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A Historical Perspective of Robotics Development In the Space Station Program

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Abstract. The research field in robotics has grown tremendously in the 80ís because of the technology push from automobile industry and from the space station program. While the automobile industry pushed for implementation of robots to perform repetitive tasks in the assembly line, the space station program pushed for development of either large-scale and light weight tele-operative robots, or intelligent robots for extravehicular activities and exploration of distant planets. Recently, more knowledge of assembly in space became available that it seemed inevitable for a need of intelligent robots in the assembly sequence as well as in operation of the space station. This paper presents a review of the original goal for a space-oriented robotics research program, the historical aspect of robotics development in the space program, and the resulting current robotics technology.

1. INTRODUCTION

Robotics field is traditionally a discipline of developing and utilizing machines to replace humans in performing repetitive tasks. These tasks normally required dexterous and manipulative capabilities often provided by human's unique arm-hand-finger system. Initially, robots were controlled either by simple program with little feedback (for simple and repetitive tasks), or by human operator from a remote location (to avoid danger of being at the site of operation). With research effort from academic institutions and demand from private sectors, automation was developed to handle a more complex task with minimum supervision from human. The goal (and perhaps, the vision) was to replace humans totally with robots capable of functioning independently.

The space program has created demand for intelligent autonomous robot to do unmanned exploration at distant planets and to perform dangerous extravehicular activities outside orbital spacecraft. In this exploration setting, a robot is sent to a distant planet for initial exploration. The time delay for a control signal from earth to reach the robot would be critical enough to slow down the tele-operation significantly [1]. Therefore, it is obvious that such planetary robot must have autonomous capabilities to function with minimum supervision. In the operation of orbiting spacecrafts/space station, it was concluded that extravehicular activities were [2:Fisher-Price Study] crucial to maintain the hardware components. It was further recommended that these extravehicular activities were performed by robots to reduce risks [2].

The space station was originally designed with a 30-year life-cycle. It was obvious that the original construction will be based on the available technology. However, an evolution path exists to provide the incorporation of new technology matured during that 30-year span. Automation is one of the technologies that is expected to mature and be incorporated into the space station environment. Automation can be described as the ability to function automatically and independently with minimal human supervision. The development of autonomous capabilities has intro-

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duced different branched disciplines: machine vision, artificial intelligence, genetic algorithm, artificial life, etc. In addition, established disciplines such as automatic control, decision theory, and sensory devices were advanced further to accommodate this new demand.

During the design phase of the Space Station, there were significant developments (in this program) that advanced the technology in robotics field. These developments can be transferred back into private sector for commercial benefits. These technologies include better sensors, more intelligent thinking machines, better processing capabilities, and new concepts in integrating compact robots for household use. While the space program has a long term commitment, the technology transfer into private sector can be seen as harvesting immediate benefits from it.

This paper presents the original goals that NASA set for its robotics effort at the beginning of the Space Station program, historical review of technology development in the robotics discipline, and achievements/advancements that continue to be made. The paper also outlines mature technology ready for transfer into private sector for immediate impact on human lives on earth. Direct consequence in terms of commercial benefits and hidden costs are briefly examined for this technology transfer effort.

2. HISTORICAL REVIEW

Even though the term ìrobotî was coined in 1921 in a science fiction play at Broadway, it was not until World War II that machine was designed to handle radioactive material at the Atomic Energy Commission in Albuquerque. In the late 60ís, Japan implemented the manipulator in its automobile assembly line to reduce human resource requirement and at the same time assure constant quality. The US followed this trend in Detroit in the early 70ís. These machines were initially used in assembly line to perform simple but tedious tasks, i.e., tightening screws and bolts, moving heavy parts, and painting exterior areas. The objective of using robot was to reduce cost of human resources, increase safety, and assure constant quality performance. These tasks were easily programmed into a controller because they were repetitive and did not require any significant intelligent reactions. The robot manipulator would be activated for a certain assembly task when a part was positioned to a predefined space recognized by the gear that moved the line. When the robot finished its tasks, it sent out a signal that moved the line again. The implementation of assembly tasks is depicted in Figure 2.1.

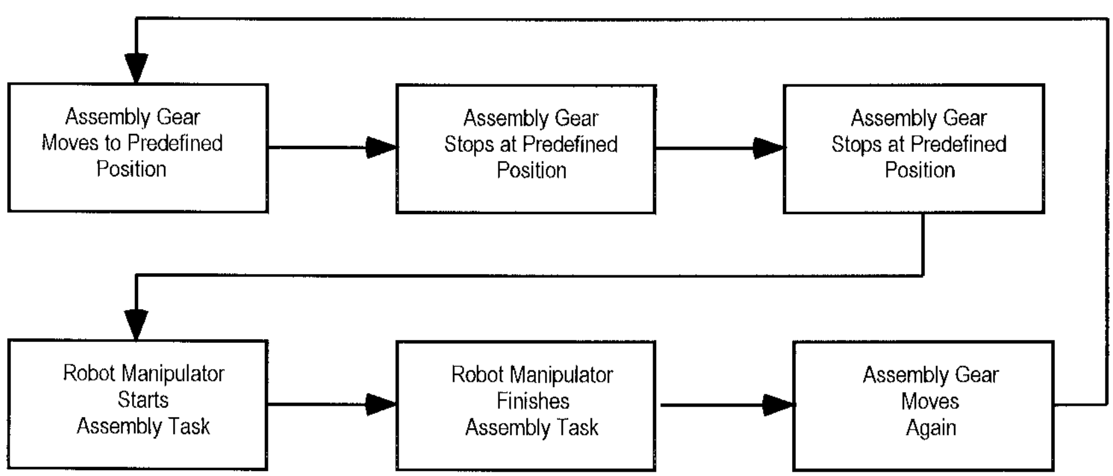


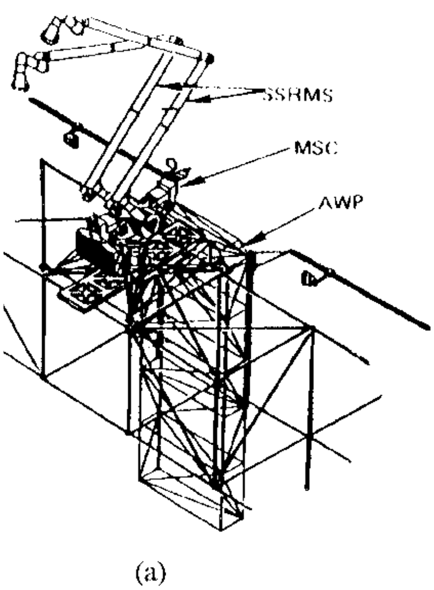
Figure 2.1. Fundamental of Task Scheduling in an Assembly Line.

In the space program, the Shuttleís Remote Manipulator System (RMS) has played a major role in assisting deployment of large objects such as satellites [Ref], and experimental truss structure [Ref]. Figure 2.2 depicts such operations. In order to reasonably accomplish these tasks, human was inserted in the control loop to provide the intelligence. This tele-operation has been the only way used since the birth of the first space shuttle. The following technologies were developed for the operation of the RMS: force feedback controller (to provide some sense of touch), and combining of different controllers into a single one (for treating special cases).

The Space Station program has endured several redesigns and modifications. In the beginning, the baseline design [3,4] of the Space Station Freedom included delivering of several robotics components, i.e., a Space Station Remote Manipulator System (SSRMS), a Mobile Transporter (MT), a Flight Telerobotic Servicer (FTS), and a Special Purpose Dexterous Manipulator (SPDM). In addition, the international partner Japan was also to provide a smaller robotics manipulator similar to the SSRMS.

The new Space Station Alpha [Ref] has retained the following robotics components: the Space Station Remote Manipulator System (SSRMS), Mobile Remote Servicer (MRS), Mobile Base System (MBS), the Japanese manipulator, and Special Purpose Dexterous Manipulator (SPDM). Note that all robotics components will be provided by the international partners, reducing the US participation in the space robotics effort to a mere simulation of these components for training, verification, and analysis of integration.

In addition, the new space station design also provided components that might utilize automation technology. These components include Automated Transfer Vehicle (ATV), and Assured Crew Return Vehicle (ACRV); all developed and provided by the international partners. Again, the US role in automation in the space program was reduced to research and development for future evolution path.



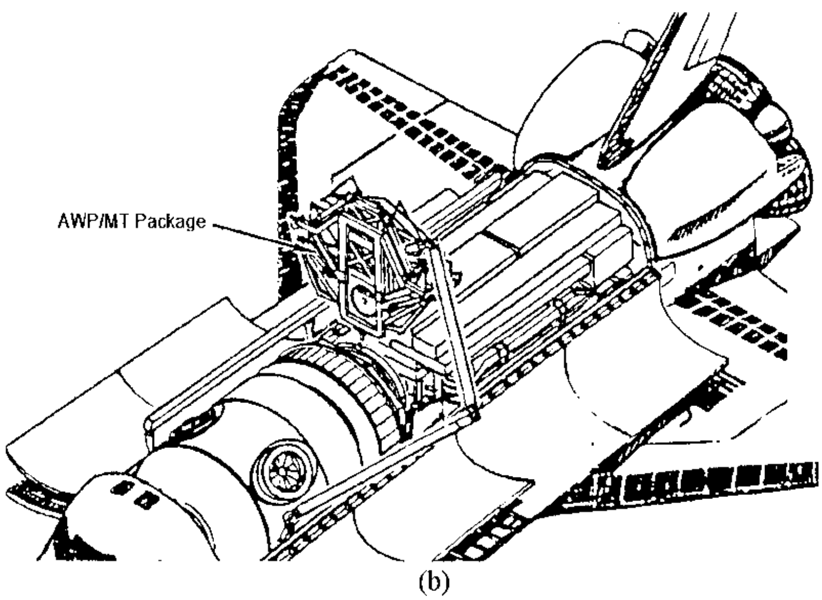


Figure 2.2. Robotics Operation in Space: (a) SSRMS Initializes a Concept Keel Construction, (b) Shuttle-RMS Lifts AWP/MT Package from the Shuttle Cargo Bay

Currently, the US research effort has reached a stable level [Ref: Clintonís assessment on research]. Our research participation in robotics and automation was mostly confined to academic environment (in terms of research grants), and to government laboratories. Most of the academic research concentrated on theoretical aspect to advance the technology. Most of the research conducted in the laboratories focused on the development of a prototype product to address a specific need. Due to severe funding limitation, almost all major space contractors no longer support (or provide very little) independent research in the fields for space use.

3. TECHNOLOGY REVIEW

In this section, we present the development path of robotics technologies in the Space Station Program.

3.1. Vision and Goals. In the early 80ís, two major initiatives for robotics were presented: the recommendation of the Advanced Technology Advisory Committee (ATAC) [6], and the Automation and Robotics Implementation Plan for the Space Station Program [7]. In addition, another report in the early 90ís, the Fisher-Price Report [Ref], provided sufficient data to require robotics components in the operation of the Space Station.

The ATAC report stated the recommended goals as follows: (i) development of teleoperation robotics components with collision avoidance capability for the initial configuration of the Space Station, (ii) development of intelligent systems to increase automation in the operation of robotics components toward the mature stage of the Space Station. In this report, robotics components were seen as tools for aiding the inspection and replacement of orbital replaceable units, repairing complex systems, and handling fuel and hazardous material. In addition, robotics components were planned to perform retrieval and servicing of satellites. Table 3.1 summarizes these goals.

The Automation and Robotics Implementation Plan for the Space Station Program outlined implementation steps for robotics components into the Space Station. Concepts for space robots were examined and evolution paths were presented. This report also identified a crucial technology expected to mature, machine vision, to impact on the positive development of robotics research. Machine vision will be an intelligent eye to provide feedback data for automatic control motion of mechanical parts of robots.

In the early 90ís, the Fisher-Price Report [Ref] confirmed the needs for robotics devices for maintenance of the Space Station. The report identified the required effort to maintain the station to be more than the available resource from astronauts. Therefore, it was essential that additional resource from robotics components be used to supplement human effort to maintain the station.

Table 1. Initiatives for Robotics In Space Station Program

ATAC Report	A&R Implementation Plan	Fisher-Price Report
❑ Vision: • Automation and Robotics in Space Station Program ❑ Goals: • Initial Space Station Robots Having Collision Avoidance Capability • Final Space Station Robots Having Intelligent Capabilities.	❑ Implementation Plan Goal: • Initial Capabilities (teleoperation) ❑ Evolution Plan Goal: • Desired Capabilities (automation and intelligent semi-supervisory mode)	❑ Needs for Maintenance of Space Station ❑ Recommendation for Robotics Usage

3.2. Robotics Programs. Since the start of the Space Station Design, NASA had initiated several robotics programs to study concepts and evaluate prototypes. Three major programs [Ref] were started in the mid 80ís: (i) Flight Telerobotics Servicer (FTS) at Goddard Space Flight Center, (ii) EVA Retriever at Johnson Space Center, and (iii) Man Equivalent Telerobot (METR) at Langley Research Center. Figure 3.1 illustrated these concept prototypes.

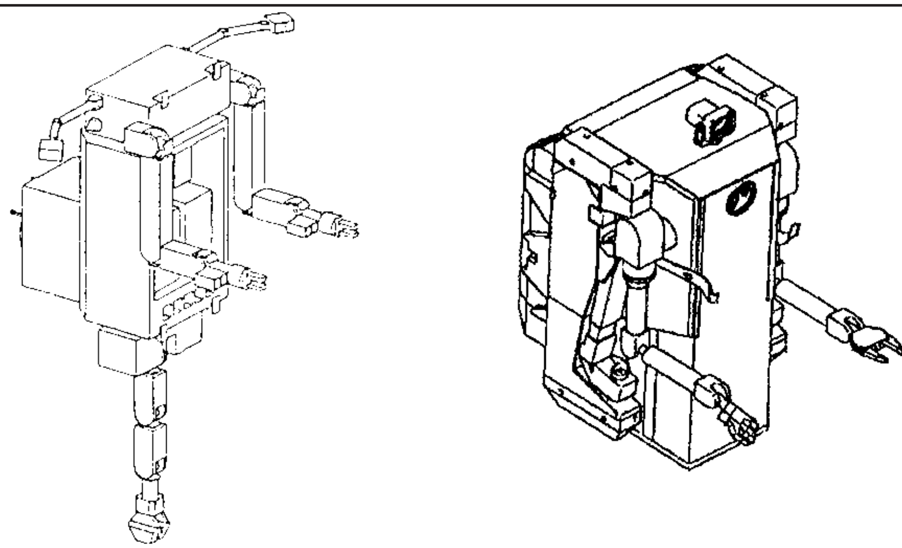


Figure 3.1. Concept Prototypes: (a) FTS, (b) EVA-Retriever, (c) METR.

The FTS was targeted to assist the assembly of the Space Station. It was designed to be attached to the Space Station RMS (for transporting to a local work site) and operated remotely by operators. The FTS had three manipulators: one to stabilize the body by locking on a fixture structure, two to perform dexterous tasks. The operator will control these manipulators remotely by using control devices. The FTS body was equipped with a wide range of tools for assembly tasks.

The EVA Retriever was targeted to retrieve loose tools and rescue EVA crewmen. It was an autonomous freeflyer capable of operating under minimum supervision from human. The EVA-Retriever has two manipulators. The robot moved by a backpack Man Maneuvering Unit (MMU). The two manipulators were equipped with hands for grasping small tools. The two manipulators were also designed to handle large object in a bear-hug posture.

The METR was a hybrid of telerobotic and autonomous capabilities. It was designed to function independently but capable of switching to teleoperation when interfered by human operators. The hybrid concept was developed in this prototype that has two manipulators to provide dexterous capability equivalent to that of an astronaut in EVA suit.

It was clear that the three concepts mentioned above outlined three approaches to operate robots: (i) teleoperation, (ii) automation, and (iii) supervisory automation.

3.3. Accomplishments. It was clearly demonstrated through these robotics studies at NASA that there are two major thrusts: (i) a telerobotics capability for immediate implementation, and (ii) intelligent and autonomous capabilities for future implementation.

The telerobotics approach [9] was feasible with the available technologies. This approach inserted human in the control loop to provide intelligent capability in observing external environment, controlling mechanical motion, and coordinating task planning and execution. The basic system involved hardware configuration, hand control units, cameras, and force/tactile sensors.

The following technologies were identified and investigated toward a teleoperation robot: (i) force-feedback controller, (ii) lighting illumination, (iii) clearance analysis, (iv) time-delay effect, and vibration analysis (in large structure).

The intelligent and autonomous approach [10] required additional sensors on external environment and ability to interpret data provided by these sensors. In addition, reasoning capability was required to plan a task (by partitioning it into a sequence of subtasks), execute these subtasks, and monitor status/environment. In addition, a freeflyer must be able to navigate in a three-dimensional space.

The following technologies were identified and investigated toward an intelligent/autonomous robot: (i) machine vision (object recognition, altitude determination, depth perception, stereo vision, processing techniques), (ii) navigation and control (path planning, automatic control, propulsion, impingement effects, dynamic modeling, collision avoidance), (iii) task planning (artificial intelligence), and (iv) man-machine interface (voice recognition, object recognition).

A concurrent development to these robotics efforts is the computer simulation project. This is the use of computer to simulate the behavior of these robotics devices and illustrate the results in a three-dimensional graphic environment. The simulation output is normally used for training and analysis of different scenarios. For simulation, new modeling and fast numerical techniques have been developed for a real-time capability and high-definition visual environment.

3.4. Current Efforts. From the above programs, several projects were spinned off to investigate specific capability/functionality. At Johnson Space Center, the following robotics projects are currently studied: machine vision, architecture for intelligent robots, task planning, autonomous free flyer camera, and teleoperation.

The machine vision project provided stereo vision, object recognition, color processing, motion coordination, and tracking capabilities. The goal of the project is to provide a sensing capability that can perceive depth, recognize surrounding scenes, provide guidance for mobile platform, and feedback for controlling manipulators. The project currently experiment with the PRISM vision system mounted on a mobile Cybermotion robot.

The architecture for intelligent robots investigated the software architecture for intelligent robots. The main goal is to develop a configurable architecture for experimental robots that can change the operational configuration. For example, a robot might change hardware (different end-effector tools, varied payload), or change motion capability (locking redundant joints), etc. Another goal for this project is to propagate high level command into detailed level of execution steps. Learning capability will be implemented for the real-time experience gained during execution. The task planning project is concurrently investigated with the architecture study.

The autonomous free flyer camera project investigated the use of free flyer robot to provide additional vision cues for operators who control the manipulator remotedly. Currently it is building a robot called AERCAM (Autonomous Extravehicular Robotic Camera). This is a light-weight free flyer unit (around 50-90 kg) capable of flying around a space station site for inspection and aiding teleoperation with additional vision view.

At JSC, several facilities such as Mobile Robot Laboratory (multi-robot coordination), Full Immersion Telepresence Testbed (FITT) and Dexterous Anthropomorphic Robotic Testbed (DART) were dedicated for robotics research. Simulation environment are also providing high-fidelity software simulation of these robotics plaforms for training and testing.

In addition, Jet Propulsion Laboratory is currently taking leadership in rover robotics (a mobile platform equipped with manipulators) for exploration of distant planets. The development in robotics of the

4. TECHNOLOGY TRANSFER

Technologies have been developed both within and from outside the space community. The transferring flow was dictated by the differential gradient in technical capabilities between the space community and other sectors. The flow into the space program happens when new technology was developed in private sectors and can address a space need. The flow out of the space program happens when new technology was developed in a space program can be applied to address a commercial demand.

4.1. Technology Transfer into Space Program. The most obvious technology transfer into the space program is the computer technology. With a fast pace of research and development, new and more powerful computers were rapidly introduced into the general market in which the space sector is a consumer. Since robotics component employed the use of computer heavily, a more powerful computer will mean a more effective robot with better precision in handling objects. However, there are other robotics technologies being transferred into the space program such as digital image sensors, data processing, etc. Figure 3.1 illustrates these inflows.

Basically, a technology developed in the private sector for commercial purpose can be seen as a solution to a particular space problem. This technology is then transferred into the space program through commercial acquisition, licensing, support contract, or staffing of experts. This transfer can be represented in form of a tangible product or some added value to the already existing products.

4.2. Technology Transfer into Private Sectors. Technology transfer to commercial sectors had been emphasized at NASA through licensing effort, encouragement of innovative use of NASA-developed technologies. The purpose of this effort is to cultivate private business with new technologies for new business, to stimulate the economy with new products developed from these new technologies, and to inform the general public of the favorable results of technological investments.

Space Technology	**Application**
Fuzzy Logic / Neural Network	Autofocus Cameras
Machine Vision / Signal Processing	Graphics Chips
Parallel Processing / Neural Network	New Generation CPUs
Virtual Reality Simulation	Computer Games
Light Weight Manipulator	Prosthetic Limbs
Aerospace Optical Glass	Chameleon Artwork Decoration
Simulation	Training / Recreational Games
Robotics Control	Robotics Cleaning System
Robotic Hand	Artificial Hands
Automations	Automatic Inspection Systems
Task Planning	Automatic Scheduling Software

Figure 3.1. Technology Transfer in the Robotics Field.

While a complete robotics technology for space application is not matured for transfer into private sector, certain individual techniques, technical methods can be identified as having potential. Namely, the numerical methods to improve mathematical calculation had been implemented in different application. The design of several prototype CPU models that employed neural net capability to predict the calculation flows in a parallel scheme is one prime example. The fast graphical chips is a combination of advancement in digital signal processing and machine vision algorithms. The use of fuzzy control chips in controlling the focusing of camera lens is an example of applying altitude determination (machine vision) and fuzzy logic (artificial intelligence). Figure 3.1 summarizes such technologies being transferred.

5. CONCLUSION

The robotics field has gone through different phases in the space program, during which technologies were developed. There were two major approaches, teleoperation and automation. The teleoperation was designed for immediate implementation while automation was for future upgrade. Because of the strong demand for robotics in the Space Station program, state-of-the-art technologies had been advanced. These technologies, in addition to fulfilling the original goals for the Space Station, have potential for application on earth to directly benefit humankind in the everyday lives. Current effort in robotics, embedded in individual projects focusing on specific aspect, indicates that intelligent capabilities will be the future of robotics systems in space.

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