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Laboratory Testing of Candidate Robotic Applications for Space

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Abstract

Robots have potential for increasing the value of man's presence in space. Some categories with potential benefit are: 1) performing extravehicular tasks like satellite and station servicing, 2) supporting the science mission of the station by manipulating experiment tasks, and 3) performing intravehicular activities which would be boring, tedious, exacting, or otherwise unpleasant for astronauts.

An important issue in space robotics is selection of an appropriate level of autonomy. In broad terms ~~we can define~~ three levels of autonomy can be defined: 1) teleoperated - an operator explicitly controls robot movement, 2) telerobotic - an operator controls the robot directly, but by high-level commands, without, for example, detailed control of trajectories, and 3) autonomous - an operator supplies a single high-level command, the robot does all necessary task sequencing and planning to satisfy the command.

~~We~~ Researchers chose three projects for our exploration of technology and implementation issues in space robots, one each of the three application areas, each with a different level of autonomy. The projects were:

~~A.~~ 1. satellite servicing - teleoperated
~~B.~~ 2. laboratory assistant - telerobotic
~~C.~~ 3. on-orbit inventory manager - autonomous

~~This paper describes~~ These projects are described and ~~summarizes~~ some results of ~~our~~ testing are summarized.

1.0 Introduction

The Space Station is intended primarily to be a facility for the advancement of science. It is not possible to predict precisely the future course of scientific discovery. But, based on our historical experience, we can expect that when new tools, methods, and the proper mind set are combined, then progress and discovery will follow. The Space Station provides such an opportunity. Scientists of the future will make these discoveries to the extent that they have time to immerse themselves in scientific problems. The key to making the Space Station valuable for science is ensuring that those scientists on orbit do not spend all their time in station keeping but on science. We view robotics as a major tool for accomplishing the science mission of the station by making crew time available for science and by automating part of the science task itself.

This paper presents an overview of three robotics system test projects conducted in the Boeing Space Station Robotics Laboratory in Huntsville. Assembly and test were conducted with subcontractor support from Essex Corporation, Georgia Tech Research Institute, Transitions Research Corporation, and Westinghouse Electric Corporation.

2.0 Component Technology and Integration Issues

Our overriding theme in this work was integration of systems having embedded robots for applications useful in space. The idea of focusing on systems may seem paradoxical, but the problems of integrating the robotic system were more important to us than the component technologies. Of course, we were obliged to address the component technologies to make the systems work. One interesting system-level descriptor of a robotic application is its level of autonomy. The level of autonomy of a robot can be thought of in two ways: one, the more autonomous a robot is, the more abstract are the instructions which operate it and, two, the longer it can act without human intervention. For our own convenience we defined three levels on the autonomy continuum:

a. Teleoperated - an operator directly controls each action of the robot. Typical control devices include joystick, teach pendant, and master-slave device.

b. Telerobotic - an operator controls the robot by giving medium level commands like, "move to position A" or "load sample #2."

c. Autonomous - the operator makes a single request for a logically complete service. The robot does whatever planning, obstacle avoidance, etc., which are necessary to complete the service.

We wanted to explore these three levels of autonomy and transition paths for systems with low autonomy to higher autonomy.

The component technologies and issues we wanted to address by incorporation into our systems were: teleoperation time delay, compliance, man-machine interface, sensors, robot control language, multi-arm control, video/lighting, vision, end effectors, and hand controllers.

3.0 Selected Robot Projects

Based on our systems interests and relevant component technologies, we selected three projects. Each project was chosen to be at a different level of autonomy. The component technologies were shared among the projects in such a way as to permit exploration of those technologies but without burdening any one project with too many integration problems. Figure 1 shows the allocation of component technologies and level of automation to our selected projects.

PROJECT ISSUE	SERVICING TELEOPERATOR	LABORATORY ASSISTANT ROBOT	LOGISTIC ROBOT
Time Delay	X	X	
Compliance	X	X	X
Human Interface	X	X	
Sensors		X	X
Control Language		X	
Multi-Arm Control			X
Video/Lighting	X		
Vision			X
End Effectors	X	X	X
Hand Controllers	X		
Level of Autonomy	TELEOPERATED	TELEROBOTIC	AUTONOMOUS

FIGURE 1 ALLOCATION OF TECHNOLOGY ISSUES TO PROJECTS

The robotic systems were assembled in our Huntsville Space Station Laboratory. Figure 2 shows the laboratory floor plan. It consists of two major floor areas: a staging area for robot systems and an acoustically isolated control room.

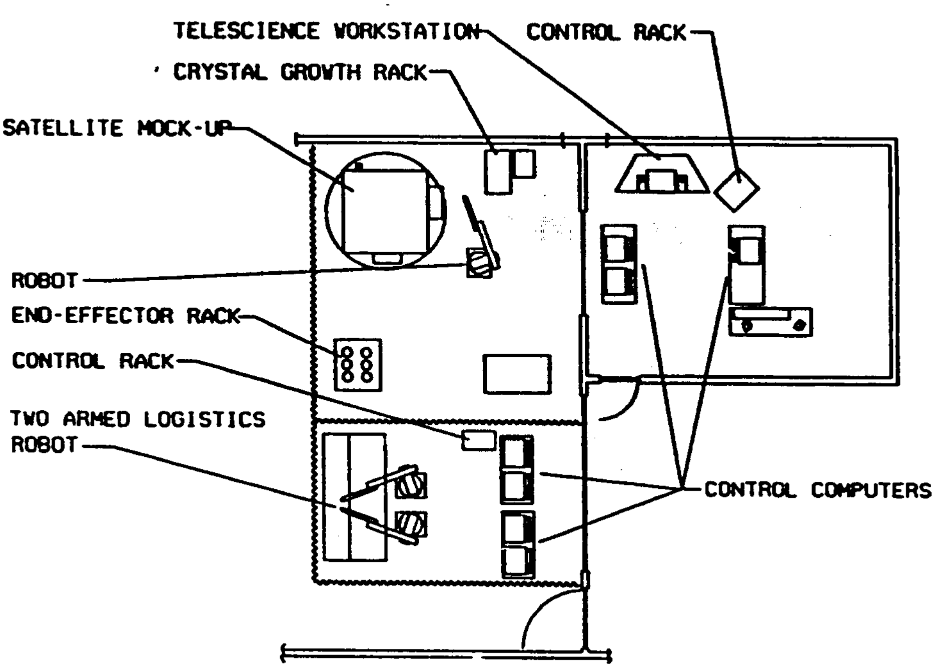

FIGURE 2 BOEING-HUNTSVILLE SPACE STATION ROBOTICS LABORATORY

The staging area is equipped with a variety of special lighting types and black stage curtains. The workstation is located in the control room. A window between the two areas permits viewing during test setup but is equipped with a blind for visual isolation during testing.

3.1 Teleoperator for On-Orbit Servicing

This system provides one-g simulation of a teleoperated robot for characteristic on-orbit servicing tasks. Our objectives in this task were to drive out servicer and human operation design requirements. Figure 3 shows the general test configuration. The servicing tasks were represented on a half-scale satellite mock-up with simulated Orbital Replacement Units (ORU's): Flight Guidance Equipment, Rate Sensing Unit, Battery, and Multimission Modular Spacecraft Module (MMS). These replaceable units are attached to the mock-up by different space-type fasteners and in different orientations. Obstacles can be located to increase difficulty of changeout. The robot arm is a Unimation Puma 560. A black and white CCD camera is attached to the robot wrist (see figure 4). Two other color cameras with remotely operable pan-tilt-zoom-focus are placed for worksite viewing. Several end effectors were developed for this test: MMS tool, gripper, hexdriver, scissors, and insulation holder. The end effectors are electrically driven and mate to a common interface. For this test the workstation is configured with three video monitors, robot control screen, and keyboard voice-driven video controllers and robot controllers.

Six Boeing employees were chosen as subjects in the human factors testing. They had no prior experience with manipulator controls. All had normal or corrected visual acuity as determined by a Class II Flight Visual Examination. Two Skylab astronauts also participated.

The first testing stage was used to develop learning curve data and to compare user preference for teach pendant and joystick. Subjects completed approximately 400 runs with 80 hours of testing. Figure 5 gives an example of learning curve data. The subjects unanimously selected the joysticks over teach pendant as the controller they would choose to do a difficult task. The data showed that subjects learned more and produced faster times with joysticks.

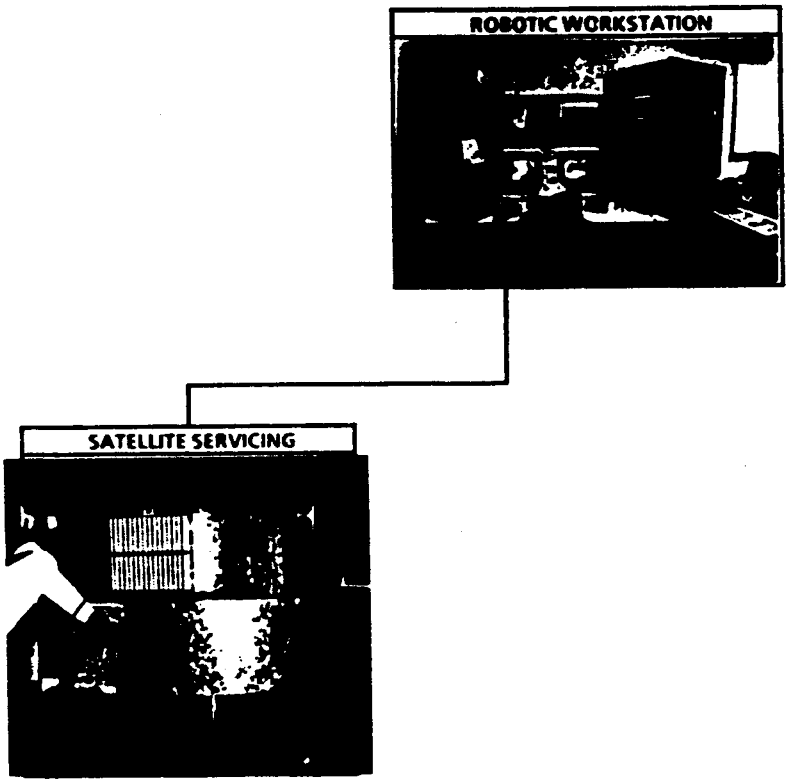

FIGURE 3 CONFIGURATION FOR TELEOPERATOR TESTING

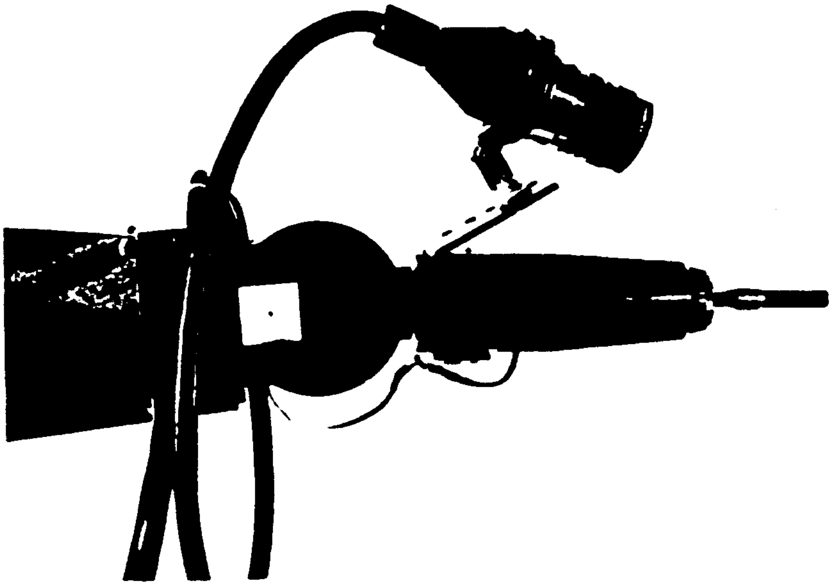

FIGURE 4 HEX DRIVE END EFFECTOR WITH CAMERA

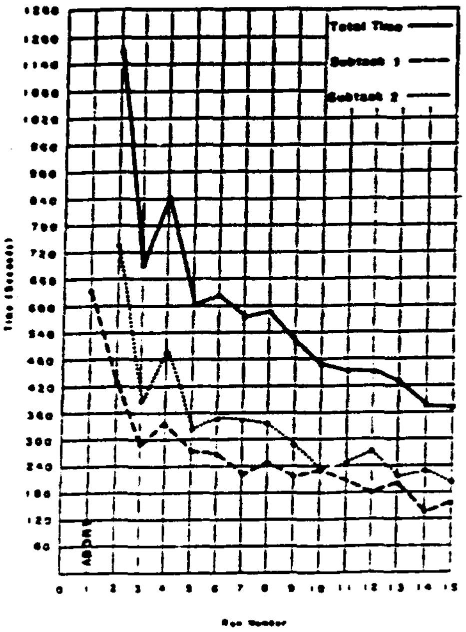

FIGURE 5 EXAMPLE INDIVIDUAL LEARNING CURVE

The second testing stage was used to assess the impact of communication time delay on task performance. By the time we started this testing, the subjects each had a minimum of thirteen hours of manipulator control experience. Only the joysticks were used. Figure 6 lists the tasks and subtasks we used. As an example, Figure 7 shows the J-hook fastener used in one of the tasks. Figure 8 shows how task completion time and arm movement time depended upon time delay.

TASKS

Task	Subtask
J-Hook	o Loosen the hex bolt
	o Unlatch the J-hook
	o Latch the J-hook
	o Tighten the hex bolt
	o Return the arm to the start position
Drive Screw	o Place of the tool on the drive screw
	o Engage the connector
	o Disengage the connector
	o Return the arm to the start position
FGE ORU Removal	o Grasp the EVA Handhold
	o Remove the ORU
	o Return the arm to the start position

FIGURE 6 TASKS USED IN TIME-DELAYED TELEOPERATION

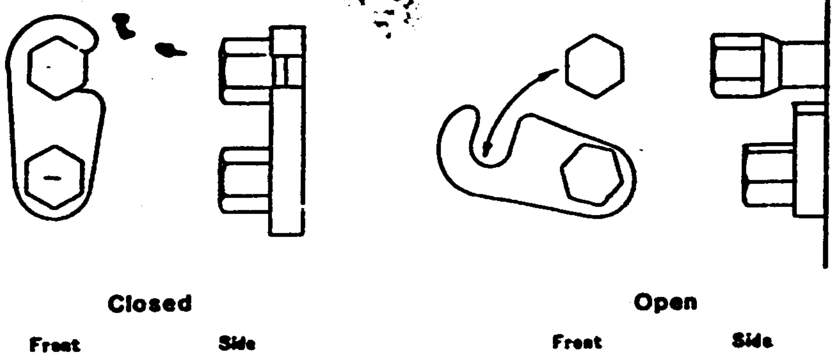

FIGURE 7 EXAMPLE TASK - J-HOOK FASTENER

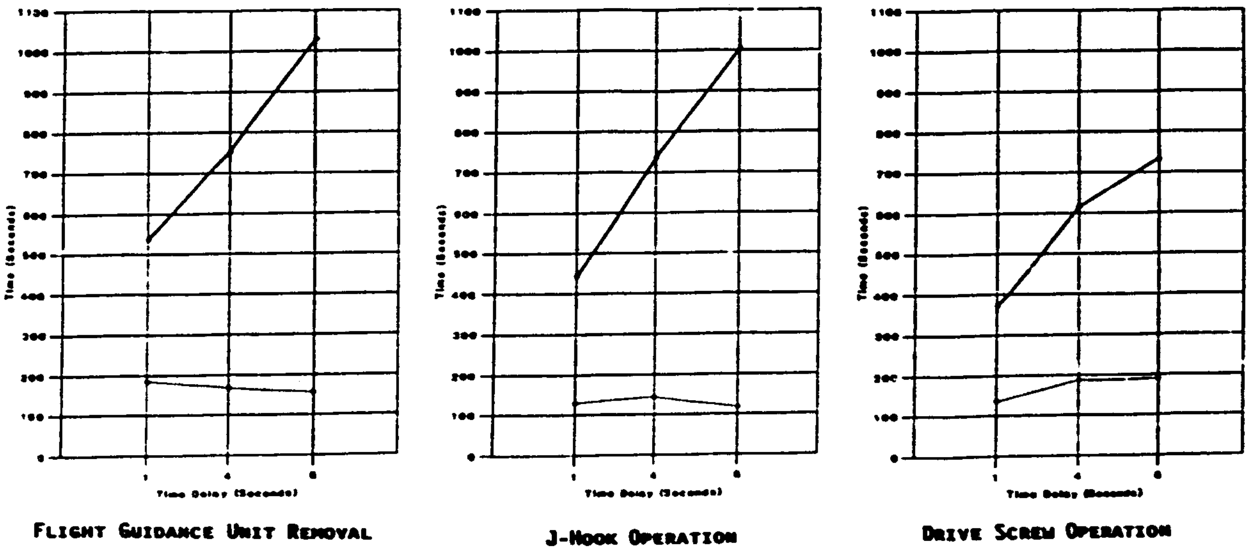

FIGURE 8 EFFECT OF TIME DELAY ON TASK TIME AND ARM MOVEMENT TIME

———— TASK TIME

.... ARM MOVE TIME

After our teleoperation testing was complete, we were given the opportunity to install the teleoperator on a Space Station Module mock-up. In this case the task was to evaluate control of the teleoperator from an Element Control Workstation in a debris shield inspection mode.

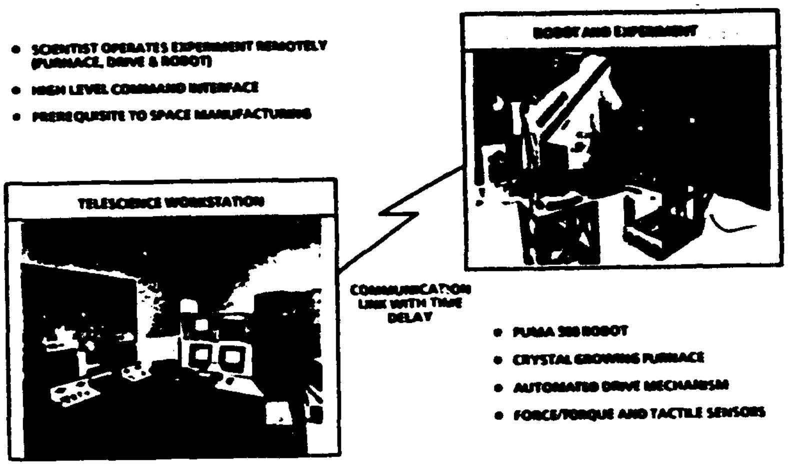

FIGURE 9 TELEROBOTIC LABORATORY ASSISTANT

3.2 Telerobotic Laboratory Assistant

Our teleoperation work in the previous section showed that many manipulative tasks can be performed under direct control even with a significant time delay. Direct teleoperation should not, however, be considered an acceptable long-term solution. Two important factors score against it: The cumulative risk of damage is high and a highly skilled human operator is required.

This application addressed the use of a robot in telescience. Astronauts will most usually be skilled generalists. We cannot, however, expect them to be experts in all aspects of Space Station sciences. One way to get best use out of the Space Station is to permit a ground-based scientist to conduct his experiment on orbit with the feeling of "being there." This project integrates a telescience workstation with process control of a chemical vapor transport (CTV) furnace, mechanical control of embedded experiment automation, and a laboratory assistant robot

Figure 9 shows the general arrangement for this project. The robot control is at a higher evolutionary level than in our direct teleoperator work. A hierarchical control structure has been built up from very low-level commands. Error conditions are sensed and handled at the lowest practical level. Conditions which cannot be handled by the system are presented to the operator for resolution.

A configuration schematic is shown in Figure 10. The Unimate standard programming language VAL II was used. However, some special-purpose routines were coded in assembly language to facilitate sensor and command port communications. Ultimately, movement of an object was achieved with a VAL MOVE command. We implemented several ways to move an object: normal, shielded, constrained, or compliant.

Shielded motion helps to prevent damage to a robot and its payload. This "force shield" stops motion if forces and torques measured by the wrist sensor exceed expected threshold levels. Threshold levels might be exceeded if, for example, the tool or payload comes in contact with an unexpected surface.

Constrained motion involves shielded motion to the vicinity of a target point and additional movements until expected force and torque values are reached.

Compliant motion uses force/torque feedback to complete an action such as insertion of a tool into a hole. If a threshold is exceeded using complaint motion, but it is not the success constraint value, then attempts are made to comply by altering the robot path based on direction of the experienced forces.

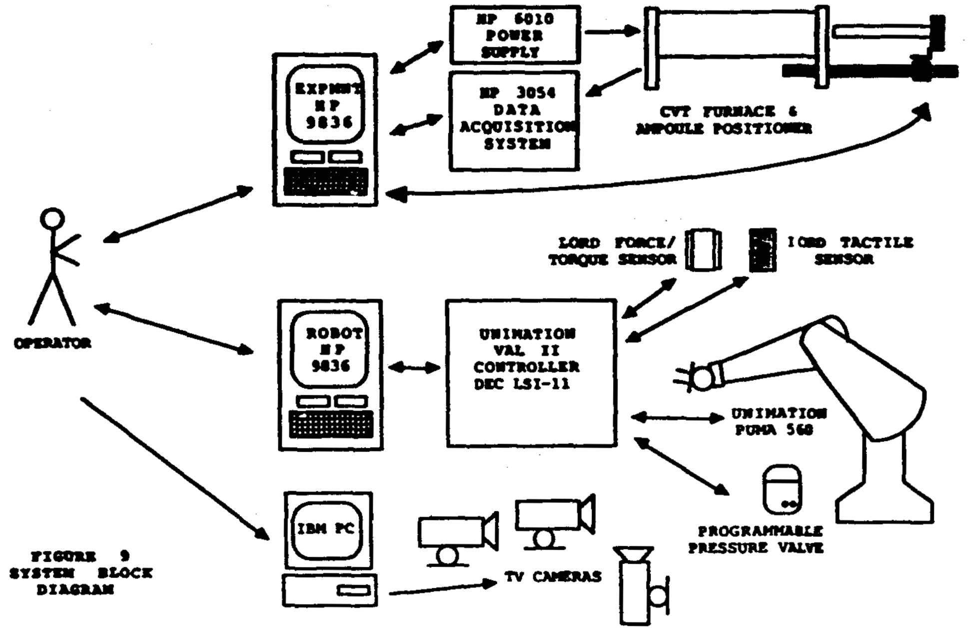

FIGURE 10 CONFIGURATION DESCRIPTION FOR LABORATORY ASSISTANT

Additional control primitives allow for object alignment and slip detection using a tactile sensor pad in the gripper. These control primitives were combined in a hierarchical fashion to permit commands like: "grip selected ampoule," "insert ampoule," etc.

Remote operation of a CVT crystal growth experiment was simulated by placing the CVT equipment rack within reach of the robot and by placing control computers and monitors in the adjacent control room. The telescience workstation contained three video monitors: two were normally used to view the work area and one to monitor crystal growth.

The scenario began by the robot attempting to find a reference location on the rack. This was a small post on the rack front surface. The robot grasped the post and used the force/torque sensor to fine-tune the location of the post relative to the robot. The CVT system was initialized by moving the ampoule positioning mechanism to a home location so that an ampoule could be loaded without coming into contact with the furnace. The robot was then commanded to grip a selected ampoule, insert into the positioner, and then to release the ampoule. The positioner was then commanded to insert the ampoule into the furnace. The predefined furnace temperature and ampoule positions were then executed. The telescientist viewed crystal growth with the microscope-video system, changing temperature and position parameters as necessary. When the crystal growth was complete, a sequence of commands was made to remove the ampoule, place in a cooling rack, and stow for shipping.

3.3 Autonomous Logistic Robot

The two projects described thus far each required more or less continuous human supervision. Certainly supervision in the telescience case was at a higher level, but there was no intent to ignore the system until the job completion. In this project our goal was to integrate a system which would complete an entire task without human guidance or intervention. In order to make this possible, we chose a rather structured environment: a mock-up of a Space Station logistic module. We did not fully structure the problem space in that we did not require objects to be precisely located. Figure 11 shows the general system arrangement. Figure 12 shows the equipment configuration.

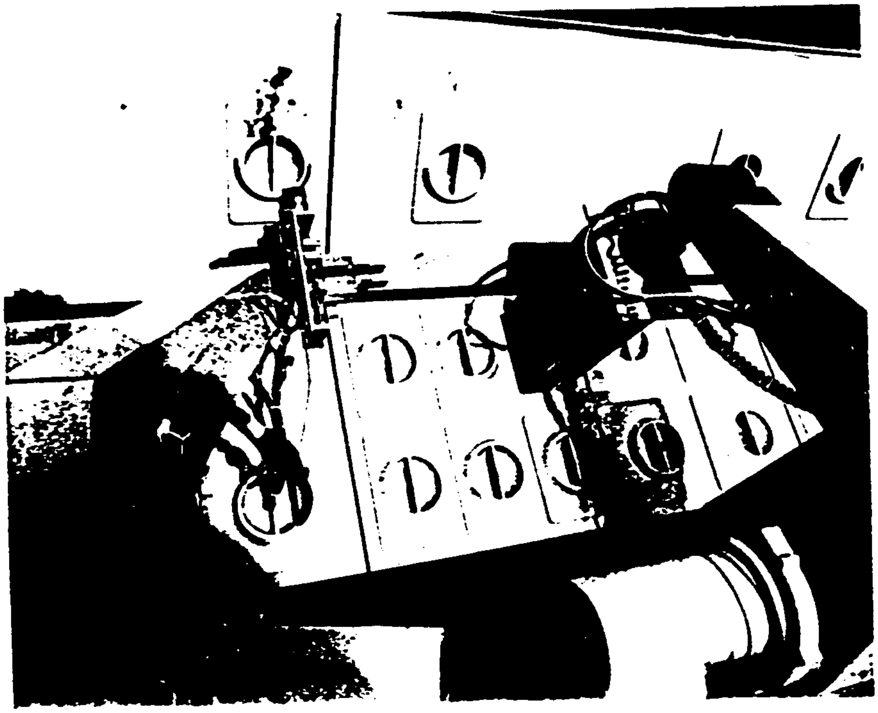

FIGURE 11 TWO-ARMED LOGISTIC ROBOT

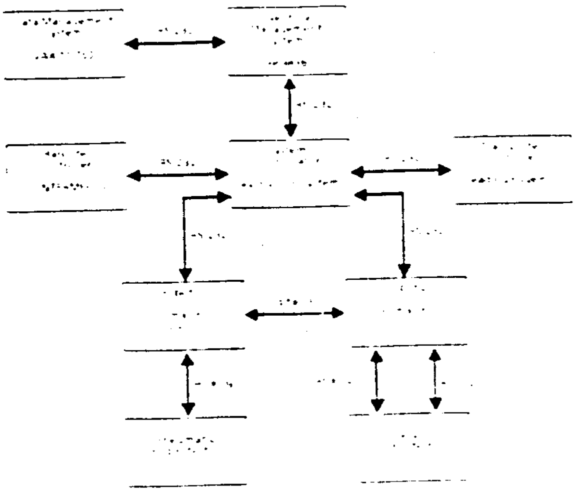

FIGURE 12 LOGISTIC ROBOT EQUIPMENT CONFIGURATION

The logistic module segment mock-up of a radial configuration was approximately half-scale. The drawers and racks were mounted so that articles would fall if not constrained. For test purposes, a set of simple tools was used to represent typical on-orbit inventory items. The purpose of the rail-based transporter was to grossly position the robot in the area of its target and to allow the robots by means of force and vision to accomplish its task.

The robot consisted of two Puma 560 arms mounted on a transporter carriage. The arms shared a common work space. Arm-to-arm messages were used to synchronize arm movements.

Each arm had a different gripper. One had an integral barcode reader. It was primarily for identifying drawers and racks and for grasping handles. The other hand had a servo gripper which was equipped with automatically interchangeable fingers: one set for gripping handles, the other for picking up small objects. The servo feature allowed measurement of position velocity and force parameters.

The Automatix AV-5 vision system was used to identify items in a drawer and to locate open areas where they could be placed. The AV-5 also served as system coordinator.

Test scenarios have allowed us to automatically identify, store, and retrieve inventory items, racks, and drawers. Two-arm activities are coordinated at least to a collision prevention level. Removal of a full rack was a two-armed activity and required fully cooperative two-armed motion.

4.0 General Observations

In order to build systems with embedded robots, we found it necessary to use several different computers, operating systems, and programming languages - not that it was a surprise, but it was a nuisance. If the level to which standards are used in a discipline is one measure of its maturity, then robotics is immature. We need to apply some standards which will permit interconnection and cooperative use of diverse equipment (e.g., vision, arms, grippers, etc.). A layering standard along the lines of the ISO-OSI definitions is essential for design of reusable components and evolving robot autonomy. We don't want to stifle research, but those who must build real systems for space will be greatly aided by standards.

Our teleoperator servicing tests were based on existing satellite design. It didn't take us long to decide that existing satellites would be extremely difficult to service by robot and that two arms would be required. A review of the manipulative difficulties also showed that those tasks could have been designed for relatively simple one-arm operation. The systems we expect to manipulate in space should be designed for robotic attention. Our industrial experience tells us that a task designed for robots can be performed better by humans.

Our time-delay work showed that typical tasks can be done by teleoperation. They just take longer with time delay. The situation is really a bit more complicated. Our test subjects were not repairing a multimillion-dollar satellite. There was a test observer with a panic button carefully watching for the robot to get into trouble. In fact, a significant number of runs were aborted to protect equipment or to release a jammed tool.