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Technology Demonstration of Space Intravehicular Automation and Robotics

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ABSTRACT

Automation and robotic technologies are being developed and capabilities demonstrated which would increase the productivity of micro-gravity science and material processing in the space station laboratory module, especially when the crew is not present. The Systems Integration Branch at NASA Langley has been working in the area of Intravehicular Automation and Robotics (IVAR) to provide a user-friendly development facility, to determine customer requirements for automated laboratory systems, and to improve the quality and efficiency of commercial production and scientific experimentation in space. This paper will describe the IVAR facility and present the results of a demonstration using a simulated protein crystal growth experiment inside a full-scale mockup of the space station laboratory module using a unique seven-degree-of-freedom robot.

1. Introduction

On-orbit laboratory experiments have been performed successfully by astronauts on Shuttle missions, and current plans call for them to perform similar duties on the space station. However, during the space station crew-tended phase there will be long periods in between visits in which the astronauts will be away and unable to perform these duties. Automation and robotics could increase productivity by servicing experiments while the astronauts are not present and, even when the space station is permanently inhabited, could free the crew for more complex and skilled tasks. Furthermore, principal investigators desire the ability to monitor the progress of experiments, to change the operating conditions and to rerun samples more often than allowed by timelines based on astronaut availability. If automation and robotics were available, these tasks could be performed by investigators from the ground, with or without the astronauts present, and productivity of the space science experiments would increase.

Automation and robotic technologies developed for the space station could also potentially benefit terrestrial laboratory processing and manufacturing by reducing the number of manual operations, particularly those of material transportation and manipulation. Productivity in a terrestrial setting would increase through reduced costs resulting from greater throughput and lesser requirements for human labor.

The Systems Integration Branch at NASA Langley has been working in the area of Intravehicular Automation and Robotics (IVAR) to develop and demonstrate technologies which increase the productivity of space science experiments. Overall objectives of the program are to: (1) determine customer requirements for automated laboratory systems; (2) improve the quality and efficiency of commercial production and scientific experimentation in space; (3) provide a more direct role for the customer through interactive monitoring and control of production and experiments; (4) establish cost/benefit guidelines and criteria for the appropriateness of automation; (5) assist in improving terrestrial lab automation through the technology transfer of hardware and software system designs; (6) compile and maintain a library of proven design practices; and (7) deliver a space qualifiable laboratory automation system preliminary design. Automation and robotic technologies are to be demonstrated in a realistic environment with the level of experiment hardware simulation fidelity matching that used for astronaut payload operations training.

In this paper automation and robotic technologies are applied to a simulated protein crystal growth (PCG) experiment using the Robotic Intravehicular Assistant (RIVA), a unique seven-degree-of-freedom manipulator arm, inside a full-scale mockup of the space station laboratory module . The IVAR facility is described and some preliminary results are presented.

2. Facility Description

The IVAR laboratory consists of the five major hardware components:

(1) **full-scale mockup of the space station laboratory module,** as shown in figures 1 and 2, to provide a realistic environment for simulating automation and robotics in space. Selected experiment hardware is mounted in the IVAR module experiment racks in figure 2 and techniques for automated servicing of the experiments are developed using the manipulator arm.

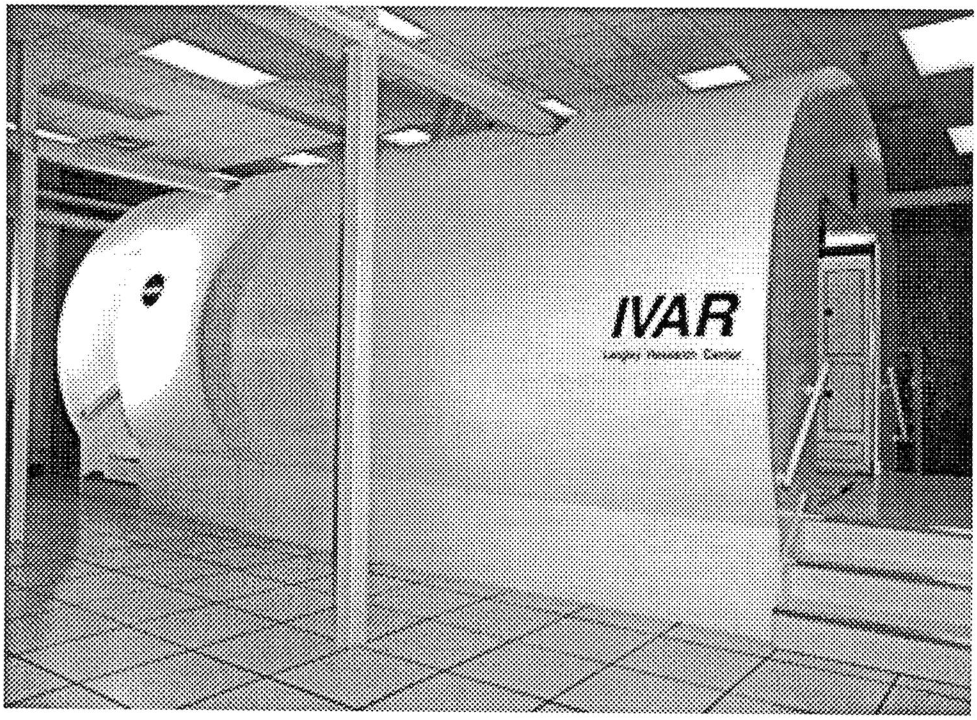

Figure 1. Exterior view of Intravehicular Automation and Robotics (IVAR) Module

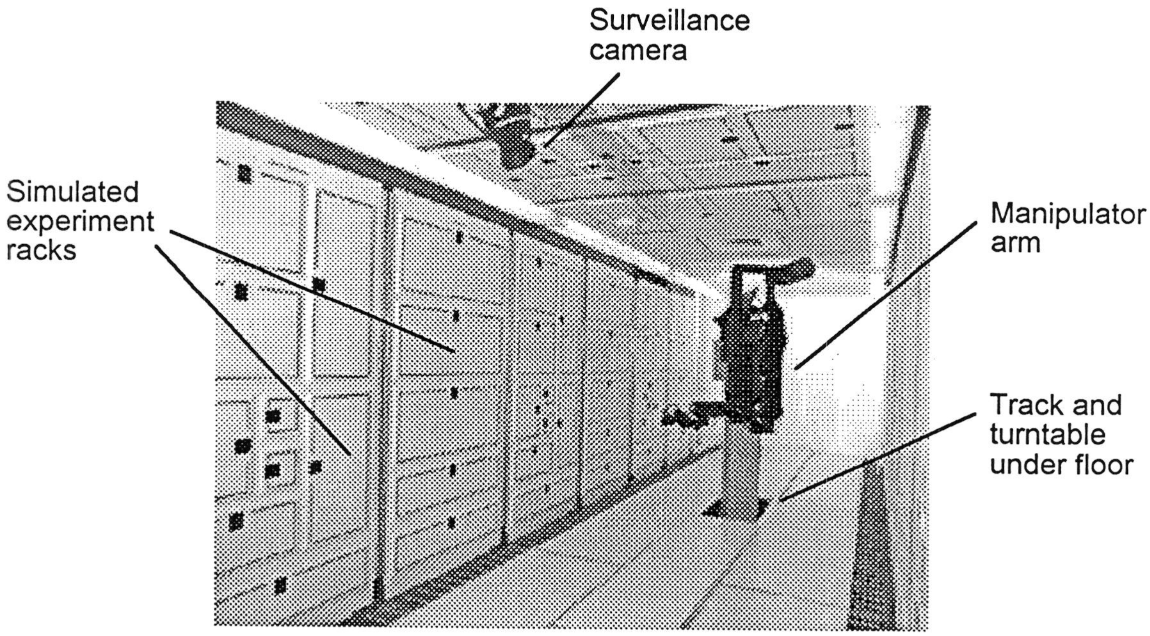

Figure 2. Manipulator arm inside IVAR module

(2) **simulated protein crystal growth experiment** (figure 3). This is the first onboard experiment selected for automation in IVAR; face plate of experiment is later shown housed in one the experiment racks indicated in figure 2. The PCG experiment is housed in a thermal enclosure system (TES) mockup designed by Space Industries.

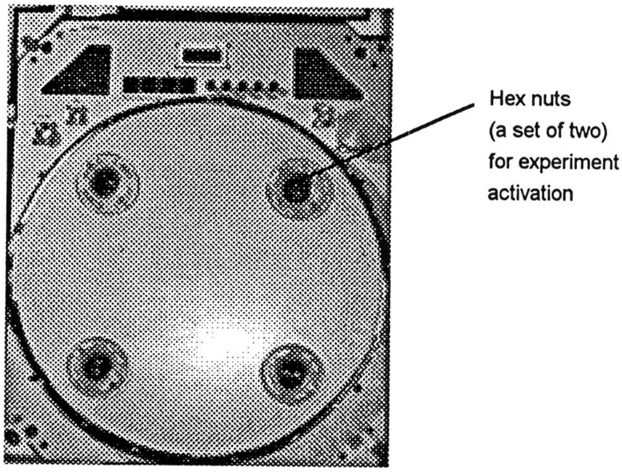

Figure 3. Simulated protein crystal growth experiment hardware

(3) **redundant seven-degree-of-freedom manipulator arm** (shown in figure 2) to provide assistance in module. The base of the arm is mounted on the tracked carriage and turntable system, hidden beneath the floor of the IVAR module to permit transport to service multiple experiments. The base of the arm remains fixed for the single experiment described in this paper.

(4) **operator control station** (figure 4). From here, the operator has numerous input capabilities including control of the manipulator with keyboard or handcontroller inputs, execution of automation scripts, progress monitoring, data collection, camera view choices, and graphic simulation of operations. In this paper, script execution is emphasized, without operator intervention.

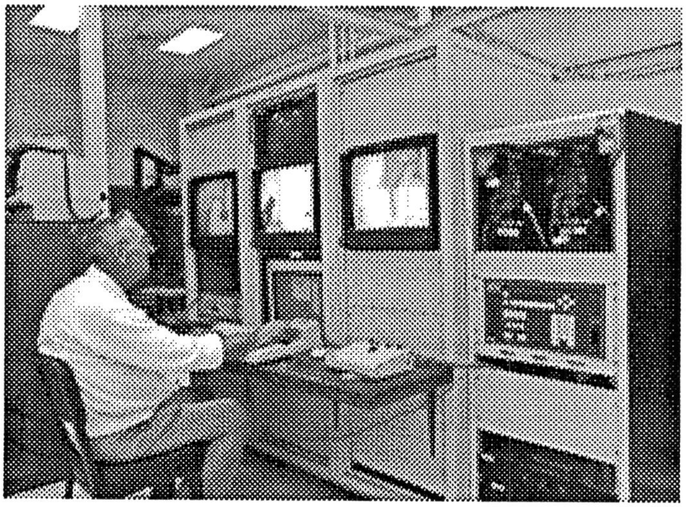

Figure 4. Operator control station

(5) **real-time, three-dimensional computer-generated graphics simulation** (figure 5). The module, manipulator arm, and the experiment hardware are simulated on a Silicon Graphics computer. This simulation can provide a look-ahead view of the current trajectory to flag potential problems, such as reach limits or singularities. New control algorithms can be tested and scripts reviewed without risking damage to the hardware.

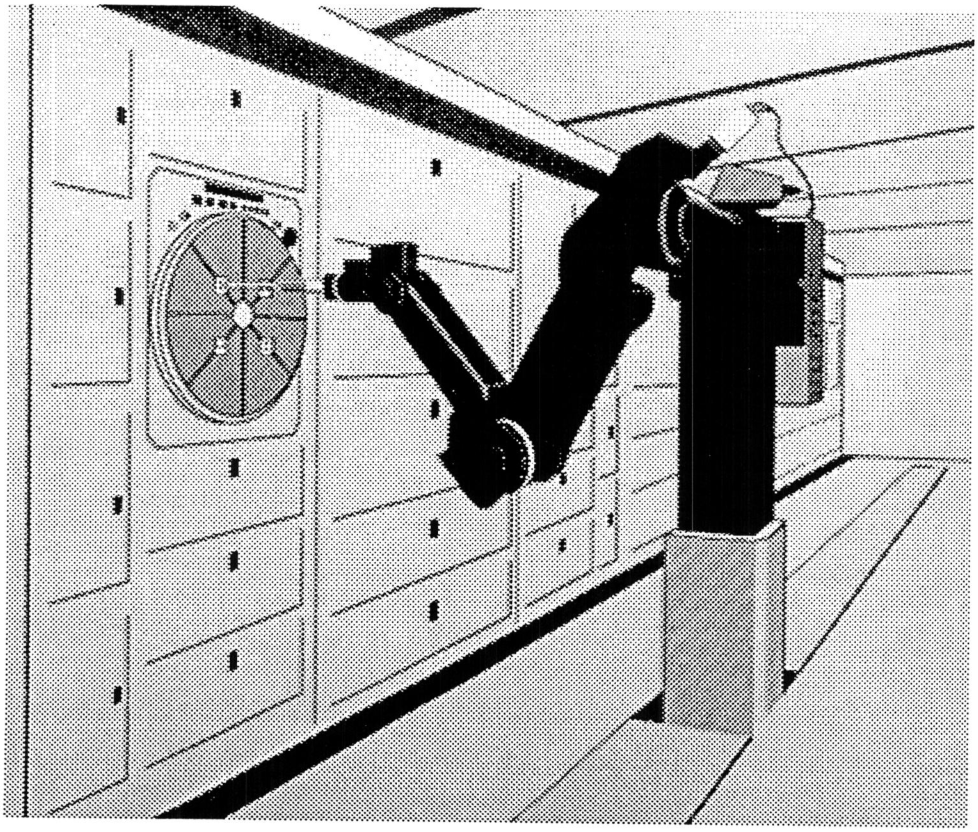

Figure 5. Graphical representation of RIVA manipulator

The IVAR laboratory was designed as a ground based testbed to permit initial evaluation of automation and robotic techniques for on-orbit space science experiments. This initial system is intended to be used as a learning tool from which more sophisticated experiment operations and monitoring processes can be developed. Each additional demonstration will focus on a different full-size mockup of a selected laboratory experiment. Lessons learned from previous demonstrations will be incorporated into the next technology demonstration. Details of the various laboratory subsystems follow.

2.1 IVAR Module

The full-scale mockup of the space station laboratory module has a length of 299 inches (24 feet, 11 inches), with a diameter of 168 inches (14 feet). There are two entrance locations, one at the front and one at the rear of the mockup. Internally, the dimension from the ceiling to the floor is 82 inches, and the distance between the walls is also 82 inches (refer to figure 2). The mockup has 12 space station racks, each having an 80.2-inch height and 41.5-inch width. The racks are configured to accept space station experiment hardware, such as the protein crystal growth experiment (examined in this paper), the crystal growth furnace facility, etc. Fluorescent lights provide lighting inside the mockup.

2.2 Tracked Carriage and Turntable

The tracked carriage and turntable [1] are used to position the manipulator within the IVAR module. The tracked carriage allows the robot to travel the full length of the module, while the turntable rotates approximately 180 degrees to allow access to all twelve experiment racks.

2.3 Robot Arm

The IVAR laboratory uses the Robotic Intravehicular Assistant (RIVA), an electrically driven robot (figure 6). RIVA is a modification of the Laboratory Telerobotic Manipulator (LTM), a bilateral force-reflecting telerobot [1]. The modification was implemented to increase the operational working envelope of the robot arm.

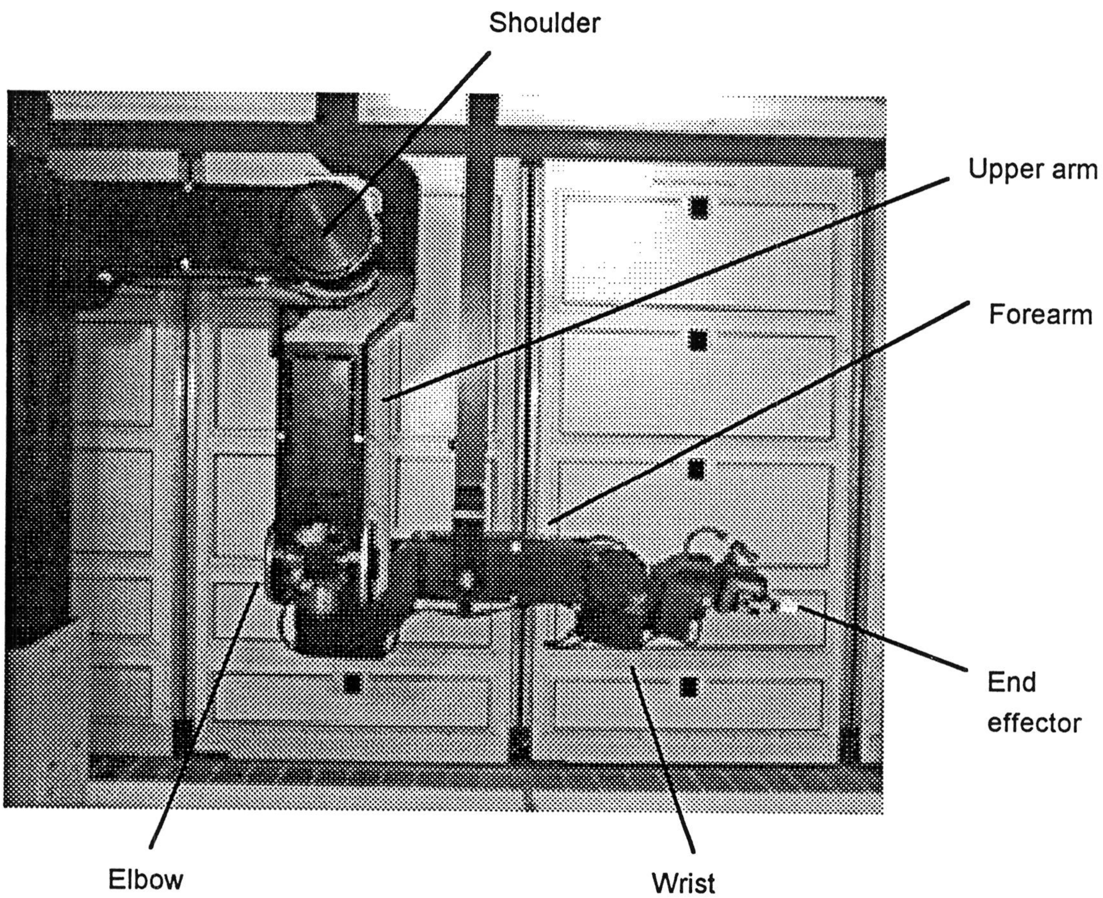

Figure 6. Robotic Intravehicular Assistant (RIVA)

Although RIVA has seven degrees of freedom, only six are used to position the end effector (appendix). The RIVA arm is made up of three links: upper arm, forearm, and wrist. Movement of each link is resolved by a differential traction drive joint [3] producing a pitch/yaw relative motion. The wrist link differs slightly in that a rotational degree of freedom is provided in addition to pitch and yaw.

Two electronic boards, a joint processor logic board and a joint processor power board, are housed in each arm link where sensory information is locally assimilated and processed. The logic board monitors and processes sensor output components while the power board supplies power and reference voltages to arm link components. A transceiver on the power board communicates bidirectionally over a single optical fiber to the control electronics.

2.4 End Effector

The RIVA arm employs a Telerobotics Inc. EP 75/30 general purpose end effector to grasp and handle objects of diverse size and weight (figure 7). The EP 75/30 is capable of gripping objects with a maximum force of 66 lbs. For the technology demonstration, the end effector was used in a three position mode (full open, half open, and closed) under computer control. The end effector is mounted on a JR[3] Universal Force-Moment Sensor System which, in turn, is mounted to the wrist joint of the RIVA arm.

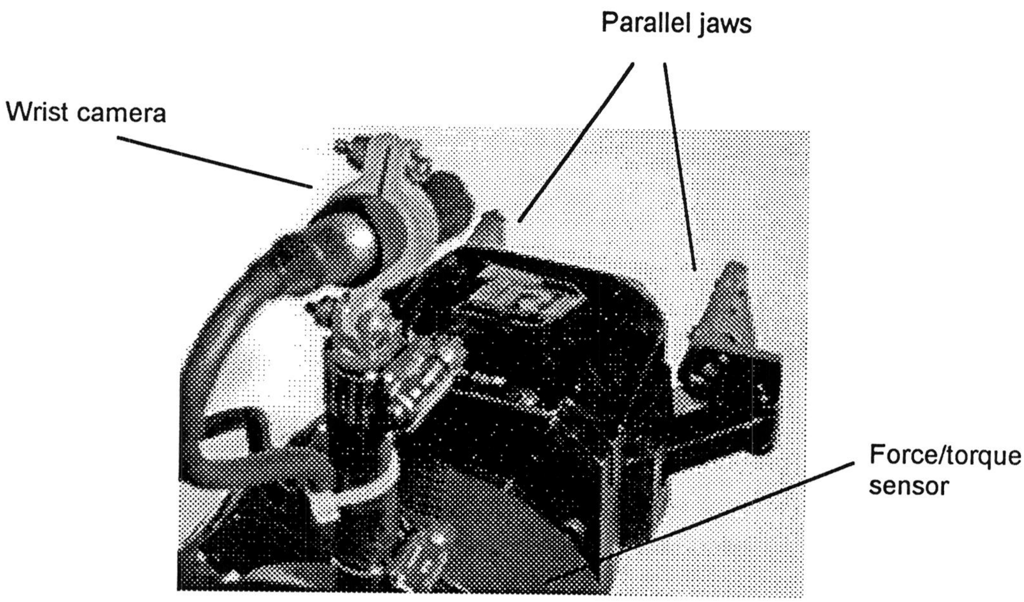

Figure 7. TRI EP 75/30 End Effector

2.5 Video Cameras

Four cameras are located within the IVAR laboratory module to provide several perspectives of the RIVA arm and experiment hardware. Two facility cameras are mounted on the ceiling at each end of the module to provide left and right overall views of the RIVA arm and laboratory equipment. A third camera is located near the RIVA shoulder joint to view general orientation of the arm. Finally, a small wrist camera resides on the end effector (see figure 7) to provide a close up view of the end effector jaws, to visually detect end point errors, and to display experiment configuration and equipment status.

2.6 Thermal Enclosure System

The onboard experiment selected for the first IVAR automation study was the thermal enclosure system (TES) which houses the protein crystal growth experiment (figure 3). The flight TES was designed by Space Industries, Inc. for specific use within the mid-deck of the space shuttle. Space Industries also developed the full size mockup for the IVAR laboratory. The TES cavity provides a stable, hermetically sealed, thermal environment to service experiments such as materials solidification and protein crystal growth. Four Vapor Diffusion Apparatus (VDA) trays (figure 8), each holding several protein crystal growth chambers, reside within the TES cavity (figure 9).

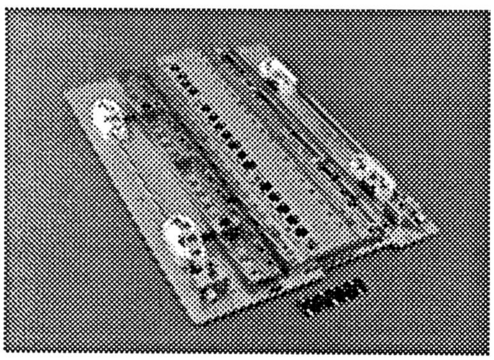

Figure 8. Vapor diffusion apparatus tray

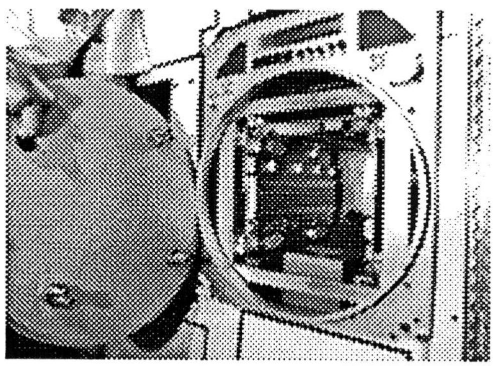

Figure 9. TES cavity

The protein crystal growth experiment is activated by rotating hex nuts on the front face of the TES experiment hardware (refer to figure 3) 180 degrees to unplug the double-barreled syringes holding protein-rich solution on each VDA tray. A second set of hex nuts are then rotated 180 degrees to inject a drop of protein solution into each crystal growth chamber. Programmed timelines command the TES to change chamber temperature and to collect temperature data at various points within the TES cavity while the crystals are growing. When growth is complete, the experiment is deactivated by turning the hex nuts in reverse order and direction to draw the protein crystals back into the syringes and to plug the syringes for storage.

Figure 10 shows the tool used by the RIVA to rotate the hex nuts in the protein crystal growth experiment. The bevelled socket seats over the hex nuts. Grooves are located in the handle of the tool to prevent rotational slippage between the grippers of the robot. A rough surface was added in between the grooves to prevent translational slippage between the grippers. The tool has a ratcheting capability to allow for continuous rotation on the hex nuts. The ratcheting capability was required to compensate for the limited wrist roll of the manipulator. The tool is also torque limiting to prevent torque buildup between the robot and the experiment apparatus. Bevels on the socket and compliance in the stem make the seating operation easier and more reliable.

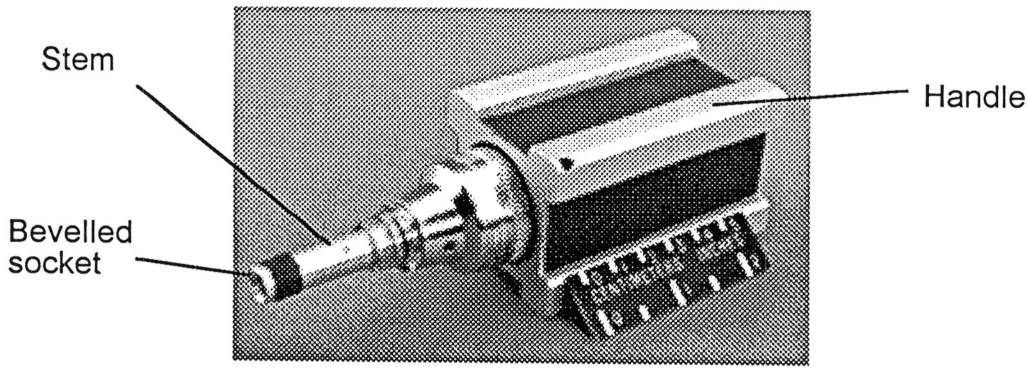

Figure 10. Tool used in protein crystal growth experiment

The TES mockup is designed to operate similarly to the flight system with respect to controls and displays [2]. The TES mockup can be operated manually via an LCD output display and a four button keypad or remotely via RS232 communication signals. The menu driven interface (figure 11) displays TES cavity temperature, experiment timelines, and various system parameters. This menu can be observed by the robot's wrist camera to monitor TES experiment progress and to aid in error recovery.

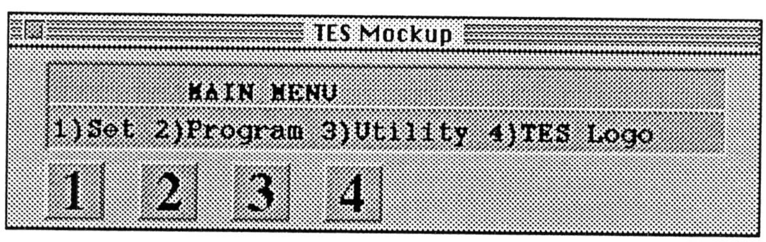

Figure 11. Thermal enclosure system main menu

2.7 Computer Control System

Various computer systems are used in the IVAR laboratory to operate the tracked carriage, the robot arm, and the video cameras (figure 12). The computer systems communicate either serially or are networked in some fashion. A Macintosh computer controls the tracked carriage and turntable, camera tracking, and data collection. A graphical simulation is controlled by a Silicon Graphics computer. Two VME bus systems control arm movement and coordination for the robot arm while translating robotic scripts as input. Description of the computational control system, the executive program for robotic control, and the graphical simulation follow.

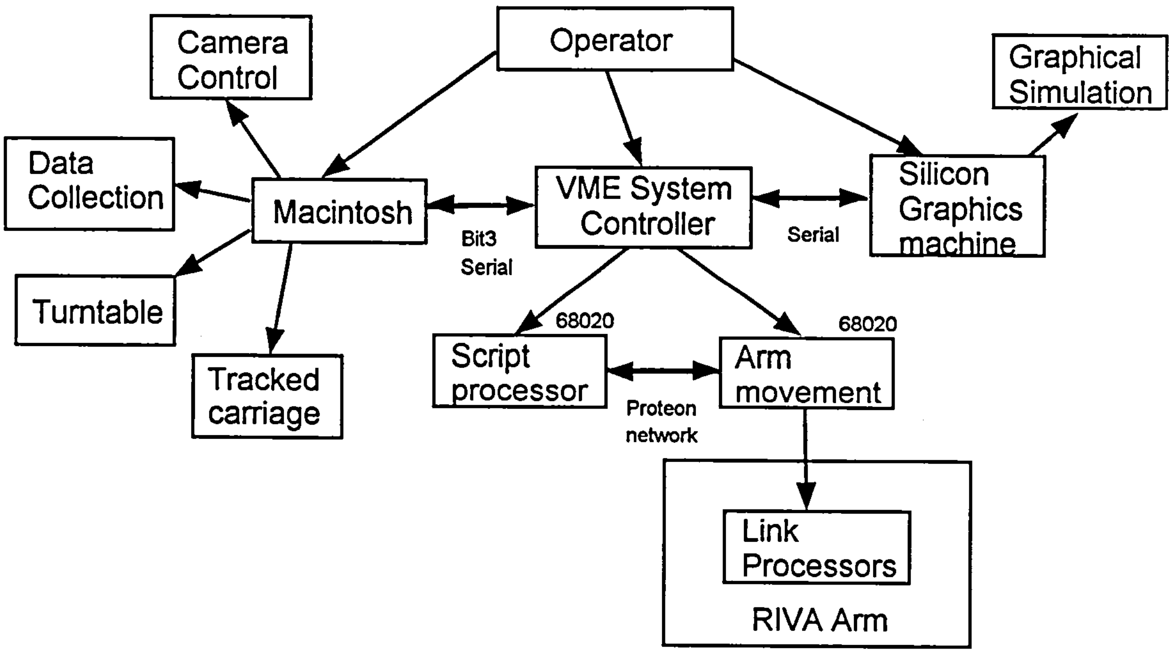

Figure 12. Operational scenario for IVAR computer control

2.7.1 Computational System

The robot arm is controlled by two Motorola 68020 single-board computers operating over a VME bus system. One system controls arm movement and coordination while the other system performs control algorithm calculations which translates robotic scripts as input. Communication between each system is established through a high-speed serial Proteon network (refer to figure 12). A system controller is used to enhance basic VME operation by providing global interrupts, memory expansion, and full VME arbitration between the systems.

A scripted robotic move is processed on the 68020 control algorithm computer and placed in a common block bus location where it is then transferred to the computer that coordinates arm movement which, in turn, is sent to a link processor board. Commanded joint position, velocity, and torque information is then transferred to the appropriate joint processor board on the RIVA arm (figure 6). Other commands are communicated similarly between the VME system and the RIVA arm through a full duplex fiber optic serial link between the link processor in the 68020 computer system and the joint processor located on the RIVA arm. Closed-loop control is accomplished when joint processors transfer position, velocity, torque, and temperature data from the RIVA arm back to the VME system.

The VME bus system houses a Bit3 high-speed serial interface card which permits the Macintosh computer to gain access to real-time position values for camera tracking and data collection. The VME system also contains various serial ports used for data monitoring, force/torque data transfers, and the graphical simulation.

2.7.2 IVAR Control Loop

The RIVA arm operates through the use of scripted commands. An executive program translates script commands into resolved-rate commands [4] for the RIVA arm (figure 13). Scripted cartesion position commands (Δx_{pos}) are received at 33 Hertz and then compared to actual robot position values. An error signal between the commanded and actual positions is then calculated. The cartesian command is then transferred across the Proteon network where the joint rates are calculated by the inverse Jacobian. Joint rates are then input to the PID loop at 500 Hertz where the corresponding PID output drives the RIVA arm.

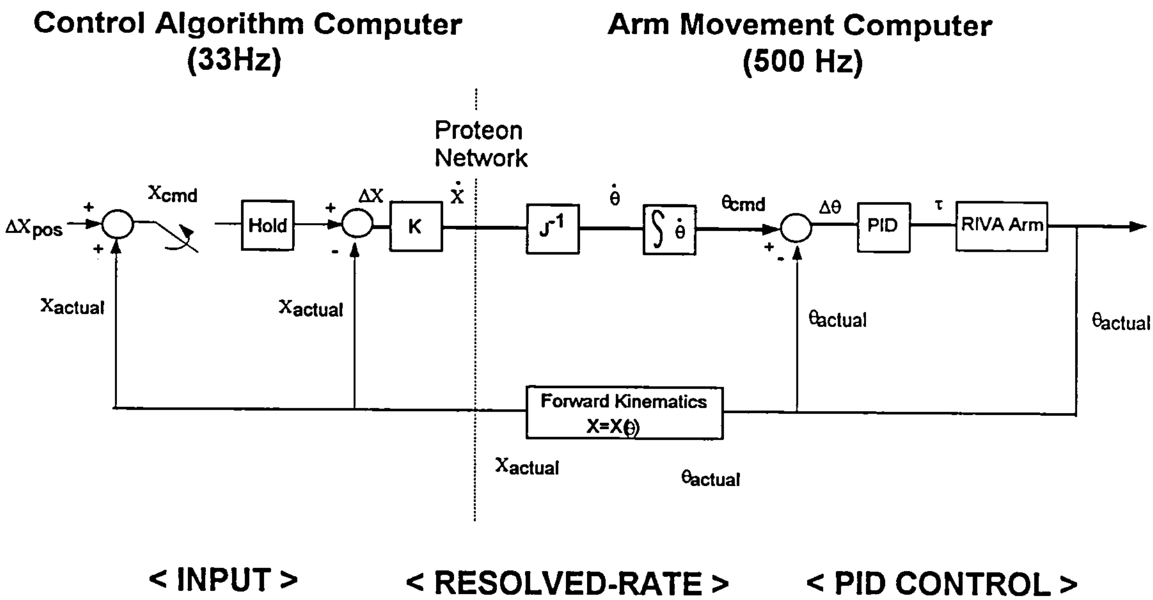

Figure 13. IVAR Resolved-Rate Control Loop

2.7.3 Graphical Simulation Control

A Silicon Graphics machine was used to develop a graphical simulation of the RIVA arm and the IVAR module, including experiment apparatus and video camera viewing perspectives (figure 5). The graphical simulation was developed to anticipate possible problems in an experiment scenario, to teach points for script development, and to determine optimal path planning options for the RIVA arm. The simulation also serves as a useful operator display. Control between the graphical simulation and the RIVA arm is bidirectional through a high-speed serial interface (refer figure 12). The graphical simulation can be used as an output device to test scripted robotic moves. In this mode, the simulation displays RIVA arm configuration from the actual measured joint angles accepted from the manipulator hardware. The graphical simulation can also be used to control manipulator hardware by feeding current simulation joint angles into the 68020 computer system to drive the actual RIVA arm.

3. Demonstration of Intravehicular Automation and Robotics

The manipulator follows a script of sequenced events to demonstrate intravehicular assistance and robotics in the operation of full-scale, PCG hardware. The experiment task is to remove a tool (figure 10) from its storage compartment and sequentially rotate two hex nuts on the front of the thermal enclosure system experiment hardware (figure 14) to activate the PCG experiment. The first nut rotation unplugs a syringe; the second rotation simulates the injection of a crystal growth solution from the syringe. The manipulator then returns the tool to its holder, closes the door on the storage compartment, and returns to home position.

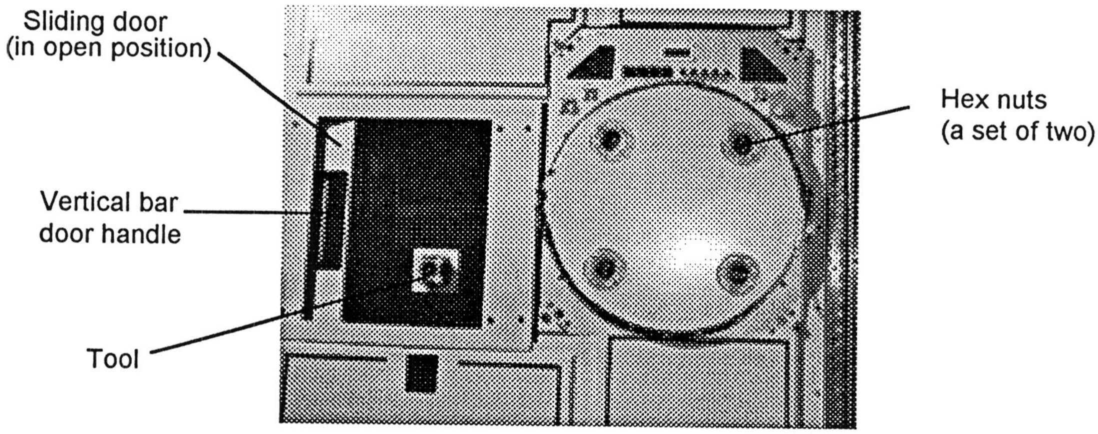

Figure 14. Tool storage compartment and TES front

3.1 Run Description

The robotic task is to activate the experiment apparatus. This task breaks down into three basic subtasks as follows: (1) acquire tool; (2) rotate hex head screws; and (3) replace tool.

Acquire Tool

The tool is acquired from behind the closed sliding door by first opening the door. The manipulator first approaches the door handle (Event 1) and opens its gripper to straddle a vertical bar-type handle on the front of a sliding door (Event 2). Then, the gripper fingers move laterally, sliding the door open and exposing the tool within (Event 3). The gripper moves away from the door handle (Event 4) and then aligns itself with the tool inside the compartment (Event 5). The gripper fingers move forward to straddle the tool (Event 6). After the gripper fingers close on the tool (Event 7), the gripper removes the tool from its spring-loaded socket holder by drawing it directly away from the face of the experiment (Event 8). The manipulator moves the tool further away from its housing (Event 9).

Rotate Hex head Screws

The next step in the agenda is to seat the socket tool on the hex head nuts (sometimes called Plug Nut and Syringe Nut, because of their function), which are located in a recessed area of Plexiglas on the front of the experiment module (figure 14).

The manipulator moves the tool toward the experiment module (Event 10), then toward the recessed area (Event 11) and then close to the recessed area (Event 12). Once inside the recessed area (Event 13), the tool moves to the Plug Nut (Event 14). The contour of the recessed area provides passive guidance to the tool in sliding down on the nut (Event 15). The nuts are turned with manipulator wrist roll motions; however, wrist roll motion is limited. The tool rachet mechanism provides sufficient turning capability. Unplugging the syringe requires a clockwise rotation of 270 degrees. The ratchet rotates counterclockwise from 0 degrees to 90 degrees (does not rotate the nut), then clockwise from -90 degrees to 180 degrees (rotates nut 270 degrees), and finally back counterclockwise to 0 degrees (does not rotate nut) (Event 16). The tool is then moved off the Plug Nut (Event 17), remaining within the recessed area in the Plexiglas.

Next, the tool moves within the recessed area (Event 18) to seat on the Syringe Nut (Event 19) and to rotate it (Event 20) exactly like the Plug Nut was previously rotated. The tool is then backed off the Syringe Nut (Event 21) and then withdrawn from the recessed area (Event 22) away from the module.

Replace Tool

The manipulator moves the tool back to the tool storage compartment for replacement (Event 23) and inserts the tool into its holder (Event 24). After reinserting the tool into its socket holder, the gripper releases the tool (Event 25). The gripper is then moved slowly away from the tool (Event 26) and toward the sliding door (Event 27). The gripper closes in on the door handle (Event 28) and pushes the sliding door closed (Event 29). Finally, the manipulator returns to it's home position (Event 30).

3.2 Script

Initially, the script commands the manipulator to move from its current position to home position (bent-elbow stance, shown in figure 1A of appendix). The entry in the script looks like this:

```
new_pos[0] = 0.0;          /* meters */
new_pos[1] = -.5842;
new_pos[2] = .5080;

new_pos[3] = 0.0;          /* radians */
new_pos[4] = 0.0;
new_pos[5] = 0.0;

rate = 15;                 /* millimeters/sec */

absolute_move(new_pos, rate);
check_accuracy(5);         /* millimeters or radians */
```

where the first three entries are the commanded coordinates and the second three entries are the commanded Euler angles of the end effector with respect to a fixed reference frame at the manipulator's shoulder (appendix). These target position values are placed into computer memory. The rate entry is a commanded average translational rate for the move. If there is no commanded translation, the effect of this rate is null. The absolute_move function continually drives the manipulator toward the target values in computer memory. When the end effector moves within a specified accuracy of the target values, the check_accuracy function okays the script to issue its next move command. A time_check routine keeps track of time throughout the script and how much time it takes for each move.

Table 1 shows the complete script for the PCG experiment activation. The script consists of 30 events. Although not shown, a set of coordinates and Euler angles are associated with the end-point of each move. The first 9 events in the script are to acquire the tool; the next 12 events are to rotate the hex head nuts; and the final 7 events are to return the tool to its holder and move the manipulator back to its home position.

Each move has a required end-point accuracy for translation and an end-point accuracy for rotation. For instance, in Event 1: the manipulator is to move its end effector to the door handle on the tool storage compartment. The move is not completed until the end-point accuracy is satisfied; that is, each coordinate of the end effector is within 5 millimeters of its commanded value, and each Euler angle is within .005 radians of its commanded value. Event 2 can not begin until the end-point accuracy of Event 1 is satisfied.

The straight-line distance of a move is the square root of the sum-of-the-squares of the coordinate errors (commanded end-point coordinates minus current coordinates). Dividing this distance by the commanded average rate shown in table 1 gives a time. Essentially the manipulator moves its end effector over the distance more slowly for larger values of time. If no translation is commanded, this time is zero and does not influence the motion. Hence, there are not entries for the translational rate in move 16 (rotating the PLUG) and move 20 (rotate SYRINGE) in table 1. In these cases, current coordinates are being maintained as target values.

Event			End-point accuracy required		Commanded average rate
Subtask	No.	Move	translation, mm	rotation, rad	translational, mm/sec
Acquire Tool	1	Move to front of door handle	5.000	.0050	15.000
	2	Move in on door handle	3.000	.0030	12.500
	3	Slide door open	4.000	.0040	20.000
	4	Back away from door handle	5.000	.0050	12.500
	5	Position gripper in line with tool	5.000	.0050	12.500
	6	Close in on tool	4.000	.0040	10.000
	7	Close gripper on tool	0.500	.0005	2.000
	8	Remove tool from holder	2.000	.0020	3.000
	9	Pull back with tool from holder	5.000	.0050	10.000
Rotate Hex Heads	10	Move tool toward hexheads	5.000	.0050	12.500
	11	Move tool closer to hexheads	2.000	.0020	10.000
	12	Move tool even closer to hexheads	2.000	.0020	10.000
	13	Move tool inside Plexiglas	0.500	.0005	0.300
	14	Move tool closer to PLUG	2.000	.0020	2.500
	15	Capture PLUG	1.000	.0010	1.200
	16	Rotate PLUG	20.000	.0200	-
	17	Back off PLUG	3.000	.0030	0.500
	18	Within Plexiglas, move toward SYRINGE	3.000	.0030	0.500
	19	Capture SYRINGE	0.500	.0005	0.500
	20	Rotate SYRINGE	20.000	.0200	-
	21	Back off SYRINGE	5.000	.0050	0.500
	22	Back further off SYRINGE	5.000	.0050	10.000
Return Tool	23	Move tool to holder	3.000	.0030	12.000
	24	Move back in with tool toward holder	0.750	.00075	10.000
	25	Replace tool (release)	0.500	.0005	2.000
	26	Move gripper back from tool	3.000	.0030	5.000
	27	Move gripper in front of door handle	4.000	.0040	12.500
	28	Move in on door handle	3.000	.0030	10.000
	29	Close door	4.000	.0040	20.000
	30	Back away from door handle --> Home	5.000	.0050	10.000

Table 1. Script for PCG experiment activation

3.3 Results and Discussion

The manipulator follows 30 sequential move commands in a script to perform the protein crystal growth task. The objective is to determine typical times and end-point positioning accuracies for each of the moves in the script. An event is associated with each move in the script; for example, the first event in the script is to move to the front of the door handle (in table 1).

Results are based on 11 sequential data runs. Upon completion of a run, an operator initiates the next run.

3.3.1 Average Event Time and End-Point Accuracy

Each of the events in the script has a completion time in each of the 11 data runs. For a given event, the average event time is the mean of the times for this event in the 11 data runs. Each event in the script has a specified end-point accuracy (empirically determined) that must be met prior to initiating the next event in the script.

The last column of Table 2 shows the average time for each of the 30 moves in the script; for example, in Event 1, the manipulator moves its gripper in front of the door handle on the tool storage compartment. The average completion time for this move is about 11 seconds. The final-point accuracy is 5 mm in translation (coordinates) and .005 rad in rotation (Euler angles). Figure 15 shows a stack column graph of the average time and end-point accuracy for each event.

Move time depends on the distance to move, speed, and the end-point accuracy. The move is complete when the end-point accuracy is satisfied.

Most Stringent End-Point Accuracies

The events with the most stringent end-point accuracies are:

(1) Event 7 --- Acquire tool
(2) Event 13 ---Move tool inside Plexiglas
(3) Event 19 --- Capture Syringe
(4) Event 25 --- Replace tool

The end-point accuracies for each of these events were .5 mm in translation and .005 in rotation.

<u>Acquire Tool</u>

There is very little tolerance (by design) between the width of the gripper fingers and the space between the grooves on the tool (figure 10). Consequently, the accuracy requirement is stringent. An improper grip of the tool jeopardizes completion of the task, because the tool can no longer be accurately positioned. Future studies should include a means of knowing when this error occurs and pertinent software to put the tool back and reacquire it.

Move tool inside Plexiglas

To get to the PLUG, the manipulator first moves the tool forward into the recessed area. If the tool fails to enter the recessed area, the manipulator will still push the tool forward against the Plexiglas. Either the tool slips backward between the gripper fingers, causing a misconception that the accuracy requirement has been satisfied, or the tool does not slip, which causes an excessive force to build between the end of the tool and the Plexiglas. An operator recognizes this situation by visually monitoring the task and by torque readout.

Capture Syringe

It is important that the tool remain within the recessed area as the tool moves from the PLUG to the SYRINGE (as discussed above).

Replace tool

Inaccurate tool replacement means inaccurate tool acquisition of the next run. This error can be alleviated by tool-holder design.

Longest Average Event Times

Rotating the Plug Nut (Event 16) and the Syringe Nut (Event 20) each take about 1 minute. This is fast enough not to be boring and slow enough to allow the manipulator to maintain its translational position while the wrist rotates the tool.

Some events take longer because they need accurate end-points, such as:

(1) Event 7 --- Acquire tool (52 sec)
(2) Event 19 --- Capture Syringe Nut (76 sec)
(3) Event 25 --- Release tool (63 sec)

These events are three of the four with the most stringent accuracy requirements. Moving inside the Plexiglas (Event 13) also has a stringent accuracy requirement, but the movement is small.

Event			End-point accuracy required		Commanded average rate	Average time
Subtask	No.	Move	translation, mm	rotation, rad	translational, mm/sec	sec
Acquire Tool	1	Move to front of door handle	5.000	.0050	15.000	11.454
	2	Move in on door handle	3.000	.0030	12.500	9.363
	3	Slide door open	4.000	.0040	20.000	17.000
	4	Back away from door handle	5.000	.0050	12.500	11.636
	5	Position gripper in line with tool	5.000	.0050	12.500	14.636
	6	Close in on tool	4.000	.0040	10.000	16.909
	7	Close gripper on tool	0.500	.0005	2.000	52.363
	8	Remove tool from holder	2.000	.0020	3.000	25.454
	9	Pull back with tool from holder	5.000	.0050	10.000	31.818
Rotate Hex Heads	10	Move tool toward hexheads	5.000	.0050	12.500	27.909
	11	Move tool closer to hexheads	2.000	.0020	10.000	23.909
	12	Move tool even closer to hexheads	2.000	.0020	10.000	1.454
	13	Move tool inside Plexiglas	0.500	.0005	0.300	37.181
	14	Move tool closer to PLUG	2.000	.0020	2.500	10.727
	15	Capture PLUG	1.000	.0010	1.200	32.700
	16	Rotate PLUG	20.000	.0200	-	64.600
	17	Back off PLUG	3.000	.0030	0.500	34.400
	18	Within Plexiglas, move toward SYRINGE	3.000	.0030	0.500	40.700
	19	Capture SYRINGE	0.500	.0005	0.500	75.666
	20	Rotate SYRINGE	20.000	.0200	-	61.300
	21	Back off SYRINGE	5.000	.0050	0.500	29.272
	22	Back further off SYRINGE	5.000	.0050	10.000	7.272
Return Tool	23	Move tool to holder	3.000	.0030	12.000	34.363
	24	Move back in with tool toward holder	0.750	.00075	10.000	40.545
	25	Replace tool (release)	0.500	.0005	2.000	62.818
	26	Move gripper back from tool	3.000	.0030	5.000	21.181
	27	Move gripper in front of door handle	4.000	.0040	12.500	14.181
	28	Move in on door handle	3.000	.0030	10.000	20.272
	29	Close door	4.000	.0040	20.000	17.363
	30	Back away from door handle --> Home	5.000	.0050	10.000	9.900

Table 2. Average times for each event in script

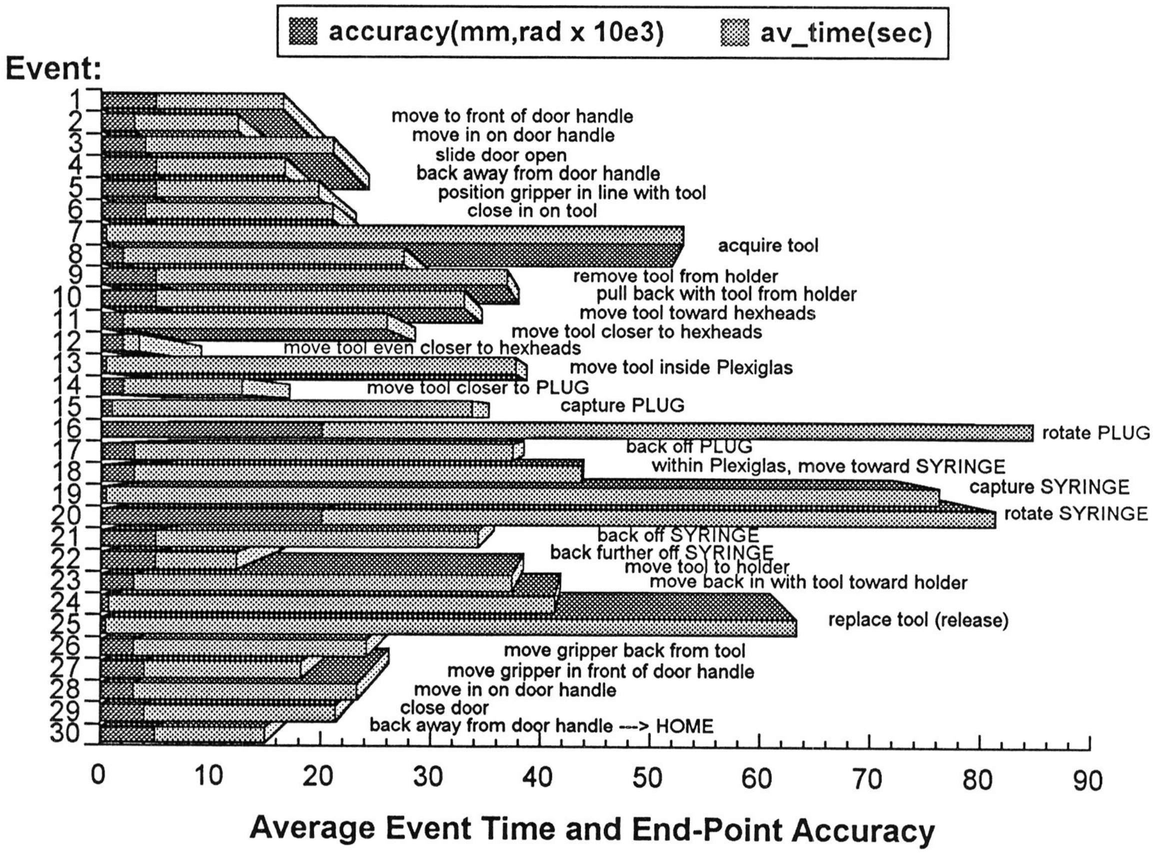

Figure 15. Stacked column graph

3.3.2 Fluctuations in Event Times

Figure 16 shows the average event times, plus and minus one standard deviation. The events with the largest fluctuation in time are:

(1) Event 7 --- Acquire tool
(2) Event 13 --- Move tool inside Plexiglas
(3) Event 19 --- Capture Syringe
(4) Event 25 --- Replace tool

These are the same events that have the most stringent end-point accuracy requirements. Toward the end of a move, the target values are continually commanded until the required accuracy is attained. However, since the stringent accuracy condition is not placed on a move until close to the end-point and since there is friction in the system, there is variation in the conditions at which the final end-point convergence begins. The fluctuation in move time is due mainly to the variation in the convergence time at the end of a move.

The times to rotate the hex nuts (Event 16 and Event 20) also have large variations for the different data runs. Perhaps, the accuracy requirment on translation is too lenient, making orientation convergence more difficult. This needs to be examined in a future study.

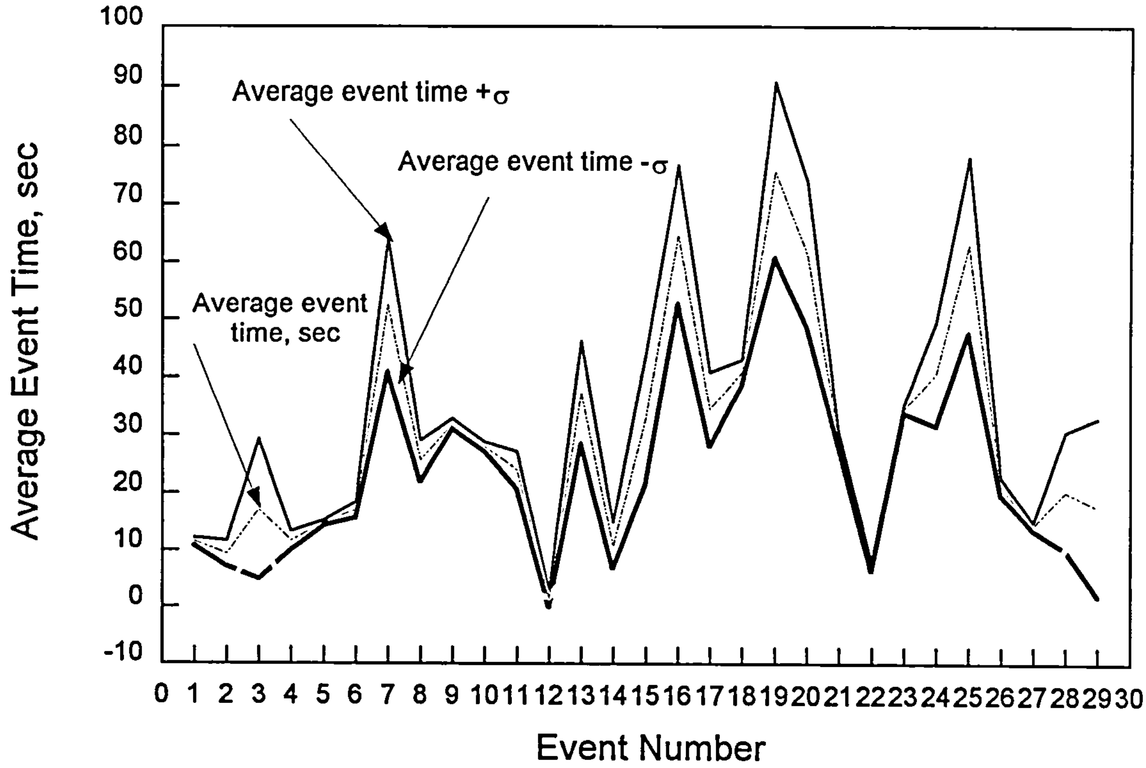

Figure 16. Average event time, plus and minus one standard deviation

3.3.3 Commanded Average Speed and End-Point Accuracy

Figure 17 is an area graph showing the commanded average speed and the end-point accuracy requirement for each event move in the script. The commanded average speed correlates well with the accuracy requirement. After the part of the move based on the average speed is completed, the script continually commands the end-point until the desired accuracy is achieved. Average speed is an empirical value chosen for acceptable end-point overshoot and to reduce move time. If this value is too large, the overshoot may not be tolerable. The average speed is slower when trying to attain greater accuracy at the end-point. Since average translational speed does not affect rotation of the hex nuts, no comparison of average speed and end-point accuracy is made.

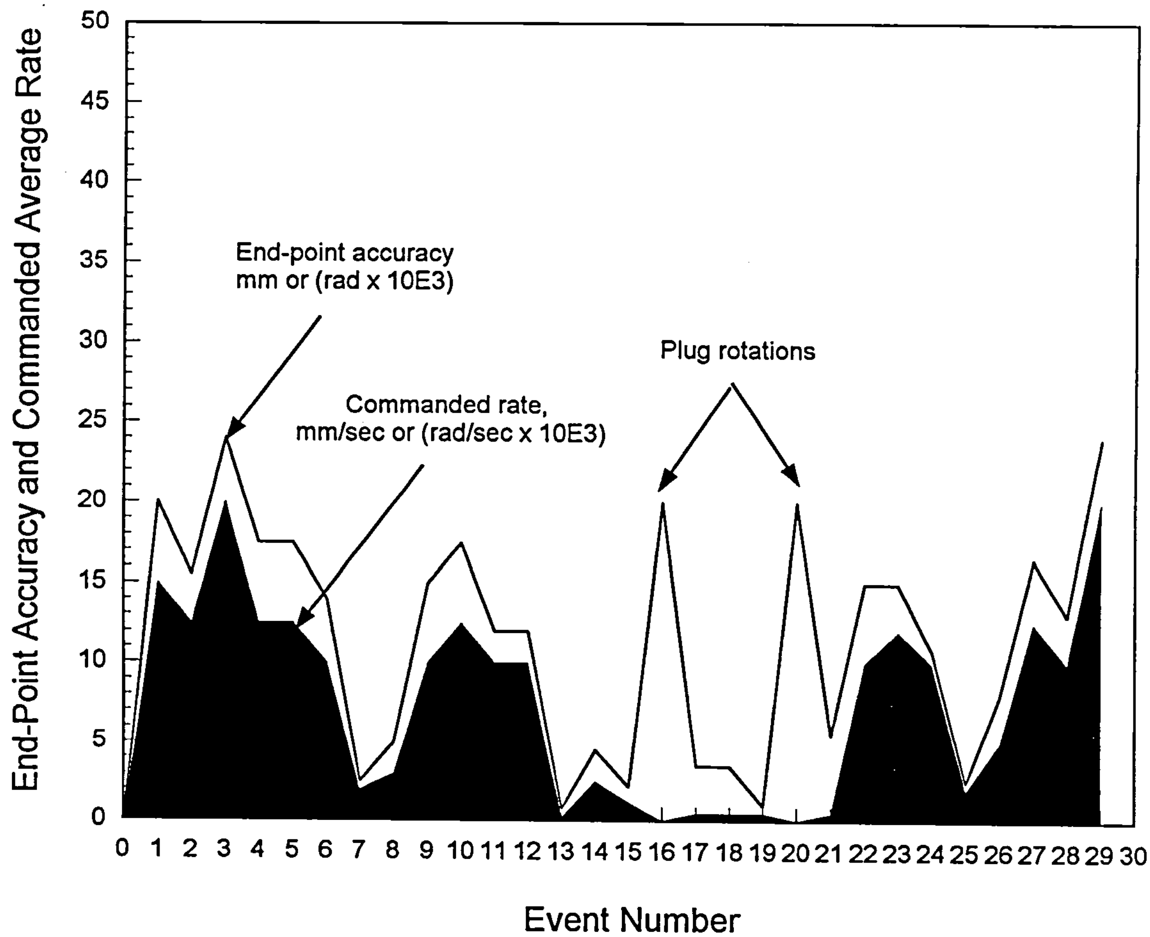

Figure 17. End-point accuracy and commanded average rate for each event

3.3.4 Robustness

Sliding Door Open

Opening and closing the sliding door on the tool housing compartment is tolerant to errors. The script calls for the gripper to slide the door without grasping the handle. This makes the move more tolerant to error. Extra force is automatically exerted if the door becomes sluggish. After opening or closing the door, the gripper moves slowly away from the door to avoid any possible jumps due to force buildup. The operation is reasonably fast and tolerant of errors.

Acquiring and Rotating Hex Head Screw

After the tool moves inside the cutout in the Plexiglas, the sloped wall of the cutout aids in guiding the tool to acquire and descend on the screw. Even if the rachet does not seat on the screw, the ensuing pressure on the top of the screw is sufficient to make the desired rotation.

Accuracy Checks

A particular move concludes on end-point accuracy, not on time. The time depends on how long it takes to achieve the end-point accuracy. End-point accuracy checks the buildup of previous errors. In the script, an operator influences final time by specifying average speed to the proximity of an end-point and end-point accuracy.

Stringent end-point accuracy (empirical) reduces error and allows completion of different task phases at a cost in time. The operator has the option of intervening at any time throught the task to put the motion back on course.

4. Possible Areas of Enhancement

The IVAR laboratory as a whole will be evaluated and modified during a series of demonstrations to test possible productivity enhancements, components, and devices to the system. These demonstrations will involve both dedicated automation and telerobotic approaches with the goal of providing space intravehicular telerobotic and experiment automation. The following items can be incorporated into subsequent demonstrations to enhance automation and robotics in the IVAR laboratory: (1) criteria and experiment design guidelines; (2) task-space databases or world models; (3) compliant control; (4) disturbance compensation; (5) enhanced video techniques; (6) predictive displays with time delays to study ground control techniques; (7) an object-oriented graphics interface and expert system assistance for error detection, analysis and replanning; and (8) error recovery capability on the part of the operator, that is, the operator's ability to stop a sequence, adjust or fix a problem, and then continue the sequence from the correction point.

5. Summary

There will be long periods between visits in which astronauts will not be available to perform on-orbit laboratory experiment tasks. Automation and robotics technologies can increase productivity by servicing experiments while the astronauts are away and, even when the space station is permanently inhabited, could free the crew for more complicated skilled tasks. This paper describes a simulated protein crystal growth experiment serviced by a unique seven-degree-of-freedom robot in the Intravehicular Automation and Robotics laboratory, a full-scale mockup of the space station laboratory module. The results indicate that automated operations are feasible and reliable even for precise tasks (such as seating sockets). It is important to design robotic operations carefully (high accuracy for critical steps) to insure the success and increase the reliability of microgravity experiment automation. The times and accuracies in this paper at least represent values for which the automated robotic operations can be done.

APPENDIX

MANIPULATOR JOINT ANGLES AND TWO BASIC CONTROL FRAMES

Symbols

X, Y, Z	end effector axes
X_s, Y_s, Z_s	fixed reference axes (at manipulator's shoulder)
x_s, y_s, z_s	coordinates in the fixed reference frame
θ_i	joint i rotation angle
ϕ, θ, ψ	Euler angles of end effector frame relative to fixed frame

Figure A1 depicts the manipulator in its home position. In this paper, a script commands the manipulator to move its end effector through a sequence of movements. A movement is specified by a set of coordinates (x_s, y_s, z_s) in the fixed reference frame and a set of Euler angles (ϕ, θ, ψ), along with a specified end-point accuracy that must be met before the next move is initiated. Resolved rate control is used to move from the current position to the new commanded position.

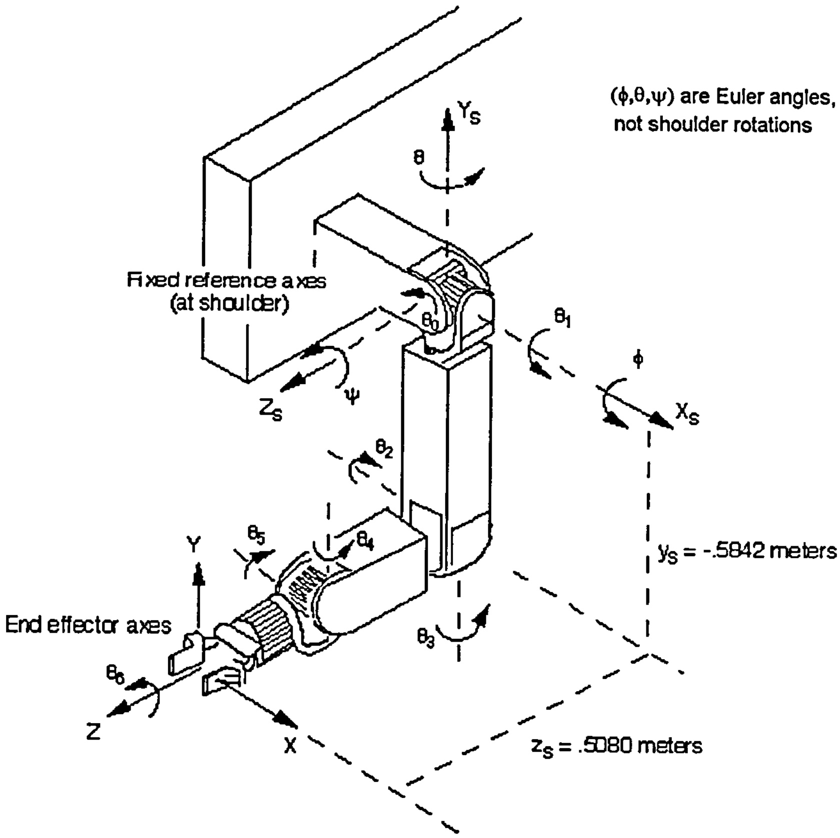

Figure A1. Home position of manipulator

The following table shows the seven joint angles for the home position and lists the joint angle limits.

Joint, i	Home position, deg	Lower limit, deg	Upper limit, deg
0	-90	-106.7	-52.7
1	0	-182.3	177.7
2	90	30	130
3	90	45	135
4	0	-25	90
5	0	-45	45
6	0	-160	160

Table A1. Home position and joint angle limits

In this paper, the shoulder roll joint angle θ_0 is maintained at home position; hence, the manipulator operates as a six-degree-of-freedom robot arm and redundancy is not used.

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Automation and robotic technologies are being developed and capabilities demonstrated which would increase the productivity of micro-gravity science and materials processing in the Space Station laboratory module, especially when the crew is not present. The Automation Technology Branch at NASA Langley has been working in the area of Intravehicular Automation and Robotics (IVAR) to provide a user-friendly development facility, to determine customer requirements for automated laboratory systems, and to improve the quality and efficiency of commercial production and scientific experimentation in space. This paper will describe the IVAR facility and present the results of a demonstration using a simulated protein crystal growth experiment inside a full-scale mockup of the Space Station laboratory module using a unique seven-degree-of-freedom robot.

14. SUBJECT TERMS
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