KEY TECHNOLOGY ISSUES
FOR SPACE ROBOTIC SYSTEMS

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Abstract

Robotics has become a key technology consideration for the Space Station project to enable enhanced crew productivity and to maximize safety. There are many robotic functions currently being studied, including Space Station assembly, repair, and maintenance as well as satellite refurbishment, repair, and retrieval. Another area of concern is that of providing ground-based experimenters with a natural interface that they might directly interact with their hardware onboard the Space Station or ancillary spacecraft.

The state of the technology is such that the above functions are feasible; however, considerable development work is required for operation in this gravity-free vacuum environment. Furthermore, a program plan is evolving within NASA that will capitalize on recent government, university, and industrial robotics research and development (R&D) accomplishments.

This paper provides a brief summary of the primary technology issues and provides physical examples of the state of the technology for the initial operational capability (IOC) system as well as for the eventual final operational capability (FOC) Space Station.

Introduction

There is a world-wide interest in the automation technology that will significantly free humans from having to perform mundane, time-consuming, and in many cases, dangerous tasks in space. This author, as well as many other individuals involved with automation technology, robotics being a subset of automation technology, have reviewed the state of the technology in Europe, the Far East, and within the United States, only to find that we are all pursuing the same goals, i.e., progressively more "dexterous" and "intelligent" robotic systems for a variety of applications. Conversely, very little has been accomplished in the recent past that examines the peculiarities associated with the operation of robotic systems in space. MIT, Stanford University, JPL, a few industrial concerns, and the NASA centers, on the other hand, have been chipping away at specific, related-technology issues. The intent of this paper is to summarize and expound on these issues, then provide a summation on the state of the applicable technology to present the reviewer of this paper with a feel for technical feasibility.

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Operational Requirements Versus Feasibility

Space Station will service a number of unmanned vehicles in space, support commercial laboratories, and provide for efficient management of itself. Because of the fact that the crew of six to eight astronauts and mission specialists will have to operate and maintain a research laboratory, a permanent observatory, a transportation node, a storage depot, and a base for staging missions to higher orbits, "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" (Ref. 1). Therefore, robotics are essential to the Space Station mission. Furthermore, it is entirely feasible to implement robotics on Space Station in the projected time frame. Space flyable arms, the Remote Manipulator System (RMS), and the Protoflight Manipulator Arm (PFMA) (Figure 1) have been developed and, in the case of the Canadian RMS, successfully flown onboard Space Shuttle. We have also successfully flown two sterilized manipulators to Mars and successfully operated them for Mars sample acquisition as shown in Figure 2.
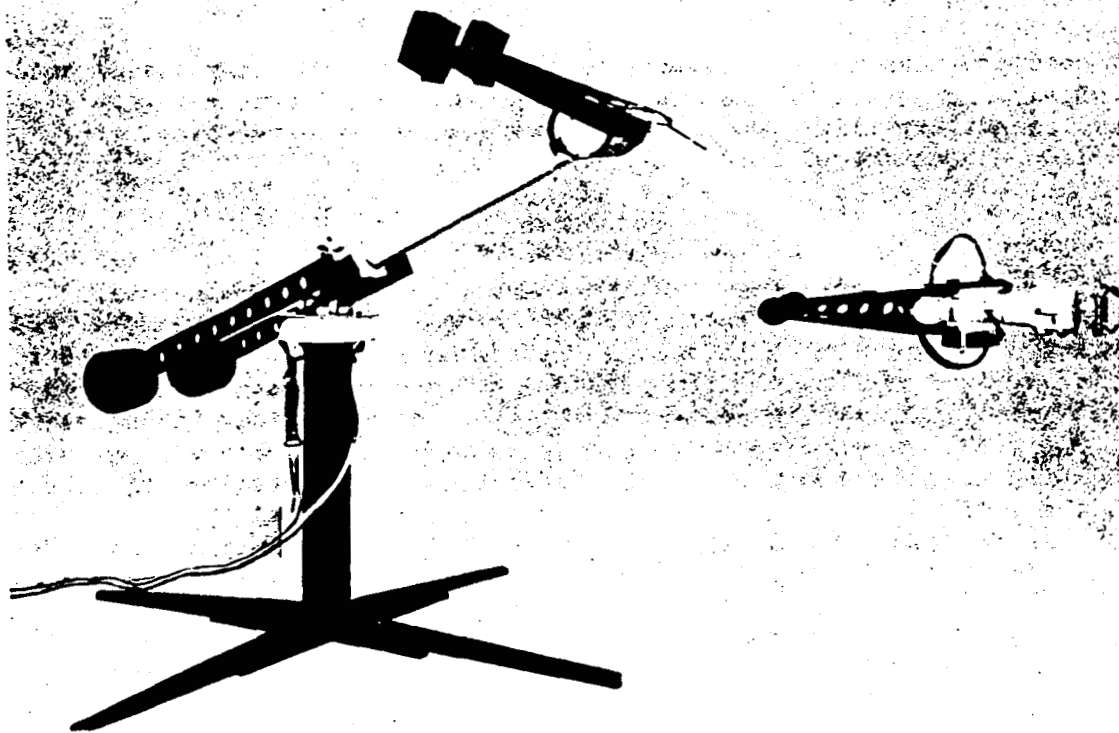

Figure 1 Protoflight Manipulator Arm

Figure 2 Viking Spacecraft

Therefore, it is not a question of "is it feasible?", but rather how functional and reliable can we make them to maximize on-station productivity? The answer, of course, is not immediately obvious and will evolve as a result of functional requirements emanating from the anticipated NASA/GSFC Phase B Flight Telerobotic Servicer study (Ref. 2). Furthermore, the technology issues discussed below will affect the ultimate Space Station robotic system.

Primary Technology Issues

The primary technology issues that must be considered for deployment of robotic systems in space are as follows:

(1) Safety with respect to the crew and Space Station itself;
(2) Mission requirements specification;
(3) Robotic system performance specification;
(4) Human interaction;
(5) Space qualification;
(6) Design for growth;
(7) Performance test, evaluation, and training (0 g);
(8) Telepresence;
(9) Modularity and maintainability;
(10) Standard interfaces and commonality.

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Safety

The safety issue is a key issue because we have not been overly concerned with humans interacting with or working in close proximity to robots or for that matter, with robots destroying expensive components of a system such as Space Station. We traditionally "fence off" industrial robots and accept the losses if they destroy a replaceable workpiece. There are, however, several mechanizations that must be evaluated and implemented where applicable to prevent a catastrophic event resulting from loss of, as an example, servo control of a manipulator joint in space. The following are some safety considerations that warrant further evaluation:

(1) Logical application of traditional redundancy, self-test, and failure mode analysis techniques.

(2) Consideration of manipulator sensors at the joints that would terminate operation and/or "safe" the system; implementation of three-axis acceleration measurement sensors in the wrist or end effectors to sense operation outside of a preselected acceleration level to shut down and/or "safe" the system.

(3) Design of the proximity sensor system to "sense the human presence" and perhaps move the manipulators at a slower rate.

(4) Consideration should be given to the use of new techniques such as "Electro-Rheological Fluids" that would be resident in the manipulator joints in a clutch-type system, whereby the human who is in close proximity activates a small transmitter that in turn activates an electric field, stopping the robot manipulators by solidifying the fluid.

The fact of the matter is that, although thus far we have not had to face this safety problem, there are solutions at hand even for a scenario where the robot works in close proximity to the human.

Mission Requirements

The specific functional requirements must be specified early because of the effect on (1) size, (2) number of manipulators, (3) type of end effectors and tools, (4) joint ordering, etc. Engineering practices such as modularity, Figure 3, and interchangeable end effectors and tools will enable some flexibility; however, no single robot design will be adequate for all anticipated Space Station functions when considering Space Station assembly, operations, maintenance, and housekeeping as well as satellite servicing and, potentially, experiment interaction.

Robotic System Performance Specification

Up to this point, the development of space robotics has been determined by the need for demonstrations of technical feasibility at both the system and subsystem levels. The technology has developed rapidly and the lack of a mature technical base has made it very difficult to critically assess new developments. Feasibility demonstrations have thus far played an important role in establishing confidence in the emerging technology. As a result of

these preliminary efforts, both NASA and the Air Force are initiating major space robotic programs. These will result in operational systems that will have important roles in the development and evolution of both Space Station and the SDI systems. With this transition from systems designed to demonstrate general feasibility of technology to the development of major operational systems, methods must be developed to:

o   Specify manipulator system performance in terms of well-defined dynamic (as well as static) criteria;

o   Relate system functional requirements to the same set of criteria;

o   Provide techniques for assessing system performance in both design and hardware development phases.

Failure to develop and apply such a rigorous and nonambiguous approach could have serious consequences that could jeopardize the success of the operational robotic systems as well as the systems they are designed to support.
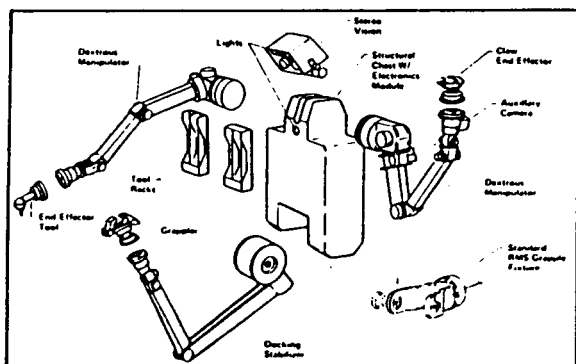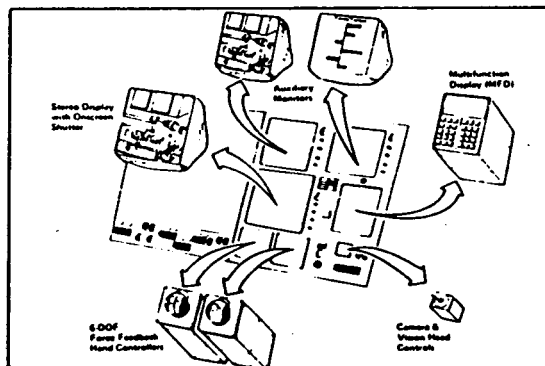

Exploded Work Station

- Dextrous Robotic Flight Demonstration System
- Provides Space Technology Development Test Bed
- Addresses Multipurpose Mission Requirements
- EVA Equivalent Performance
- Control Station/Work Station Definition Including Shuttle Interfaces
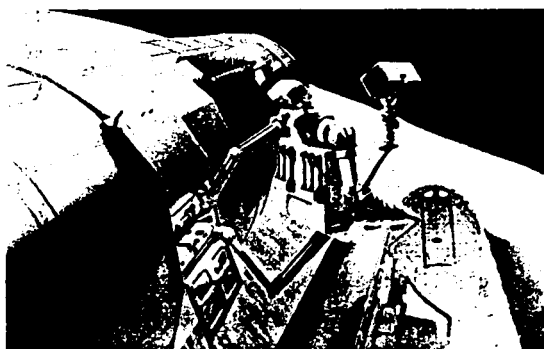
TWS Performing a Module Changeout Onorbit

Exploded Control Station

In more mature technologies, the cycle of performance requirement specification and end-product performance validation is well established. In the development of an aircraft or missile system, the designer is governed by government performance specifications that cover static and dynamic characteristics as well as reliability and safety. While there are some performance criteria that can be applied to robotic systems, the relationship to desired system performance is often vague.

Figure 4 shows the "ideal" situation that should emerge in the arena of robotic systems as large monetary commitments make the penalties for faulty intuition much higher. In Block 1, detailed functional requirements are established that reflect the full range of tasks the candidate system must perform. Necessarily, these must be developed at a low level and reflect a deep understanding of the specific mission. Figure 5 gives a hypothetical example of such a breakdown.
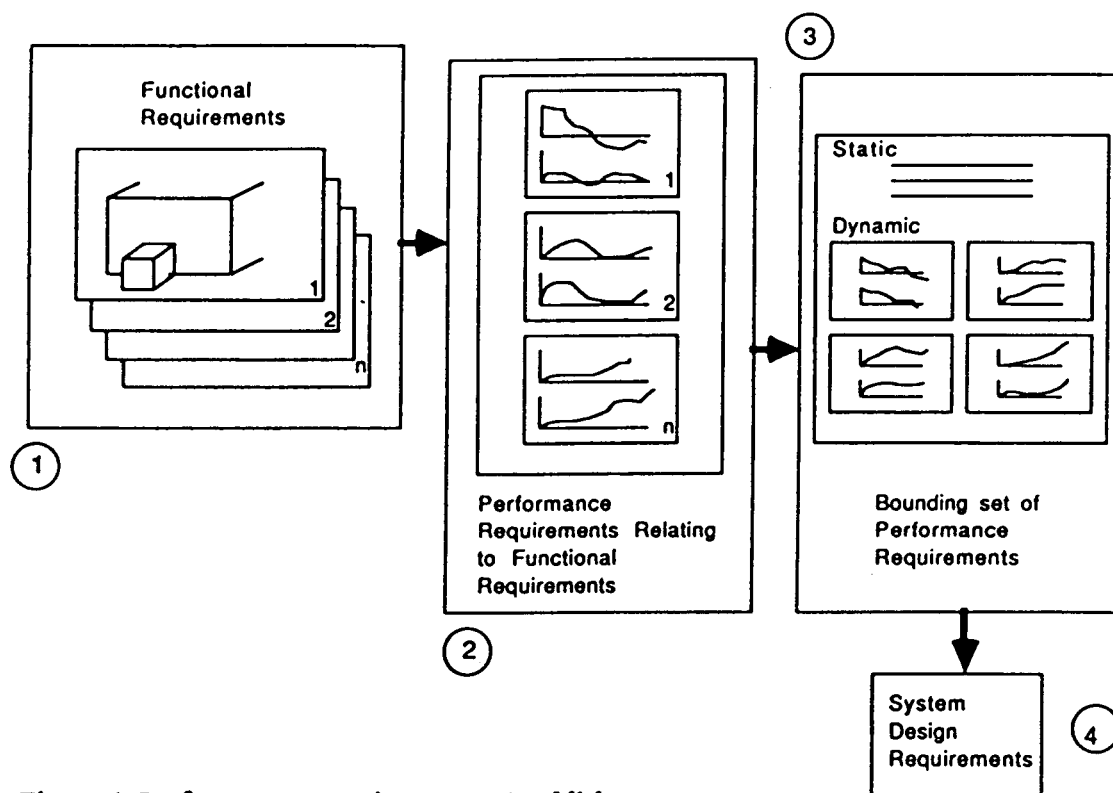

Figure 4 Performance Requirements Establishment

By decomposing complex tasks into sequences of generic or "primitive" tasks, detailed performance criteria for each primitive operation can be established as shown in Block 2 of Figure 4. In Block 3, the requirements established for the primitive operations are combined to yield a single set of performance specifications that serve (Block 4) as the robotic system design requirements.

In addition to a method for developing the robotic system performance requirements, an approach is also required for estimating system performance as the design evolves and validating system performance once hardware has been developed. This process is shown in Figure 6. The software package to support the activities shown in Figure 6 would have to be standardized to ensure consistency in the interpretation of results. Ideally, this would be a government-furnished item. Efforts toward this end have already been initiated, e.g., the Robotic Simulation (ROBSIM) package at NASA/LaRC.
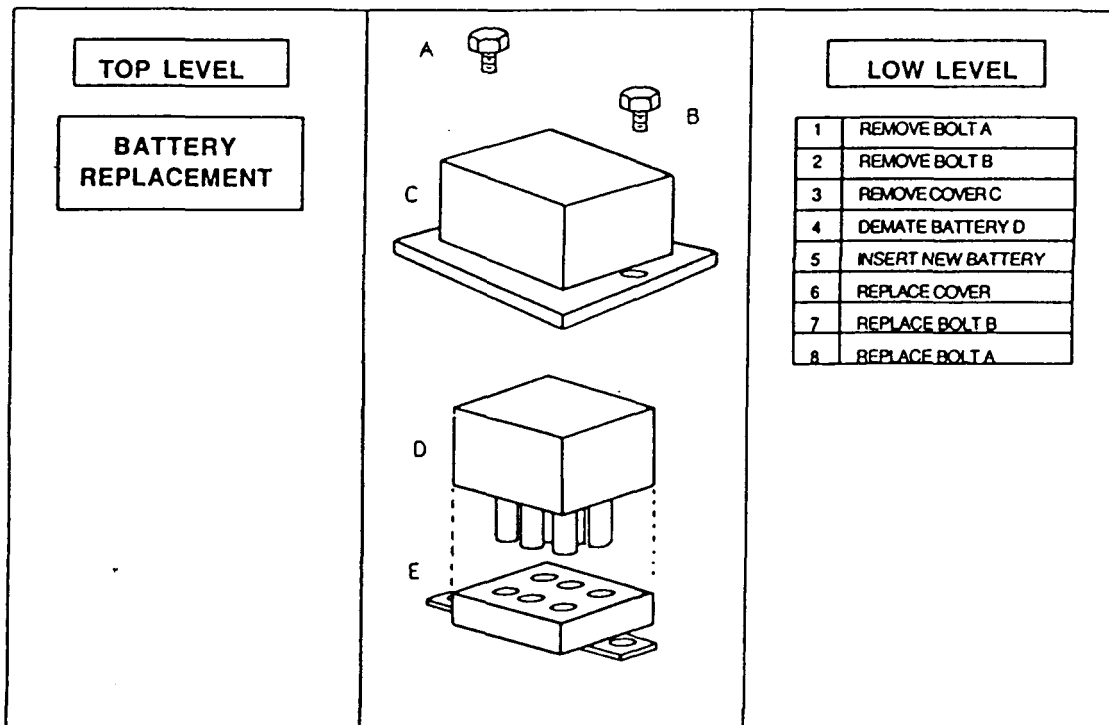
Figure 5 Hypothetical Battery Replacement Task

TOP LEVEL
BATTERY REPLACEMENT

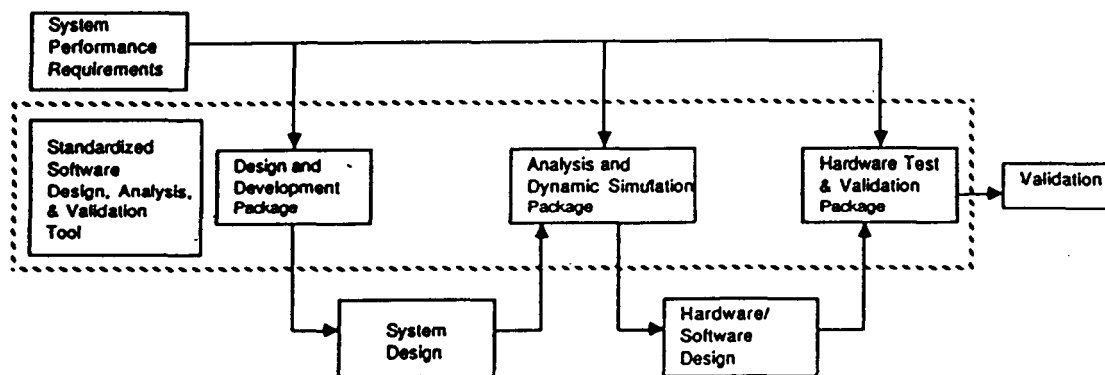|	LOW LEVEL
1	REMOVE BOLT A
2	REMOVE BOLT B
3	REMOVE COVER C
4	DEMATE BATTERY D
5	INSERT NEW BATTERY
6	REPLACE COVER
7	REPLACE BOLT B
8	REPLACE BOLT A

Figure 6 System Performance Definition

In the preceding paragraph, a general structure has been outlined that would support a systematic approach to components of robotic system development such as manipulator system performance specification. Missing from this discussion, however, is a specific way in which manipulator performance can be characterized such that the subjective quality, "dexterity," can be captured in terms of measurable dynamic parameters.

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Human Interaction - Human interaction and human factors considerations have received a lot of attention by the aerospace community; however, the robotics community is still in a quandary about how to best implement a "friendly" robotic interface. Training time and costs, available operator console volume, skill levels of the operators themselves, control mode desired, and more importantly, number of manipulators to be positioned must all be considered. There are currently at least five available options:

(1) Hand controllers, either joystick or ball type;
(2) Replica controllers;
(3) Exoskeleton controllers;
(4) Preprogrammed controllers to perform specific functions;
(5) Intelligent planner-driven controllers.

Very few individuals, even in the robotics community, have had the opportunity to evaluate all techniques listed above and therefore are somewhat biased by what they are familiar with in their own laboratories. All of these techniques can be made to work with sufficient training and within specific performance and time constraints.

Hand controllers are the traditional method used by the aerospace community. As an example, the Shuttle RMS arm is controlled in this manner. Hand controllers can be implemented to operate in both the commanded position as well as rate modes. They can also be implemented in several forms as shown in Figure 7. The joystick hand controller has been implemented as 3 degree of freedom (DOF), 6-DOF, and 6-DOF with force reflection as shown.
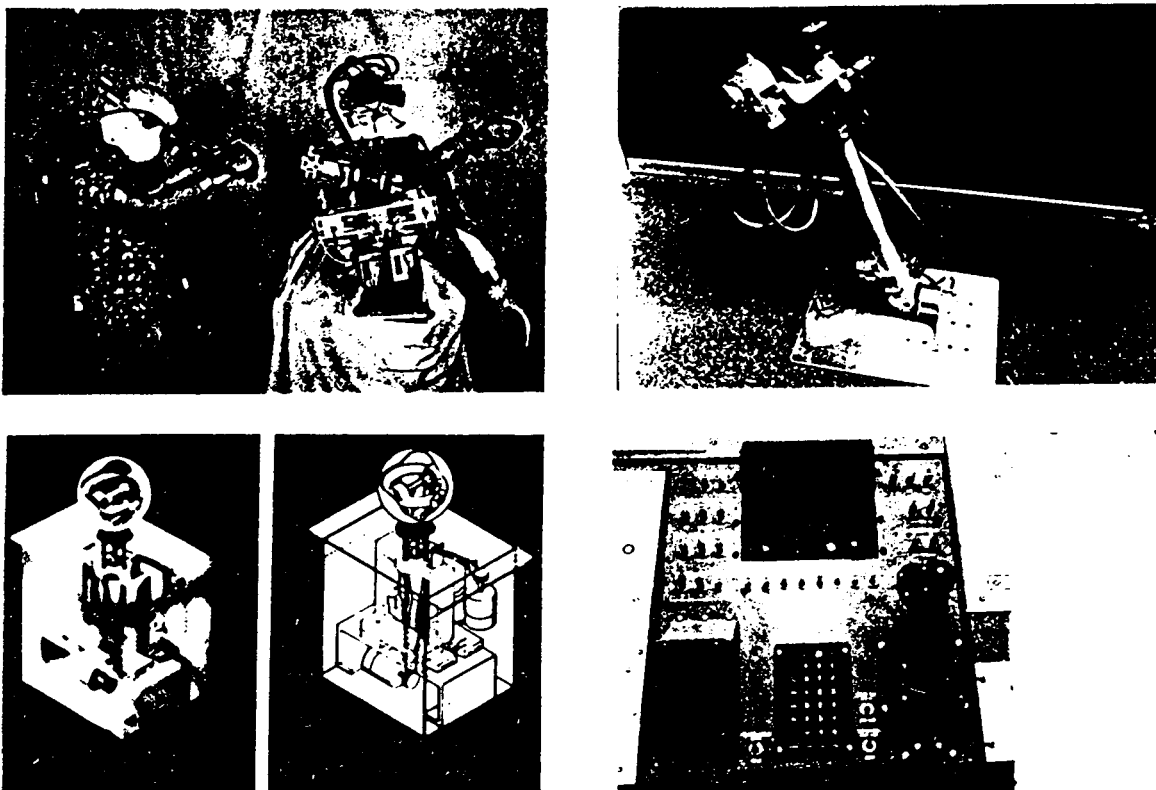

Figure 7 Hand Controller Capabilities

Another form of hand controller is the ball hand controller. Variations of this have been developed by CAE of Canada and the DFVLR of the Federal Republic of Germany. Martin Marietta Denver Aerospace recently developed a 6-DOF ball hand controller with force reflection as shown in Figure 7, which is currently undergoing laboratory testing.

Replica controllers have been in use by the nuclear industry for over 40 years and although they do provide a "more natural" human interface, the master controllers do require considerable volume. This technique is currently in use at Oak Ridge National Laboratories (ORNL) in Oak Ridge, Tennessee as shown in Figure 8. Although they enable a more natural interface, they do require considerable training because of camera location and multiple views required to see around the manipulators.

Figure 8 Replica Control Station

Exoskeletons, such as the Naval Ocean Systems Center (NOSC) system, provide an extremely natural human interface, but are probably the least studied approach. The NOSC system as shown in Figure 9 requires very minimum operator training even without force reflection, because of the fact the arms and head track the human operator in a one-to-one manner. Furthermore, the helmet-mounted stereo vision system provides a "natural" stereo presentation to the operator. Conversely, it must have the ability to see around the manipulators and end effectors if it is to be a viable contender for space.

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Storage of the exoskeleton must also be a consideration. Martin Marietta is currently in the process of adding a force/torque wrist and a more capable end effector to this system. Laboratory evaluations will commence in March 1987.
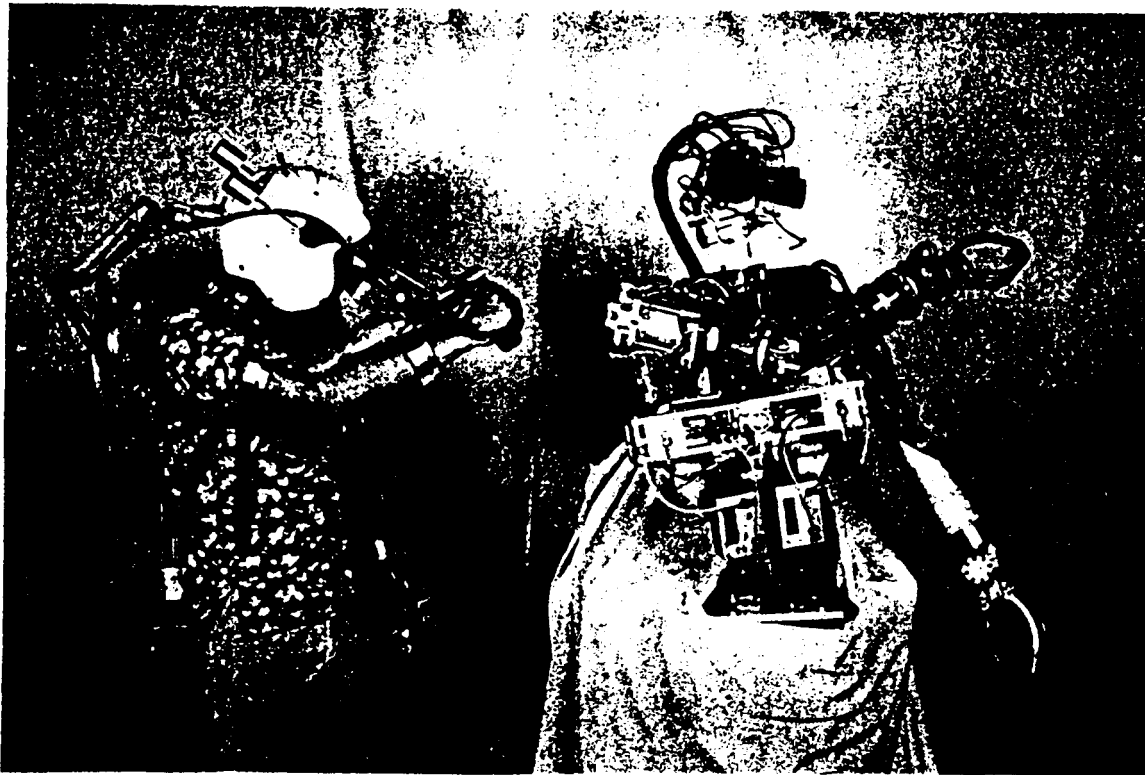

Figure 9 NOSC Exoskeleton and Anthropomorphic Robot

Preprogrammed robotic systems are commonly used in applications such as automobile manufacturing and are very effective when performing repetitive tasks. In the space application scenario, it would require the development of many standard interfaces and good computer definition of the worksite. It could be exercised on the ground; have sufficient sensory perception, i.e., tactile, proximity, and vision to locate objects; and to autonomously perform its assigned tasks as envisioned by Martin Marietta and NASA/MSFC for the Integrated Orbital Servicing System (IOSS) shown in Figure 10. This is an excellent and realizable approach, provided the world model is in fact as stored in the fixed program and provided there are no physically damaged components on the workstation. On the other hand, if one were to add a teleoperation capability, as envisioned by MSFC, this approach would enable the handling of contingency events such as we experienced on Apollo and Skylab, i.e., the fuel cell and solar panel malfunctions. It is anticipated that preprogrammed robotic functions will be implemented, if for no other reason, to alleviate the operator from performing monotonous tasks such as hardware removal in all future space robotic systems.
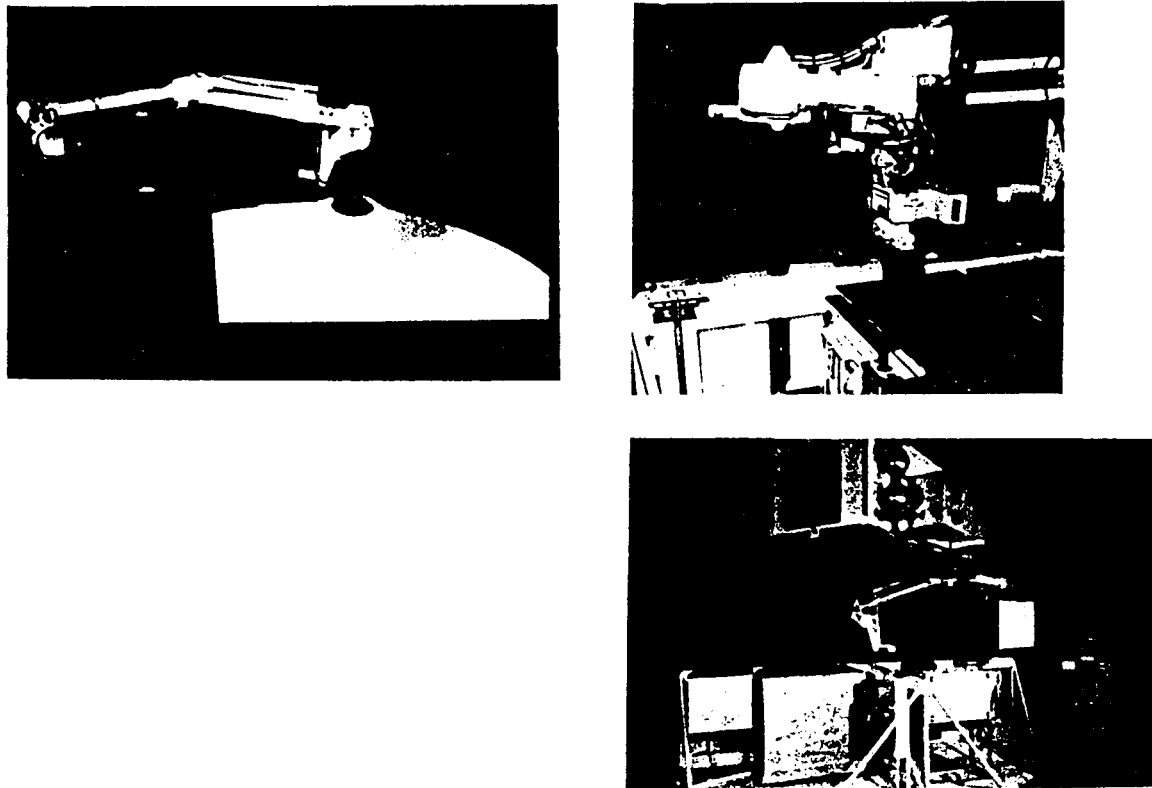
Figure 10 Engineering Test Unit of the Integrated Orbital Servicing Center

Intelligent robotic systems are on the horizon, but will probably not be available for the IOC Space Station. The DARPA/AFWAL-sponsored Intelligent Task Automation (ITA) system shown in Figure 11, is a prime example of future robotic systems. It consists of the elements shown in Figure 12. The ITA program has focused attention on capabilities required for autonomous task execution in unstructured environments. Emphasis has been on the incorporation of artificial intelligence (AI) systems to decompose high-level goals to executable robotic system actions. The hierarchical nature of the ITA implementation provides for the autonomous decomposition of goals into successively lower form until the system has, in effect, programmed the hardware system to accomplish the requested goals. AI planning techniques are used in determining task sequences, in detailed task planning, and in task execution and monitoring. An online path planner determines collision-free trajectories for manipulator motions. The system provides for sensor update of the world model data and sensor-based manipulator control. Of critical importance for autonomous operation is a framework for dealing with unexpected events. This execution

handling capability provides for diagnosis and plan modification or replanning as required to accomplish the original goals if possible.
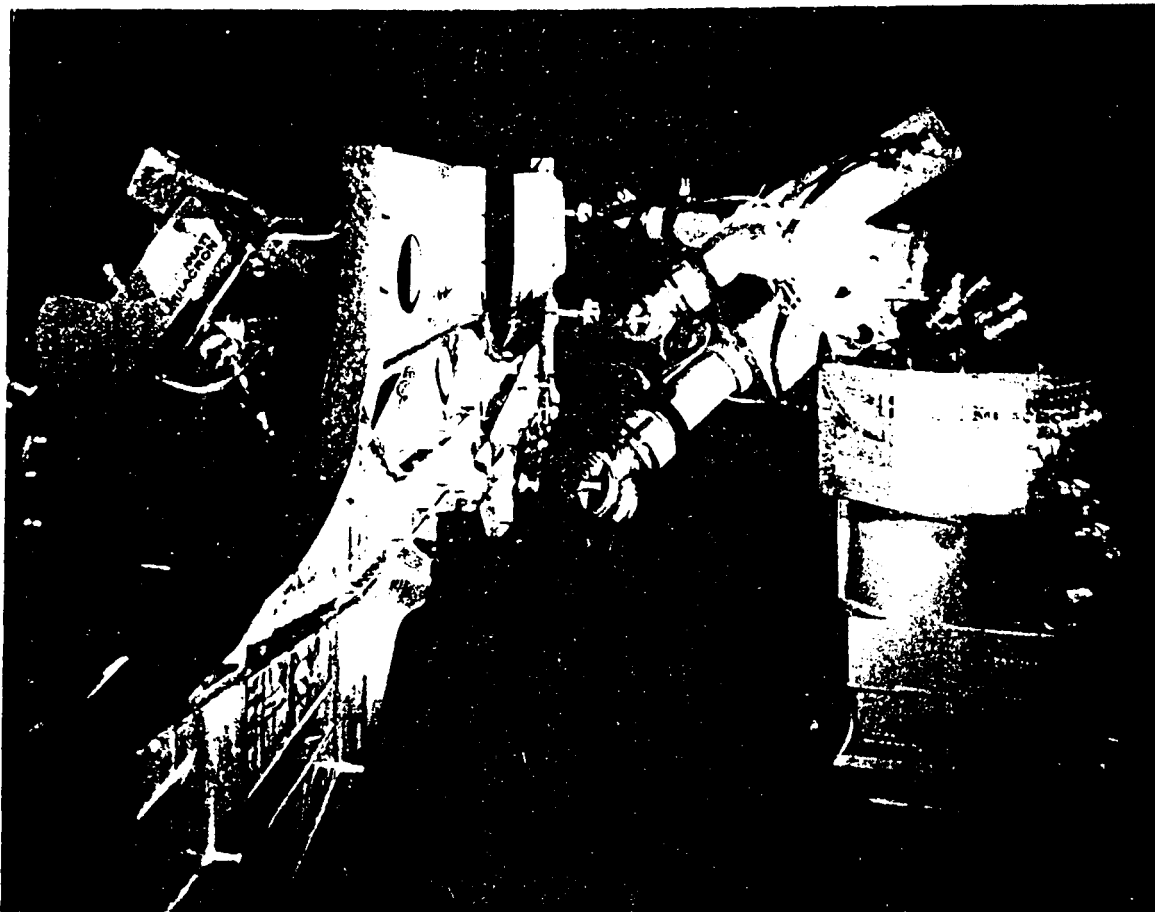

Figure 11 Intelligent Task Automation System

Research into systems such as ITA have provided considerable insight into the design considerations for highly capable intelligent systems. This information will aid in the design of systems that must build on current technology and transition from highly interactive, man-intensive teleoperated systems to supervised autonomy systems envisioned for many space applications. Although the ITA program is demonstrating many of the technologies required for autonomous systems, such systems are not readily available for near-term deployment. Systems such as ITA require sophisticated computer architectures not currently available for flight systems. Sophisticated data and knowledge bases are also required to support the AI planning and perception capabilities of an ITA system. Considerable sensory perception capability is required to maximize the effectiveness of the intelligent planning system, especially with regard to the exception handling system. Current progress, however, has shown that such intelligent systems are feasible and must be considered as viable solutions to future automation applications.

Space Qualification

Space-qualifiable hardware will have a serious effect on the flight system development because of the traditional considerations such as being rad hard and having minimum outgassing.
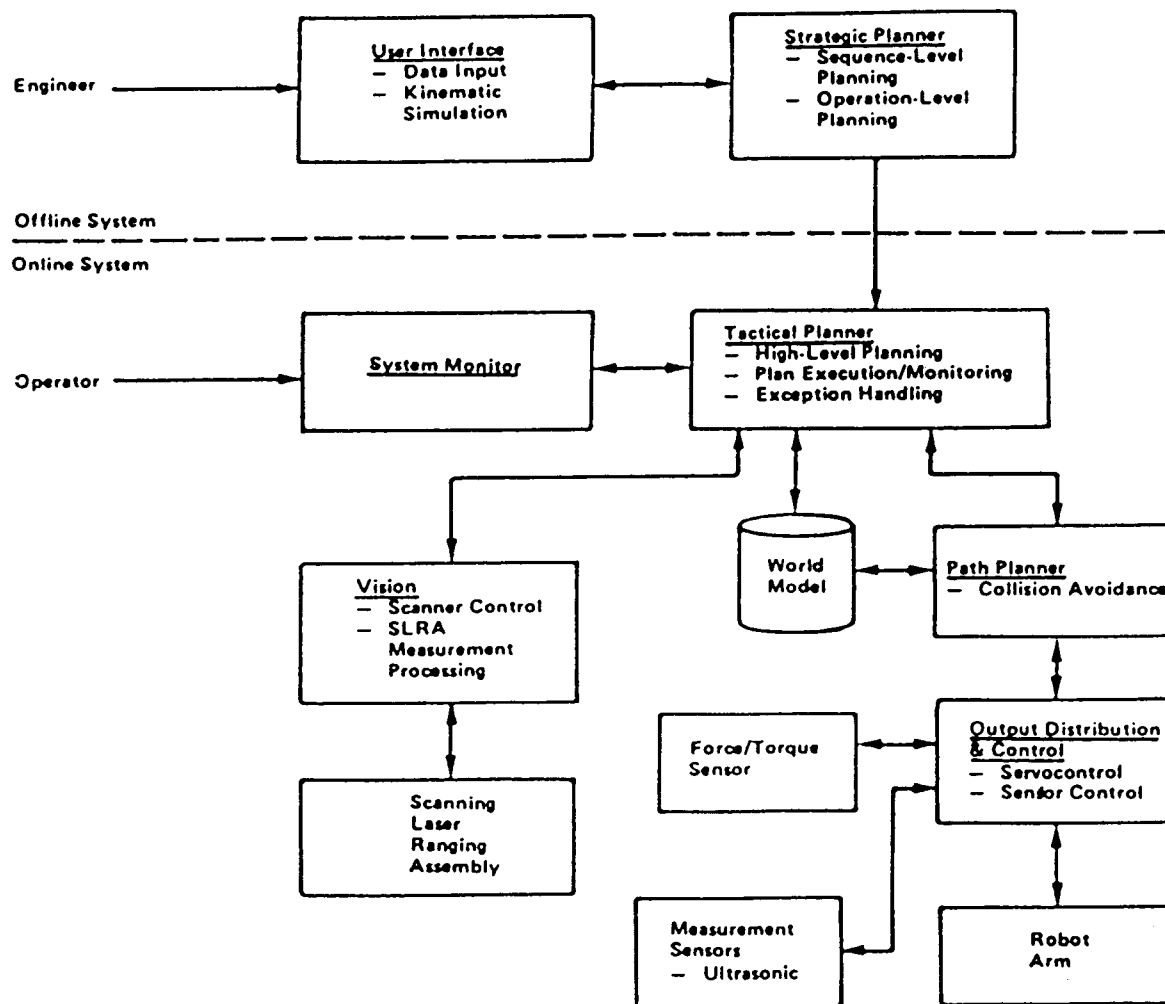
Engineer ⟶

User Interface
- Data Input
- Kinematic Simulation

Strategic Planner
- Sequence-Level Planning
- Operation-Level Planning

Offline System
— —
Online System

Operator ⟶

System Monitor

Tactical Planner
- High-Level Planning
- Plan Execution/Monitoring
- Exception Handling

Vision
- Scanner Control
- SLRA Measurement Processing

World Model

Path Planner
- Collision Avoidance

Scanning Laser Ranging Assembly

Force/Torque Sensor

Output Distribution & Control
- Servocontrol
- Sensor Control

Measurement Sensors
- Ultrasonic

Robot Arm

Figure 12 ITA Block Diagram

Design for Growth

This issue is of particular significance if we are to evolve to progressively higher levels of supervisory control. This can be accomplished provided we establish standard interfaces at inception for connectors, removable modules, etc., and implement a multiprocessor control system that will enable the eventual interfacing of an intelligent planner and a sensory perception system. An example of this is shown in Figure 13, where at Martin Marietta we have taken the Phase I ITA system that is planner driven and added a teleoperation control capability via the 6-DOF pedestal joystick and ball hand controller with force reflection and the exoskeleton. The key to this implementation is the multiprocessor control system.

Other considerations include the development and the implementation of standard interfaces for grappling with the workstation for stabilization. Modularization and standard mechanical interfaces would also provide an essential dimension for accommodating new end-effector designs and arm segments. Space-qualified hardware is costly and therefore must be versatile and have a long life expectancy. Versatility implies the accommodation of new technology in the form of components and software.

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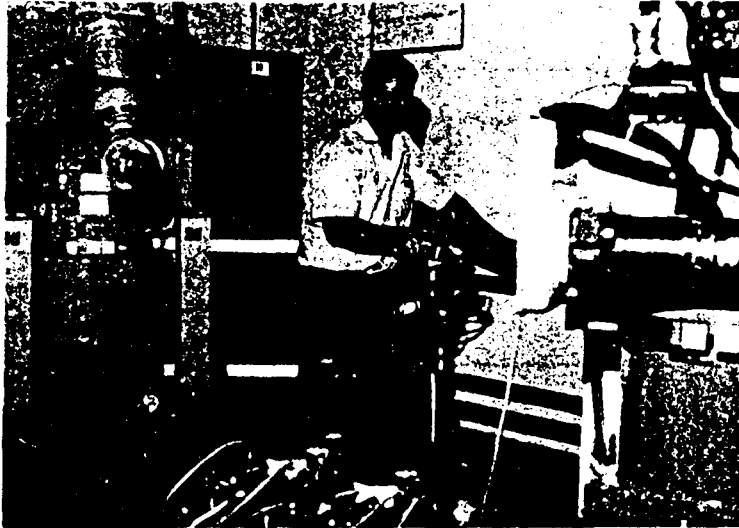
Figure 13
Dual Cincinnati Milacron T3-726 Manipulators in a
Teleoperation Mode

Performance Test, Evaluation, and Training (0 g)

Unlike complex, large space structures, it is feasible to assemble and
dynamically test a space robotic system on Earth. We have used (planar) two-
axis and also counterbalanced physical testing at NASA, SPAR of Canada, and at
Martin Marietta. Workstation reaction torques can be simulated as was demon-
strated for the Skylab Astronaut Maneuvering Unit and the current Manned
Maneuvering Unit (MMU) shown in Figure 14 in the Space Operations Simulation
Laboratory at Martin Marietta in Denver. The neutral buoyancy work of Akin at
MIT and at NASA/JSC in Houston is of particular relevance. There will always
be concerns regarding stability resulting from 0 g effects such as gear loading
and friction; however, it is feasible to simulate and evaluate these effects.

With respect to operator training, the physical simulators will also
perform in this role as they have done in the past for the RMS and MMU.'

Telepresence .

This is a key technology issue that will be affected by communication
bandwidth limitations, communications time delays, and operator dexterity and
cognitive processing skills. It is currently envisioned that the remote
operator(s) will have the benefits of vision (perhaps stereo), tactile sensing,
and for some functions, force reflection. The operator will also have a visual
presentation of other parameters relating to the health and status of the
robotic system. Human interaction may include voice as well as touchscreen
display.

Simulating Space Activities

Martin Marietta's Space Operations Simulator (SOS) laboratory conducts real-time, man-in-the-loop, space operations simulations.

For more than two decades the SOS laboratory has provided real-time, man-in-the-loop simulations to support all phases of development of manned and remotely controlled space operations. These simulations focus on requirements analysis; conceptual design; hardware and software design, development, and analysis; flight and ground crew training; mission timelining; and crew activity planning.

Day-to-day simulations are typified by rendezvous and docking activities, payload operations, satellite servicing, and onorbit assembly of structural components. Such simulations commonly incorporate manipulator systems, free-flying devices, crew systems, and advanced controls and displays.

Figure 14   Space Operations Simulator

In addition to improvements in control and display technologies, the man-machine interface will be influenced by the development of AI-based operator's assistance. Such expert systems will allow for the execution of routine functions autonomously; provide maintenance support; enhance the capability of one operator to control multiple robotic systems; enhance fault management systems including fault detection, isolation, and workaround; and generate command macros that combine the sequence of commands into one command to enhance operator productivity.

Modularity and Maintainability

These issues have been examined by ORNL for the nuclear fuel reprocessing application, which resulted in the manipulator design and development shown in Figure 15. The advantages are obvious in that modularity will enable reconfigurable manipulators. Furthermore, modularity will enable the incorporation of new manipulator segments, end effectors, and tools, and simplify maintainability.

Standard Interfaces and Commonality

These are extremely critical issues that must be thoroughly resolved during the Space Station Phase C/D design because of their eventual effect on assembly, servicing, and refurbishment. This affects hardware such as connectors, module support hardware, fluid transfer couples, and expendable film canisters.
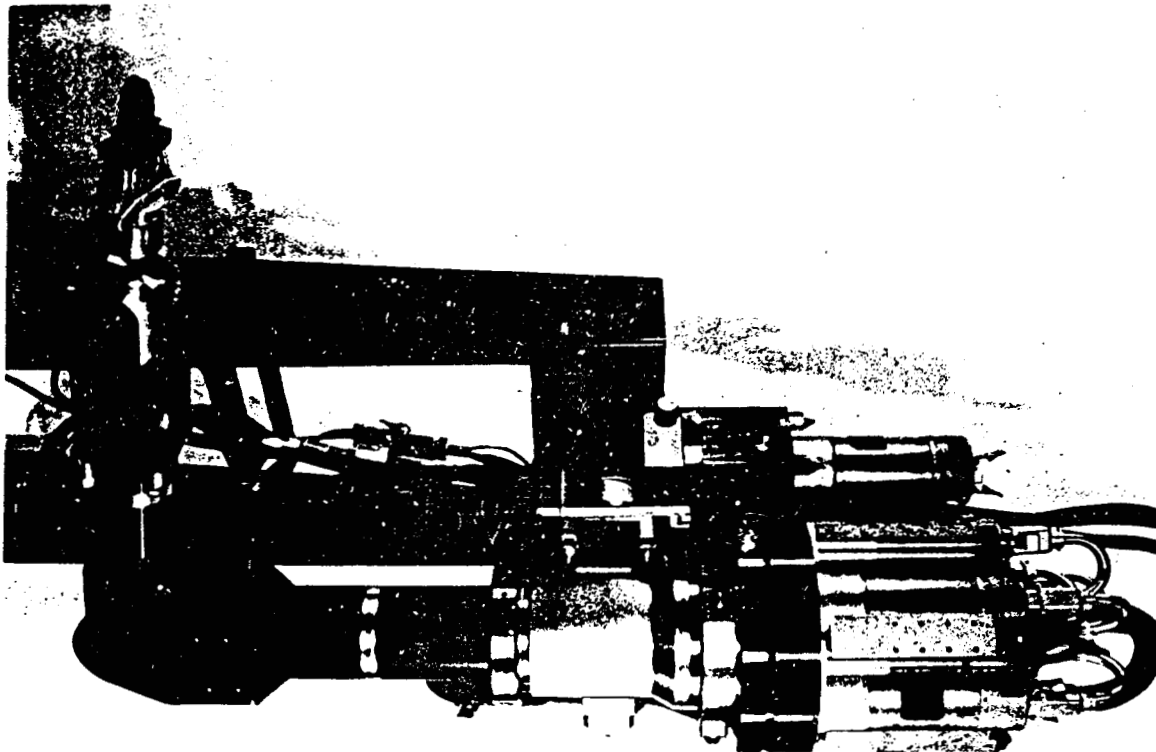

Figure 15 ORNL Modular Manipulator Development System

Summary

It is the opinion of this author that when considering life-cycle costs, the expected higher initial costs incurred by the inclusion of automation technology will result in much greater safety, higher productivity, and significantly lower operating costs. This can also be stated for the nuclear power industry, the mining industry, the constructions industry, as well as industrial manufacturing. Unfortunately, they do not often enjoy the benefits of a totally new start and are having to find a more economically feasible approach for implementation of robotics as is currently under way in Japan. This is, therefore, an ideal opportunity to "do it right the first time" and to "design for growth" as much as is technically feasible to reap the benefits of this evolutionary robotics technology. It is apparent this technology will in turn benefit the civil sector via industrial application to manufacturing.

The bottom line is that it is feasible to effectively implement the essential robotics technology on Space Station with no technological show stoppers.

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