoted to productive functions by a factor of two to three. (Although the Skylab technology[3] used in the comparison is not a realistic option for the Station, it is the only U.S. long term experience and, therefore, a useful baseline for comparisons). As we shall see again later, such a productivity increase by a factor of two to three has been noted by other analysts.

The issue of which specific A&R technologies have the greatest leverage on Space Station productivity was studied by the Automation and Robotics Panel (ARP), a group of over 30 leading technologists. The results of their six-month analysis are summarized in Fig. 3 (ARP, 1985). For each one of the three broad classes, the panel indicated the specific technologies where NASA should, respectively, lead, leverage, and exploit. As we examine this table, we find that, in the range of autonomy development shown in Fig. 4, the Space Station thrust is in teleoperated and supervised control. These technologies are at the leading edge for applications to flexible manufacturing and information management, the major frontiers in terrestrial applications.

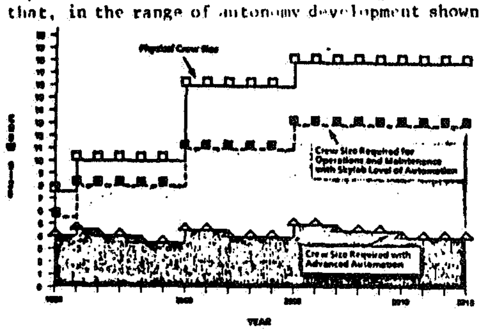

Fig. 2. Space Station Productivity Projection

CHARACTERISTICS OF SPACE STATION

There are four characteristics of the Space Station that render it an excellent setting for developing the technologies described.

Costs and Benefits

The cost of implementing any one of the A&R applications currently considered for the Station is comparable to that of implementing the equivalent terrestrial one and is quite substantial, ranging from the low 10^6 dollars to the high 10^7 dollars. However, on Space Station, the ensuing productivity gains have extraordinary value: 10^4 - 10^5 dollars/work-hour saved, depending on whether it is for IVA or EVA, and also depending on the valuation method. Thus, the high initial investment is much more

[3]For example: Open-cycle life support system; semi-active thermal control; inertial, solar, and z-vertical attitude control. No self-checking, trend analysis, etc. (NASA, 1977).

Manual	Unaided IVA/EVA, with simple (unpowered) hand tools
Supported	Requires use of supporting machinery or facilities to accomplish assigned tasks (e.g., manned maneuvering units and foot restraint devices)
Augmented	Amplification of human sensory or motor capabilities (powered tools, exo-skeletons, microscopes, etc.)
Teleoperated	Use of remotely controlled sensors and actuators allowing the human presence to be removed from the work site (remote manipulator systems, teleoperators, telefactors)
Supervised	Replacement of direct manual control of system operation with computer-directed functions although maintaining humans in supervisory control
Independent	Basically self-actuating, self healing, independent operations minimizing requirement for direct human intervention (dependent on automation and artificial intelligence)

Fig. 4. Range of Autonomous Operation

Class	Man/Machine-Robotics	Information Management	Communication & Mechanical Infrastructure
NASA Leads	Space Manipulators Materials Handling Technologies Robot Mobility in Space Man/Machine Interfaces	Expert System Mission & Payload Control, Planning & Directing "Smart" Simulations Fault-Tolerant, Reliable Software Tools CAE Standards Software Language Standards Automation Design for Integrating Technology	Lightweight Structure & Assembly Spare Parts & Repair Technology Fluids Transfer Technologies
NASA Leverages	Robot Sensors/Integration Reconfigurable & Repairable Robots High-Level Robot Programming Language	Space-Related Custom Hardware Communications Networks Distributed Large-Scale Databases CAD-Directed Programming Knowledge-Based System Development Sensing Algorithms Real-Time Systems Facility "Seed" Funding	New Fabrication Technologies
NASA Exploits	Terrestrial Robots and Manipulators Lightweights Motors	Computer Architecture Chip Technologies Speech Technologies	Local Area Networking Display Technologies High Bandwidth Technologies Communication Technologies

Fig. 3. Space Station Classes of A&R Technology

readily justifiable in space than in terrestrial applications where a typical work-hour is worth $10 - 10^2$ dollars.

Environment

The space environment is relatively well structured and foreseeable, by comparison with that of an urban or an office setting, where a multitude of living entities interact unpredictably, and thus, it lends itself to the modeling that is indispensable to autonomous systems. It is also very complex, with millions of parts, intersecting control loops, cascading interactions from subsystem to subsystem, and multi-layered hierarchies of functions that are very taxing for humans, specially when working under pressing time constraints. Finally, because of its complexity and notwithstanding its relative predictability, this environment has a sufficiently large variety of possible configurations that preprogrammed automation or even detailed procedural prescriptions for all foreseeable eventualities are not feasible. Thus, humans can be very effectively elevated to the supervisory role, once the machines are endowed with autonomous local sensors and feedback, with sufficiently comprehensive declarative models, and with overrides for untested or unmodeled circumstances.

Users

The exceptional qualifications of the space users, who are all expert and trained technologists and scientists able and interested in contributing to the development of the technology, are of significant advantage in developing the operator interfaces, often one of the most difficult and little understood areas.

State of the Art

The situation presented in Fig. 3, which shows that there are areas where NASA must lead, others where it can adapt and leverage current advances, and others yet which it can exploit, indicates the breadth of the range of approaches available for R&D and the ample possibilities for advancing the state of the art.

HISTORICAL SUMMARY

The Congress of the United States sought to take advantage of this unique setting and of the historic opportunity to foster A&R by requesting in 1984, that the Office of Technology Assessment conduct a workshop (March 1984) to explore the relationship between the Space Station Program and advanced A&R (OTA, 1985) and by including A&R in the Space Station enabling legislation.

Public Law 98-371 mandates that NASA identify Space Station systems that would advance A&R technologies beyond what is in use in current spacecraft. Congress further requested that an Advanced Technology Advisory Committee (ATAC) be established to fulfill the mandate and to report to Congress every six months on NASA's progress.

At NASA's direction, five aerospace firms examined, "without regard to cost," the A&R applications that might be included in the Station as it evolves. The contractors' six-month studies focused on these areas:

Boeing Companies: Operator-system interface (BOEING, 1984);

General Electric Company: Manufacturing in space (GE, 1984);

Hughes Aircraft Company: Subsystem control and ground support (HUGHES, 1984);

Martin Marietta Aerospace: Autonomous systems and assembly (MARTIN, 1984);

TRW: Satellite servicing (TRW, 1984).

In addition, NASA funded SRI International to conduct an assessment of the studies from the viewpoint of artificial intelligence technology (SRI, 1985) and the California Space Institute to organize the ARP - mentioned earlier - and conduct an independent study. This panel confirmed that advanced A&R would improve productivity on the Station and yield benefits nationwide; recommended a major NASA investment in related R&D (climbing rapidly to between 100 to 200 million dollars/year); and stated clearly the requirement that the Station program must be designed for growth from the beginning (ARP, 1985).

The findings of all these studies were consolidated by the ATAC in its first report to the U.S. Congress (ATAC, 1985a). The committee, recognizing the difficulty of accommodating the ambitious proposals and the projected budgets articulated its position in 13 recommendations segregated into two groups. The first group of eight - to be implemented within the nominal budget - focused on: A&R as a significant element of the Space Station Program; maximum adoption of current R&D; the requirement to design for growth; the importance of verification and validaton; and the use of A&R for the management process. The second group of five recommendations focused on aggressive development of advanced A&R, conditional on budget augmentation.

In November 1985, the U.S. Congress expressed desire that greater and faster progress be made in A&R than what would be possible within the normal Space Station budget and provided, in successive augmentations, additional funding for a flight telerobot. This will be a versatile system to be used as an aid in Station assembly and maintenance, and in payload servicing tasks, and it will be transportable in-space by a variety of carriers based on Station and on shuttle, Fig. 5.

Additional insight into the need and role of A&R is provided by a White Paper from the Astronaut Office (ATAC, 1985b), which recommended: application to repetitive, time consuming, time critical, taxing, hazardous, boring tasks; performance of early flight tests; provision for human override.

More recently, the need for A&R was also present in the call for the development of telescience by the Space and Earth Sciences Advisory Committee (SESAC, 1986) through its Task Force on Scientific Uses of Space Station. Specifically, the task force recognized the projected evolution from space science (principally observatory in character) to laboratory science in space (principally experimental). Telescience is described as the ability to conduct experiments and reprogram them quickly - and remotely - as current results are understood and new opportunities uncovered. This also requires advanced forms of telecommunications and automation using supervisory control.

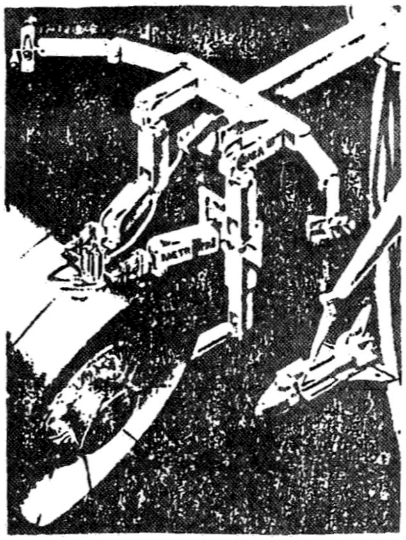

Fig. 5. Flight Telerobotic System: A Concept

APPROACH TO AUTOMATION AND ROBOTICS AND STATUS

The Space Station is now nearing the end of the definition and preliminary design phase which will be completed in December 1986. The four Space Station Lead Centers: Marshall Space Flight Center, Johnson Space Center, Goddard Space Flight Center, and Lewis Research Center and their eight industrial contractors have been performing preliminary designs and evaluations of over a hundred different A&R concepts for specific applications. Evaluation criteria include: reduction of crew time devoted to operations and maintenance; initial costs and operation savings; system availability; safety; terrestrial spin-offs; design risk; and impact on ground operations.

In addition, experimental and theoretical R&D efforts are led by the Ames Research Center (for cognitive functions) and by the Jet Propulsion Laboratory (JPL) (for manipulative functions). Demonstrations of their R&D are planned at approximately two to three year intervals in collaboration with the Space Station Lead Centers. The first demonstration is scheduled to be by JPL, on telerobotics, in 1988.

NASA contractors (BOEING, 1986; GE, 1986; MARTIN, 1986; MCDONNELL, 1986; RCA, 1986; ROCKETDYNE, 1986; TRW, 1986; ROCKWELL, 1986) have identified over 100 useful A&R applications for the initial configuration of the Station and ATAC (1986) has culled the list to about 18 cognitive, eight manipulative and four additional applications requiring more advanced techniques. Of principal interest in the first category, we find: system management and crew activity planners; data base management; power system control and management; and monitoring and fault detection for life support systems. In the second category: Space Station assembly, inspection and repair; payload servicing; and docking.

The studies conducted at the NASA Centers, and at the contractors, confirm the selection of this approach to A&R for the Space Station: the human operator, who is in charge of the task at all times, assigns to the machine, directly or by default, those operations that, in his judgement, can be well performed automatically at that time. The operator reserves the option to resume control during the execution and complete the operation directly. The "level of abstraction" of the operator's actions can be adjusted dynamically: the machine functions similarly to the apprentice of a master craftsman. Thus, the terminology: "astronaut assistant" or "aide." This approach is well suited to the traditions and needs of the manned space endeavors and is conceptually and technically different from that generally followed in the unmanned space flight (Pivirotto, 1986; Varsi, Man, and Rodriguez, 1986), where machines are given complete autonomy, but within narrower bounds, specified in advance (e.g., Viking's landing sequence).

Technically, the general area of intelligent autonomy is being pursued vigorously with special focus in the areas of sensors and world and knowledge representation. As a consequence of the approach chosen, the key technology of shared or "traded" control between operator and machine is being developed and, within it, particular emphasis is given to the control architecture and the man-machine interfaces.

Programmatically, the guidelines to the contractors for the next phase of work: design, development and construction, are expected to emphasize the themes discussed here and require a plan for the implementation of A&R applications. Information from the preliminary plans available now indicates that levels of autonomy that are technically achievable by 1993 - 1994 can increase productivity on the Station by a factor of two to three and allow recovery of the investment in about two to three years for the majority of applications. It has been shown (THURIS, 1984) that it is necessary to pay particular attention to the sequence according to which applications are developed and implemented: in financial terms, the investment hurdle of an application can be reduced by several-fold if that application is implemented as a part of a group of related applications.

AUTOMATION AND ROBOTICS BENEFITS

We shall now review three specific applications and summarize the analyses, albeit preliminary, of expected benefits.

System Management

This application is variously conceived and called "System Manager," "Station Coordinator," "Operation Manager." In its broad conception, it has the function of translating Station performance and scheduling requirements into task sequences for subsystems. It can be considered an "expert system" hierarchically controlling other expert systems.

It contains a representation of the Station and of the systems it interacts with, receives real time information on the status of the crew, the hardware and software of the Station, and the operation and science requirements, and constructs and updates schedules of activities. One configuration of this application (MCDONNELL, 1986) is expected to require about 8,000 "rules" and to cost 40 million dollars. Its yearly benefits have been estimated at 90 EVA hours, 1,350 IVA hours, and 32,000 work-hours on the ground: with a total value of about 60 million dollars.

Power Management

Three options can be considered: a ground based or "manual" system; a "conventional automation" (e.g., on-board load shedding on the basis of preprogrammed priorities); and a more advanced management (e.g., on-board resources optimization and failure recovery), based on expert system technology. On a uniform basis, the initial costs are estimated at: 45, 75, and 85 million dollars, respectively; and the operating costs at: 30, 13, 10 million dollars/year (NASA/LeRC. 1986). This example illustrates vividly the programmatic dilemma offered by A&R applications: on one hand, the 20 million dollars/year difference between the extreme cases allows recovery of the 40 million dollar difference in initial costs in only two years; on the other hand, that 40 million dollar difference represents about a doubling of the initial costs - hardly affordable program-wide. Thus, the need for a judicious selection of applications based on a careful Station-wide system analysis.

Telerobot

The Station telerobot is an evolvable system that will include the capability for both pure teleoperation with telepresence, as well as full autonomy of selected functions, the repertoire of which is designed to expand greatly during the useful life of the Station. In addition, its architecture will allow for graceful sharing of control between operator and machine. The analysis summarized here (GRUMMAN, 1986) compares EVA with the teleoperation capability only for an assembly task. This analysis uses EVA work-hours as a unit of account and sidesteps, in part, the difficulty of assigning costs when experience is uniformly lacking and, as it is the case with marginal costs, even the methods for determining them are speculative. It is generally assumed that present technology permits about 50 EVA hours per week-long shuttle flight, on the basis of two days of space adaption, two teams of two EVA and one IVA astronauts each, working six hour/day on alternate days, and one day of clean-up. The investigators found, experimentally on the ground, that, with comparable training, the execution time increases by a maximum of a factor five in teleoperation, for tasks requiring dexterity; however, the telerobot could be operated at least 16 hours/day, in shifts, for almost six days. The combination of these factors for the expected mix of assembly tasks would produce an increase of over 50 percent in production per astronaut applied to the task. If autonomous operation, even to a very limited degree (e.g., the alignment and locking steps) were considered, the advantages would be even greater.

CONCLUSIONS

The Space Station Program provides a high payoff environment conducive to the development of advanced A&R technology in the areas of: hierarchical architectures, artificial intelligence tools and prototyping technology, adaptive controls, rapid planning and replanning, and verification and validation. Notwithstanding the exceptional conditions for a high return on investment, the cost of this technology is high, both in absolute and relative terms (as shown in the example above, it can double the cost of a subsystem) and, therefore, a continuing commitment to A&R is required on the part of the program and the U.S. Congress.

The effort and the investment will not only enjoy a relatively rapid return, but, in advancing the technologies mentioned above, will specifically foster greater versatility, flexibility and "intelligent behavior" in machines and hasten the departure from preprogrammed automation, which requires very long production runs to justify its adoption. This is now the main form of automation in industrial applications: about 50 percent of all robots are used in automotive production. The need and the potential impact of the more advanced forms of A&R, which the Space Station will foster, can be gaged by the fact that over 75 percent of the total value added in manufacturing is attributable to non-mass production methods (Miller, 1986). The potential impact of the introduction of flexible automation for assembly has been analyzed recently by Funk (1984) and one representative estimate is displayed in Fig. 6. The costs are derived for a "standard" product on the basis of industrial statistics for a variety of assembly tasks.

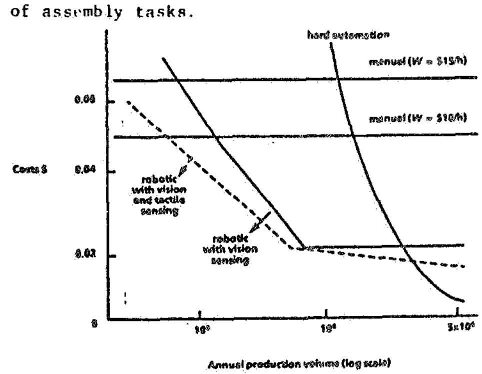

Fig. 6. Impact of Advanced Robotics on Manufacturing (Adapted from Funk, 1985)

REFERENCES

ARP (1985). Automation and Robotics for the National Space Program. Automation and Robotics Panel. California Space Institute Report CSI/85-01.

ATAC (1985a). Advancing Automation and Robotics Technology for the Space Station and for the U.S. Economy. Advanced Technology Advisory Committee (ATAC) Report to the U.S. Congress. NASA TM 87566.

ATAC (1985b). Advancing Automation and Robotics Technology for the Space Station and for the U.S. Economy. Advanced Technology Advisory Committee (ATAC) Report to the U.S. Congress. Progress Report No. 1, October 1985. NASA TM 87772.

ATAC (1986). Advancing Automation and Robotics Technology for the Space Station and for the U.S. Economy. Advanced Technology Advisory Committee (ATAC) Report to the U.S. Congress. Progress Report No. 2, March 1986. NASA TM 88785.

BOEING (1985). Space Station Automation and Robotics Study. Boeing Aerospace Company and Boeing Computer Services Company. D483 10027-1.

BOEING (1986). Automation and Robotics Plan. Boeing Aerospace Company. DR-17 Data Package WP-01, D483-50055-1, June 30, 1986.

GE (1984). Space Station Automation Study: Automation and Requirements Derived from Space Manufacturing Concepts. General Electric Space Systems Division, Contract No. NAS5-25182.

GE (1986). Space Station Definition and Preliminary Design. DR-17 Automation and Robotics Plan. WP-03. June 30, 1986, General Electric Company. DR-17, Contract No. NAS5-29300.

GRUMMAN (1986). Space Station Assembly Study. March 1986. Internally funded by the Space System division of Grumman Corporation. Private communication from Mr. G. Fischer.

HUGHES (1984). Automation Study for Space Station Subsystems and Mission Ground support, Hughes Aircraft Company, Contract No. 82-14F.

MARTIN (1984). Space Station Automation Study. Martin Marietta Aerospace, MCR84-1878.

MARTIN (1986). Space Station Definition and Preliminary Design. Martin Marietta Aerospace. DR-17 Data Package WP-01, SSP-MMC-00022, rev. A, June 30, 1986.

MCDONNELL (1986). Automation and Robotics Plan. McDonnell Douglas Astronautics Company, DR-17 Data Package WP-02, MDC H2036A, June 1986.

Miller (1986). Private communication.

NASA (1977). Skylab, Our First Space Station. NASA SP-400.

NASA/LeRC (1986). Preliminary Cost Estimate for Automation Alternatives for the Electric Power System. NASA Lewis Research Center. Private communication from J. Dolce.

NCOS (1986). Pioneering the Space Frontier. The report of the National Commission on Space. Bantam Books, Inc., New York, p. 17.

OTA (1985). Automation and Robotics for the Space Station: Phase B Considerations. Office of Technology Assessment staff paper.

Pivirotto, D. S. (1986). Unmanned Space Systems. 13th Annual Symposium Association of Unmanned Vehicle Systems. July 21-23, 1986.

RCA (1986). Space Station Definition and Preliminary Design, DR-17 Automation and Robotics Plan. WP-03. RCA Astro Electronics. Contract NAS5-29400. June 30, 1986.

ROCKETDYNE (1986). Interim Automation and Robotic Plan, DR-17. WP-04. Rocketdyne Division. Contract No. NAS3-24666. June 30, 1986.

ROCKWELL (1986). Automation and Robotics Plan. Rockwell International DR-17 Data Package WP-02, SSS85-0190A, June 13, 1986.

SESAC (1986). Space Station Summer Study Report. Space and Earth Sciences Advisory Committee (SESAC) Task Force on Scientific Uses of Space Station (TFSUSS).

SRI (1985). NASA Space Station Automation: AI-Based Technology Review. SRI Project 7268.

THURIS (1984). The Human Role in Space. McDonnell Douglas Astronautics Company, MDC H-1295.

TRW (1984). Space Station Automation Study - Satellite Servicing. Z410.1-84-160.

TRW (1986). Space Station Definition and Preliminary Design WP-04, Electrical Power Systems (EPS) - DR-17 Automation and Robotics Plan. TRW. Contract No. NAS3-24655. June 30, 1986.

Varsi, G., G. Man, and G. Rodriguez (1986). Automation of Planetary Spacecraft. Submitted to Unmanned Systems.