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User Needs, Benefits and Integration of Robotic Systems in a Space Station Laboratory

Interim Report

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16. Abstract

This Interim Report for the National Aeronautics and Space Administration/Lewis Researech Center (NASA/LeRC) summarizes the methodology, results and conclusions of the contract to date of the User Needs, Benefits, and Integration Study (UNBIS) of Robotic Systems in the Space Station Microgravity and Materials Processing Facility. Study goals include the determination of user requirements for robotics within the Space Station, United States Laboratory. Three experiments were selected to determine user needs and to allow detailed investigation of microgravity requirements. A NASTRAN analysis of Space Station response to robotic disturbances, and acceleration measurement of a standard industrial robot (Intelledex Model 660) resulted in selection of two ranges of low gravity manipulation: Level I (10-3 to 10-5 G at >1Hz.) and Level II (<=10-6 G at 0.1 Hz). This included an evaluation of microstepping methods for controlling stepper motors and concluded that an industrial robot actuator can perform milli-G motion without modification. Relative merits of end-effectors and manipulators were studied in order to determine their ability to perform a range of tasks related to the three low gravity experiments. An Effectivity Rating was established for evaluating these robotic system capabilities. Preliminary interface requirements were determined such that definition of requirements for an orbital flight demonstration experiment may be established.

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SUMMARY

The purpose of this study is to identify the potential for application of robotic systems in low-gravity orbiting laboratories, such as the planned United States Laboratory on Space Station Freedom. During the space station Phase B studies, from early 1985 through 1987, much attention was drawn to the fact that long duration and extensive experimentation would require large amounts of crewtime. Also noted was the experimenters' need to use larger processing facilities and materials, some of which are potentially hazardous, in much lower acceleration environments than previously available on the Orbiter.

Both of these findings suggested the potential for application of a robot to perform these functions:

1) Supplement the crewtime resource
2) Perform tedious operation support functions
3) Perform potentially hazardous operations
4) Provide backup for rescue, salvage and cleanup functions
5) Provide low-g, non-disturbing laboratory manipulation.

Added to these drivers within the space station conceptual design program, Congress had directed NASA to determine how 10% of program funding could be spent on automation and robotics. This seemed a clear mandate for a space station laboratory robot system; however, none was baselined into the program at the end of Phase B.

The current study was originated to clearly identify the "User Needs, Benefits, and Integration Requirements for Robotic Systems in the MMPF," which is its title. This study was initiated to provide information on the space station experimenter community's needs for low-gravity manipulation and to evaluate the impacts of providing such a capability. The first step was to define, as succinctly as possible, the experiment functional flows in a sequential and timelined fashion and define how robotic systems might perform or support these activities. Emphasis was given to defining low-g requirements and issues.

Following the definition of experiment functional flows, the anticipated space station configuration was analyzed to compare potential robot system disturbances with other potential disturbances and to determine if the background acceleration environment was conducive to microgravity-level research work. This was not found to be the case. The station configuration leads to a <1 Hz resonant response frequency. With given damping factors, the structure tends to convert impulsive inputs at various frequencies to the resonant frequency and sustain them for long periods. The long truss structure, solar panels, and mass distribution result in this low-frequency resonance.

Many planned or proposed activities, within both station operations and user operations, were found to be incompatible with microgravity acceleration levels: i.e., on the order of 10E-6 g. Based on the defined user requirements for microgravity accelerations below 1 Hz, this is a very difficult problem. Reasonable expectations based on the current space station definition would be for no better than 10E-4 to 10E-5 g below 1 Hz.

During laboratory robotic testing using LVDT motion sensors and QA-2000 accelerometers, robot motions were found to be on the order of 1 x 10E-3 to 5 x 10E-2 g. The lower level was found in the microstepping mode where base angular rotation of the robot was approximately one millionth of a complete 360 degree rotation, whereas the higher levels were seen during major movements. This level compares favorably with humans simply holding the accelerometer with no intention to move it. Human disturbances were 2 x 10E-2 to 5 x 10E-2 g which gives robots an order of magnitude better low-g manipulation capability.

Given the background environment of the proposed space station, it is still reasonable to provide the desired low-gravity robotic system to support the defined user operations. If this is done and the benefits of such robotic operations are evaluated, we find distinct advantages to robots supporting flight operations. Immediately, there are many more experiment runs possible. This is because without robotics any reasonable operations scenario (six to eight crew) finds that crewtime is the limiting resource. The limiting resource is the one that is used up first, causing operations to cease. If analyses are performed for larger crews, a curious thing happens. Rather than increasing the number of experiment runs, they actually decrease as a result of the added burden of crew which consumes food, oxygen, weight, volume, etc. This results in loss of resources for experiment operations, hence, a reduction in number of runs. For a given complement of experiments there is an optimum balanced level of resources for most efficient operation. All of these analyzed scenarios benefited dramatically from the addition of a robot.

The benefits of robotics can be quantified in terms of greater number of experiment runs for given amounts of other resources. The Payload Production Planning Program (PAYPLAN) computer model also placed dollar values on experiment products and found doubling and tripling of output with the addition of a single robot, since it can be operated around the clock.

The costs of evaluated space robot configurations are estimated to be between \$2M and \$15M for robots ranging from the simple single arm with two-finger gripper (\$2M) to the complex dual-arm system with a dexterous hand (\$15M). Both include the ground teleoperations station, software, and onboard safety computer. Robots are, after all, relatively simple machines tied to simple computers, and the primary cost is not the hardware or software, but rather the cost of test, verification, validation, and flight qualification. The operational cost for ground crew is very modest, requiring two technician/software personnel per shift with a full-time system engineer on call. Yearly operational cost is estimated to be less than \$1M, including maintenance.

Based on the relatively low cost when measured against its ability to pay for itself by increased production within the first 90-day mission, it is advisable to provide the maximum-capability system. In a recently completed survey of personnel with backgrounds in robotics and/or flight systems development, performance was identified as the key weighting factor, scoring at 44% of 100%, well ahead of resource consumption at 31%, and cost and other factors totaling 25%.

Interfacing a robotic system with the proposed space station laboratory includes structural/mechanical, data/communications, video, and power interfaces. The requirements for these key interfaces are within the bounds of the current designs, save one: the desired structural attachment is by a ceiling-mounted rail or a pair of rails. This would be no problem to the subsystem and rack designers if one or two strips 2 inches wide on the face of the racks at the junction of the standard rack subsystem panel were reserved from the outset. It is desirable that this be done prior to PDR in 1990.

Numerous facets of low-gravity robotics have been identified as needing further study, research, and development. Motor and drive techniques are key areas for development if future, truly microgravity laboratories are to be operated. Techniques for counteracting the motion of joints to minimize acceleration of manipulated samples and base reaction forces should also be developed. Finally, and of immediate importance to the space station program, development of a flight demonstration should be initiated to verify low-gravity operational performance characteristics of a laboratory robot.

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1. INTRODUCTION

This Interim Report covers work performed by Teledyne Brown Engineering's Space Programs Division between October 1987 and January 1989 for Lewis Research Center under contract number NAS3-25278, Study of User Needs, Benefits and Integration for Robotic Systems in MMPF.

1.1 BACKGROUND

Space station Phase B studies, 1985 through 1987, indicated a shortage of crewtime based on proposed experiment operations and requirements for space station operations. There was also a user requirement to handle potentially hazardous materials to be used in processing, and to perform these experiments in a "microgravity" environment. This study was initiated to provide information on the space station experimenter community's needs for low-gravity manipulation and to evaluate the impacts of providing such a capability.

1.2 CONCURRENT STUDIES AND DEVELOPMENT ACTIVITIES

The Flight Telerobotic Servicer (FTS) contracts are concurrent to this study and plan the development of a system which operates telerobotically outside the pressurized modules and reduces the crew EVA requirements. This program has been identified as the key A&R facet of the Space Station Program. As it solves one problem, excessive EVA and radiation exposure, it does however create another problem for inside experiments. As the FTS is planned to be a space station crew operated system, it will require valuable crewtime to operate and will reduce further the crewtime available for experiment operations.

The international partners, Canada, NASDA and ESA are all pursuing robotic developments applicable to space station Freedom operations. Canada has the Mobile Remote Manipulator System (MRMS) in development, which will be operated telerobotically from the modules, in a manner similar to the FTS. NASDA's module and pallet will have a robotic arm for transfer of assemblies, supplies and samples to and from the module's airlock and the outside, "exposed" pallet assembly. The Europeans are currently developing a flight experiment for a shuttle Spacelab mission which will place a small robot arm entirely enclosed within a rack.

1.3 SCOPE OF UNBIS STUDY EFFORT

The purpose of this study is to provide a better understanding of experiment manipulation requirements and the acceleration environment onboard an orbiting low-gravity laboratory. The study effort is composed of seven tasks, as shown in Figure 1-1:

Task I required the definition of the experimenter's needs in terms of operational flow, acceleration limits, manipulation requirements, timing and potential for disturbance to other experiments. This data

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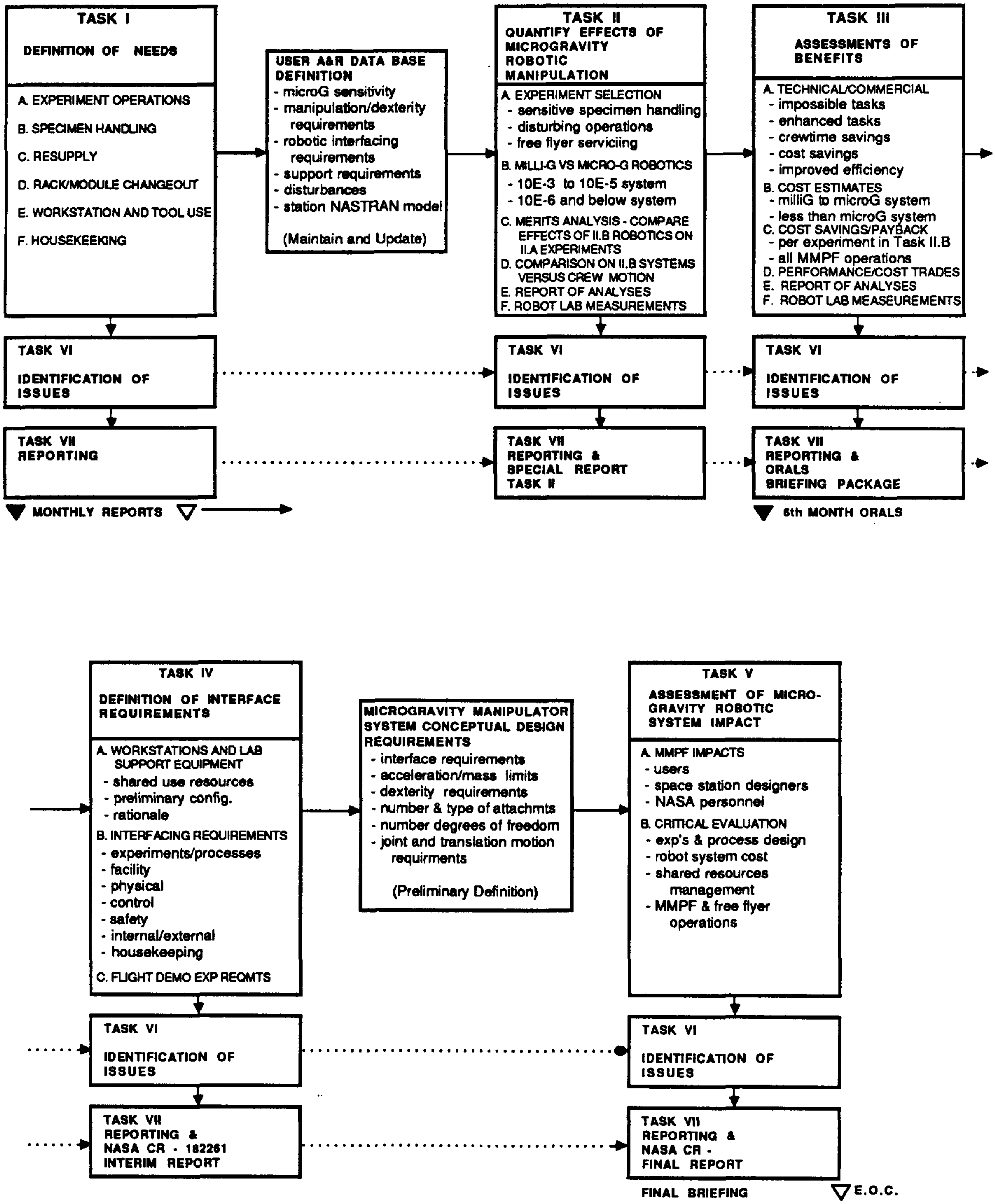

FIGURE 1-1. UNBIS STUDY COMPONENTS

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was defined for ten typical experiments and placed in a data base which is being maintained for the final report. Another data base was established which defined other (external to the experiment) disturbing sources to the experiment's acceleration environment.

Task II identified three of the ten defined experiments for further detailed evaluation of the acceleration impacts to their operation and their potential operation using robots. These analyses were based on a NASTRAN model of space station developed during the Phase B study at work package two, JSC. To this model were added robotic and outside disturbance sources to evaluate the acceleration impact to experiment operations. Also required was the laboratory acceleration measurement of typical robotic motions to determine potential for low-gravity manipulation.

Task III required evaluation of the cost of various robotic system configurations and the benefits of operation of experiments by these systems, such as enhanced low-gravity environment or added capabilities. These benefit evaluations used the Payload Production Planning, or PAYPLAN, computer program developed in 1986 by Teledyne Brown Engineering to parametrically analyze resource consumption by given sets of experiments and optimize the laboratory output within those resource limitations.

Task IV is still in work and requires the definition of interface requirements between the potential low-gravity robotic system, the laboratory facilities and experimenters. Preliminary definition of requirements for flight demonstration is also required.

Task V will be to provide an evaluation of the impact of robotic system impacts to the various affected parties: NASA centers, station system designers and experiment developers.

Tasks VI and VII are for identification of key issues and reporting. These activities run concurrently with the five previous tasks and continue throughout the study.

Each of these completed and on-going tasks will be reported and discussed in detail. The appendices contain much of the pertinent data and graphics developed during this study with the relevant discussion included under the appropriate task heading.

The conclusions and recommendations are those that can be drawn from the study to date and could of course be altered by later findings or a more thorough analysis of the preliminary data now coming from the laboratory accelerometer measurements. There is some fascinating data here that does suggest more work to be done, particularly in terms of a Shuttle/Spacelab flight demonstration experiment. This must be initiated soon, if it is to be of a major consequence to the space station Freedom design and early operations.

1.4 PROCEDURES AND FACILITIES

The development of the Lewis low gravity robotics, or UNBIS, database utilizes the currently available Microgravity Materials Processing Facility (MMPF) database as a starting point. To that base is added the acceleration requirements at each step, the point to point manipulation requirements in X, Y and Z coordinates, and the time for step completion. The data was derived from the experimenters and others familiar with their experiment configuration and protocols. The database was originally established on a PC/AT but is now on a MAC II and available to the engineers and analysts working on this study.

The Disturbance Database was also established on the PC/AT. This is currently much smaller although as more becomes known about the details of proposed systems and operations it must necessarily grow. In future mission planning activity for space station data such as these will be required for proper assessment of expected acceleration environments, just as power, crewtime and other resources are now planned and timelined.

The analyses of disturbance and reaction effects were done by a dynamicist using NASTRAN on a VAX. The model was originally developed at work package two and later used in the Space Station Pressurized Volume Utilization (SSPVU) Study. The model was verified using reported case studies after transfer to our VAX.

Teledyne Brown Engineering's Robotics Laboratory was modified and used for the purpose of performing the Task II accelerometer measurements.

The PAYPLAN computer program developed at Teledyne was used to perform part of the benefits assessment. This runs on a PC/AT or MAC II with the MS-DOS option.

2. SPACE STATION USERS REQUIREMENTS

Two key goals of this study are 1) to define space station laboratory user experiment operations in detail and 2) then to identify how robotic systems might benefit those operations. The starting point to achieve these objectives is a close examination of the proposed experiments for flight aboard the space station laboratory. These experiments are generally being flown to take advantage of the low-gravity environment of low-Earth orbit.

2.1 USER NEEDS DATABASE

The greatest need for low-gravity comes from the materials processing community whose requirements are defined in the Microgravity and Materials Processing Facility (MMPF) Study and Database.

The MMPF study and its' database focused on the step by step definition of processing requirements with emphasis on required resources, such as, power, crewtime, consumable supplies and support equipment. The MMPF Study's purpose was to attempt the complete definition of requirements for materials processing on space station. During the course of the current study it was recognized that microgravity is itself a resource and this was added to the Lewis Low Gravity Robotics Database derived originally from the MMPF Database. Our database has ten experiments which were selected as representative of the classes of materials processing experiments in the MMPF Database of over 200 experiments.

To the MMPF data base structure was added the low-gravity level needed, manipulation coordinates for start and stop, and timing requirements for each step, if any. Data inputs came from contacts with over 90 different organizations. The 1986 MMPF Microgravity Workshop Proceedings were reviewed along with the MMPF database to achieve a comprehensive understanding of the low-gravity experimentation and processing requirements. Existing contractor reports, NASA documents, published literature and personal contacts were used to add to the basis for this definition of needs. Study inputs were obtained from the Space Station Pressurized Volume Utilization Study, Space Station Phase B Studies, Langley Research Center Space Station Studies, and the 1986 Williamsburg Technology Conference Proceedings.

2.2 USER LOW-GRAVITY REQUIREMENTS

One conclusion of the MMPF Microgravity Workshop Proceedings is that being in orbit does not guarantee a "microgravity" environment. The proceedings found that the total acceleration naturally resulting from atmospheric drag, gravity gradient, and attitude of the station is such a level as to be a concern to materials processing. The theoretical experiment sensitivities and past flight acceleration measurements are shown in Figure 2-1. As shown, the lower frequency disturbances are not as well tolerated as the higher frequency ones. This curve attempts to summarize a great deal of theoretical and analytical data and was derived by members of

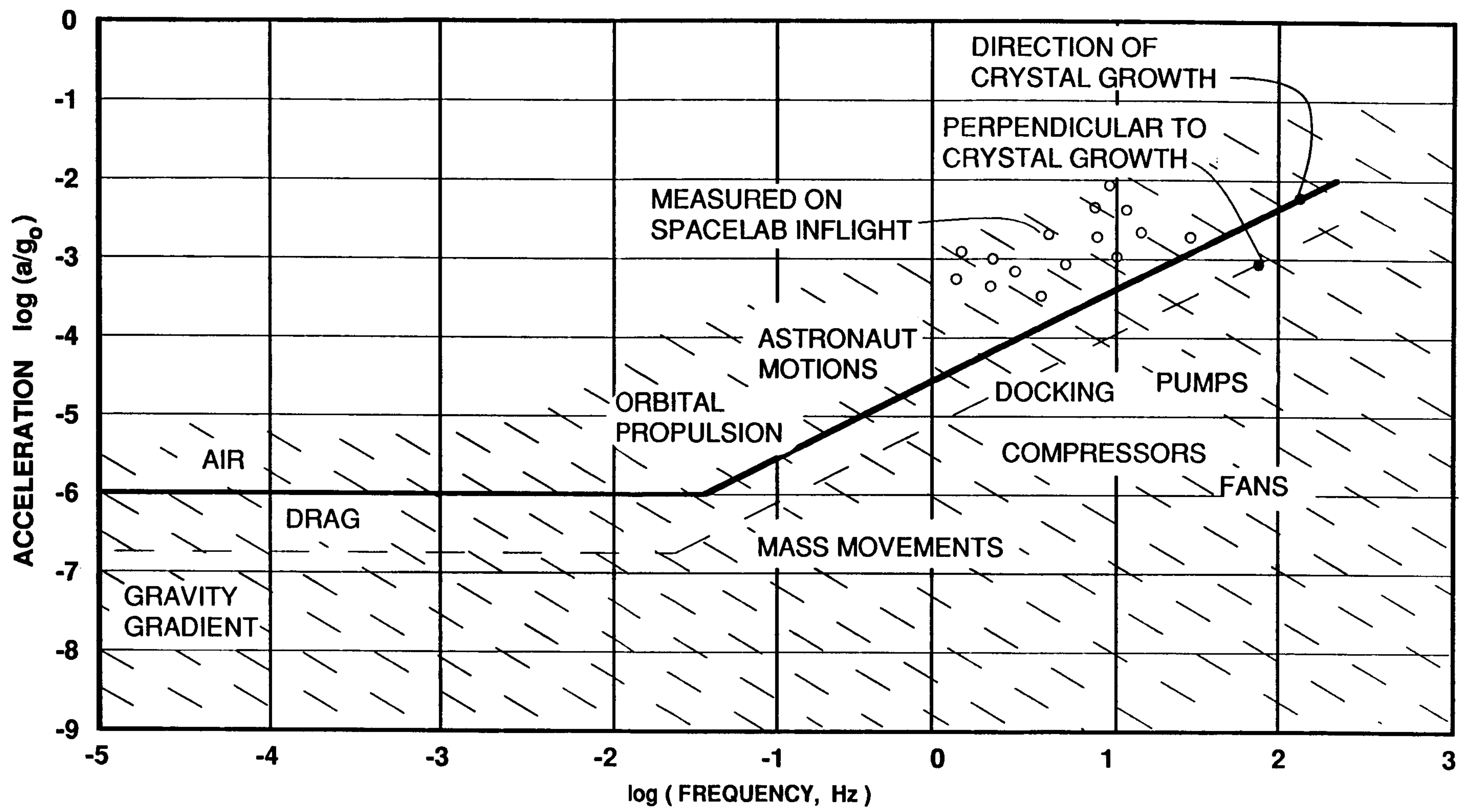

FIGURE 2-1. MICROGRAVITY ACCELERATION SENSITIVITY OF PROCESSES

materials processing community. To date no experiments have actually been conducted which have met the requirements as defined by this curve.

A key point is that the proposed acceleration requirements for the space station are based on the best estimates of physical requirements for the classes of material processing experiments currently being planned for flight. There is a range of expert opinion as to the discrete requirements for particular experiments. The basis of these requirements is the projection of data from Skylab or Shuttle/Spacelab experiments where samples of crystalline materials were grown or purified in a predominately milligravity environment and later analyzed on the ground.

Another key point to be made is that the community of experiments can in themselves be one of the main contributors to acceleration disturbances. Motors, pumps, fans or other mechanisms are often a source of impulsive or continuous vibration.

As a part of our analyses, the potential for mutual disturbance between experiments was also evaluated in terms of manipulation effects of the gross kind, such as the impact of opening a furnace door on neighboring experiments. It is beyond the scope of this study to determine the finer, yet non-trivial detrimental effects, such as, pump or fan operation.

To better define the expected space station acceleration environment, other processes and experiments not in the MMPF data base were added to our analyses. These included potential disturbance sources, such as, the life science experiments, truss attached slewing experiments (telescopes and antenna pointing), the Mobile Service Center, OMV and Orbiter docking and other space station proximity operations.

2.3 AUTOMATION AND ROBOTICS FUNCTIONS

In the development of the database it was important to identify all of the functions during experiment operation and sample processing with potential servicing via automation or robotic mechanisms. Functions required by the various users include experiment facility operations, sample changeout and storage, experiment module changeout, facility rack changeout, facility housekeeping tasks, laboratory support equipment (glovebox, microscope, etc.) and other common-use hardware operation, and housekeeping tasks.

Each function was addressed in terms of manipulation skills such as:

1. Complexity and level of automation

2. Mass, speed, end points, path, etc.

3. Frequency and duration of operation

4. Manipulation type

5. Shared/dedicated facilities

In order to accomplish these functions the use of leading edge, conventional technology is assumed. Thus, in our analyses of manipulation actions required and their predicted reactions, we assume the use of state-of-the-art technologies operating under normal physical laws.

Another consideration of the robotic manipulation activity is quite challenging to maintaining low-gravity. Most processes are sensitive only during the growth, separation or active experiment phase of operations. For these experiments robotic manipulation is generally not a direct impact, but rather the structurally transferred base reaction forces due to robotic activity with another experiment. These forces tend to be damped and absorbed by the station and laboratory module structure. One class of experiments, Protein Crystal Growth, is sensitive, after active growth, to disruption of their delicate crystalline structure. These samples must be manipulated directly by a robotic mechanism with very low acceleration levels. This challenges currently available robot techniques.

2.4 EXPERIMENT AND HOUSEKEEPING USER NEEDS

Ten typical experiment facilities were identified that represent the classes of material processing experiments in the MMPF database. This database was expanded to provide complete information on manipulation, processing and housekeeping. The ten typical experiment facilities are:

1. Acoustic Levitator
2. Alloy Solidification
3. Atmospheric Microphysics
4. Continuous Flow Electrophoresis
5. Droplet Spray Burning
6. Float Zone
7. Fluid Physics
8. Large Bridgman
9. Protein Crystal Growth
10. Vapor Crystal

A brief description of these facilities and their functions are found in Appendix 9.1. The complete experiment processing flows for all ten of these were carefully analyzed. The requirements for supporting equipment to completely process the experiments was also identified. These required support items are shown in Appendix 9.2. By contract direction three of these experiments were eventually selected for further detailed study based on their unusually difficult manipulation or disturbance sensitivity requirements.

The three selected experiments are items 7, 8 and 9 above. The detailed experiment processing flows for these three experiments are found in Appendix 9.3. As seen at the top of the data sheets, skill level, operation description, mass, acceleration limits, start and stop positions in X, Y and Z coordinates, and time limitations are all defined for each step in the timelined flow.

2.5 COMMON USE EQUIPMENT AND SAMPLE HANDLING REQUIREMENTS

Evaluation of the operations related to the laboratory support equipment, housekeeping activities and other crew related tasks resulted in identification of 37 items, 18 of which are support items, five laboratory subsystems, and 14 characterization items as shown in Appendix 9.2.

Evaluation of needs was completed on each of these items in terms of limits of motions, compressive strength, tensile strength, acceleration limits, temperature, and other parameters. Results of these analyses are shown in Table 2-1, Space Station Laboratory Manipulator Functional Requirements; Table 2-2, Sample Handling Requirements; and Table 2-3, Laboratory Support Equipment.

2.6 ACCELERATION DISTURBANCE SOURCES

An analysis of low-gravity disturbance sources to the space station found many sources both internal and external to the pressurized modules. The Disturbance Database is shown as Table 2-4.

Most notable disturbance sources are the required daily exercise activities of the crew, and rack or experiment module changeout within the laboratory. Less frequently, but at higher disturbance levels are the OMV and shuttle docking activities. Data on the Mobile Service Center was scanty at best, however, the proposed "dual tread, peg in hole and pull" method of locomotion on the truss would undoubtedly pose low frequency, low-gravity disturbance problems, especially considering the combined masses of the MSC, MRMS and manipulated payload to be moved.

TABLE 2-1. SPACE STATION LABORATORY MANIPULATOR FUNCTIONAL REQUIREMENTS

CATEGORY	FUNCTION	SPECIFICATION		
			MAXIMUM	MINIMUM
TRANSLATION	LEFT / RIGHT	DISTANCE	11.8 M(38.7ft)	2 mm (0.08 in)
		MASS	30 kg (66 lb)	0.004 kg (0.009 lb)
		SIZE	0.23x0.33x0.4m(9x13x16in)	1.1x3.8x0.025 cm (0.4x1.5x0.01in)
		FORCE	98 N(22 lbf)	3 N(0.6 lbf)
	UP/DOWN	DISTANCE	231 cm (84 in)	2 mm (0.08 in)
		MASS	2.25 kg (5 lb)	0.0045 kg (0.01 lb)
		SIZE	30.5x5x5 cm (12x2x2 in)	
		FORCE	116 N(26 lbf)	3 N (0.6 lbf)
	IN/OUT	DISTANCE	5 cm (2 in)	0.2 cm (0.078 in)
		MASS	2.25 kg (5 lb)	0.0045 kg(0.01 lb)
		SIZE	2.5 cm (1 in)	0.6 cm (0.25 in)
		FORCE	249 N(56 lbf)	1.4 N(0.3 lbf)
	ALL AXES	SPEED/ ACCELERATION		
		ACCURACY		5 mm (0.2 in)
		REPEATABILITY		1 mm (0.04 in)
ROTATION	CW/CCW	INCREMENT	1 degree	0.1 degree
		RATE	180 degree/sec	1 degree/sec
		EXCURSION	340 degrees	
		TORQUE	20 N-m (14.75 lb-ft)	3.8 N-m (2.8 lb-ft)
		ACCURACY		0.1 degree
		REPEATABILITY		0.02 degree
MANIPULATION	GRAB / HOLD / RELEASE	DISPLACEMENT	7.5 cm (3 in)	0
		MASS	2.25 kg (5 lb)	0.0045 kg (0.01 lb)
		SIZE	10 cm (4 in)	0.32 cm (0.13 in)
		FORCE	260 N (59 lbf)	1.4 N (0.3 lbf)
	CONTACT	SENSITIVITY	10 N (2.2 lb)	0.01 N (0.0022 lb)
	USE	TRACKING FREQUENCY		1 Hz
		DAMPING RATIO		0.7
ENVIRONMENTAL	ULTRASONIC DETECTION	CONFIGURATION		COMBINED TRANSMITTER/ RECEIVER
		RANGE	1.5 M (5 ft)	0.3 m(1 ft)
		RESOLUTION		0.3 cm (0.12 in)
	INFRARED DETECTION	CONFIGURATION		FOCUSED RECEIVER
		RANGE	1.5 M (5 ft)	0.3 m(1 ft)
		RESOLUTION	2.5 cm (1 in)	7.5 degrees
	VISUAL	CONFIGURATION		TWO ORTHOGONAL CAMERAS
		RANGE	2.5 cm (1 in)	12.2 m (40 ft)
		RESOLUTION		0.025 cm (0.01 in)
		FRAME RATE	30 fps	0.5
		GRADATION		256
		SENSITIVITY		3.0 lux (3 ft-c)
	AUDIO	RANGE		VOICE OUTPUT / TONE OUTPUT
		RESOLUTION		VOICE INPUT
		(INPUT)		12.2 m (40 ft)
				100 Words, speaker independent

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TABLE 2-2. SAMPLE HANDLING REQUIREMENTS

FACILITY	SAMPLE MATERIAL	SAMPLE DIA X THK (CM)	MAXIMUM TENSILE FORCE (LBS)	MAXIMUM COMPRESS FORCE (LBS)*	MAXIMUM TORQUE (IN-LBS)	COMMENTS
ACOUSTIC LEVITATOR	FLUORIDE GLASSES	1.0 X 1.0	N/A	150	17	BRITTLE MATERIAL
ALLOY SOLIDIFICATION	FOAMED ALUMINUM	2.0 X 2.0	17	31	6.7	FOAMED MATERIALS HAVE LOW STRENGTHS
ATMOSPHERIC MICROPHYSICS	WATER AND ICE	0.5 X 0.01	0.95	0.084	0.32	NOT DIRECTLY HANDLED, VALUES FOR CONTAINER
CONTINUOUS FLOW ELECTRO.	BLOOD CELLS	0.5 X 0.01	0.95	0.084	0.32	HANDLED THROUGH A CONTAINER MUST BE REFRIGERATED
DROPLET SPRAY BURNING	TOLUENE	0.5 X 0.01	0.95	0.084	0.32	SAMPLE WILL NOT BE HANDLED VALUES FOR CONTAINER
FLOAT ZONE	GALLIUM ARSENIDE	2.0 X 2.0	15**	15**	5**	FREE ARSENIC IS A TOXIC MATERIAL
FLUID PHYSICS	SILICONE OILS	6.0 X 0.1	114	0.70	92.64	HANDLED THROUGH A CONTAINER. VALUES FOR CONTAINER
LARGE BRIDGMAN	MERC.- CAD-TELLURIDE	8.0 X 8.0	750	150	100	FREE Hg, Cd and Te ARE TOXIC MATERIALS
PROTEIN CRYSTAL	INTERFERON	0.05 X0.001	0.0095	0.0084	0.00032	SAMPLE WILL NOT BE HANDLED VALUES FOR CONTAINER
VAPOR CRYSTAL	MERCURIC IODIDE	0.5 X 0.5	0.95	0.084	0.32	TOXIC MATERIALS VALUES FOR CONTAINER

* COMPRESSIVE FORCE IS CALCULATED AT 1/5 THE COMPRESSIVE STRENGTH WITH A PAD OF 1/2 THE SAMPLE/CONTAINER DIAMETER

** LOCAL EFFECTS GREATLY REDUCE LOADS DUE TO THE LACK OF AN AMPOULE.

TABLE 2-3. LABORATORY SUPPORT EQUIPMENT

ID NUMBER:	EQUIPMENT NAME:
SUP-01	Battery Charger
SUP-02/03	Camera/Camera Locker
SUP-04	Centrifuge, Refrigerated
LAB-01	Chemical Supply Storage Facility
SUP-05	Cleaning Equipment
SUP-06/14	Cutting/Polishing System
CHR-01	Differential Scanning Calorimeter
SUP-07	Dimensional Device(s)
CHR-02	Electrical Conductivity Probe
CHR-03	Ellipsometer
SUP-08	Etching Equipment
SUP-09	Fluid Handling Tools
CHR-04	FTIR (Fourier Transform Infrared)
SUP-10	Freeze Dryer
SUP-11	Freezer
CHR-05	Gas Chromatograph - Mass Spectrograph
LAB-02	Glovebox, Materials Processing
CHR-06	Hall Probe
CHR-07	High-Performance Liquid Chromatograph (HPLC)
SUP-12	Incubator
SUP-13	Mass Measurement Device, Small
CHR-08	Microscope System
CHR-09	Nuclear Magnetic Resonance Spectrometer
CHR-10	Optical Refractometer
CHR-11	pH Meter
SUP-16	Refrigerator
CHR-12/SUP-17	Scanning Electron Microscope
SUP-18	UV Sterilization Unit
CHR-13	UV/VIS/NIR Spectrometer
LAB-03	Video Facilities
LAB-04	Waste Disposal System
LAB-05	Water Deionizer/Depyrogenizer
CHR-14	X-ray Facility - General Purpose

TABLE 2-4. DISTURBANCE DATABASE

LOW GRAVITY DISTURBANCES
TO THE SPACE STATION

DATE:08/06/88

ACTION / LOCATION	FORCE (lbs)	LOCATION (feet from CG) X	Y	Z	NOTES
Additude control / Along station flight path.	-0-	0.00	0.00	0.0	Based on shuttle experience loads will be 1.0E-3g or greater.
	TYPE:-0- FREQUENCY MAX: 10.0000 FREQUENCY MIN: 0.10000				
Aerodynamic force / Along leading edge of station.	-0-	0.00	0.00	0.0	total g disturbance is 10-6 to 10-8 g.
	TYPE:-0- FREQUENCY MAX: 0.00034 FREQUENCY MIN: 0.00030				
Bone Density Measurements / US Lab.	0.1000	65.5	23.0	23.	Bone density will be performed to determine the crew condition.
	TYPE:Impulse FREQUENCY MAX: 1.00000 FREQUENCY MIN: 0.10000				
Computer data entry. / Resource Node.	0.1000	98.5	23.0	82.	Data may be entered into the computer at any of several locations in the SS.
	TYPE:Impulse FREQUENCY MAX: 10.0000 FREQUENCY MIN: 0.10000				
Crew Exercising. / Hab Module.	150.00	65.5	23.0	82.	Crew using exercise equipment. Force limited to crew weight.
	TYPE:Impulse FREQUENCY MAX: 1.00000 FREQUENCY MIN: 0.10000				
Docking / Along station flight path.	-0-	0.00	0.00	0.0	Based on shuttle experience loads will be 2.0E-2g or greater.
	TYPE:-0- FREQUENCY MAX: 0.01000 FREQUENCY MIN:-0-				

ACTION / LOCATION	FORCE (lbs)	LOCATION (feet from CG) X	Y	Z	NOTES
Draw blood from crew. / US Lab.	0.1000	65.5	23.0	23.	Blood will be drawn for analysis of crew condition.
	TYPE: Impulse FREQUENCY MAX: 1.00000 FREQUENCY MIN: 0.10000				
Gravity Gradient / Along lines of Stations CG away from	-0-	0.00	0.00	0.0	total g disturbance is 10-5 to 10-7 g.
	TYPE:-0- FREQUENCY MAX: 0.00010 FREQUENCY MIN: 0.00000				
light pressure / light side of station's exterior	-0-	0.00	0.00	0.0	total g disturbance is 10-8 to 10-9 g.
	TYPE: light pressure FREQUENCY MAX: 0.00017 FREQUENCY MIN: 0.00015				
Mass Dumping / Various	-0-	0.00	0.00	0.0	Based on shuttle experience loads will be 1.0E-3g or greater.
	TYPE:-0- FREQUENCY MAX: 10.0000 FREQUENCY MIN: 0.10000				
Measurement of Retnal Stone Risk Fa / US Lab.	0.1000	65.5	23.0	23.	Measurements will be taken to determine the crew condition.
	TYPE: Impulse FREQUENCY MAX: 1.00000 FREQUENCY MIN: 0.10000				
OMV Docking. / Resource Node.	25000.	98.5	23.0	82.	OMV docking may force the experiments to stop operations.
	TYPE: Impulse FREQUENCY MAX: 10.0000 FREQUENCY MIN: 0.10000				

ACTION / LOCATION	FORCE (lbs)	LOCATION (feet from CG) X	Y	Z	NOTES
Pumps Transients / Various	-0-	0.00	0.00	0.0	Based on shuttle experience loads will be 5.0E-4g or greater.
	TYPE:-0- FREQUENCY MAX: 10.0000 FREQUENCY MIN: 0.10000				
Rack change-out / In the USL	150.00	65.5	23.0	23.	Crewman moving the rack in and out of the lab. Maximum force limited to crew.
	TYPE:Impulse FREQUENCY MAX: 1.00000 FREQUENCY MIN: 0.10000				
Rack subsystem installation / In the USL	50.000	65.5	23.0	23.	Crewman connecting the rack utilities to the structure. Force limited to crew.
	TYPE:Impulse FREQUENCY MAX: 1.00000 FREQUENCY MIN: 0.10000				
Rack subsystem Operations. / In the USL	50.000	65.5	23.0	23.	Rotating hardware, such as pumps, fans, and other reciprocating equipment.
	TYPE:Continuous FREQUENCY MAX: 100.000 FREQUENCY MIN: 1.00000				
Reboost / Along station flight path.	25.000	0.00	0.00	0.0	-0-
	TYPE:-0- FREQUENCY MAX: 0.01000 FREQUENCY MIN:-0-				
Shuttle Docking. / Resource Node.	.230E6	98.5	23.0	82.	Shuttle docking will force the experiments to stop operations.
	TYPE:Impulse FREQUENCY MAX: 10.0000 FREQUENCY MIN: 0.10000				

ACTION / LOCATION	FORCE (lbs)	LOCATION (feet from CG) X	Y	Z	NOTES
Skeletal Growth of Rats- Group selc / US Lab.	0.1000	65.5	23.0	23.	Movement of rats into groups after 20 days on-orbit.
	TYPE:Impulse FREQUENCY MAX: 1.00000 FREQUENCY MIN: 0.10000				
Skeletal Growth of Rats- Injection / US Lab.	0.0500	65.5	23.0	23.	Injection of the various groups with various drugs for controlled experiments.
	TYPE:Impulse FREQUENCY MAX: 1.00000 FREQUENCY MIN: 0.10000				
Skeletal Growth of Rats- move setup / US Lab.	0.1000	65.5	23.0	23.	Movement of the rats to and from their cages.
	TYPE:Impulse FREQUENCY MAX: 1.00000 FREQUENCY MIN: 0.10000				
Skeletal Growth of Rats- Tissue ret / US Lab.	0.0500	65.5	23.0	23.	Injection of the various groups with various drugs for controlled experiments.
	TYPE:Impulse FREQUENCY MAX: 1.00000 FREQUENCY MIN: 0.10000				

3. ANALYSIS OF EFFECTS OF LOW-GRAVITY MANIPULATION

After the definition of the user requirements for low acceleration and manipulation, the second task in this study was the analysis of the effects of the required manipulations on both the general acceleration environment and to experiment samples being manipulated. To do these analyses a reduced set of three experiments was selected. The basic questions were:

1) how much do experiment operations disturb one another;

2) what are the base reaction forces from robotic actions;

3) what are the end-effector accelerations on samples; and

4) how do robot disturbances compare to other ambient sources?

3.1 EXPERIMENT/PROCESS SELECTION

After a thorough review of the ten typical MMPF experiments, three were identified as the ones for further, in-depth analysis. A brief description of all ten is found in Appendix 9.1. The selected experiments facilities and the rationale for their selection is as follows:

1) Large Bridgman Furnace (LBF) - a two double rack wide facility with a massive 1800 kilogram assembly which must be opened between runs; the experiment is sensitive to 10E-6 g during operation and it is clearly a disturbance threat to its neighbors during door opening or closing;

2) Protein Crystal Growth (PCG) Facility - a multichambered facility which can grow between 50 and 200 protein crystals during a single run; the samples are manipulation sensitive both during and after growth to 10E-4 g;

3) Fluid Physics (FP) Facility - an unique facility which contains a module to be released as a free-flyer during certain experiment operations to determine fluid behavior at very low g.

The stepwise timelined functional flows for these three experiments is found in Appendix 9.3. It was determined that these three experiments placed the most challenging requirements on the potential robotic manipulation system. They present a large range of difficult manipulations including handling a 1800 kilogram door, moving a small delicate crystal and releasing a low g free-flyer with little or no residual acceleration. These experiments also have low-g requirements during their operation and after growth, as in the case of PCG, and are therefore sensitive and susceptible to outside disturbances.

3.2 DEFINITION OF LOW-GRAVITY LEVELS

In order to determine a range of low g levels for robotic systems that are required and achievable, the user stated requirements, station ambient environment and state-of-the-art robotic systems and components must be analyzed.

The user community is asking for a 10E-6 g quiescent acceleration level during processing and is particularly concerned with the frequencies below 1 Hertz. Based on the PCG experiment requirements there is also a requirement for post processing sample handling at 10E-4 g or less.

Thus, there are two problems to be solved by any robotic manipulation system:

1) manipulation without transferring disturbances through the robotic base attachment to the laboratory, and

2) direct manipulation with the robotic end-effector without disturbing the experiment or samples.

In terms of expected station dynamic environment, during the earlier part of this study the SSPVU Study was the source of the JSC WP02 space station dynamic model. That model showed the station's natural frequency to be about 2/3 Hertz. Recently the LaRC model has been used to confirm and expand the earlier analyses, and it shows a station natural frequency even lower, at about 1/6 Hertz. The low-g experimenters will not find these predictions to their liking since they would like the resonance to be as high as possible and preferably greater than 1 Hertz.

State-of-the-art robotic systems and components are exemplified in the Intelledex 660 system. It is designed for precise, clean laboratory operations and uses both stepper motors and harmonic drives. As will be seen later in the laboratory measurements, Section 4.0, this excellent system, even in the fine microstepping mode, still produces milligravity level acceleration.

3.2.1 Robot Base Reaction Force Analysis - Based on elementary laws of physics, for every action there is an equal and opposite reaction. This means that all proposed manipulations (acceleration and deceleration of mass) have an undesired counter acting acceleration of mass. For example, for a crewman or a robot to move themselves they must push or pull against the laboratory which is in turn moved in the opposite direction. The mass of the laboratory and station is far greater than the man or the robot and the resultant station acceleration is well below human perception. Though not perceived by humans these accelerations can be measured and they can pose a problem to certain very low-g experiments. In simple terms the problem can be seen as a 200 pound crew member accelerates from zero to a velocity of one foot per second in 1/3 of a second by pushing through the centerline of a 200,000 pound space station. The resultant space station acceleration, A, is:

$$m \times a = M \times A$$
$$200 \times (1 \div 1/3) = 200000 \times A$$
$$A = 200/200000 \times 3$$
$$A = 3 \times 10E{-3}\ ft/sec/sec$$
$$\text{or}\quad A = E10{-4}\ g$$

This example is much simpler than reality because forces are rarely through the centerline, thus yielding rotational torques, and the structure of the station is not a rigid body and will exhibit various modes of X, Y, Z and torsional/rotational damped oscillations as it moves away from the stimulating force.

The key factors influencing the dynamic response of a given experiment to robotic manipulation are as follows:

1) total station mass,
2) station center of gravity (c.g.) or center of mass,
3) location of disturbance source from station c.g.,
4) location of experiment from station c.g.,
5) station mass moments of inertia,
6) disturbance frequency,
7) station natural frequency and other resonances,
8) station structural damping factors and berthing mechanism stiffness between modules, and
9) local vibrational isolation of the source or of the experiment.

To understand the potential impact of required manipulations on the low-g environment via base reactions (accelerations transferred into the laboratory module by way of the robot mounting base), a robot manipulator computer model was built to examine reaction forces to be expected from required manipulations.

For this simulation the translation of the LBF experiment's 1800 kilogram mass was rounded up to 2000 kg (includes robot and sample mass) and was taken as a worst case manipulation scenario for evaluation. The NASTRAN model from the Space Station Pressurized Volume Utilization Study, Figure 3-1, was used early in this study. Recently Langley Research Centers' OF-2 configuration model with alpha and beta joints, Figure 3-2, was used. The robot arm model was based on a PUMA industrial manipulator since it's dynamic characteristics are well documented.

By combining the load and trajectory, robot, and space station models the following cases were analyzed:

1) SSPVU model - a. forcing function for a fixed robot with direct and elastic coupling, and
   b. forcing function for a fixed crewman based on a 50 pound force with direct coupling to station.

2) OF-2 model - c. forcing function for a floating crewman based on 25 pound step push-off, and
   d. forcing function for 250 pound impulsive force.

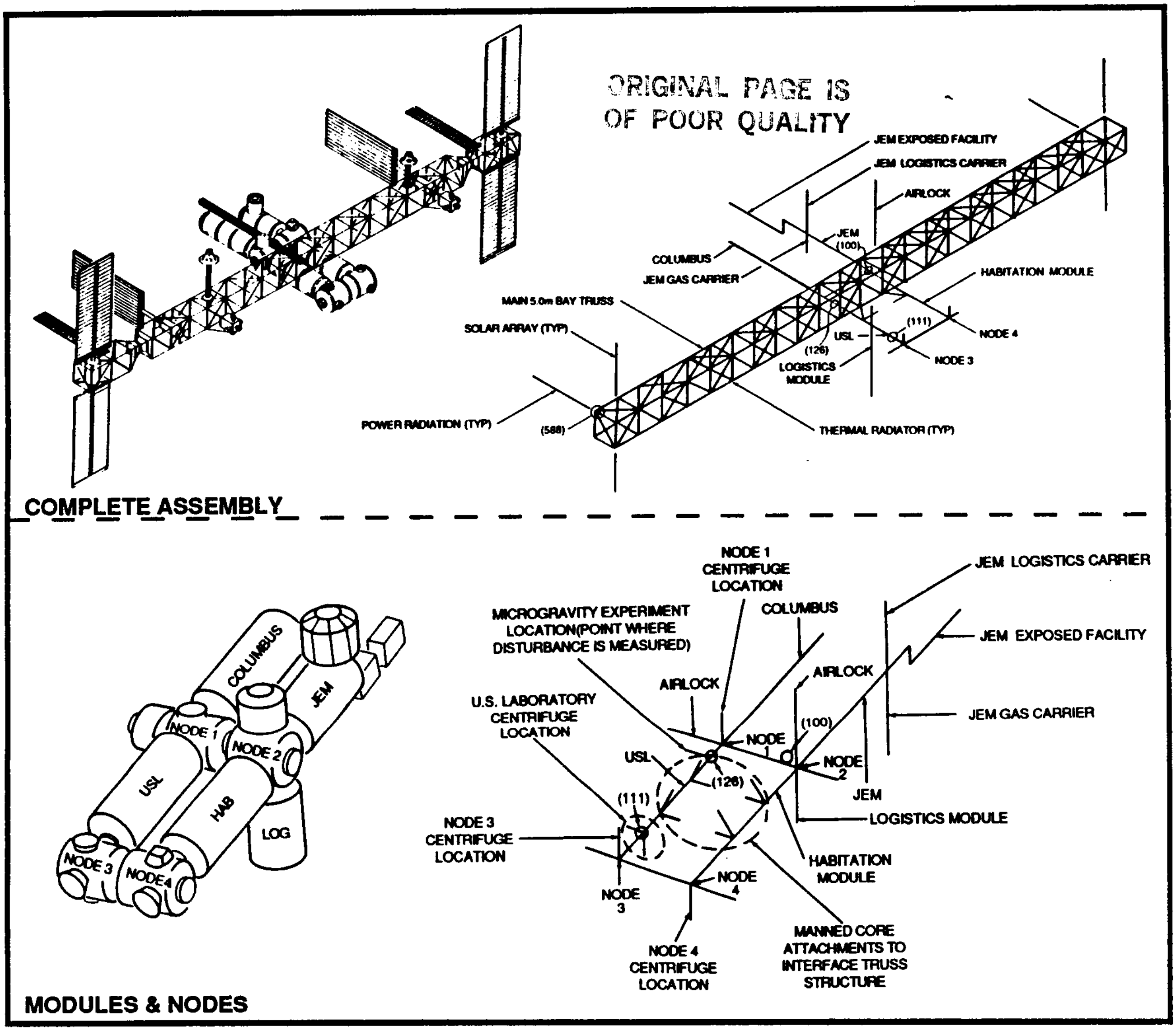


FIGURE 3-1. SSPVU SS NASTRAN MODEL (1986)

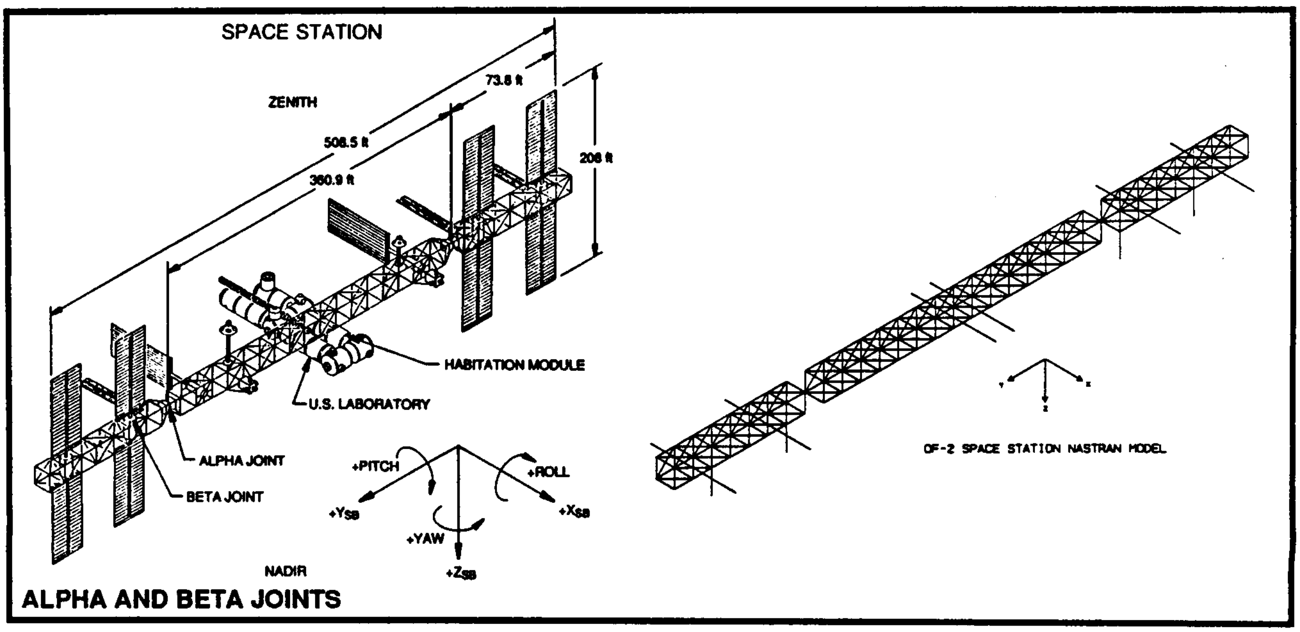
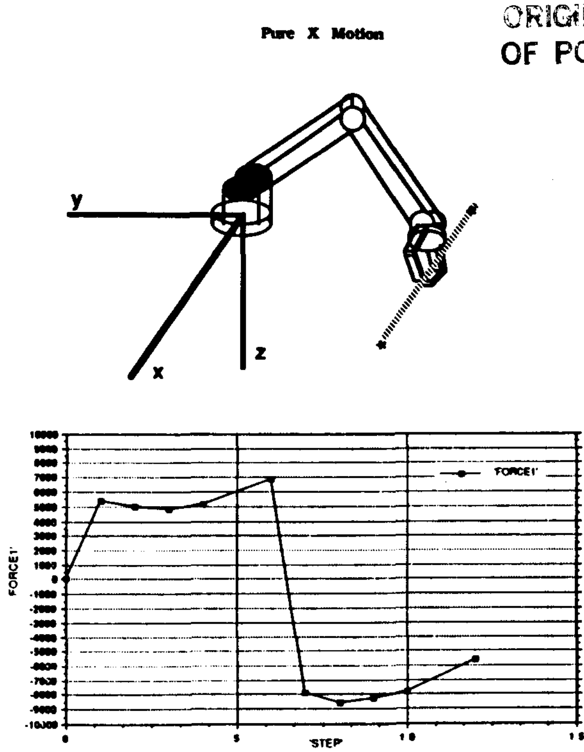
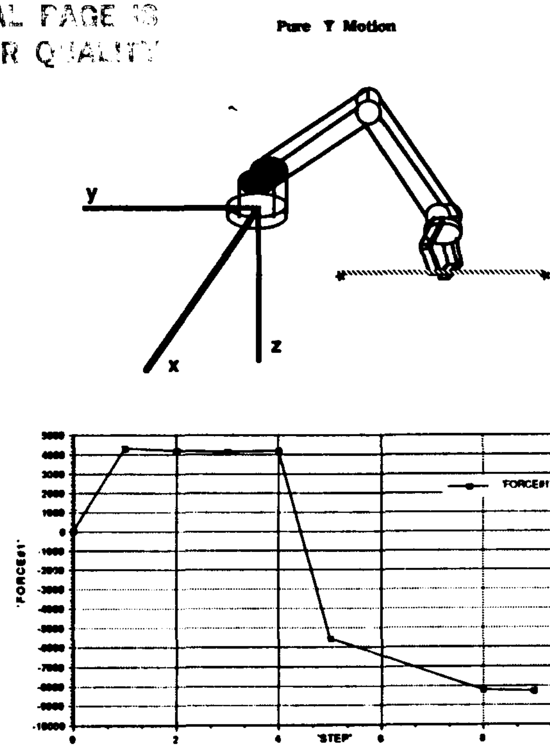


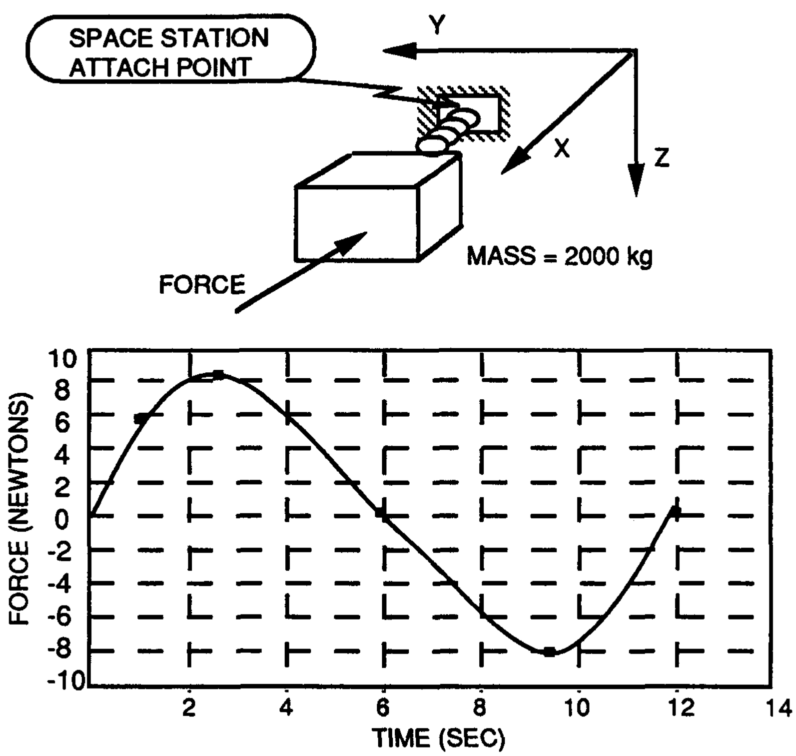
FIGURE 3-2. LaRC 1988 SS NASTRAN MODEL (OF-2)



(a)DIRECT MANIPULATOR FORCING FUNCTION IN X DIRECTION



(b)DIRECT MANIPULATOR FORCING FUNCTION IN Y DIRECTION



(c) USING ELASTIC COUPLING

FIGURE 3-3. FORCING FUNCTION COUPLING REACTIONS FOR LABORATORY MANIPULATORS

These fixed robot analyses were based on three manipulations of the LBF experiment's assembly imparting motion in a pure X and then a pure Y direction. An elastically coupled evaluation was performed by sinusoidal displacement of a point mass by +/- one meter in the X direction. The resulting robot base reactions are shown in Figure 3-3.

Other forcing functions were analyzed with impulses of 3.0, 1.0 and 0.1 seconds duration. These simulated the impact of various moving masses, including crew movements, on the laboratory structure in each of the three axes. Tables 3-1 and 3-2 summarize the results of these analyses. The slower the push-offs, the lower the acceleration, but also the lower the impulsive input frequency to the station. In the case of elastic coupling, the elastic element stiffness (i.e., robot base to station) was varied between 100 and 500 N/m. The results indicate a direct correlation between stiffness and disturbance acceleration amplitude and frequency, such that as the stiffness increases, so does the acceleration amplitude and frequency.

Figure 3-4 shows representative time histories of the laboratory response of a robot step forcing function in the X direction. The model indicates a wide range of acceleration responses from 400 to 5,000 micro-g's depending on the position and direction of the forcing function. A peak acceleration of 6,000 micro-g's is reached during the rigid body response (the first 12 seconds).

Figure 3-5 shows representative time histories of the response of the OF-2 station model to a crewmember push-off in the X direction at the aft of theUSL. The magnitude was 25 pounds at a duration of one second. The resonant frequency in this model is 0.15 Hertz where the SSPUV model was 0.7 Hertz.

A key feature of all these analyses is the finding that regardless of the characteristics of the input stimulus, the space station structure tends to absorb the energy and convert it to the resonant frequency. Thus, all disturbances, of whatever frequency, should be avoided to minimize the absorption and conversion of energy to the low frequency station resonance. Also note that the lower the actual space station resonant frequency turns out to be, the longer the damping time to be expected from disturbances. Such a structurally "floppy" space station provides a less than desirable low-gravity environment for the scientific community.

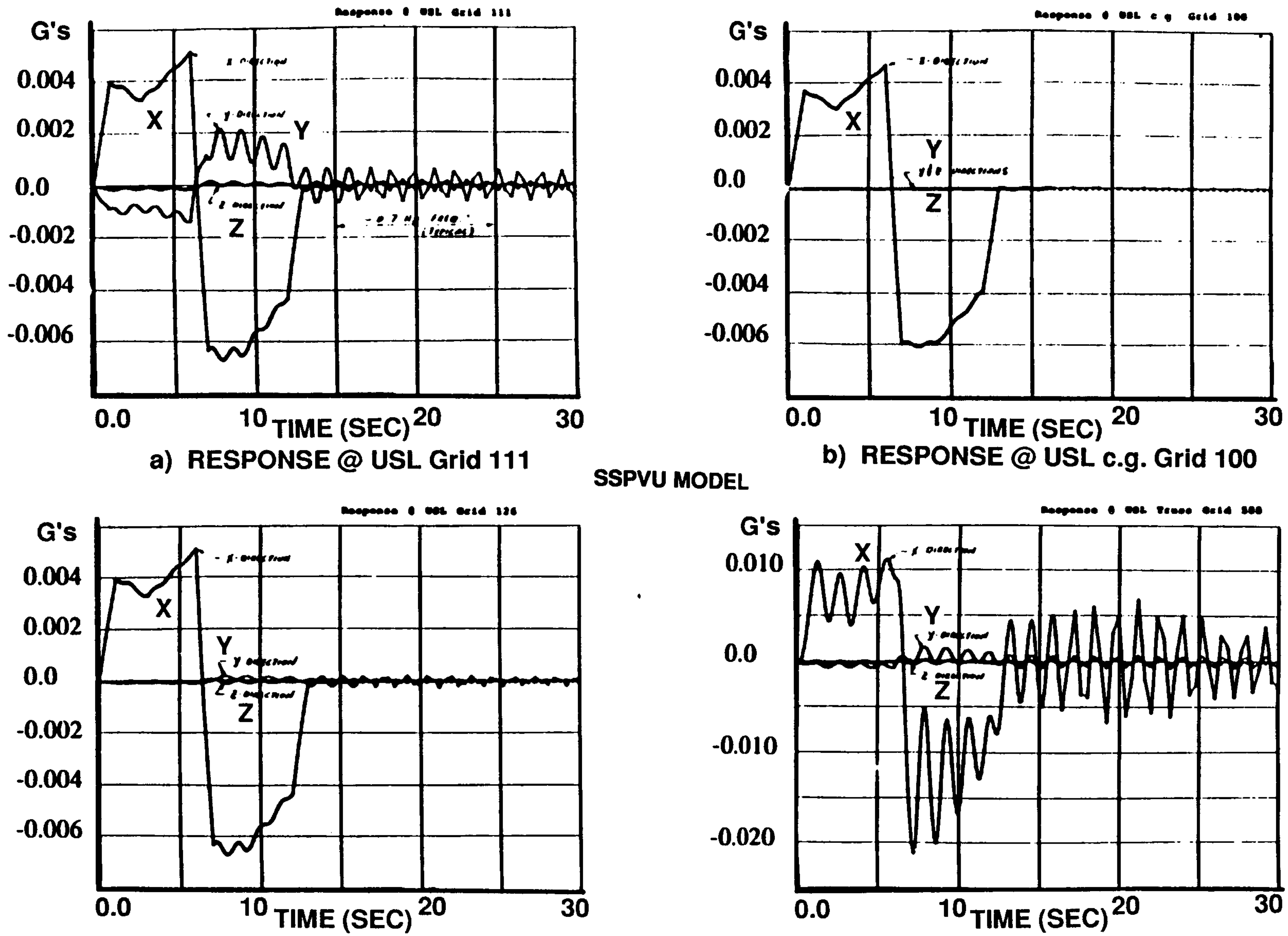
3.2.2 Robotic Manipulation of Samples and Analysis - With base reactions there are isolation methods to minimize the coupling of disturbing reaction forces originating within the robot and carrying through the laboratory structure to the experiment and the sample being processed. When the robot is required to directly manipulate a sample the isolation possibilities are limited. The last motor and its gears in the wrist joint are likely to be the limiting factor in determining the minimum acceleration capability of the robot in question. Thus, for any low-g robotic system, the capabilities of motor and gear assemblies are key to determining how "good" the system is for direct low-g manipulation.

FIXED ROBOT										
FORCING FUNCTION			WORST-CASE RESPONSE (MICRO-G'S)							
LOC AXIS	COUPLING	PROFILE	@USL-FWD		@USL-AFT		@CG		@ TRUSS-END	
			PEAK	DYNAMIC	PEAK	DYNAMIC	PEAK	DYNAMIC	PEAK	DYNAMIC
USL-AFT X	DIRECT	STEP	5,000(X)	300	5,000(X)	300	3,700(X)	100	20,000(X)	5,000
USL-AFT Y	DIRECT	STEP	3,100(Y)	200	3,000(Y)	180	2,800(Y)	100	3,000(Y)	750
USL-AFT X	DIRECT	SINUSOIDAL	5,700	12	--	--	--	--	15,000	300
USL-AFT X	ELASTIC (K=100)	SINUSOIDAL	0.12	--	--	--	--	--	0.25	--
USL-AFT X	ELASTIC (K=500)	SINUSOIDAL	0.6	--	--	--	--	--	--	--
FIXED CREWMEMBER										
USL-AFT X	DIRECT	STEP	177	10	175	8	150	10	680	390

TABLE 3-1: WORST-CASE ACCELERATION RESPONSE SUMMARY FOR FIXED ROBOT AND CREWMEMBER (SSPVU NASTRAN MODEL)

FORCING FUNCTION				WORST-CASE RESPONSE (MICRO-G'S)					
LOC	AXIS	COUPLING	PROFILE	@USL-FWD		@USL-AFT		@CG	
				PEAK	DYNAMIC	PEAK	DYNAMIC	PEAK	DYNAMIC
USL-FWD	X	DIRECT	25-lb STEP(1 sec)	60	30(Y)	60	14	54	7
USL-FWD	Y	DIRECT	25-lb STEP(1 sec)	133	116	45	29	50	13
USL-FWD	Z	DIRECT	25-lb STEP(1 sec)	162	48	75	46	54	21(Y)
USL-FWD	X	DIRECT	250-lb IMPULSE (0.1 sec)	600	64(Y)	600	28	540	14
USL-FWD	Y	DIRECT	250-lb IMPULSE (0.1 sec)	1,333	259	467	65(X)	424	20
USL-FWD	Z	DIRECT	250-lb IMPULSE (0.1 sec)	1,626	110	751	105	544	49(Y)
USL-AFT	X	DIRECT	25-lb STEP (1 sec)	60	30(Y)	60	4	54	7
USL-AFT	Y	DIRECT	25-lb STEP (1 sec)	45	12	49	12	49	6
USL-AFT	Z	DIRECT	25-lb STEP (1 sec)	76	47	77	47	53	21(Y)
USL-AFT	X	DIRECT	250-lb IMPULSE (0.1 sec)	335	67(Y)	335	26	260	13
USL-AFT	Y	DIRECT	250-lb IMPULSE (0.1 sec)	489	26	474	26	417	15
USL-AFT	Z	DIRECT	250-lb IMPULSE (0.1 sec)	606	109	744	122	482	54

TABLE 3-2: WORST-CASE ACCELERATION RESPONSE SUMMARY FOR FREE-FLOAT CREWMEMBER AND/OR OBJECT (OF2 NASTRAN MODEL)



a) RESPONSE @ USL Grid 111

b) RESPONSE @ USL c.g. Grid 100

c) RESPONSE @ USL Grid 126

d) RESPONSE @ TRUSS Grid 500

FIGURE 3-4. RESPONSES TO X-AXIS FORCE APPLIED AT GRID 126

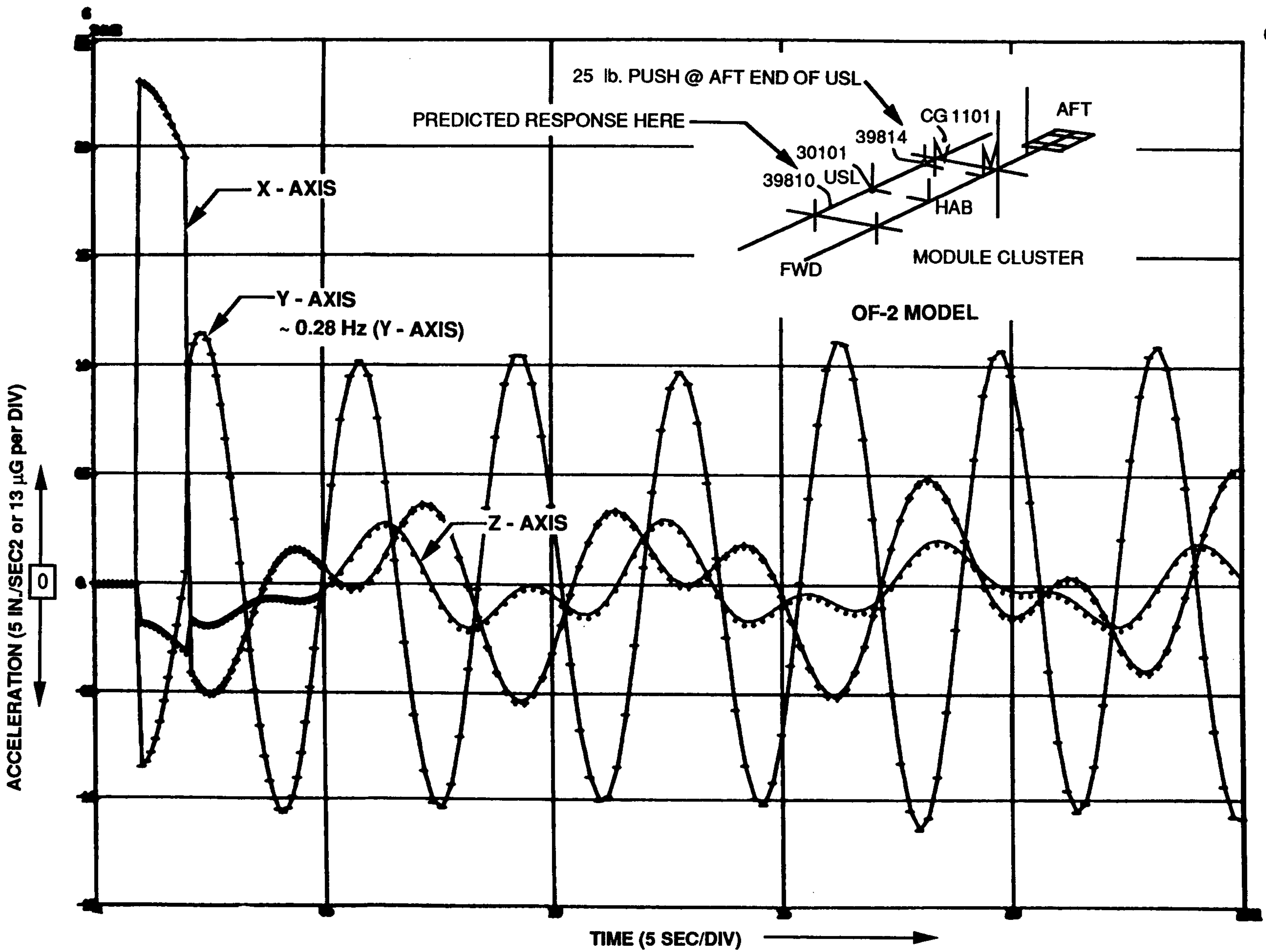


FIGURE 3.5 a. SPACE STATION OF2 BASELINE DYNAMIC BALANCE TIME AND μ-g.

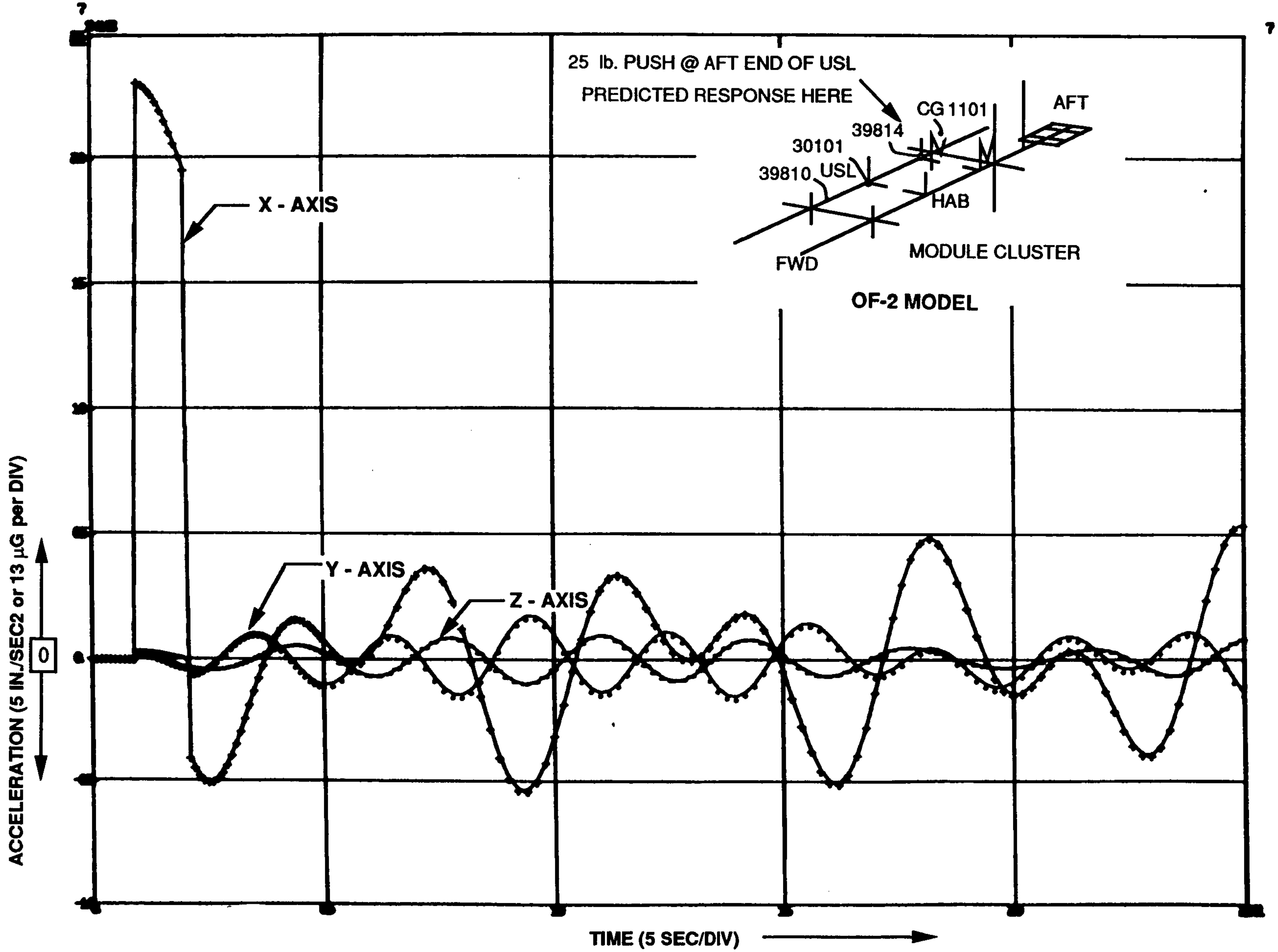


FIGURE 3.5 b. SPACE STATION OF2 BASELINE DYNAMIC BALANCE TIME AND μ-g.

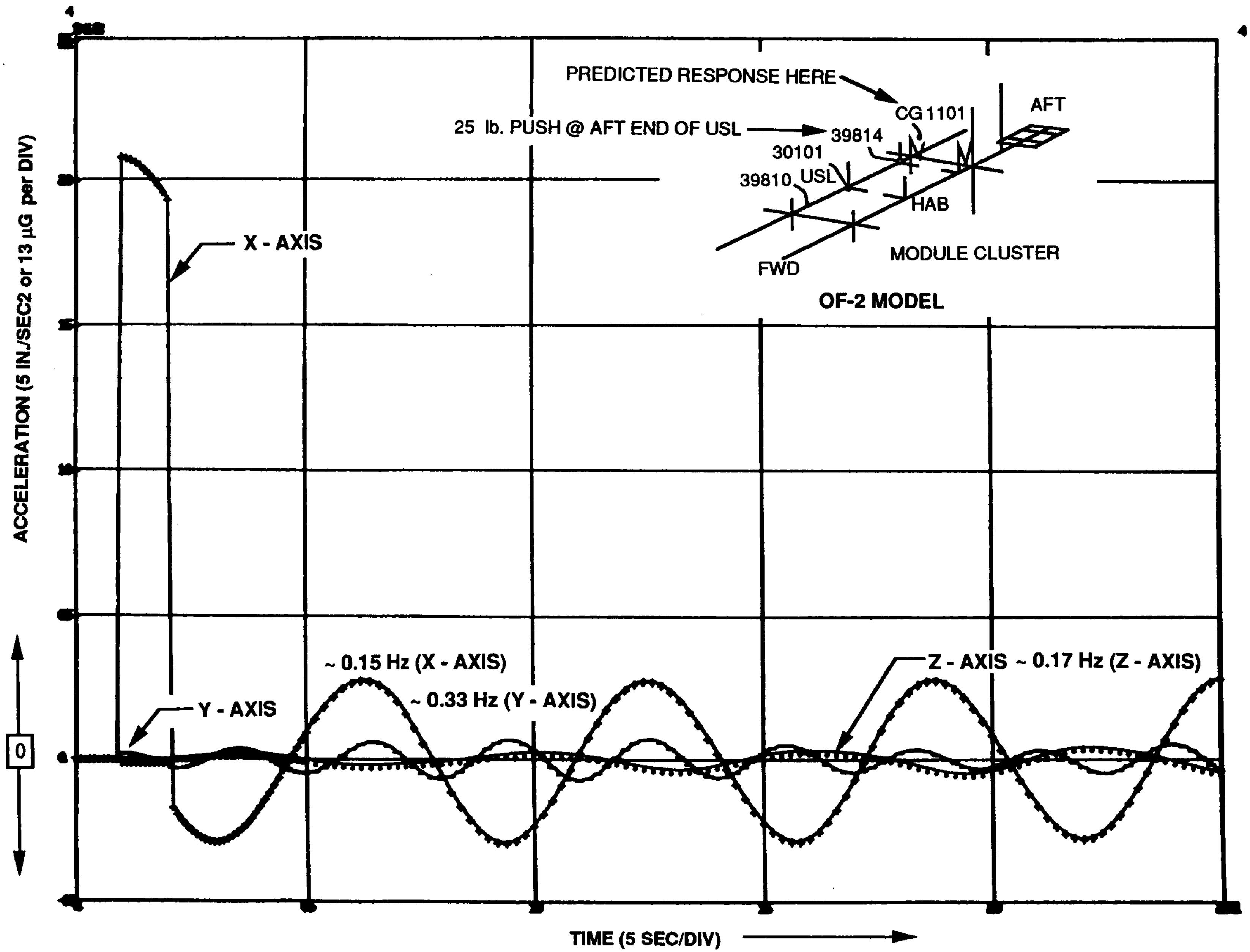


FIGURE 3.5 c. SPACE STATION OF2 BASELINE DYNAMIC BALANCE TIME AND μ-g.

Many types of motor and gear systems are available and currently in use. The servo and stepper motor systems are the most popular and are often combined with pinion, worm, screw or harmonic gears. Each has advantages and limitations. Most have varying degrees of backlash or "slop" when changing direction. Some are backdrivable and some are not (backdrivable is a safety advantage in a manned and changing physical environment).

To evaluate direct robotic manipulation, the Intelledex 660 waschosen since it possessed an anthropomorphic arm with harmonic drive wrist. This made it appear to have the low-gravity manipulation characteristics desired. The Model 660 had been chosen for use in the Teledyne Brown Engineering Robotics Laboratory in 1986 for these and other reasons, such as being clean room and vacuum rated. Data on it was, therefore, on file and readily available.

In the analysis of the Model 660, the dynamics were assumed to be pure Lagrangian, with rigid members and point masses. Intelledex supplied data from which was derived mass, c.g., and moments of inertia for the robot arm segments. Stepper motor data from the joint motor manufacturer, Superior Electric, were used to define joint torque during microstepping. Viscous and coulomb friction information was not available and had to be estimated. Based upon the model generated using these data, the end-effector acceleration was predicted.

Table 3-3 contains performance data on the Model 660 which reveals its performance is quite good in conventional terms. Robots are generally designed for accuracy and repeatability for use in high speed "pick and place" assembly line applications. These characteristics of speed and repeatability are not those required by a robotic system designed for space applications that include diverse tasks requiring very low acceleration.

Using the above data (but assuming a minimum step of 0.0001 degrees) and mathematical analyses, the predicted minimum acceleration is 3.6 milli-g. This analysis is given in Appendix 9.4.

ACCURACY:	+/- 0.002 IN.
REPEATABILITY:	+/- 0.001 IN.
AXES:	6
ANGULAR RESOLUTION (MOTOR):	0.0001 DEGREE (JOINT 0)
ANGULAR RESOLUTION (ENCODER):	0.0018 DEGREE (JOINT 0)
LINEAR RESOLUTION (TIP):	0.0005 IN.
REACH RADIUS:	29.1 IN.
ACTUATOR:	STEPPER MOTOR (JOINT 0 - SUPERIOR ELECTRIC MODEL M093FD409

TABLE 3-3. INTELLEDEX 660 ROBOT CHARACTERISTICS

3.3 RELATIVE MERITS OF LOW-GRAVITY ROBOTIC MANIPULATION

From the Space Station Phase B Study, the estimated available laboratory crewtime is approximately 8 hours per day, for each of two men in an 8 crew station. Over a 90 day mission, 75 days of which are usable (no shuttle, OMV, EVA, maintenance or logistics activity) this yields 1200 hours. Some evaluations of servicing and maintenance indicate 1200 hours may be optimistic and the real crewtime availability is closer to 900 hours. Based on the crewtime summaries for various experiment complements, in excess of 2000 hours of crewtime is required just for the desired US Laboratory low-gravity experiment operations. This does not include international and external user operations.

If the crewtime shortage was the only reason for proposing a robot for the space station, it would clearly be justifiable. This is not the only reason, however. Another key merit of robotics is that by analysis it was shown to be capable of milligravity operations on a par with or better than the humans, since the robot also does not contribute to the impulsive, push-off disturbance category to the extent the crew does during normal work and especially in exercise periods. The robot system will work around the clock, seven days a week where the crew does not. It can be designed to operate safely in the presence of crew; it can do tedious chores and pick up after the crew; it can operate in hazardous conditions should an accident occur in the lab; it can even provide a measure of improved safety since it can provide crew retrieval and transport in case of debilitation. And it can do these things at milligravity and lower accelerations.

The key advantages that robotics provides in a low-g laboratory environment is:

1) the ability to move and manipulate objects in a precise, non-disturbing, minimum reaction force fashion,

2) the low-gravity manipulation of sensitive samples;

3) pre-programmable and ground control at varying and appropriate limits of disturbance, which is not practical or possible with human crew members.

In Section 5.0, Assessments of Benefits, a more detailed presentation of these findings is given. Several of the pertinent analyses are also in the appendices.

3.4 COMPARING DISTURBANCES FROM OTHER SOURCES

Based on the collection of disturbances identified in Task I and reported in section 2.7 of this report, and based on the analysis of robot and crew motions in section 3.2, it is now possible to compare the relative magnitudes of these disturbances with the analyzed state-of-the-art robot.

The large mass movements and docking activities of Shuttle, OMV, Logistics module and MSC/MRMS are clearly disturbing to any low gravity laboratory experimentation. The empty weight of the Orbiter is 160,000 pounds and with OMS fuel and payload is about a quarter million pounds and beginning to rival the Space Station weight. The OMV is about 25,000 pounds and may carry payloads of 40,000 pounds. The loaded logistics module may weigh 40,000 pounds. The total MSC/MRMS weight is unknown to these authors but it must be able to handle payloads such as the Log module, OMV, etc., and might easily be as much as 15,000 pounds.

Based on current system designs and considering the mass it is evident that these systems can not be moved about without significant disturbance to the low-gravity space station laboratory environment.

Operation of the attached payload experiments presents potential for disturbance to the low-g environment. This is primarily due to the outside pointing experiments which include earth viewing, solar and astronomical instruments. Based on prior experiences with Skylab and Spacelab missions, instruments with common viewing requirements will generally be clustered together and co-aligned on a pointing platform. The fully loaded instrument pointing platform may be 10,000 to 20,000 pounds. With each orbit the instrument pointing platform will be slewed to pick up the next in a list of targets. Slewing of such a massive system would impart acceleration disturbances in excess of a laboratory robotic system. In addition lower level acceleration can be generated by the simple tracking process as the platform points at a target while the station moves in it's orbit. During active pointing the instrument pointing platform itself will be trying to minimize coupling to the station to provide vibration free images.

Internal station experiments will also provide a source for low-gravity disturbances. Experiments such as life sciences that require animals and crew activity to establish or collect data are potentially more disturbing than the robotic manipulation system. The life sciences centrifuges and animals are a potential source for vibrational and impulsive disturbances. Much has been written about the potential for vibration isolation mechanisms and techniques but very little relevant data has been published about performance in flight conditions. These techniques, however, are currently being evaluated and considered for use by Lewis Research Center and Teledyne Brown Engineering.

Finally, the basic station subsystems are a potential source for almost continuous low-g acceleration disturbance. The number, size and location of pumps, fans and other motorized or electromechanical equipment can only be hypothesized until the station's Preliminary Design Review in 1990, but there are likely to be hundreds of them. Some of these will certainly provide significant and measurable accelerations. From our analysis of crew motions in section 3.2, it is clearly evident that crew motions can and will exceed the disturbances generated by the robotic manipulation system.

4. ROBOTIC LABORATORY ACCELEROMETER MEASUREMENTS

At the beginning of this study and based on work with laboratory robots, the authors believed that analysis would show that very fine robotic manipulations would be possible and within the realm of 10E-4 to 10E-5 g with state-of-the-art robotic systems.

However, analysis did not live up to these expectations and it was determined that laboratory testing was required to verify the analytical findings. These laboratory measurements on the Intelledex Model 660 were performed in two steps: first, using a Linear Variable Differential Transformer (LVDT) for displacement measurements; and second, with QA-2000 accelerometers to measure actual acceleration levels. These methods confirmed the analytical modeling results and techniques: 10E-3 g was our minimum acceleration. It should be noted that the Model 660 has various speeds, but all of our measurements were made at the slowest speed to provide the minimum acceleration.

A summary of these acceleration measurements is shown in Tables 4-1 through 4-4. Background and robot mounting table resonances are shown in Table 4-3. Detail source plots are shown in Appendices 9.5 and 9.6.

4.1 EXPERIMENTAL SETUP

The LVDT measurements were made by mounting the instrument to the base joint of the Model 660. The base motor is a stepper motor and was controlled down to "minor displacements" which were about equal to the robot's specified accuracy of 0.002 inch. We also used a "major displacement" which could be observed and was equal to approximately 0.3 inch. The instrumentation setup for these measurements is shown in Figure 4-1. One LVDT was used to measure up to 0.004 inch displacements at the robot base and another was used to measure up to 0.5 inch displacements. Velocity and acceleration were determined from the first and second derivatives of the monitored displacement profiles.

Sunstrand QA-2000 accelerometers were used for robot acceleration measurements and the instruments were configured as shown in Figure 4-2. For these measurements the robot system's encoders were disabled, thus permitting singular microstepping of the joint motors. (Additional discussion on the microstepping problem is found in section 7.2, paragraph 3.) In this system the robot system was decoupled from local disturbances by using four layers of one inch plastic bubble wrap packing material. The accelerometer was mounted at locations 1, 2, 3, and at the end-effector as shown in the photograph, Figure 4-3. A low noise signal conditioning amplifier, using a LF-156 FET operational amplifier was used between the accelerometer and the analyzer.

This same general configuration was also used to collect data on humans. The individuals tested were asked to hold the accelerometer as still as possible between their thumb and fingers, with their arm and hand resting on the robot system table assembly (~400 pounds) while seated in a chair. They were also asked to hold the accelerometer carefully at arms length while seated in a chair.

SENSOR POSITION / ORIENTATION	MOTOR INCREMENT		MAXIMUM ACCELERATION (MILLI-G's)	DOMINANT FREQUENCIES (Hz)	NOTES
	RADIANS	DEGREES			
JOINT 0 BASE	0.000001	0.000057	0.8	7 - 13	ENCODER DISABLED
	0.0002	0.0115	1.8	20 - 42	ENCODER ENABLED
	0.05	2.86	16	4 - 30	ENCODER ENABLED

TABLE 4-1. ROBOT BASE ACCELEROMETER MEASUREMENTS WITH ROBOT JOINT 0 ROTATIONS

SENSOR POSITION / ORIENTATION	MOTOR INCREMENT		MAXIMUM ACCELERATION (MILLI-G's)	DOMINANT FREQUENCIES (Hz)	NOTES
	RADIANS	DEGREES			
END-EFFECTOR X	0.000001	0.000057	11.2	12 14	ENCODER DISABLED
	0.0002	0.0115	10	12 14 4	ENCODER ENABLED
	0.05	2.86	48	10 30 40 18	ENCODER ENABLED
END-EFFECTOR Y	0.05	2.86	4.8	60 100 12 7 4	ENCODER ENABLED
END-EFFECTOR Z	0.05	2.86	16	60 25 30 12 7 4	ENCODER ENABLED

TABLE 4-2. END-EFFECTOR ACCELEROMETER MEASUREMENTS WITH ROBOT JOINT 0 ROTATIONS

SENSOR ORIENTATION (REF. ROBOT COORDINATES.)	SENSOR POSITION	STIMULUS	PEAK AMPLITUDE (MILLI-G's)	DOMINANT FREQUENCY (Hz)
+Y	#2 (TABLETOP)	NONE (AMBIENT)	0.2	60
+Y	#2 (TABLETOP)	TABLE LIFT/RELEASE	27	7
+Y	#2 (TABLETOP)	TABLE EDGE TAP	5	4
-X	#1 (TABLE EDGE)	0.1 RADIAN JOINT 0 ROTATION	14	4

TABLE 4-3. SUMMARY OF TEST ENVIRONMENT CHARACTERIZATION DATA

SUBJECT	ACCELEROMETER CONDITIONS (SENSOR POSITION VERTICAL)	MAXIMUM AMPLITUDE (MILLI-G's)	DOMINANT FREQUENCY (Hz)
K	HAND HELD, WRIST SUPPORTED	19	8 - 15
	HAND HELD, ARMS LENGTH	48	8 - 10
J	HAND HELD, WRIST SUPPORTED	37	8 - 9
	HAND HELD, ARMS LENGTH	49	2 - 15
A	HAND HELD, WRIST SUPPORTED	20	8 - 13
	HAND HELD, ARMS LENGTH	33	2 - 9

TABLE 4-4. MEASUREMENT OF HUMAN VIBRATION RESPONSE

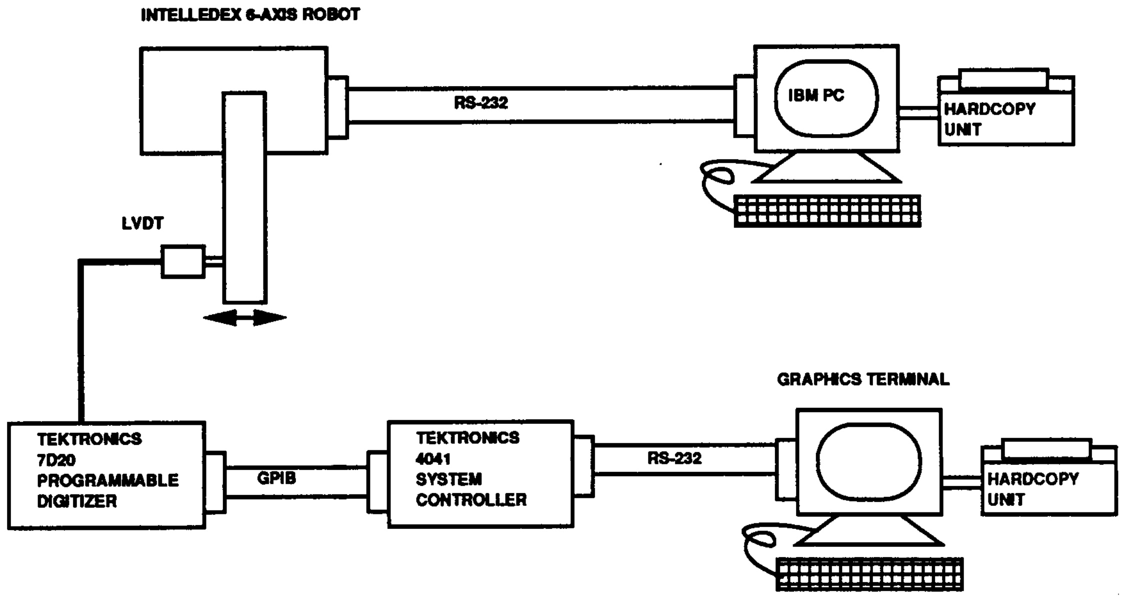


FIGURE 4-1. SET-UP FOR MANIPULATOR MICROSTEPPING EVALUATION

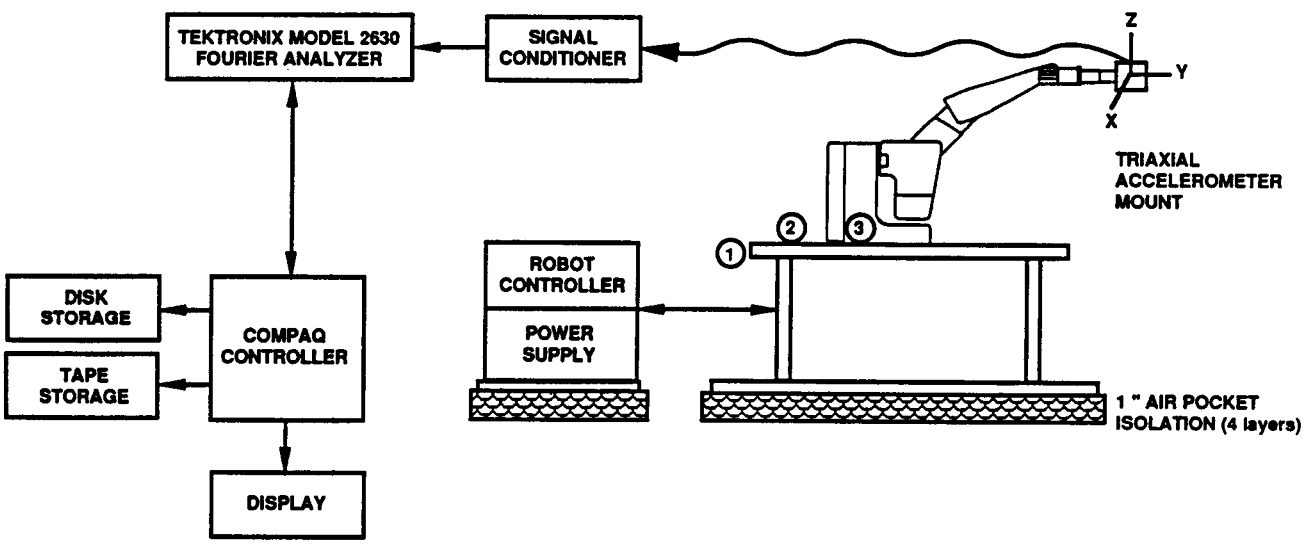
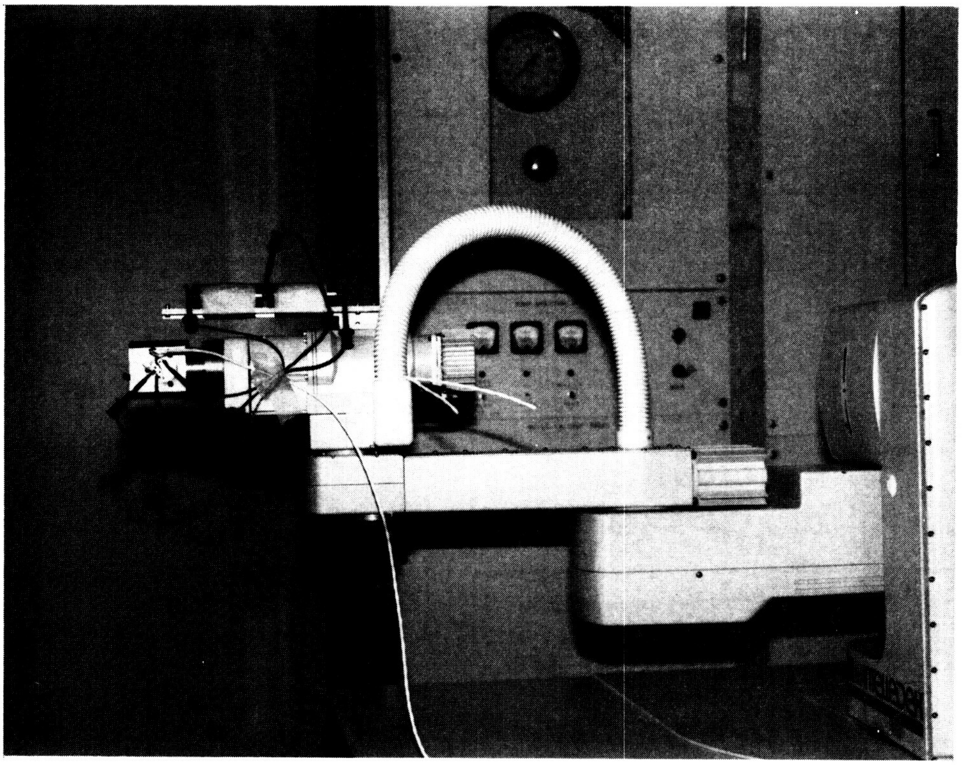
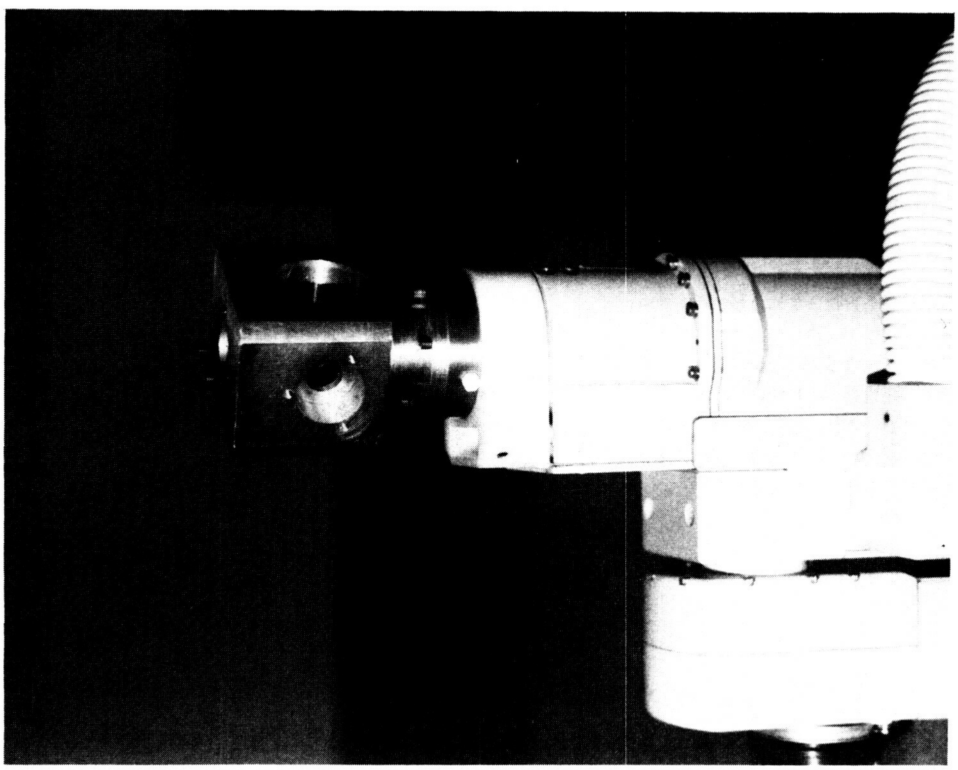


FIGURE 4-2. SET-UP FOR QA-2000 ACCELEROMETER MEASUREMENTS



A. ROBOT ARM AND TRIAXIAL BLOCK WITH ACCELEROMETER, BATTERY AND CABLES ATTACHED



B. TRIAXIAL ACCELEROMETER BLOCK MOUNTED ON INTELLEDEX 660 TOOL PLATE (END EFFECTOR)

FIGURE 4 -3. END EFFECTOR ACCELEROMETER MEASUREMENT SETUP

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4.2 ROBOTIC MANIPULATION

LVDT measurement data for a 0.0002 radian base movement is shown in Figure 4-4. The results of the LVDT measurements are summarized in Table 4-5.

	MOTOR INCREMENTS (RADIANS)	MOTOR INCREMENTS (DEGREES)	LINEAR DISPLACEMENT (IN.)	MAXIMUM VELOCITY (IN/SEC)	MAXIMUM ACCELERATION (MILLI-G)
MINOR MOTION	0.0005 0.0002	0.0286 0.0115	0.0027 0.0013	0.032 0.0125	3.1 0.9
MAJOR MOTION	0.05	+/- 2.86	0.37	0.25	5.5

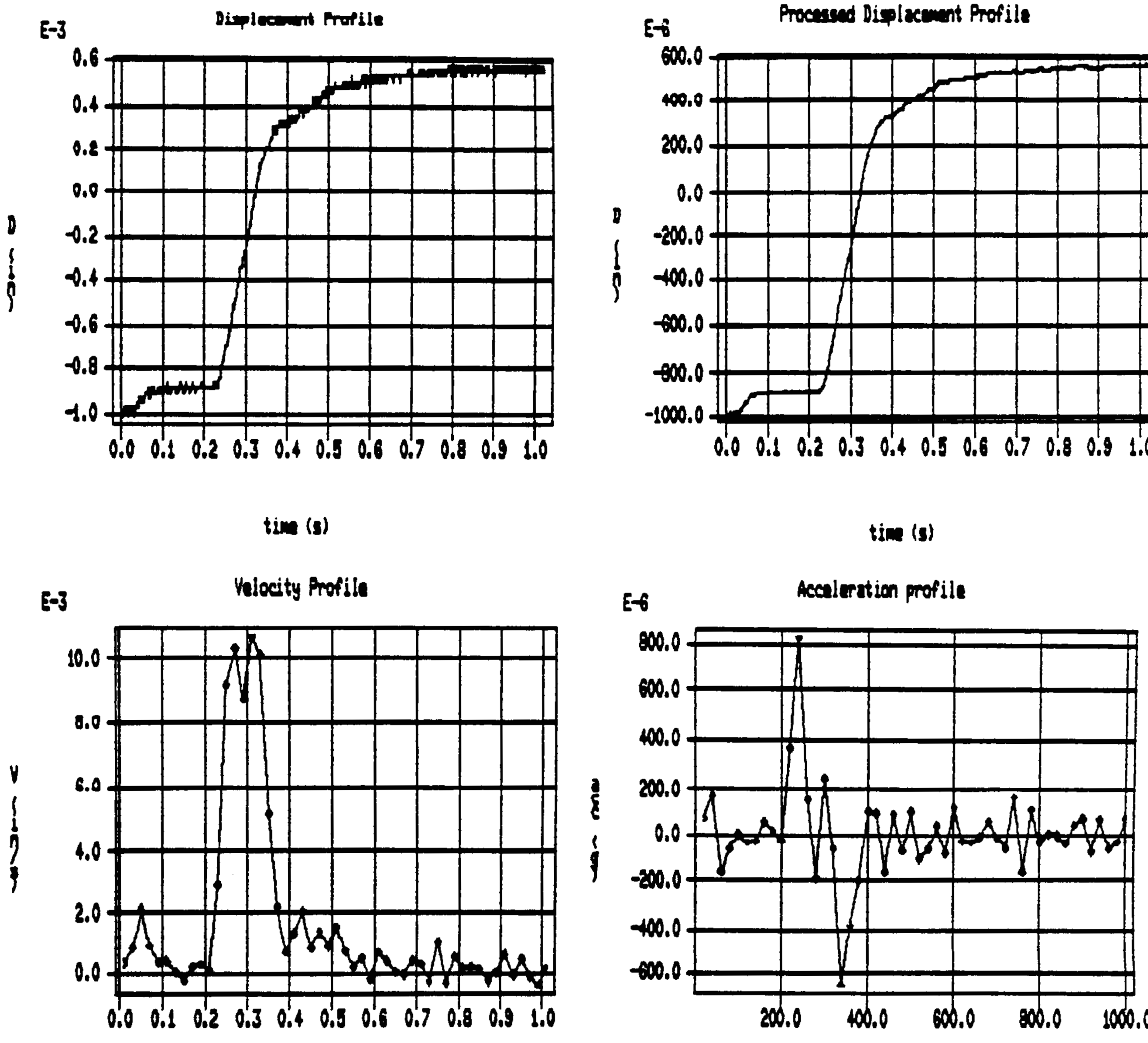
SPEED = (0,0,0), MAX = 0

TABLE 4-5. LVDT MEASUREMENT AT ROBOT BASE

The summary of results of the QA-2000 accelerometer measurements were shown earlier in Tables 4-1 through 4-4. An example of raw data from the analyzer is shown in Figures 4-5 and 4-6. In Figure 4-5 a microstep base rotation is measured at the base and acceleration is found to be 1.4 milli-g peak-to-peak. It dampens within about 0.1 seconds. Figure 4-6 shows a 0.0002 radian base rotation with the robot arm extended. This results in measurement at the end-effector of about 18 milli-g peak-to-peak. This dampens out within 0.5 seconds.

4.3 HUMAN MANIPULATION

The samples of humans tested in holding an accelerometer very still indicates that direct, low-gravity, i.e., milli-g, manipulation of samples by humans is impossible. When comfortably seated in a chair, arm and hand resting on a 400 pound steel table the pulse pressures and neuro-muscular system generate 20 to 35 milli-g acceleration as shown in Figure 4-7. When the accelerometer was held calmly and steadily at arm's length the results indicated a 40 to 60 milli-g vibrational acceleration as shown in Figure 4-8.



IMOVE0 -0.0002
CASE I
SPEED (0, 0, 0)
MAXSPEED 0

FIGURE 4-4. LVDT ROBOT BASE MEASUREMENTS AND DERIVATIVES

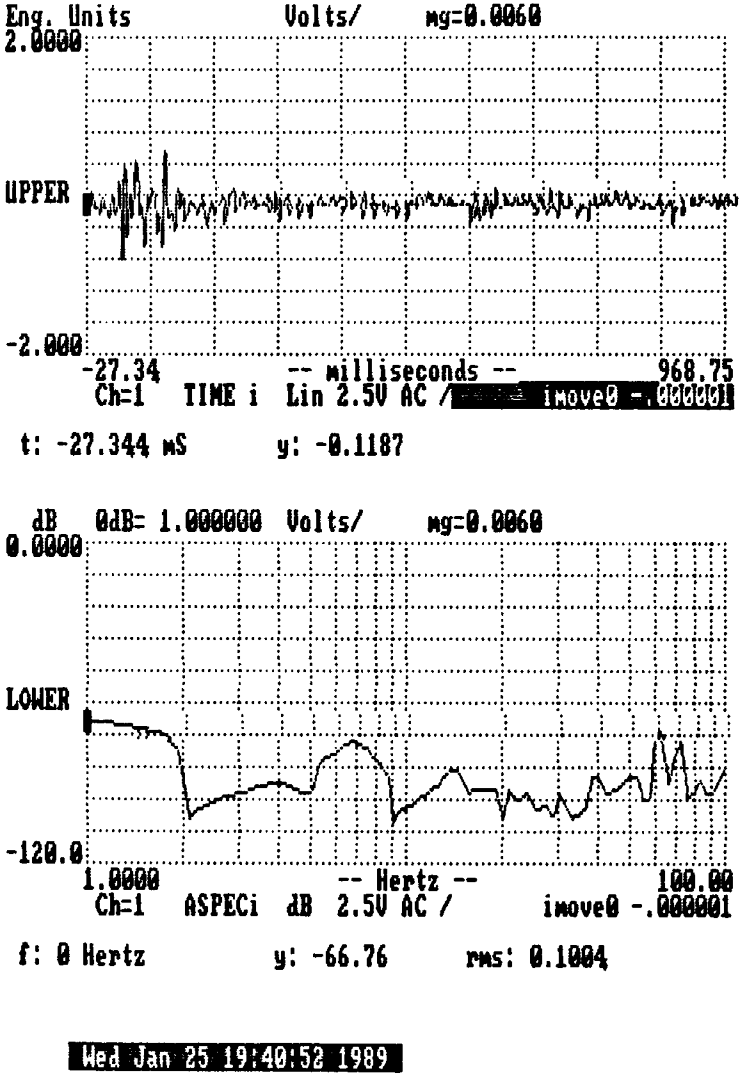


FIGURE 4-5. MICROSTEP ACCELEROMETER MEASUREMENTS

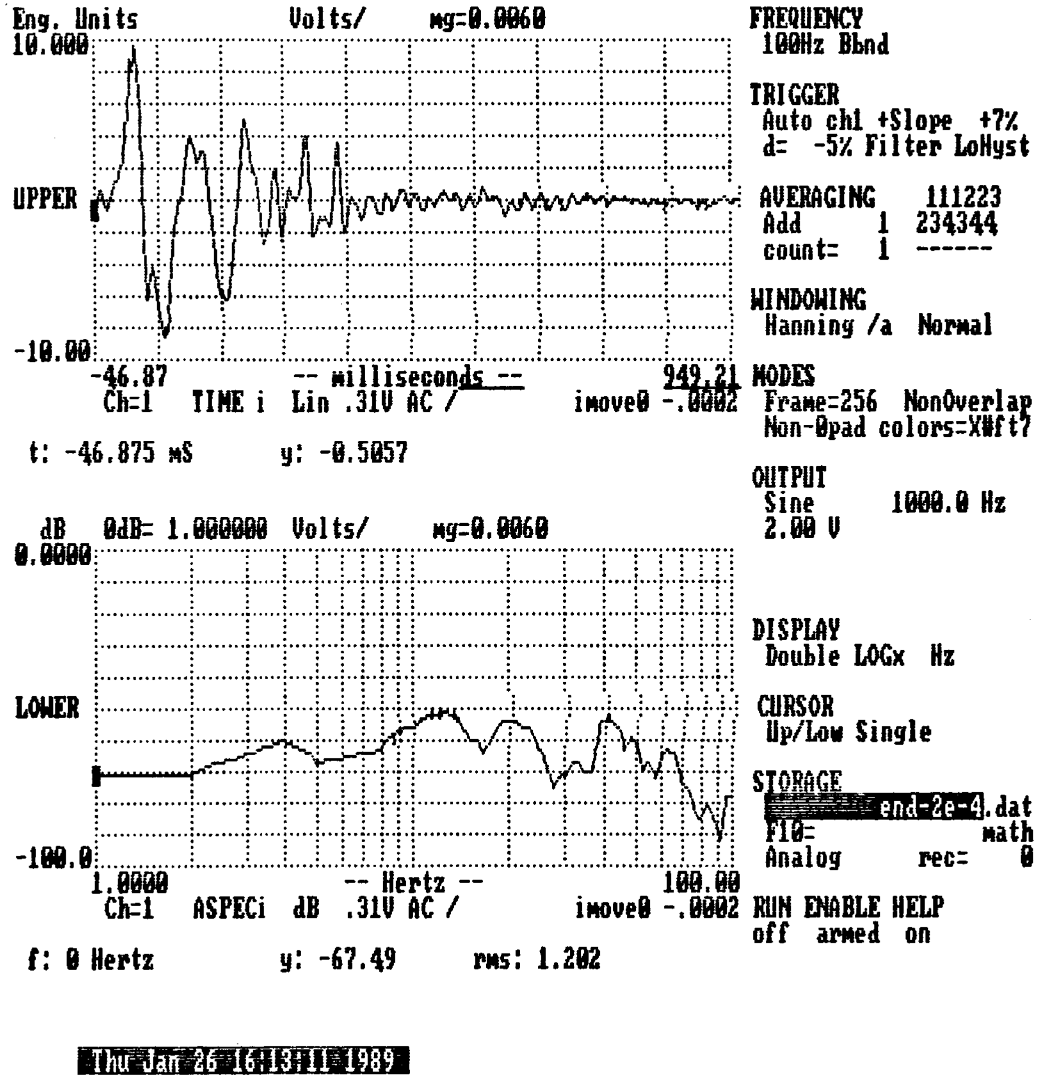


FIGURE 4-6 MINOR STEP (0.0002 rad) ACCELEROMETER MEASUREMENTS

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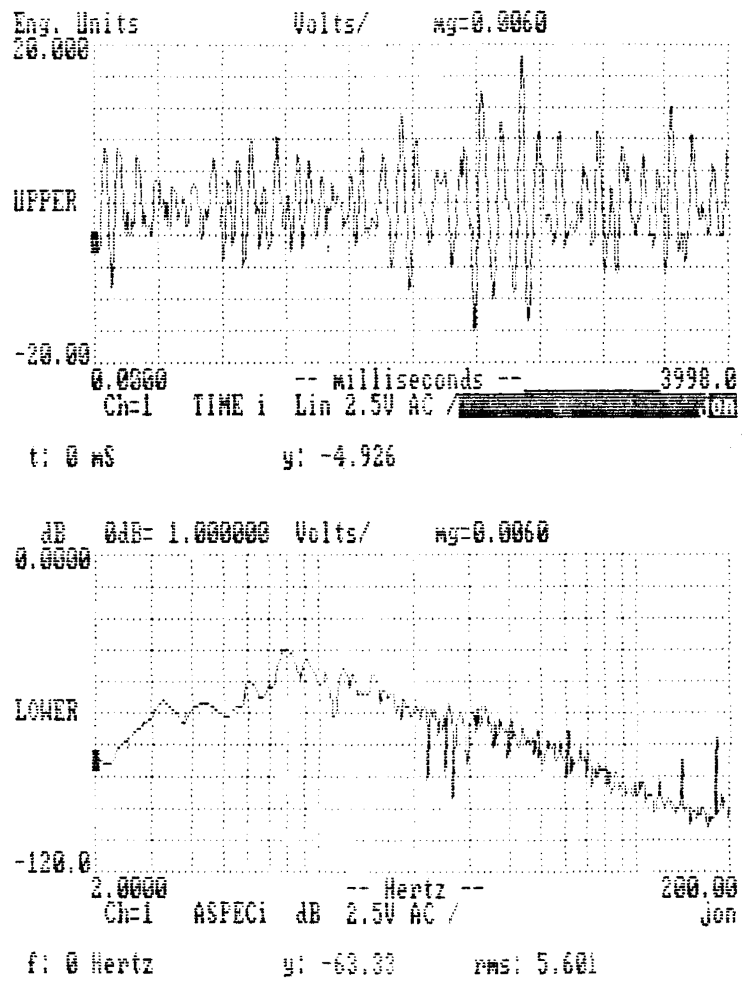

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FIGURE 4-7 HUMAN (STABILIZED) ACCELEROMETER MEASUREMENTS

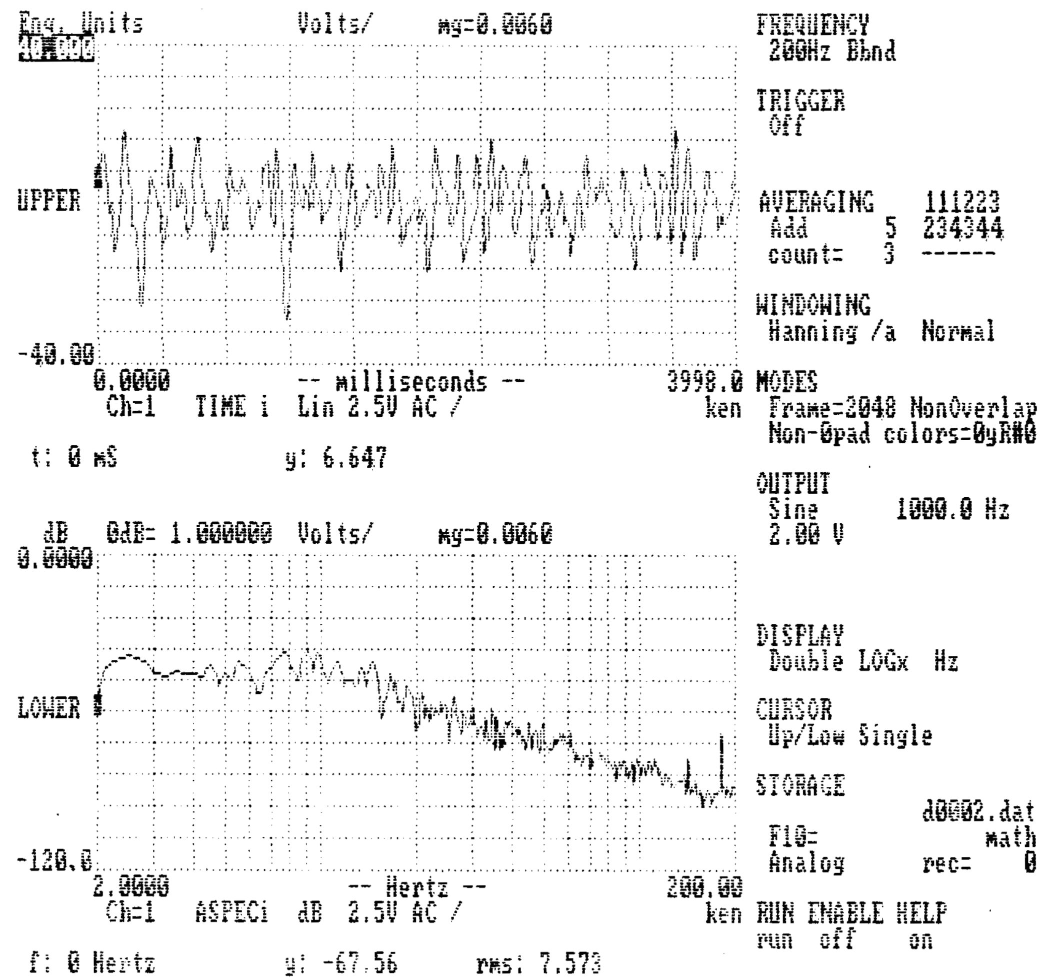

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FIGURE 4-8 HUMAN (ARM EXTENDED) ACCELEROMETER MEASUREMENTS

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5. ASSESSMENT OF BENEFITS

To determine the many, long range benefits of robots in a low gravity space station laboratory is difficult. Based on previous development of technologies for space, such as vapor deposition on films (aluminized mylar) and medical monitoring, the spin-off activities can dwarf the original notions of what the value was thought to be. However, tangible benefits are the ability to do certain low-g manipulations that cannot be done by humans directly, the ability to perform greater numbers of experiment runs than with humans alone, and the relief of crewtime from tedious chores.

5.1 TECHNICAL AND COMMERCIAL BENEFITS OF LOW-GRAVITY ROBOTS

Results of early analysis of the MMPF Study experiment database indicated that a laboratory robot is necessary to augment crewtime and enable production in the man-tended mode, when no crew is permanently on-station, as is shown in Table 5-1. The availability of a reactionless low-gravity manipulator that will not disturb the required Space Station low-gravity environment, would allow operation of sensitive experiments or processes during translation or manipulation of other masses. Since the absence of a 1 g bias on a manipulator in orbit conceptually allows larger payloads to be movedwith equivalent accuracy, then operations not feasible on Earth could be executed on orbit for additional benefit.

EIGHT EXPERIMENT SET	TOTAL CREW TIME (HRS)	AUTOMAT-ABLE TIME (-)	CHARACT-ERIZATION TIME (-)	RAPID SAMPLE RETURN(+/-)	CONSULT-ING TIME (-)	MAN-TENDED MINIMUM
CFES	157.3	32.7	26.7	73.0	20.0	31.6
PCG	206.8	27.5	56.3	72.8	16.8	89.7
DB	252.5	56.7	50.0	0	50.0	95.8
DS	155.7	34.0	84.1	0	10.0	27.6
SIA	520.0	160.8	181.3	131.2	50.0	127.9
VPCG	204.4	22.7	81.6	75.0	40.0	60.1
MLS	366.5	28.3	66.7	0	25.0	246.5
ACP	433.6	24.3	199.0	0	20.0	190.3
TOTALS	2296.8	387.0	745.7	352.0	231.8	869.5

TABLE 5-1. EARLY (1985) CREWTIME OPS IMPACTS - REQUIRED ROBOTICS TIME

Benefits of robotic manipulation using "reactionless" robots to control the level of microgravity disturbance were assessed by comparing the capabilities and limitations of various robot systems with increasing levels of ability to perform the three experiments chosen in Task II. As shown in Figure 5-1, these robot systems consist of three basic types of end-effectors and two arrangements of manipulator arms:

END-EFFECTORS:	MANIPULATOR ARMS
1. Two Finger	1. Single Arm Anthropomorphic
2. Three Finger	2. Dual Arm Anthropomorphic
3. Three Finger Dexterous	

These system components are further described in Appendix 9.7. By comparing the capability of each combination of end-effector and manipulator arm, the crew tasks that can be accomplished for each of the three experiments was determined. The associated crewtime saved and savings in cost were evaluated. This data was tabulated on a spread sheet and indicates that crewtime savings range from roughly 40% average to over 90% as shown in Appendix 9.8.

5.2 COST ESTIMATE FOR REPRESENTATIVE SYSTEMS

Preliminary cost estimates of the representative robot systems were derived from industrial robot system costs for anthropomorphic arms and comparative end-effectors. These costs range from $2 million to $15 million. The comparative costs for single arm and dual arm manipulator systems are shown in Appendix 9.9. It also gives the comparative costs of terrestrial (commercially available equipment with functional modifications for concept demonstration), Flight Modification and Flight Qualified versions of each system. Total system cost is the sum of manipulator selected plus the end-effector. These costs were analyzed with respect to Teledyne Brown Engineering data on flight design requirements including thermal, mass, electrical, flight testing and certification, and installation on orbit.

5.3 COST SAVINGS AND MONETARY BENEFITS

Cost savings and potential commercial monetary benefits have beenderived based on the Payload Production Planning (PAYPLAN) program data base as well as further refinement of operations cost. Cost savings by the use of robotics to perform housekeeping and experiment servicing has been determined to be in excess of $6000 per hour for each crew hour saved. This is based on a ROM estimated labor rate (crew cost) on station of $7000/hr, and on a 15 year prorated capital and installation charge for the most advanced form of robot system under consideration ($200/hr). Adding teleoperation, maintenance, and down time costs, the total robot operating cost is expected to be less than $1000/hr.

Total commercial value of the experiments include not only costs prevented, but also the national priority and technology transfer attributes. The national priority factor represents the relative social/political value of the experiment product, such as its military or medical value as perceive by the public, Congress and NASA. The technology transfer factor is the relative probability that the experiment will yield data or techniques that will improve or create a new ground-based product, process, or procedure. A high

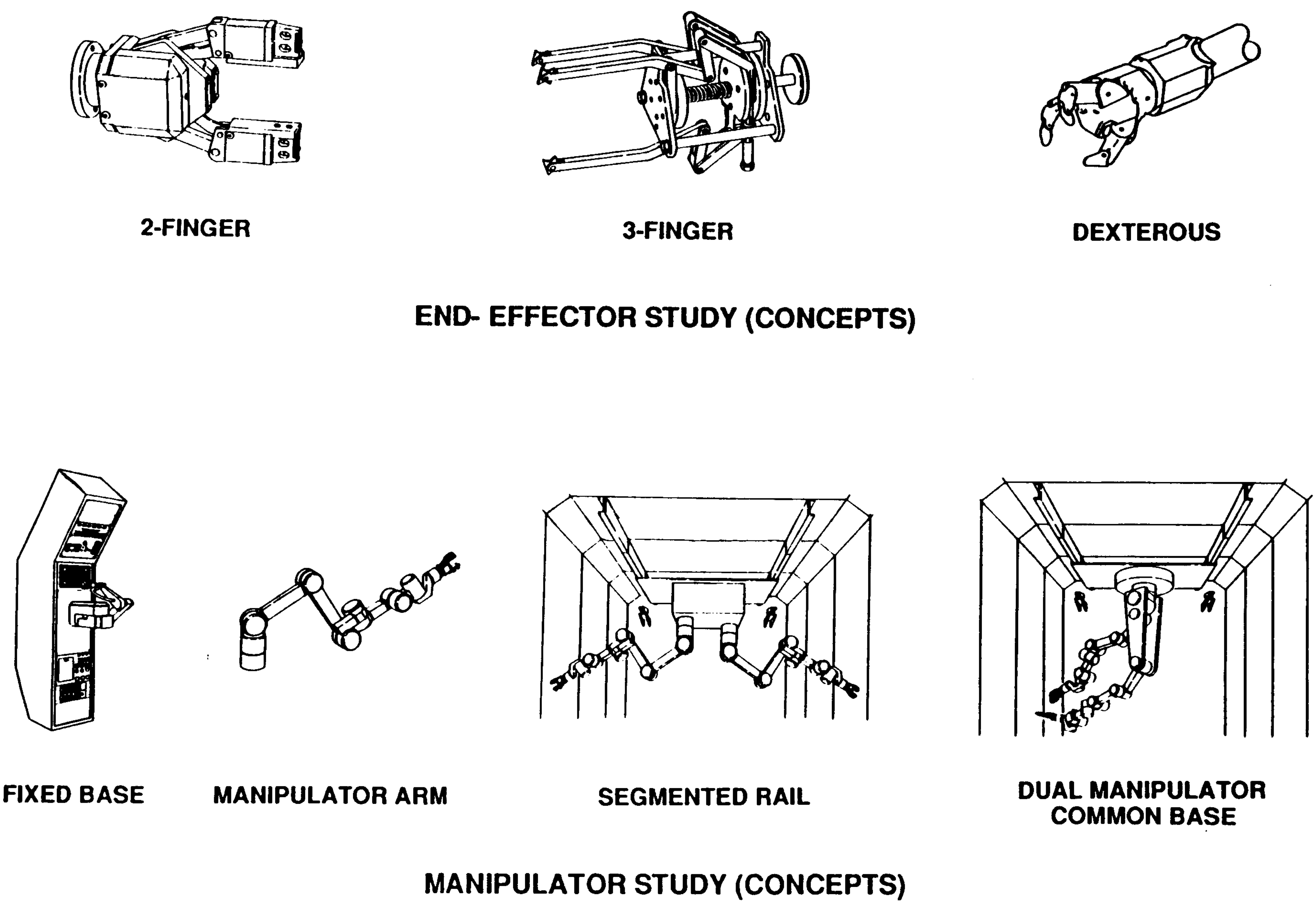

FIGURE 5-1. END-EFFECTOR AND MANIPULATOR CONCEPTS

technology transfer factor implies that the new process, procedure and/or product will lead to new markets. Overall impact of new-generation technology is implicit, i.e., computer technology spin-off from Apollo/Saturn V programs engendered a whole new range of technologies and resultant world markets.

The comparison of production using one crewman, versus one crewman aided by a robotic manipulator system, indicates a significant productivity enhancement. Numerous cases using different science mixes of experiments in payload complements of three to 300 experiments and various scenarios for operations, such as 90, 120 or 180 day missions were evaluated. Typical and indicative of these evaluations are the findings shown in Table 5-2. Using a 90 day cycle, 10 experiment case; productivity can be improved from roughly five times, whether in terms of dollar values or number of experiment runs. By proper balancing of resources and experiment complements some scenarios indicate production improvement in excess of $200 million per 120 day mission interval.

It is clear from model analyses that the crewtime shortage is alleviated by the addition of crew members or robotics. A interesting finding, however,is that to add more human crew members beyond the currently planned eight is counter-productive. While crewtime is clearly provided by new crew members what also occurs is the reduction of supplies and resources for the experiments in order to provide for crew members. Thus, there comes a point of diminishing return when adding crew members to provide crewtime to increase laboratory output.

5.4 COST AND PERFORMANCE VERSUS BENEFITS

A trade off study has been accomplished to determine the relative value of the various robot systems. Appendix 9.10 describes the system factors that were traded off. To maximize both the objectivity and accuracy of the trade study, a survey is underway, to be made of agencies with USL responsibilities and experience in flight systems design, including MSFC, LeRC, LaRC, TBE, JSC, and JPL. Figure 5-2 shows a sample survey form. This survey is nearing completion. A relative weighting of the key factors (Performance versus Resources versus Cost and Other Factors) was determined based on this survey. The results indicated a prioritization of the key factors driving design as follows:

Performance	44%
Resources	31%
Cost Factors	25%

The preliminary results of this survey are given in Table 5-3. These numbers and individual factor weightings were then used to compare the various robot configurations. Results of this Trade Option Evaluation are given in Appendix 9.11.

BASED ON: 90 DAY RESUPPLY CYCLE WITH 4500 KG FOR MTL
Permanently Manned Configuration (PMC) — 1 CREWMEN AND 0 LEMS
EXPERIMENT FILE: TENNOCH AT 15 kW POWER LEVEL

EXPERIMENT NAME	OUTPUT PER CYCLE	RUN TIME	CREW TIME	$ PER HR RT	# OF RUNS	LIMIT IS	OUTPUT PER REVISIT CYCLE
ALF	$120,000	19.4	4.4	6186	7	CTE	$840,000
AMPF	$15,000	14.6	14.6	1027	6	CTE	$90,000
ASF	$375,000	17.0	7.4	22059	6	CTE	$2,250,000
DSBF	$15,000	39.9	16.6	376	6	CTE	$90,000
CFES	$450,000	147.3	8.1	3055	6	CTE	$2,700,000
FPF	$15,000	30.4	7.4	493	6	CTE	$90,000
FZF	$15,000	32.9	8.1	456	6	CTE	$90,000
LBF	$485,000	54.4	27.0	8915	5	CTE	$2,425,000
PCG	$366,000	105.5	24.6	3469	5	CTE	$1,830,000
VCGF	$337,500	45.2	8.3	7467	5	CTE	$1,687,500
TOTALS		2,853.9	703.5	4237	58		$12,092,500

TOTALS REMAINING: CTE= 1.7 HRS CONSUM= 906.1 KG ENERGY=24621.0 KWH

a) NOMINAL OUTPUT: ONE CREWMAN & NO ROBOTS

NOTE: BOTH a) AND b) SCENARIOS ARE CREWTIME LIMITED

BASED ON: 90 DAY RESUPPLY CYCLE WITH 4500 KG FOR MTL
Permanently Manned Configuration (PMC) — 1 CREWMEN AND 0 LEMS
EXPERIMENT FILE: TENCH AT 15 kW POWER LEVEL

EXPERIMENT NAME	OUTPUT PER CYCLE	RUN TIME	CREW TIME	$ PER HR RT	# OF RUNS	LIMIT IS	OUTPUT PER REVISIT CYCLE
ALF	$120,000	31.8	9.2	3774	5	CTE	$600,000
AMPF	$15,000	14.9	6.9	1007	5	CTE	$75,000
ASF	$375,000	18.9	12.5	19841	5	CTE	$1,875,000
DSBF	$15,000	54.8	21.8	274	5	CTE	$75,000
CFES	$450,000	150.1	10.9	2998	5	CTE	$2,250,000
FPF	$15,000	30.4	7.4	493	5	CTE	$75,000
FZF	$15,000	33.7	8.9	445	5	CTE	$75,000
LBF	$485,000	55.7	28.4	8707	5	CTE	$2,425,000
PCG	$366,000	105.4	24.6	3472	5	CTE	$1,830,000
VCGF	$337,500	47.3	10.2	7135	5	CTE	$1,687,500
TOTALS		2,715.0	704.0	4040	50		$10,967,500

TOTALS REMAINING: CTE= 1.2 HRS CONSUM= 2073.1 KG ENERGY=23621.0 KWH

b) NOMINAL OUTPUT: ONE CREWMAN & NO ROBOTS - ADD LAB ANALYSES

TABLE 5-2. SPACE LABORATORY PRODUCTIVITY ANALYSIS

BASED ON: 90 DAY RESUPPLY CYCLE WITH 4500 KG FOR MTL
Permanently Manned Configuration (PMC) — 1 CREWMEN AND 2 LEMS
EXPERIMENT FILE: TENCH AT 15 kW POWER LEVEL

EXPERIMENT NAME	OUTPUT PER CYCLE	RUN TIME	CREW TIME	$ PER HR RT	# OF RUNS	LIMIT IS	OUTPUT PER REVISIT CYCLE
ALF	$120,000	31.8	9.2	3774	10	CONS	$1,200,000
AMPF	$15,000	14.9	6.9	1007	10	CONS	$150,000
ASF	$375,000	18.9	12.5	19841	10	CONS	$3,750,000
DSBF	$15,000	54.8	21.8	274	10	CONS	$150,000
CFES	$450,000	150.1	10.9	2998	10	CONS	$4,500,000
FPF	$15,000	30.4	7.4	493	10	CONS	$150,000
FZF	$15,000	33.7	8.9	445	10	CONS	$150,000
LBF	$485,000	55.7	28.4	8707	10	CONS	$4,850,000
PCG	$366,000	105.4	24.6	3472	10	CONS	$3,660,000
VCGF	$337,500	47.3	10.2	7135	10	CONS	$3,375,000
TOTALS		5,430.0	1408.0	4040	100		$21,935,000

TOTALS REMAINING: CTE=2259.0 HRS CONSUM= 1.6 KG ENERGY=17722.0 KWH
COST OF GROUND CREW SUPPORT FOR THIS MISSION SCENARIO IS $ 250555.6

c) DOUBLED OUTPUT WITH ROBOTICS - CONSUMABLES LIMITED

BASED ON: 90 DAY RESUPPLY CYCLE WITH 10000 KG FOR MTL
Permanently Manned Configuration (PMC) — 1 CREWMEN AND 2 LEMS
EXPERIMENT FILE: TENCH AT 15 kW POWER LEVEL

EXPERIMENT NAME	OUTPUT PER CYCLE	RUN TIME	CREW TIME	$ PER HR RT	# OF RUNS	LIMIT IS	OUTPUT PER REVISIT CYCLE
ALF	$120,000	31.8	9.2	3774	30	CTE	$3,600,000
AMPF	$15,000	14.9	6.9	1007	30	CTE	$450,000
ASF	$375,000	18.9	12.5	19841	30	CTE	$11,250,000
DSBF	$15,000	54.8	21.8	274	29	CTE	$435,000
CFES	$450,000	150.1	10.9	2998	13	RUN T	$5,850,000
FPF	$15,000	30.4	7.4	493	29	CTE	$435,000
FZF	$15,000	33.7	8.9	445	29	CTE	$435,000
LBF	$485,000	55.7	28.4	8707	29	CTE	$14,065,000
PCG	$366,000	105.4	24.6	3472	18	RUN T	$6,588,000
VCGF	$337,500	47.3	10.2	7135	29	CTE	$9,787,500
TOTALS		12,251.6	3666.8	4317	266		$52,895,500

TOTALS REMAINING: CTE= 0.2 HRS CONSUM= 81.9 KG ENERGY= 1335.6 KWH
COST OF GROUND CREW SUPPORT FOR THIS MISSION SCENARIO IS $ 250555.6

d) FIVE FOLD INCREASED PRODUCTION WITH ROBOTICS AND ADDED CONSUMABLES

TABLE 5-2. (CONT'D) SPACE LABORATORY PRODUCTIVITY ANALYSIS

RELATIVE IMPORTANCE (%)	ITEM/CATEGORY	RELATIVE IMPORTANCE (1-10) (1 - Low, 10 - High)
________	RESOURCES CONSUMED BY SYSTEM	
	Power	____
	Data Storage	____
	Video/Communications	____
	Thermal	____
	Volume	____
	Mass to Orbit	____
	Uplink/Downlink	____
	Low Gravity	____
	Crew Time	____
	Setup	____
	Maintenance/Operations	____
________	PERFORMANCE OF SYSTEM	
	Tasks Performable (0-100%)	____
	Housekeeping	____
	Telescience	____
	Time Accomplished	____
	Redundancy	____
	Reliability	____
	Repeatability	____
	Accuracy	____
	Safety	____
	Crew Sharing Volume with Robot	____
	Crew Emergency	____
	Task Recoverability	____
	Low Gravity Compatibility	____
________	COST AND OTHER FACTORS	
	DDT&E	____
	Flight Costs	____
	Ground Support Costs	____
	Training Costs	____
	Flight Crew	____
	Ground Crew	____
	Technology Development/Transfer	____
	Reactionless Mechanisms	____
========		
TOTAL = 100%		

FIGURE 5-2. WEIGHTING FACTORS SURVEY

FIGURE 5-3.

WEIGHTING FACTORS SURVEY

CATEGORY PARAMETER	RELATIVE IMPORTANCE VALUE \	TBE											\ MSFC				\ KSC \	IND \	LeRC				\ TOTAL
RESOURCE	30	35	40	40	30	35	25	30	35	30	30	32.7	40	20	40	33.3	30	25	25	25	25	25.0	31.05
POWER	10	7	8	8	8	7	6	8	7	8	4	7.4	8			2.7							7
DATA STG	8	8	4	3	8	7	3	3	8	3	5	5.5	7			2.3							6
VIDEO/COM	8	8	5	3	8	8	8	3	10	3	10	6.7	7			2.3							7
THERMAL	8	6	3	8	4	6	5	3	6	3	8	5.5	6			2.0							6
VOLUME	5	7	3	3	4	7	8	5	5	5	6	5.3	3			1.0							5
MASS/ORBIT	5	9	3	3	7	6	8	5	3	5	7	5.5	3			1.0							5
UP/DOWNLINK	8	7	4	4	7	6	8	6	2	6	8	6.0	4			1.3							6
LOW GRAVITY	9	10	5	3	9	10	8	10	10	10	9	8.5	6			2.0							8
CREW TIME	10	10	5	5	9	7	7	10	10	10	10	8.5	5			1.7							8
SETUP	6	5	6	3	4	1	3	6	10	6	7	5.2	3			1.0							5
MAINT	10	9	7	2	8	8	10	6	10	6	9	7.7	9			3.0							8
PERFORM.	40	45	40	30	50	40	50	40	45	40	50	42.7	25	40	40	35.0	60	40	70	50	50	56.7	44.47
TASKS PERF.	8	8	5	5	9	9	8	5	9	5	9	7.3	7			2.3							7
HOUSEKEEP'G	10	5	4	3	7	7	4	2	9	2	8	5.5	6			2.0							6
TELESCIENCE	7	8	8	2	9	9	8	10	9	10	8	8.0	4			1.3							8
TIME ACCOMP.	7	6	3	3	6	6	4	2	6	2	5	4.5	4			1.3							5
REDUNDANCY	9	8	5	4	5	7	6	2	8	2	6	5.6	7			2.3							6
RELIABILITY	8	10	9	5	7	10	9	5	8	5	9	7.7	8			2.7							8
REPEATIB.	7	8	8	2	7	10	9	7	8	7	4	7.0	6			2.0							7
ACCURACY	8	9	8	3	7	9	10	7	10	7	8	7.8	5			1.7							8
SAFETY	9	10	5	5	10	10	10	10	10	10	10	9.0	5			1.7							9
CREW SHARE	7	10	10	1	10	10	10	6	5	6	10	7.7	9			3.0							8
CREW EMERG'C	9	10	10	3	8	8	6	6	10	6	4	7.3	2			0.7							7
TASK RECOVER.	6	8	6	2	7	8	8	5	8	5	7	6.4	5			1.7							6
LOW GRAV COMP	9	9	6	3	8	9	7	10	10	10	9	8.2	7			2.3							8
COST/OTH	30	20	20	30	20	25	25	30	20	30	20	24.5	35	40	20	31.7	10	35	5	25	25	18.3	24.47
DDT&E	5	7	7	8	7	3	7	2	5	2	7	5.5	7			2.3							6
FLIGHT COSTS	9	8	5	8	8	1	5	10	10	10	7	7.4	8			2.7							7
GND SUPPT COS	7	6	4	4	8	8	8	2	2	2	7	5.3	5			1.7							5
TRAINING COST	6	7	5	5	7	8	9	2	10	2	7	6.2	5			1.7							6
FLIGHT COSTS	7	8	7	4	8	6	9	2	10	2	8	6.5	5			1.7							6
GROUND CREW	6	6	5	2	6	8	9	2	5	2	7	5.3	3			1.0							5
TECHN. DEVELO	6	10	3	2	8	10	1	5	5	5	8	5.7	9			3.0							6
REACTIONLESS	8	10	5	2	8	7	2	4	8	4	8	6.0	6			2.0							6
CHECK	100	100	100	100	100	100	100	100	100	100	100	100.0	100	100	100	100	100	100	100	100	100	100.0	100

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6. PRELIMINARY DEFINITION OF INTERFACE REQUIREMENTS

The preliminary robotic system concepts in section 5.0, Assessment of Benefits, were defined in order to be able to evaluate the benefits associated with their use. To determine the relative effectiveness of each system a trade study was performed with weighting factors for:

1) Performance

2) Resource Requirements

3) Cost and Other Factors

Each of these categories was further broken down into a total of about 30 factors for consideration in selecting the most desirable system concept. Against this system concept (two armed and dexterous hand) the interfacing requirements are now being identified so that the operation of the definable experiments can be properly performed.

6.1 ROBOTIC SYSTEM CONFIGURATION REQUIREMENTS

Of importance in the identification of the robotic system capabilities was the identification of laboratory subsystems, support facilities, and support equipment items including multipurpose instruments (Appendix 9.2) used by several materials science disciplines for analysis and characterization of processed samples. These needs identify specific interface requirements for the robot system selection.

As pointed out in section 3.0, the system configuration must satisfy the specific user needs for manipulation at the same time minimizing the disturbances to other experiments. Vibration isolation, counteracting robotic movements and other techniques to meet that requirement may be required as an integral part of the system configuration.

At this point it should be noted that a flight robotic manipulator system will be similar to, but unlike anything on the ground. Today's robots are relatively simple systems which "pick and place" very accurately and rapidly, over and over again. Some are coupled with "vision" systems and have ingenious algorithms which permit corrective manipulations when work pieces are slightly out of place.

For a flight robotic system many things are moved out of place. No two experiments in the same furnace will be run exactly the same (samples will be different on every run). The sample storage locations will be constantly changing through the course of a mission. Gross repeatability barely exists. High speed in ground applications is highly sought after, but in a low-g laboratory is undesirable. The rationale and specifications for state-of-the-art robot designs are generally counterproductive for a space based system.

6.2 INTERFACING REQUIREMENTS

The eventual space station laboratory robotic system will also require, most probably, a ceiling or floor mounted rail for transport. The DMS will be required to distribute signals to and from the station computer system. The communications system is required to uplink/downlink commands and data, and the video system is used to assist in controlling the robot in the teleoperated mode.

The requirements of the experiments, processes, and facility needs drive the interfacing requirements of the robot system. The physical size, geometry, power requirements, thermal requirements, control needs, data acquisition and display needs, data storage and down-link requirements, and safety are important design considerations. Of importance are translation needs (mass, transit time and accuracy), and maintaining the micro-gravity environment under operating conditions.

It has been determined that a two armed dexterous robot system will provide the best benefit to cost ratio of the systems under review. Though any of the robot systems under review will provide a significant benefit in crew-time savings alone, the two armed dexterous system maximizes most of the benefits, and as weighted in the trade study, is the system of choice. Further study of base options; fixed, rail mounted, and rail-maneuvering has resulted in proposing the rail mounted configuration for the initial installation. A fixed base station drastically limits the advantage of incorporating robot capability. The rail-walker should be considered for evolutionary design, and is considered a viable option for extended duration missions such as the Mars or other deep space mission.

Preliminary Requirements for a robot system are:

.1 Physical Size: System to be configurable into a secure 'parked' or 'home' location not to exceed 20 cu.ft.

.2 Geometry : Geometry is to be such that the final full evolutionary configuration does not impede crew operations during worst case task accomplishment. Design is to preclude dangerous configuration; i.e. sharp edges, exposed pinch zones, etc.

.3 Power Requirements: Power should not exceed 1000 watts average during worst case translation, 1500 watt peak.

.4 Thermal Requirements: Not to exceed power requirements.

.5 Data Requirements: Not to exceed (TBD) with video systems supporting predictive display and implementing neural network system for calibration of control system.

.6 Control: Control to include predictive display and control of a teleoperated system with remote user interface.

.7 Dexterity, Accuracy, Repeatability: Dexterity to include twin anthropomorphic manipulator arms supporting twin fully dexterous end-effectors. System to include torque sensing, back-drivability of major extensions (arm) with ability to reach any control surface requiring access for specified tasks. Dexterity necessary to recover 95% of tasks from any task point is required. Accuracy: +/- 0.005" worst case assisted by alignment system Repeatability: +/- 0.005" worst case.

.8 Low-gravity capability: Able to accomplish required tasks while maintaining reactionless environment within the following limits: Level I: <1 milli-g
Level II: TBD

.9 Maintainability: Accessability and repairability of all motive and control elements and all structural elements with a minimum of operations. Design should be reviewed with a full reverse engineering study prior to implementation. Design should be modular, with interchangeability between arms and between successive joints where possible. Self diagnostics should be included in software systems.

.10 Plugs/Interface: Interface between mechanical and electrical trunks/manifolds to be modular and quick change type. Plugs preferably should allow disconnection of power, controls, video, and optics simultaneously. Mechanical attachments should be quick change to allow rapid removal for diagnostics and repair.

.11 Safety: Multi-level failure detection and shut-down. These are sensors directly related to motion and object detection.

.12 Sensation: Tactile feedback is required for accomplishing tasks. Sensation directly supports the necessary degree of dexterity, accuracy and repeatability.

These requirements are preliminary and are intended to stimulate interested individuals within NASA and the contractor or university community to react and provide further inputs of their own in future definitions.

6.3 PRELIMINARY REQUIREMENTS FOR FLIGHT DEMONSTRATION

To provide a design for a space station system with as many unknowns as the laboratory robot manipulator system, demands that verification and proof of principle be clearly demonstrated. For this purpose the Orbiter has been designated as the proving grounds for advanced technologies requiring flight demonstration testing prior to transfer to space station. The technologies requiring flight demonstration are low-gravity performance of the near reactionless robotic system and safe operation in the presence of crew, both while under teleoperated control.

Critical issues to be addressed for a flight demonstration include:

1) minimization of weight and volume,
2) low gravity manipulator performance measurement using end-effector and base accelerometer and reaction force monitoring during manipulation and sample movement,
3) resource conservation for power, thermal and volume,
4) maximization of ability to share equipment and resources,
5) ease of interface and operation/maintenance by crew, and
6) safety of the system.

Telerobotic Laboratory Experiment Manipulator (TLEM) is a specific and well evolved concept which began at Teledyne Brown Engineering (Farnell, 1985), while working on the Space Station Phase B Study. In order to address the crewtime problem, which was just then quantified with early MMPF Study data, the engineer's imperative was followed: before raising a red flag on a problem, try to come up with a solution. It was thus that the space station laboratory robot concept was logically created to solve the crewtime problem. An independent research and development project ensued and in late 1986 this concept was formalized in an outreach technology development proposal to NASA. TLEM satisfies the requirements for a telerobot flight demonstration experiment, that is largely ground controlled, to operate experiments in an orbiting laboratory, such as the Spacelab or later Space Station's US Laboratory. A schedule for how this development might flow into the development of space station is shown in Figure 6-1.

The TLEM experiment objectives are to verify manipulator dynamics in low-g, safety in the presence of crew, control techniques, realtime predictive display operation, and ground simulator performance. A TLEM flight demonstration will permit ground operators to perform and test many of the routine experiment tasks that would otherwise require precious flight crew time.

This experiment is expected to demonstrate that the addition of a telerobot with 24 hours per day of operation via ground crew control provides synergism with the flight crew that can greatly enhance the output of a space laboratory constrained by crewtime. The measurement of current capability will provide baseline information supportive to NASA decision making processes for robotic applications to Space Station and future deep space and planetary explorer missions. Finally, the operational bounds of a telerobotic system within the TDRSS and NASA's overall communications system will be defined.

The proposed TLEM contains unique features which must be flight verified. No telerobotic systems have been a part of an orbiting or manned system. The Orbiter RMS is an exterior system and controlled from within the Orbiter by crew with a real-time, direct line-of-sight to the RMS and object being manipulated. The use of a real-time overlay computer simulation on delayed downlinked video as a "predictive display" has never been demonstrated with an orbiting system, but is needed for "real-time" feel and control of operations. The TLEM will allow measurement of experiment low-gravity environment and imparted robotic disturbance levels while in flight, demonstrating robotic capability in minimizing acceleration impacts during required material handling steps. The TLEM will also allow the opportunity to couple artificial intelligence with robotics for problem solving within the experiment operations envelope, and demonstrate that a man-in-the-loop control system can be efficiently, effectively, and safely applied with state of the art design.

The preliminary definition of requirements for an orbital flight experiment primarily address concerns of measurement of acceleration, vibration isolation and experiment operations to be tested in flight. Primary requirements for this system are as follows:

1) Flight Manipulator system to include a 6 DOF manipulator arm with a 2 finger end-effector with tool point reach necessary to manipulate objects mounted on test task panels.

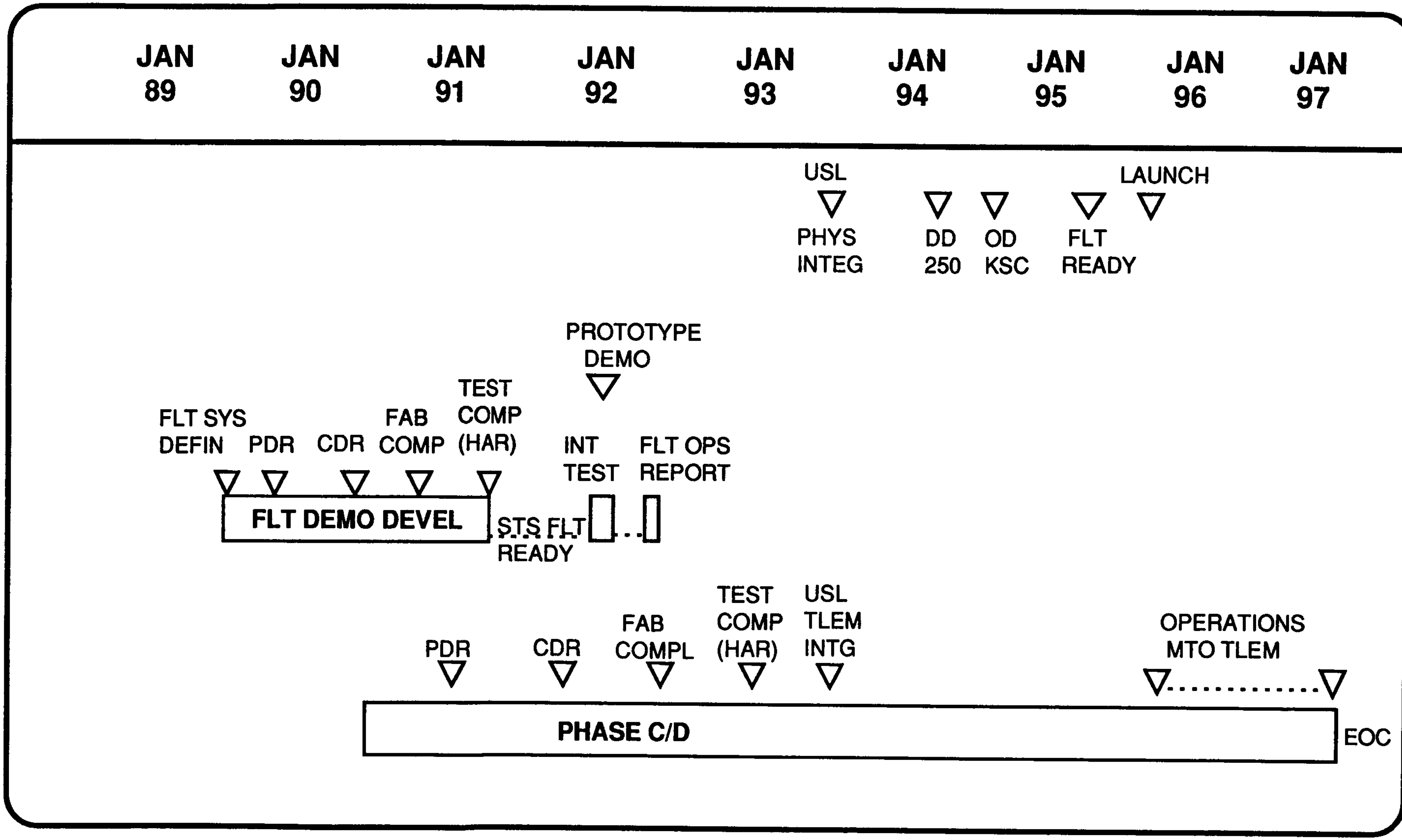

FIGURE 6-1. COMBINED TELEROBOTICS SCHEDULE

2) Flight Safety Computer to include computer and proximity sensors (i.e. infrared, ultrasonic) for crew safety.

3) Ground Control Station to include predictive display and control, that will allow robot control via man-in-the-loop in both direct and supervisory control modes (must include a high-speed graphics stand-alone work station incorporating computer control, safety monitor, and predictive display with control hardware and software).

4) Flight Task Panels will include devices so arranged that typical materials science and life science experiment motions may be tested in orbit. Typical sample masses will be handled in orbit in order to allow measurement of low-gravity disturbances and provide an opportunity to test control technique.

5) A test program must verify
   a. accuracy and repeatability,
   b. emulation of human dexterity and sensitivity,
   c. delayed visual feedback (when ground controlled),
   d. low-gravity disturbance measurement,
   e. demonstration of safety system reliability and adequacy, and
   f. demonstrate manual/automatic/man-in-the-loop modes.

The TLEM flight demonstration experiment can be packaged within a single rack envelope, with robot manipulator mounted onto or within the assembly. The rack would include the task panel, computers and necessary interfacing subassemblies. The suggested configuration for a Spacelab flight demonstration is shown in Figures 6-2 and 6-3.

Ground equipment (ground control station) can be developed from existing hardware and software systems. The flight equipment can be derived from existing industrial hardware and software, modified for flight, qualification tested, and certified for flight operations. Using current technology, hardware and software will permit minimum development time and provide a TLEM demonstration experiment at relatively low cost to orbit.

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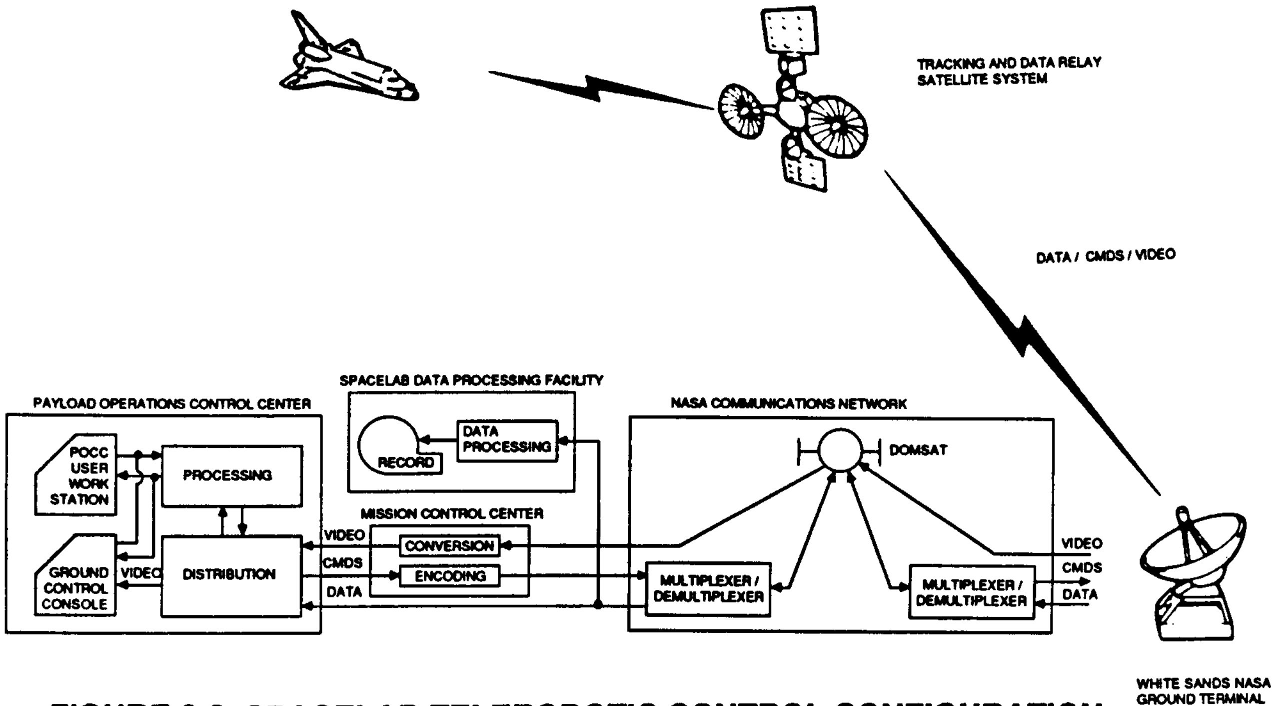

FIGURE 6-2. SPACELAB TELEROBOTIC CONTROL CONFIGURATION

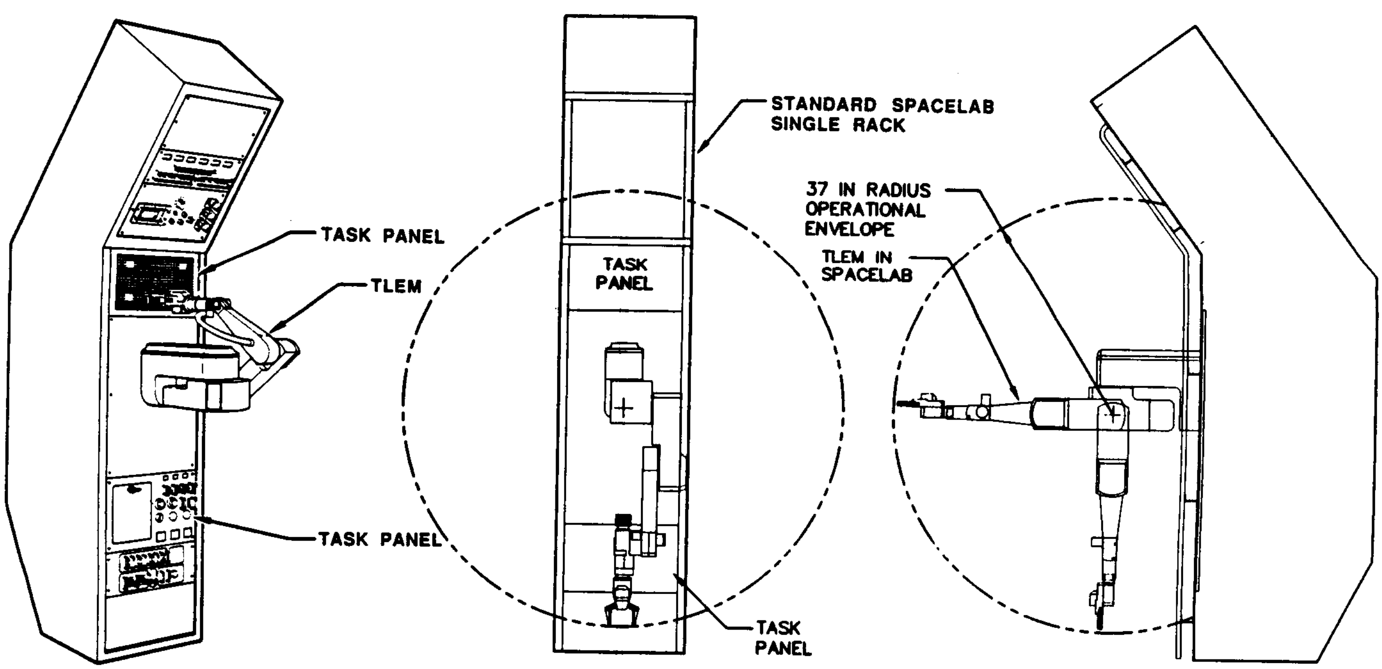

FIGURE 6-3. DEPLOYED FLIGHT ROBOTIC TLEM CONFIGURATION

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7. DISCUSSION OF RESULTS

Based on the MMPF database defined requirements for manipulation, a robotic manipulation system can be applied to effectively perform these manipulations. It also appears that interference between one experiment in process and another being manipulated can be minimal. Further, direct sample manipulation at 10E-4 g, although a power of ten below that demonstrated in our laboratory should be achievable in a microgravity environment with a small amount of development work.

7.1 MANIPULATION LIMITATIONS

Although the manipulator may be capable of doing the defined tasks with minimal perturbation, at this point in the study the results clearly indicate a serious problem in the experimenter community perception of how "good" the low-gravity environment is likely to be on-board the space station. Reviewing the potential sources for disturbances we found several and propulsion and thermal deflections were not even considered.

The MMPF database reflects very high user expectations in stating they need 10E-6 g (or microgravity) levels for many processes. Measurements on-board the orbiter have reflected that it is primarily a 10E-3 (milligravity) system. Now the same user community is asking for a 1000 times, three orders of magnitude, quieter system from the space station. These great expectations are in spite of the overall similarities in mass, systems and manned environment between the Orbiter/Spacelab system and the Space Station Freedom system. There are some design solutions to achieve improvements to the acceleration environment experienced by specific experiments on the station as a whole. But three orders of magnitude represents a vast, and probably unrealistic, improvement beyond current capabilities.

With a manned space station it is likely that a robotic manipulation system will never be a predominant disturbing factor. This is simply because humans and all animal life on earth are one g creatures. Unlike our vision sense that has a large dynamic response range, our gravitational sensitivities do not permit us to detect even a milli-g. Unable to sense low-g levels - we cannot control them.

During our experiments with accelerometers, human fingers were found to pulsate and vibrate with 10's of milli-g amplitudes. To understand what this means one can place the palms of his hands together with fingers curled up and knuckles touching. Then curl out the index fingers and brace them against the thumbs so that the tips of the fingers are just barely touching. One will find that the finger tips are actually bouncing against one another. For most individuals, this acceleration is approximately 20 milli-g's.

At this point, the reader should have a better understanding of the many ramifications and how difficult the "microgravity problem" truly is. The experimenters' requirements for an extremely low-gravity background environment is an overpowering driver to the design of the space station and robotic manipulator systems. Based on our data and analyses, it is clear that the space station will fall short of meeting these acceleration requirements. The alternative is to start planning now for a free-flyer program where 10E-5 to 10E-7 g is more likely to be achieved. This would, of course, require the development of even lower g robotic systems to support operations.

7.2 PROBLEMS AND ISSUES

Some of the problems and issues identified in the course of this study are reviewed here. The current disposition, magnitude of impact and discussion of methods of resolution are given.

1. Current state-of-the-art robots using microstepping motors and harmonic drives exceed microgravity levels for both base reaction and end-effector sample manipulation. Proposed Solution:

   a. evaluate bare motors and low-g drives and transmissions. Include stepper motors and servo motors and core-less (low intertia) motors.

   b. evaluate various types of materials and manipulator construction techniques to minimize jaw closure contact shock and jaw opening release acceleration on the captured mass yet maintain strength and positioning accuracy.

   c. study active and passive damping techniques, including reactionless geometries in robotics design (active counterbalancing techniques), trajectory control, and damping materials for robot mounting and manipulator construction.

   d. investigate shape memory (bi-metallic structures), magnetic isolation (for bearings and load-bearing structures), and other potentially low-g drives (including piezoelectric motors, micro-motors, etc.)

   e. evaluate harmonic drives and roller drive transmissions.

2. The movement of the loaded orbiter, which weighs about 230,000 pounds must be accomplished with the MSC end-effector exerting a maximum of 15 pounds force. This provides a low frequency micro-g disturbance source. Other external sources are also of concern. This problem, identified early in Task II has been addressed by two NASTRAN studies of the space station. Analysis has shown that the space station resonant response is in the 0.7Hz to 0.15Hz range.

3. Early tests of the Intelledex 660 indicated that the off-the-shelf controller did not permit joint motor micro-stepping directly. It was found that the position sense encoder used by the manufacturer was not of high enough resolution to properly indicate positional changes in the micro-radian ranges desired. In later tests the encoder signal was disabled and the controller was free to execute the 1,250,000 steps per revolution desired. The actual displacement was confirmed by an LVDT. Later tests of disturbance levels by accelerometer indicated the disturbance levels in the microstepping mode to be approximately one milli-g. (Problem Resolved)

4. The micro-gravity disturbance levels to be expected on-orbit are not fully understood. Additionally, the robotic disturbance levels to be expected from actual servicing of experiments is

approximated from incremental laboratory experiments. Measurement of actual environmental disturbance levels and evaluation of actual robotic capability to work within user required levels of disturbance is needed. Proposed Solution:

a. Use a Neutral Buoyancy Tank to test a prototype Telerobotic Laboratory Flight Experiment Manipulator as a verification of requirements for an orbital test. Robot hardware and control techniques can be evaluated and optimized.

b. A Telerobotic Laboratory Experiment Manipulator test flight is crucial to quantifying actual robotic micro-gravity disturbances on-orbit. Additionally, the measurement of crew and external disturbance levels may be measured on such an experiment. Isolation methods and user requirements for low-gravity can also be further defined.

5. User needs for low-gravity should be validated.

Proposed Solution: Step through each experiment (using physical mockups) and simulating the material handling/manipulation steps of the experiment with accurate mass and cyclic motions. Test of prototype experiment will allow measurement of the experiment imparted disturbance levels. Measurement of human versus robotic manipulation imparted disturbances can be measured and evaluated. The user may compare this disturbance level to his measured requirements.

During the course of this study significant issues of both technical and non-technical nature which are sources of concern have been identified and reported in parallel with other tasks of this study. Some of these represent newly identified concerns as study progress has been made. Other concerns are related to state-of-the-art needs, and are related to incremental findings or identification of problems.

As identified in section 3.0 one of the greatest issues or need areas for microgravity robotics (considering the candidate experiments and/or processes, shared lab resources and MMPF housekeeping) is in handling delicate crystalline structures during and/or after processing. One of the best examples is the Protein Crystal Growth process, in which very low order disturbances can destroy the structure of the protein crystals grown.

The technology to support this manipulation and requiring immediate attention, if microgravity robotics are to become a reality for use on a space station or possibly a future free-flyer, is primarily that of motive drive, transmission, and control. Though successful demonstration of state-of-the-art equipment has shown that a 10E-4 level is within reach by microstepping motors, further development is required. To achieve the micro-g level, a thorough study of reactionless (counteracting) techniques and alternative methods of drive, transmission, and control must be made. Operation in a low-gravity environment will be of great value in determining the magnitude of reduction in g-levels needed for robotic operations in micro-g experiments.

Since data gathered during this study indicates that humans are limited to a deka-milli-g disturbance level of manipulation, prevention of disturbance levels to that below the 1 milli-g level is achievable only by alternative, non-human methods. Alternative methods include appropriately designed automated experiments in addition to robotic assist devices appropriately designed. Both the need (user experiment material handling) and limitations of options, i.e. limited crewtime, indicate some level of robotic support is needed on the space station. The potential impact on the overall space station development schedule can be minimized by implementing an orbital test of a TLEM type flight demonstration experiment. Secondly, a phased implementation of robotics onto the station should allow building on consecutive successes, starting with well developed technology and upgrading progressively. The schedule shown in Figure 6-1 shows a plan to deliver a robot system to station on a timely basis.

Finally, a logical sequence of work which could lead to reactionless microgravity robotic systems in MMPF is an implementation of a plan that includes evolutionary enhancement of robotic capability on station. The station and station systems design work is now underway. Robotics technology that is not ready for development today will be unlikely to be qualified for space flight in 1995. It is therefore best to think of the first flight systems as the simpler and more readily achievable ones. Full up, new designs take several years to get through the verification and qualification cycle. The only designs that can be turned around and flown in less than about three years, are those that are modifications to previously flown designs.

Through proper, detailed planning and the use of hooks and scars incorporated into the initial robot system, it will be possible to develop an immediately useful robotic system that is both economical and has reduced risk in development. One preliminary sequence under investigation is as follows:

1. Plan and implement a TLEM (Telerobotic Laboratory Experiment Manipulator) on a scheduled Shuttle-Spacelab flight circa 1992. This will provide the opportunity of testing actual dynamics of a robot manipulator within an MMPF environment.

2. Space station, circa 1996: Rail Mounted, Single Arm Three Finger robot. This system is to be modular such that the hooks and scars for a dual arm dexterous system can be interchanged with this robot at a later date. Based on improvements in existing technology, this configuration can be ready for startup with the Base Space Station.

3. Growth Space Station circa 1998: (Upgrade #1) The Single Arm manipulator and Three Finger End-Effector can be replaced by the Dual Arm Dexterous system within 18 to 24 months of final certification of the single arm system. This will allow time to implement changes and/or new-technology into the Dual Arm Dexterous System. Problems identified on station can be addressed, corrected and implemented for this next generation robot system. User needs on long-duration, low disturbance process runs can impact the design.

4. Final Configuration, circa 2000: (Upgrade #2) Based on results of the Dual Arm Dexterous Robot system installation and application, design of a wall-walker robot can be completed and an experimental semi-autonomous configuration installed on-station to supplement the rail mounted system. The wall-walker can be used to verify system capability and will function as a test bed for development of long-duration mission applications. The wall-walker unit would not replace the dual arm dexterous robot, but would instead be used to supplement the dual arm unit in operations. It is expected that due to its mobility, the wall-walker will be easier to maintain (ease of access), replace, and upgrade. It should also be noted that due to its mobility, the wall-walker robot (or its successors) should be available for testing on work sites other than the United States Laboratory.

This proposed sequence of development would permit a pay as you go type of development. It would also serve as the catalyst and focusing point within NASA to support the development of the required technology advancements in motors, drives, counter-balancing mechanisms, et cetera, required by the low-gravity processing community. With acceleration background levels that may far exceed user defined limits for experiments, robotic development could be in vain, if the disturbance sources on the station are not positively controlled.

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8. CONCLUSIONS AND RECOMMENDATIONS

From analyses of the user experiment flows and the results of analyses and our test laboratory accelerometer measurements, it is clear that present user defined low-gravity requirements (10E-6 g or better) exceed the present capabilities of either man or machine to accomplish. New technology in motors and drives might provide improvement to what appears at best to be a milli-g environment for most of man's machines in low earth orbit.

The quandary, over predicted experiment acceleration requirements in the absence of any previous experience with "microgravity" versus the most probable best case low-gravity environment, can not be resolved until a free flier demonstration flight is operational, such as ESA's Eureka. This will provide new low-g measurements and samples to evaluate. At that time the question about the true merits of micro-g versus milli-g should be answered.

Whatever the lowest gravity orbiting environment is that is practically attainable, it certainly will not be a permanently manned facility, but rather a free-flyer, man-tended for servicing. It may have robotics but only operational at specified active periods during the mission timeline.

If the Space Station Freedom is built along current guidelines for design and modes of operation, it is clear that low-g experiments will be included in the manifests. In order to provide the maximum low-g accommodation possible, it will be necessary to provide robotics. As demonstrated in our laboratory measurements, current robotics systems can sustain milli-g level manipulation of samples, whereas, humans can not. Human sample manipulation will be subject to at least 20 to 60 milli-g accelerations, which are essentially undetectable to the human.

It is our finding that the technology for manipulation has not specifically addressed the low-gravity problem. Development work on the motor and gear mechanisms to achieve very low disturbances is needed if robots are to operate a "microgravity" facility.

Our study has identified several other key issues which can only be verified with a flight demonstration experiment. These key issues are related to:

1) "realtime" ground control of telerobotics, via NASCOM and TDRSS, using predictive display;

2) safe, crew interactive operations in a low-g environment; and

3) performance of a telerobot in low-g.

A separate, and related to robotics, finding is that humans are generally unaware of just what a milli-g or micro-g is. Our test subjects were surprised at how "disturbing" they were to the acceleration environment. Since crew are likely to be involved directly in most planned research in low-g, special "awareness training" for astronauts on these missions should be included. Actual levels of disturbance they generate should be defined and they should learn the techniques to minimize disturbances in manipulations and movements within the laboratory.

The optimum scenario for space station operations appears to be a combination of human crew members and robots. As found in the analysis of benefits there is a serendipitous effect of having a combination of men and machines. While robots can work diligently, deliberately around the clock in low-g fashion, only the crew can instantly appreciate the complexity and solutions to unique problems requiring reasoning, agility and dexterity. The capabilities of both are limited by their creator's design and must be supplemented for maximum benefit.

9.0 APPENDICES

APPENDIX 9.1

DESCRIPTIONS OF TEN EVALUATED MMPF EXPERIMENTS

UNBIS FACILITY DESCRIPTIONS

1.0 INTRODUCTION

The following describe the science requirements and operations of the selected experiments. Also included is the rationale for selection of this MMPF facility for further study in this contract.

1.1 GENERAL ASSUMPTIONS AND GUIDELINES

The following are common assumptions and guidelines defined for all of the facilities:

1) Acceleration of 1 g at a frequency of 60 Hz was considered for the ground and transporting to the Station;
2) Acceleration of $1x10^{-2}$ g at a frequency of 60 Hz while on orbit but not running;
3) Acceleration and frequencies as determined in the MMPF database for the processes and materials considered;
4) The robot arm was considered to be at rest in the x=49 y=79.5 and z=0 (front center of the rack; dimensions in cm) position;
5) The logistics module weight is 20,000 lbs;
6) 100 man weeks to ready a facility for launch;
7) 33.33 man weeks to ready sample, etc for launch;
8) 16.67 man weeks to ready other consumables for launch;
9) 10 man weeks to integrate the facility into the shipping hardware;
10) 10 man weeks to integrate the shipping hardware into the logistics module;
11) Assuming 1 hour launch to launch 14 facilities with an 8 man crew and 14 facilities in the best scenario (launch of the lab outfitting flight), a one hour launch gives 60 x 8 / 14 = 34 crew min per facility;
12) 3 days to secure the items once on orbit; or 3 (days) x 24 (hours/day) x 60 (min/hour) x 1 (crewman) / 14 facilities = 308 man-min per facility;
13) the facility's mass, volume, power requirements, and other resources come from the MMPF database unless otherwise stated in this document.

2.0 ACOUSTIC LEVITATOR FACILITY

2.1 FACILITY DESCRIPTION

The Acoustic Levitator is a furnace chamber of 0.082 m^3. The furnace is electrically heated up to 2500 ^oC. A glass sample is inserted into the chamber and is positioned using acoustic forces, generated by an acoustical driver with a reflector in the opposite wall of the furnace. This allows the sample to be processed without contacting the furnace walls. Contact with the walls of the furnace causes nucleation points to form in the sample along the areas of contact. These nucleations will affect the quality of the material produced by disrupting the crystalline structure of the materials. Contact with the walls can also introduce unwanted contamination into the sample.

The facility has acoustic drivers/reflectors in each of three orthogonal planes. These drivers/reflectors allow the sample to be injected into the furnace, processed in a given position, rotated (if required) during process run, and moved from the furnace into a cooling chamber for solidification all without the sample ever coming in contact with the furnace or any other object. The three drivers/reflectors also allow the user to shape the sample into various geometric shapes thereby studying the sample melts physical and processing parameters. Using a force feed back system from the acoustic drivers/reflectors the user can accurately measure the acceleration, viscosity, density, and various other properties of, or acting on, the melted sample.

2.2 ACCELERATION REQUIREMENTS

The Acoustic Levitator requires an acceleration level of less than 10^{-4} g during the melt, processing, and resolidification stages of the run. The solidified glass sphere samples are insensitive to the acceleration forces. The characterization that is required on orbit does not require specific acceleration levels.

Although the process is considered to be containerless, the acoustic pressure in the carrier gas (usually GN_2) does transmit forces through the gas and into the sample. This will isolate the sample from the higher frequency accelerations but will not help the steady state acceleration driven forces from propagating into the sample. The frequencies that are considered to be damped from the samples in this process are those greater than the driver frequencies (usually 20,000 Hz). Another consideration for the acceleration environment is that the acoustic force can only overcome small acceleration driven forces. As the external forces exceed the acoustic force the sample can no longer be controlled, and the sample will leave the acoustic well and strike the wall. The value of the acoustic force is the upper limit on the acceleration for the least sensitive samples.

2.3 SELECTION CRITERION

This facility was selected for study under this contract for the following reasons:

1) The facility processes glass samples and glass has some unique properties that need to be considered from the acceleration point of view (glass has an amorphous structure);
2) The facility has unique operational requirements, operation of optical refractometers, etc.;
3) The facility is a good candidate for automation due to the large manpower requirements and repetitive task.

2.4 ASSUMPTIONS AND GUIDELINES

In addition to the common assumptions and guidelines defined in section 1.1, the following were considered for this facility:

1) The sample is fluoride glass;
2) The entire facility outlined in the MMPF report is used;
3) Each sample is characterized prior to the running of the next.

3.0 ALLOY SOLIDIFICATION FACILITY

3.1 DESCRIPTION

The Alloy Solidification facility consists of three furnaces; an isothermal furnace, a Multiple Experiment Processing Furnace (MEPF), and a precision solidification system.

The isothermal furnace is one that uniformly heats metallic samples up to 1600°C at diameters of up to 2 cm, and then rapidly and uniformly cools the samples. The sample is melted, the mixture is allowed to mix through diffusion, and then the sample is rapidly quench to freeze in the immiscible materials. This allows the user to produce homogeneous alloys that would settle out in the presence of gravity driven buoyancy forces. The rapid quench capability can be used to control the cooling rate and produce various crystal structures.

The MEPF is a furnace that can be reconfigured to process a variety of materials, such as alloys, electronic materials, and organic samples. The furnace runs at up to 1600°C with samples up to 2 cm in diameter. The MEPF also has rapid sample cooling capability. The MEPF heats the sample uniformly to the run temperature, however, the sample is directionally solidified. This directional solidification, also known as the Bridgman technique, is used to help purify the melt. As the melt is solidified a crystal matrix is formed. This matrix tries to find a particle the right type and charge to complete the matrix. The unsuitable ions are pushed ahead of this forming matrix and, therefore, are removed from the structure. In this way the sample is purged of the unwanted materials. This purging force pushing the ions out of the matrix is very small, and the acceleration driven forces of buoyancy and convection can easily overcome the pushing force, thereby causing dislocations in the forming matrix. when this process takes place in the presence of gravity. The rapid solidification capability is used in the same way as on the isothermal furnace described above.

The precision solidification system is similar to the Mephisto furnace that the Europeans flew on the Spacelab D-1 Mission. This furnace measures the properties of the solidifying materials for use in materials studies. Properties such as the forces described above, Marangoni convection (convection driven by thermal forces on the molecular level) and other solidification perturbations. This furnace processes a very small sample and is limited to 1100°C maximum operational temperature. The system is capable of controlling a high temperature gradient (up to 300 °C) with a near flat solidification front.

Operationally the isothermal and the MEPF furnaces are automated to provide up to twenty samples each without interruption, and will only require a change of the carousel(s) to begin the next run(s). The precision solidification system will only run one sample at a time, but supports multiple samples via carosel sample handling.

3.2 ACCELERATION REQUIREMENTS

The acceleration requirement for all of these furnaces is the same. This is because the materials, matrix size, ion size, solidification rate, and fluid viscosity determine the level of DC acceleration that the melt can withstand. These furnaces are all processing the same type of materials, they all respond to the accelerational input in the same manner, and the maximum DC acceleration level is 1×10^{-5} g.

3.3 SELECTION CRITERION

The Alloy Solidification facility was selected for the following reasons:

1) The facility processes metals and alloys. This group of materials will benefit from space processing, and should be looked at carefully;
2) The facility requires the use of rapid quench technique that could be a perturbation to the host facility as well as others;
3) The materials used in the facility have unique characterization equipment requirements (metallographic microscopes).

3.4 ASSUMPTIONS AND GUIDELINES

In addition to the common assumptions and guidelines defined in section 1.1, the following were considered for this facility:

1) Only the MEPF and the isothermal furnaces were considered for this analysis;
2) This arrangement occupies one double rack;
3) The mass used does not include the x ray system, the DCS, or the precision solidification system;
4) The mass total = 270 kg (for the facility as described) + 10% for packaging (27 kg) and samples (10kg assumed x 5 = 50 kg) = 347 kg.

4.0 ATMOSPHERIC MICROPHYSICS FACILITY

4.1 DESCRIPTION

The Atmospheric Microphysics facility contains an expansion chamber, a sample injector, a controlled diffusion chamber, and other devices needed to produce clouds and study their formation and coalescence. Several types of experiments can be performed in this facility.

The first class are cloud formation experiments. These experiments take advantage of the reduced gravity of space to slow down the growth of the water droplets, by allowing the diffusion of water to the seed droplet be the dominant process driver.

Another experiment to be run in the Atmospheric Microphysics facility is the production of a polydispered cloud to study the interaction of the droplets with light, temperature, and other atmospheric conditions.

Other experiments are to study the effects of a nuclear explosion on atmospheric conditions, to determine the contents of the atmospheres of other planets, and to better understand weather conditions for improving weather forecasts.

Within this facility a particle is introduced into the expansion chamber. The chamber is then filled with moist air from the diffusion chamber and then slowly, and adiabatically expanded. This expansion forces the water to condense onto the particles and form droplets. This will allow researchers to determine the time that these dust and smoke particles stay in suspension before the atmosphere "washes" them out of the air. This will then be used to update the theories on the effects of nuclear explosions (nuclear winter, greenhouse effect, etc.).

4.2 ACCELERATION REQUIREMENTS

The Atmospheric Microphysics facility will require a low g (10^{-4} g) environment for many intervals of up to 60 minutes at a time. There are many experiments that will be run back to back with only enough time between to allow the equipment to reach the desired operational temperature. The time between the experiments will require the operation of the hardware by the crew. This tends to be very laborious and time consuming. Therefore, automation would result is great time savings. The tasks required are unique; vision with depth of field, high resolution video, low accelerations induced into the sample, and others.

4.3 SELECTION CRITERION

The facility was selected for future study in this effort because it will require the sample to be free floated in the chamber. This is a unique requirement for this facility. Few facilities actually freely suspend the sample in the container. There are three other MMPF facilities that do this, the Fluids Physics Facility, the Variable Flow Shell Generator, and the Free Float Facility. The Fluid Physics facility will also be selected for this reason.

4.4 ASSUMPTIONS AND GUIDELINES

In addition to the common assumptions and guidelines defined in section 1.1, the following were considered for this facility:

1) The experiment run is a cloud formation experiment with varying temperatures and pressures to simulate varying altitudes;
2) The seed material is small water droplets;
3) Cloud analysis is done as part of the run with the cloud still in suspension, this implies that no additional characterization is required.

5.0 CONTINUOUS FLOW ELECTROPHORESIS FACILITY

5.1 DESCRIPTION

The Continuous Flow Electrophoresis facility uses an electrical charge across a flowing fluid field to separate the biological materials in the fluid by their dielectric potential. Each biological compound has a known dielectric constant. In the presence of an electrical field the compound will migrate to the point were it is neutrally charged. Then the compound can be removed at its neutral point and thereby refined. The products at the point selected will all have the same dielectric constant and be the same biological material.

5.2 ACCELERATION REQUIREMENTS

In the presense of gravity this type of separation would require a greater field strength and the samples would be separated but the resolution would not be as good. This on-orbit capability will provide the refining of drugs that could not be separated on Earth. The level at which the field strength becomes greater than the acceleration forces is currently believed to be around 1×10^{-4} g. This level has proven to be acceptable for the initial experiments on board the Shuttle. The larger systems envisioned will be trying to increase the resolution as well as the production. It does not appear that the increase in resolution will require a lessening of the gravity environment.

5.3 SELECTION CRITERION

The Continuous Flow Electrophoresis facility was selected for this study as it represents the biological experiments from the acceleration, automation, and the crew activity points of view. This experiment has the longest run time (at continuous g levels) of any of the other biological experiments. It could be automated easily once the process is defined better, and the crew requirements for sample change out are the most severe of the biological experiments. This makes the CFES a good study candidate.

5.4 ASSUMPTIONS AND GUIDELINES

In addition to the common assumptions and guidelines defined in section 1.1, the following were considered for this facility:

1) The sample is human kidney cells;
2) The characterization requires growth of the cells in a culture to determine the purity;
3) Samples are shipped freeze dried and mixed on-orbit;
4) Samples are refrigerated after processing.

6.0 DROPLET SPRAY BURNING FACILITY

6.1 DESCRIPTION

The Droplet Spray Burning facility is a combustion chamber where a single drop or a matrix of droplets of fuel are free floated in the chamber and ignited. The absence of gravity will allow the droplet(s) to be free of gravity induced convection during the burn. The oxygen required for combustion will be supplied by diffusion through the flame. This will allow the researchers to determine the portion that the diffusion process plays in the total combustion of the Earth based systems, and the methods required to prevent and fight on-orbit fires.

6.2 ACCELERATION REQUIREMENTS

The g level requirement is to be 1×10^{-4} g during the actual burn. These burns typically take only a few seconds, although Space Station runs may be up to a minute.

6.3 SELECTION CRITERION

The Droplet Spray Burning facility was selected because it represents the combustion science fields. The combustion experiments do not have long runs, but are typically very labor intensive. The run times of only a few seconds and the high labor requirement between runs, all make this experiment a good choice for the UNBIS study.

6.4 ASSUMPTIONS AND GUIDELINES

In addition to the common assumptions and guidelines defined in section 1.1, the following were considered for this facility:

1) The fuel is toluene;
2) The combustion experiment is the study of flame interactions with a 3x3x3 matrix of droplets;
3) The facility is cleaned after each run.

7.0 FLOAT ZONE FACILITY

7.1 DESCRIPTION

The Float Zone facility is similar to the MEPF furnace described under the Alloy Solidification facility. However, in the Float Zone facility the sample is not encased in an ampoule. It is allowed to melt and resolidify in the furnace without the use of an ampoule to reduce the nucleations caused by the walls of the ampoules. The Float Zone technique does not melt the entire sample at once. The sample is secured at each end. There is a small zone near one end of the sample that is melted. This melted zone is of fixed length and is moved, at a slow rate along the axial length of the sample until it is within a few centimeters of the end. The surface tension of the melt allows it to "hold" on to the solidified portion of the sample. As the floating zone moves, the impurities are forced out of the forming crystalline structure ahead of the solidification front.

7.2 ACCELERATION REQUIREMENTS

The Float Zone experiments are as sensitive to the acceleration environment as the materials described in the Alloy Solidification facility. The materials require a 1×10^{-6} g as a minimum. The matrix size, ion size, and particle size are such that the facility acceleration requirements are the same as the alloy experiments.

7.3 SELECTION CRITERION

The Float Zone facility was selected for study under this contract because it is representative of the electronic materials discipline and the float zone process is more labor intensive than the bridgman techniques.

7.4 ASSUMPTIONS AND GUIDELINES

In addition to the common assumptions and guidelines defined in section 1.1, the following were considered for this facility:

1) The sample is GaAs;
2) The translation rate is 1 cm per hour;
3) One sample per run;
4) Sample characterization includes cutting the sample into wafers, viewing under a microscope, and operation of several probes to determine the quality of the material for the next run.

8.0 FLUID PHYSICS FACILITY

8.1 DESCRIPTION

The Fluid Physics facility is used to perform a variety of fluids experiments. The facility contains optical equipment to measure fluid flows, sedimentation, and convection in the reduced gravity of the station. The experiments range from solution crystal growth, to applied science experiments, to the study of thermal bubble migration. Although a range of experiments are presented, the experiments all have some very basic requirements in common. They all are performed in a viscous fluid. The sample to be studied can either be suspended in the fluid, grown from materials saturated in the fluid, or be the actual fluid itself. The experiments can be attached to the facility or can be freely suspended inside the camber. In the latter case the fluids are monitored as the surface effects of the fluids are studied.

8.2 ACCELERATION REQUIREMENTS

The Fluid Physics facility, as it supports a variety of experiments, has an acceleration level that is hard to identify with any one experiment. The freely suspended experiments are not very susceptible to the high frequency accelerations. However, lower DC accelerations allow for longer experiment runs without the sample contacting the wall. If a crystal is being grown from solution, the same logic detailed for any other crystal would apply. With a variety of acceleration requirements bounding the experiment set, an acceleration of 1x 10^{-4} g is used.

8.3 SELECTION CRITERION

The facility that is used in this study is a candidate from the fluid group, and it will have the capability to freely suspend a sample in a chamber.

8.4 ASSUMPTIONS AND GUIDELINES

In addition to the common assumptions and guidelines defined in section 1.1, the following were considered for this facility:

1) The experiment considered is a solution crystal growth experiment similar to the FES;
2) The material is TGS;
3) The facility uses optical systems for the majority of the data gathered during the run.

9.0 LARGE BRIDGMAN FACILITY

9.1 DESCRIPTION

The Large Bridgman facility is a directional solidification furnace like the one described in the Alloy Solidification facility MEPF. The sample in this furnace is up to 10 cm in diameter and is to be pressurized to 80 atmospheres. The larger samples are required for the large scale integrated circuit designer. The high operational pressures come from the fact that the HgCdTe materials to be grown have a +1200 °C melting point. At this temperature the Mercury will be vaporized and come out of solution. Therefore, the system is pressurized to 80 atmospheres, the vapor pressure of mercury at 1200 °C, to keep it in solution. After the solidification is complete the HgCdTe is stable at room temperatures and pressures.

9.2 ACCELERATION REQUIREMENTS

With the Large Bridgman facility the sample diameter of over 8 cm presents the station with the most restrictive acceleration requirement. The sample will require a 1×10^{-6} g environment for the low (DC) frequency levels. These experiments are pre-production activities. The actual production of bulk HgCdTe will not be accomplished in the US Lab.

9.3 SELECTION CRITERION

The Large Bridgman facility was selected as it has the most restrictive acceleration requirement, requires long periods to grow the samples, and requires the movement of very heavy equipment to remove the sample on orbit. This heavy equipment is the pressure containment vessel for the facility. This vessel must be moved to service the furnace, remove samples, or to modify the hardware. This item represents the largest piece of hardware to be moved by the robot, not including the racks themselves.

9.4 ASSUMPTIONS AND GUIDELINES

In addition to the common assumptions and guidelines defined in section 1.1, the following were considered for this facility:

1) The material is HgCdTe;
2) The sample must soak at temperature for 24 hours to allow the melt to become homogeneous;
3) The translation rate is 30 cm per hour;
4) Characterization includes cutting, viewing, x-ray, various probes, and FTIR analysis.

10.0 PROTEIN CRYSTAL GROWTH FACILITY

10.1 DESCRIPTION

The Protein Crystal Growth facility is a chamber, with a controlled environment, used to allow protein crystals to form. Protein crystals are grown from vapors or solutions. Typically the vapor method is used. In this method a concentrated protein is placed near a solution which contains a high salt concentration. The salt concentration then draws the free water vapor from the concentrated solution. This superstaturates the protein solution. The superstaturated solution then nucleates and a crystal is formed. The crystal continues to grow until the solution is no longer superstaturated. The environment of the facility is conditioned to provide the solutions with the ideal temperature for the nucleation to take place. The typical protein crystal is 1 to 3 mm when grown on Earth. The few results from the Shuttle experiments show that the crystals can be grown to much larger sizes. The crystals are of no use themselves. However, when bombarded with x-rays, they reveal the structure of the proteins. This process of bombarding the crystal, called x-ray diffraction, gives the relative positions of the elements in the protein molecule. With this information the user can design drugs that function the same as the protein or combat the protein. This will be the first step in the era of drug designers. To date the drugs are developed based on theoretical data. The use of protein crystals to physically show the drug developers how to build their drugs would remove the guessing done today.

10.2 ACCELERATION REQUIREMENTS

The protein crystals are very fragile. They have been described as pickup sticks held together in a viscous fluid like honey. They have no real structure. The slightest bump will destroy them. The experience of the Shuttle flights show that they may not even be able to with stand the re-entry loads. These samples will be x-rayed on orbit to increase the effective throughput of the facility. The process of moving a grown crystal from the growth chamber to the x-ray diffractometer is a difficult task. The sample will require the mover to not exceed the 1×10^{-4} g level or the sample could be lost.

10.3 SELECTION CRITERION

There are a great number of crystals grown in one facility run, typically a thousand. There are several reasons for this large number of crystals per run. First, the x-ray system will destroy the sample after a few minutes of exposure. The x-ray pattern requires hours of exposure time and the crystals only last for minutes, this all implies that out of a thousand crystals grown, hopefully, one diffraction pattern will be obtained. The protein crystals, also, do not grow consistently. Therefore, for any given run, one out of ten crystals do not nucleate on themselves. Only the crystals that nucleate on themselves are usable. This is because these have the correct single crystal shape and planes required for the diffraction analysis. Therefore, of the thousand grown only about one hundred are usable.

These limitations on the crystal structure, the heavy crew involvement, the precise handling requirements, and the x-ray environment all lend themselves to a robotic system to support the protein crystal facility. The movement of the samples from the facility to the x-ray system will require a steady handed crewman or a robot. For these reasons this facility was selected for this study.

10.4 ASSUMPTIONS AND GUIDELINES

In addition to the common assumptions and guidelines defined in section 1.1, the following were considered for this facility:

1) The sample is Interferon grown by the vapor transport method;
2) The growth time is 10 days;
3) The finished crystals are viewed under a microscope for determining those suitable for x-ray diffractions;
4) X-ray diffraction analysis of the sample is completed before the next run is started.

11.0 VAPOR CRYSTAL GROWTH FACILITY

11.1 DESCRIPTION

The Vapor Crystal Growth facility studies the growth of crystals from a vapor. The seed crystal is placed in one end of an ampoule, and the unprocessed material placed in the other. The material is heated to just under the melting point. The seed is cooled to several degrees below the solidification point. The vapor pressure of the materials near the melting point forces the material to be driven out of the bulk material and be condensed onto the cooler seed. With the absence of gravity the transfer from the hot side to the cool is driven only by diffusion forces, not the convection that would disrupt the reformation on the seed.

11.2 ACCELERATION REQUIREMENTS

This process is a diffusion controlled experiment, as is the protein crystal experiment. The Vapor Crystal Growth facility, however, requires 1 $x10^{-5}$ g during the growth of the crystal.

11.3 SELECTION CRITERION

The Vapor Crystal facility is more sensitive than the Protein Crystal Growth experiments during the growth phase. For this reason the Vapor Crystal facility was added to the study.

11.4 ASSUMPTIONS AND GUIDELINES

In addition to the common assumptions and guidelines defined in section 1.1, the following were considered for this facility:

1) Sample is HgI;

2) Only one furnace module was used;
3) Mass included only the single rack of equipment required to support one furnace module.

APPENDIX 9.2

DESCRIPTIONS

OF

LABORATORY

SUPPORT

EQUIPMENT

EQUIPMENT NAME: Battery Charger

EQUIPMENT IDENTIFICATION NUMBER: SUP-01

DEFINITION: A compact device used to recharge small rechargeable batteries used by a number of small instruments (eg. digital thermometers, multimeters, pyrometers, etc.).

EQUIPMENT NAME: Camera/Camera Locker

EQUIPMENT IDENTIFICATION NUMBER: SUP-02/03

DEFINITION: General purpose photographic cameras with accessories (e.g. lights, mountings) and storage space. One required.

EQUIPMENT NAME: Centrifuge, Refrigerated

EQUIPMENT IDENTIFICATION NUMBER: SUP-04

DEFINITION: A 1000 to 4000 rpm high-capacity (10-100 ml) centrifuge whose internal atmosphere (pressure and composition) and temperature can be controlled. One required.

EQUIPMENT NAME: Chemical Supply Storage Facility

EQUIPMENT IDENTIFICATION NUMBER: LAB-01

DEFINITION: A vented, fire- and leak-proof locker for storage of small amounts of chemicals, reagents, acids, etchants, solvents, etc. One or two required.

EQUIPMENT NAME: Cleaning Equipment

EQUIPMENT IDENTIFICATION NUMBER: SUP-05

DEFINITION: General purpose tools used for cleaning lab equipment and general housekeeping; in particular used to clean up liquid spills. This equipment will include: wipes and towels, sponges, brushes, spray bottles, disposal containers, droppers, squeeze bulbs, syringes, (5-1000 ml capacities), etc.

EQUIPMENT NAME: Cutting/Polishing System

EQUIPMENT IDENTIFICATION NUMBER: SUP-06/14

DEFINITION: An automated facility that can precisely slice a wafer off bulk material specimens (1-10 cm in diameter), encapsulate the wafer of bulk material in a plastic support if necessary, and then polish one or more surfaces of the wafer for microscopic investigation. This unit will be operated in a glovebox.

EQUIPMENT NAME: Dimensional Device(s)

EQUIPMENT IDENTIFICATION NUMBER: SUP-07

DEFINITION: Several hand held tools for determining the dimensions of an object. These tools include micrometers, calipers, scales, and other devices. These are a subset of the hand held tools listed in the MMPF database.

EQUIPMENT NAME: Differential Scanning Calorimeter (DSC)

EQUIPMENT IDENTIFICATION NUMBER: CHR-01

DEFINITION: An instrument that can detect and quantify physiochemical changes in milligram quantities of material samples as a function of temperature by measuring differential enthalpy changes in the sample as compared to a reference blank. Such physiochemical changes include phase transformations, crosslinking, degradation, melting and softening, etc.

EQUIPMENT NAME: Electrical Conductivity Probe

EQUIPMENT IDENTIFICATION NUMBER: CHR-02

DEFINITION: An instrument used to measure the resistivity, and conduction type (mechanims), of semiconductor or conductor materials with precision. The unit uses a 4-point probe head to perform both resistivity and typing measurements.

EQUIPMENT NAME: Ellipsometer

EQUIPMENT IDENTIFICATION NUMBER: CHR-03

DEFINITION: An automated unit for measuring film thicknesses utilizing ellipsometry techniques.

EQUIPMENT NAME: Etching Equipment

EQUIPMENT IDENTIFICATION NUMBER: SUP-08

DEFINITION: The equipment necessary to chemically etch polished materials specimens. This will include etching bags, fasteners, containers, droppers, etc. (This may eventually include equipment to electrochemically etch samples.)

EQUIPMENT NAME: Fluid Handling Tools

EQUIPMENT IDENTIFICATION NUMBER: SUP-09

DEFINITION: General-purpose tools used to handle (ie. transfer, measure, mix, etc.) fluids. This tool set will include syringes (5-1000 ml capabilities), containers, squeeze bulbs, disposable droppers, (small, battery-powered) pumps and vacuum cleaners, tubing, etc.

EQUIPMENT NAME: FTIR (Fourier Transform Infrared) Spectrometer

EQUIPMENT IDENTIFICATION NUMBER: CHR-04

DEFINITION: A precision instrument that generates an infrared spectrum of the test specimen: a specimen is exposed to a beam of infrared radiation and a plot (spectrum) of radiation absorbance/transmittance (of the specimen) versus frequency of the radiation (over the infrared range: 10^{12} - 10^{14} Hz or 2.5 - 300 micrometers) results.

EQUIPMENT NAME: Freeze Dryer

EQUIPMENT IDENTIFICATION NUMBER: SUP-10

DEFINITION: A compact thermoelectric device for freeze drying biological specimens prior to storage and preparation of specimens for stain and/or sputter coating for examination under a scanning electron microscope.

EQUIPMENT NAME: Freezer

EQUIPMENT IDENTIFICATION NUMBER: SUP-11

DEFINITION: A low-temperature (0 to -80^{0}C) materials storage facility; may have an inert (N_2) atmosphere to prevent frost build-up and to inhibit growth of bacteria, etc. on or in the stored biological materials.

EQUIPMENT NAME: Gas Chromatograph - Mass Spectrometer (GC-MS)

EQUIPMENT IDENTIFICATION NUMBER: CHR-05

DEFINITION: A synergistic combination of two precison instruments: (1) a gas chromatograph separates components of a gaseous or volatile liquid sample; and (2) a mass spectrometer breaks these components down into molecular fragments and detects the fragments. With the results from the two columns, the sample and its components can be identified and concentration can be determined.

EQUIPMENT NAME: Glovebox, Materials Processing

EQUIPMENT IDENTIFICATION NUMBER: LAB-02

DEFINITION: A box with a controlled inert atmosphere, an internal glove/manipulator system and a small airlock for cycling tools and materials in and out of the glovebox. This glovebox will be dedicated to general purpose fluid handling and wet chemistry, and any small samples that generate fluid/gas. The internal atmosphere, probably N_2, will be recycled and filtered continuously to remove stray fluid droplets from the atmosphere. The environment will be sterile to allow working with biological materials.

EQUIPMENT NAME: Hall Probe

EQUIPMENT IDENTIFICATION NUMBER: CHR-06

DEFINITION: An instrument used to characterize carrier mobility in semiconductor and metallic materials by measuring the transverse voltage established in a sample placed within a permanent magnetic field with a perpendicular applied voltage.

EQUIPMENT NAME: High-Performance Liquid Chromatograph (HPLC)

EQUIPMENT IDENTIFICATION NUMBER: CHR-07

DEFINITION: An instrument capable of separating and identifying components of a liquid sample or solution. A "high-performance" liquid chromatograph is capable of other functions such as high-pressure liquid chromatography, gel permeation chromatography, reverse phase chromatography, and size exclusion chromatography, among others.

EQUIPMENT NAME: Incubator

EQUIPMENT IDENTIFICATION NUMBER: SUP-12

DEFINITION: An oven used to provide the proper conditions required to grow biological culture specimens: internal atmosphere composition and pressure, and internal temperature (20-40^{o}C) are controllable and programmable.

EQUIPMENT NAME: Mass Measurement Device, Small

EQUIPMENT IDENTIFICATION NUMBER: SUP-13

DEFINITION: A series of devices, of different capacities, that can accurately determine the mass of a liquid or solid material; most probably based on the change in natural frequency of a spring when the test material's mass is connected to the spring.

EQUIPMENT NAME: Microscope System

EQUIPMENT IDENTIFICATION NUMBER: CHR-08

DEFINITION: A system consisting of an optical microscope, a metallographic microscope, and a stereo macroscope. Accessories include polarizers and filters, light sources (visible, infrared, laser), precision hot stage, camera mounts, etc. The general-purpose supplies needed to support microscope work: slides, cover slips, probes, tweezers, labels, wipes, lens oil, filters, etc. One set required.

EQUIPMENT NAME: Nuclear Magnetic Resonance Spectrometer

EQUIPMENT IDENTIFICATION NUMBER: CHR-09

DEFINITION: Combustion Gas Sampling/Detection System that allows determination of unstable species present within flames. System consists of a microprobe and a movable magnetic and nuclear resonance cavity.

EQUIPMENT NAME: Optical Refractometer

EQUIPMENT IDENTIFICATION NUMBER: CHR-10

DEFINITION: A device used to measure the refractive properties of cut glass prisms.

EQUIPMENT NAME: pH Meter

EQUIPMENT IDENTIFICATION NUMBER: CHR-11

DEFINITION: A small hand-held, battery-powered device used to measure hydrogen ion concentration ("pH") in solutions.

EQUIPMENT NAME: Refrigerator

EQUIPMENT IDENTIFICATION NUMBER: SUP-16

DEFINITION: A large, insulated unit used to store materials internally at low temperatures (+10 to -10^{o}C). This unit may require an inert atmosphere.

EQUIPMENT NAME: Scanning Electron Microscope

EQUIPMENT IDENTIFICATION NUMBER: CHR-12/SUP-17

DEFINITION: An instrument that uses an electron beam and electromagnetic lenses to greatly magnify surface features of solid materials specimens for visual examination and photography. This unit will include (internally) a microscope and EDAX unit which is used for identification of surface features (eg. secondary phases) from x-ray diffraction and elemental analysis. This unit also includes a system to sputter deposit conductive coatings (silver, gold, carbon) onto non-conductive specimens in preparation for examination of the specimens using Scanning Electron Microscopy.

EQUIPMENT NAME: UV Sterilization Unit

EQUIPMENT IDENTIFICATION NUMBER: SUP-18

DEFINITION: A device with a built-in UV source for sterilizing small biotech tools, instruments, samples, etc. Radiation at 254 nm is 1250 micro-watts/cm^2 at 152 nm.

EQUIPMENT NAME: UV/VIS/NIR (Ultraviolet/Visible/Near-Infrared) Spectrometer

EQUIPMENT IDENTIFICATION NUMBER: CHR-13

DEFINITION: An instrument that measures the absorbance/ transmittance of electromagnetic radiation by a test specimen and generates the characteristic spectrum of that sample. The EM radiation used is varied continuously from ultraviolet to visible to near-infrared (e.g. 200 nanometers to 2.5 micrometers). The generated spectrum can identify the sample composition or detect chemical changes in the samples. Directly measures band gap energies in semiconductors.

EQUIPMENT NAME: Video Facilities

EQUIPMENT IDENTIFICATION NUMBER: LAB-03

DEFINITION: A set of video cameras (not including high resolution, high speed models) closed circuit cameras, mounts, stands, remote control, lenses, filters, etc. make up the facility. This facility is intended to provide surveillance, monitoring, and recording for laboratory equipment. It is not to be used as a scientific device as the cameras do not have sufficent resolution or frame rate for most scientific applications.

EQUIPMENT NAME: Waste Disposal System

EQUIPMENT IDENTIFICATION NUMBER: LAB-04

DEFINITION: Provides isolation and storage of waste materials for transport to earth.

EQUIPMENT NAME: Water Deionizer/Depyrogenizer Facility

EQUIPMENT IDENTIFICATION NUMBER: LAB-05

DEFINITION: Removes ions and pyrogens (bacterial wastes) from previously distilled water brought up from earth, thus producing ultrapure water.

EQUIPMENT NAME: X-Ray Facility - General Purpose

EQUIPMENT IDENTIFICATION NUMBER: CHR-14

DEFINITION: A system that generates x-ray radiation to identify and characterize crystal structure and homogeneity. Also used for characterization of degree of crystallinity; phase identification; elemental analysis.

APPENDIX 9.3

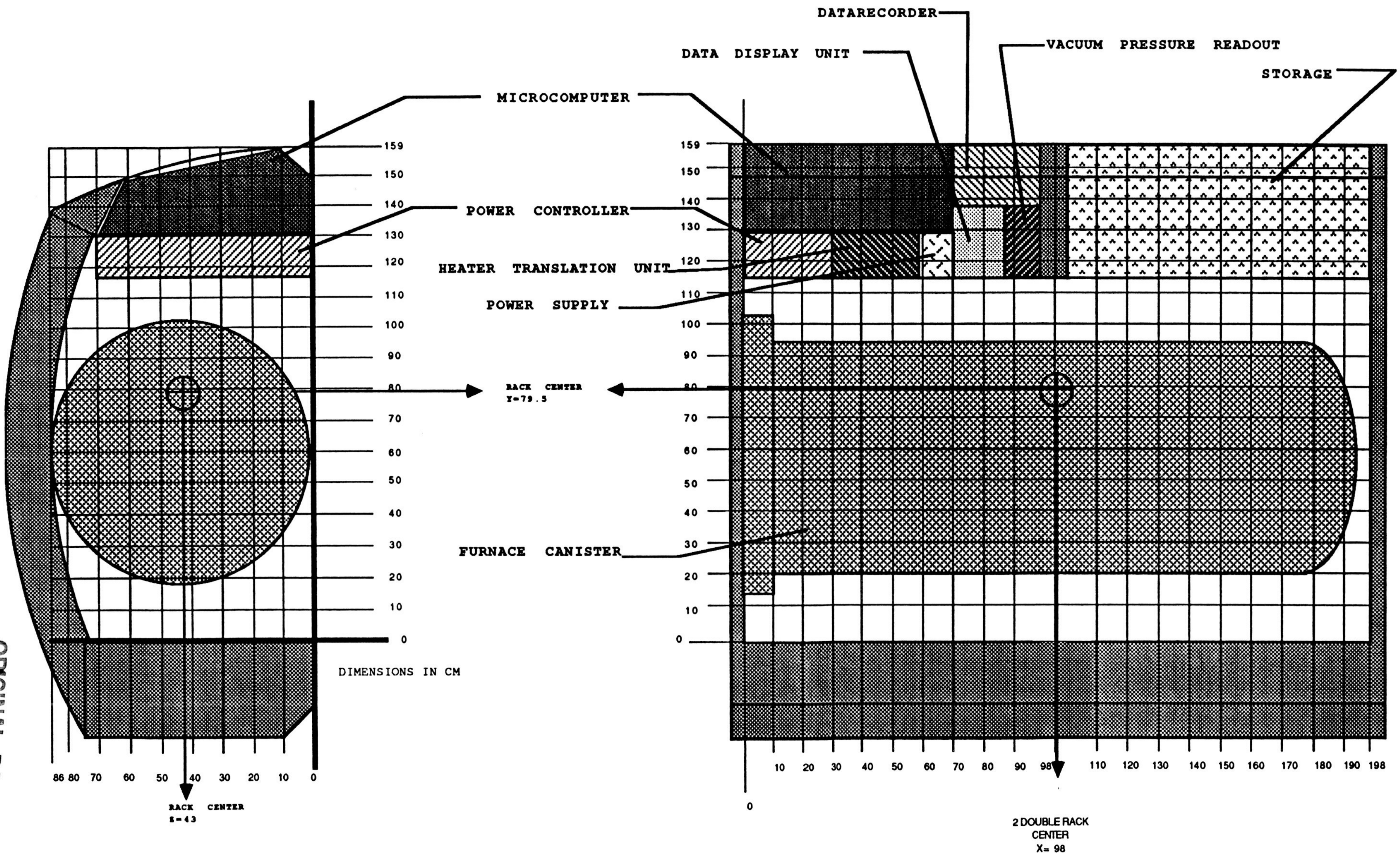
FUNCTIONAL FLOWS OF THREE SELECTED EXPERIMENTS

9.3.1 LARGE BRIDGMAN FURNACE

9.3.2 PROTEIN CRYSTAL GROWTH FACILITY

9.3.3 FLUID PHYSICS FACILITY

9.3.1 LARGE BRIDGMAN FACILITY (LBF)



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UNBIS FACILITY

Functional Flow Timeline

Experiemnt Name:Large Bridgman — Material is:GaAs and HgCdTeworth: 100.00/per gram

Step Number	Skill	Description of Operation	Key Word	When Req.	Mass of Item Moved (kg)	Path	Required Acceleration (g/go)	Frequency (hz)	Start Position X (cm)	Start Position Y (cm)	Start Position Z (cm)	End Posistion X (cm)	End Posistion Y (cm)	End Posistion Z (cm)	Step Time	Crew Time	Move Time
2.0	5	Transport facility and sample to the Space Station. *Critical Operation:	Transport	01/01/94	0.	111	10 1	60.	107.	79.5	0.	107.	79.5	0.	0.	0.	0.
3.0	3	Run preparation. *Critical Operation:	Run	01/01/94	0.	221	10 1	60.	107.	79.5	0.	107.	79.5	0.	0.	0.	0.
4.0	2	Run experiment. *Critical Operation:	Run	01/01/94	0.	221	10 6	0.001	107.	79.5	0.	107.	79.5	0.	0.	0.	0.
5.0	3	Operate minimum characterization equipment. *Critical Operation:	Operate	01/01/94	0.	221	10- 1	60.	107.	79.5	0.	107.	79.5	0.	0.	0.	0.
6.0	3	Operate additional characterization equipment. *Critical Operation:	Operate	01/01/98	0.	221	10 1	60.	49.	79.5	0.	49.	79.5	0.	0.	0.	0.
7.0	4	Review experiment data for next run. *Critical Operation:	Review	01/01/94	0.	221	10 1	60.	49.	79.5	0.	49.	79.5	0.	0.	0.	0.
2.1	5	Secure facility. *Critical Operation:	Secure	01/01/94	0.	121	10 1	60.	107.	79.5	0.	107.	79.5	0.	-0-	-0-	0.
2.1.1	5	Secure facility rack to lab. *Critical Operation:	Secure	01/01/94	150.	122	10 1	60.	107.	0.	86.	107.	0.	86.	60.	60.	30.
2.1.2	5	Secure unique equipment in facility racks. *Critical Operation:	Secure	01/01/94	1635.	122	10- 1	60.	107.	0.	86.	107.	79.5	0.	90.	90.	45.

C-2

UNBIS FACILITY

Functional Flow Timeline

Experiemnt Name:Large Bridgman — Material is:GaAs and HgCdTeworth: 100.00/per gram

Step Number / Skill	Description of Operation	Key Word / When Req.	Mass of Item Moved (kg) / Path	Required Acceleration (g/go) / Frequency (hz)	Start Position X (cm) / Y (cm) / Z (cm)	End Posistion X (cm) / Y (cm) / Z (cm)	Step Time / Crew Time / Move Time
3.1	Run preparation.	Run	0.	10- 1	107.	107.	-0-
					79.5	79.5	-0-
3	*Critical Operation:	01/01/94	221	60.	0.	0.	0.
3.1.1	Review experimental procedures.	Review	0.	10- 1	107.	107.	20.
					79.5	0.	20.
3	*Critical Operation:	01/01/94	221	60.	0.	86.	0.
3.1.2	Insert sample into the furnace.	Insert	157.	10- 1	200.	0.	30.
					40.	40.	30.
3	*Critical Operation:	01/01/94	224	60.	-43.	-43.	5.
3.1.3	Secure furnace.	Sercure	0.	10- 1	0.	0.	30.
					40.	40.	30.
3	*Critical Operation:	01/01/94	224	60.	-43.	43.	0.
3.2	Verify system.	Verify	0.	10- 1	107.	107.	-0-
					79.5	79.5	-0-
3	*Critical Operation:	01/01/94	221	60.	0.	0.	0.
3.2.1	Verify all connections and seals.	Verify	0.	10- 1	10.	10.	20.
					130.	131.	20.
3	*Critical Operation:	01/01/94	224	60.	0.	0.	1.
3.2.2	Turn-on processor facility.	Turn-on	0.	10- 1	12.	12.	1.
					130.	131.	1.
2	*Critical Operation:	01/01/94	224	60.	0.	0.	1.
3.2.3	Run master controller system test program.	Run	0.	10 1	14.	14.	2.
					130.	131.	2.
2	*Critical Operation:	01/01/94	221	60.	0.	0.	2.
4.1	Run process.	Run	0.	10- 6	107.	107.	-0-
					79.5	79.5	-0-
2	*Critical Operation:	01/01/94	221	0.001	0.	0.	0.

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Functional Flow Timeline

Experiemnt Name:Large Bridgman — Material is:GaAs and HgCdTeworth: 100.00/per gram

Step Number	Skill	Description of Operation	Key Word	When Req.	Mass of Item Moved (kg)	Path	Required Acceleration (g/go)	Frequency (hz)	Start Position X (cm)	Start Position Y (cm)	Start Position Z (cm)	End Posistion X (cm)	End Posistion Y (cm)	End Posistion Z (cm)	Step Time	Crew Time	Move Time
4.1.1	2	Transmit processing parameters. *Critical Operation:	Transmit	01/01/94	0.	221	10- 6	0.001	16.	130.	0.	16.	130.	0.	10.	10.	0.
4.1.2	1	Run furnace and sample heat up profile. *Critical Operation:	Run	01/01/94	0.	221	10 6	0.001	16.	130.	0.	16.	131.	0.	60.	2.	0.
4.1.3	1	Run experiment soak profile. *Critical Operation:	Run	01/01/94	0.	221	10- 6	0.001	107.	79.5	0.	107.	79.5	0.	1440.	600.	0.
4.1.4	1	Operate the facility to grow the crystal. *Critical Operation:	Operate	01/01/94	0.	221	10 6	0.001	107.	79.5	0.	107.	79.5	0.	180.	5.	0.
4.1.5	1	Run furnace to cool down the sample. *Critical Operation:	Run	01/01/94	0.	221	10- 6	0.001	107.	79.5	0.	107.	79.5	0.	600.	30.	0.
4.2	2	Run end. *Critical Operation:	Run	01/01/94	0.	221	10- 6	0.001	107.	79.5	0.	107.	79.5	0.	0	0	0.
4.2.1	2	Disassemble furnace as required to remove module. *Critical Operation:	Disassembl	01/01/94	1635.	224	10- 6	0.001	0.	40.	43.	0.	40.	-43.	120.	120.	0.
4.2.2	2	Remove ampoule from heater module. *Critical Operation:	Remove	01/01/94	157.	223	10 6	0.001	0.	40.	-43.	200.	40.	-43.	20.	20.	5.
4.2.3	2	Turn-off controller. *Critical Operation:	Turn-off	01/01/94	0.	224	10 6	0.001	16.	131.	0.	16.	130.	0.	1.	1.	1.

UMBIS FACILITY

Functional Flow Timeline

Experieant Name:Large Bridgman — Material is:GaAs and HgCdTeworth: 100.00/per gram

Step Number / Skill	Description of Operation	Key Word / When Req.	Mass of Item Moved (kg) / Path	Required Acceleration (g/go) / Frequency (hz)	Start Position X (cm) / Y (cm) / Z (cm)	End Posistion X (cm) / Y (cm) / Z (cm)	Step Time / Crew Time / Move Time
5.1	Operate product analysis equipment.	Operate	0.	10- 1	107.	107.	-0-
3	*Critical Operation:	01/01/94	221	60.	79.5	79.5	-0-
					0.	0.	0.
5.1.1	View and photograph boule through wall of ampoule.	View	10.	10- 1	49.	49.	10.
3	*Critical Operation:	01/01/94	223	60.	79.5	79.5	10.
					5.	84.	1.
5.1.2	Remove boule from ampoule.	Remove	155.	10- 1	0.	110.	30.
3	*Critical Operation:	01/01/94	224	60.	15.5	15.5	30.
					-15.5	-15.5	5.
5.1.3	Operate etching equipment to etch product.	Operate	2.	10- 1	110.	49.	30.
3	*Critical Operation:	01/01/94	224	60.	15.5	79.5	30.
					-15.5	43.	1.
5.1.4	View and photograph product.	View	10.	10- 1	49.	49.	10.
3	*Critical Operation:	01/01/94	224	60.	79.5	79.5	10.
					5.	84.	1.
5.1.5	Operate mass measurement equipment to measure the mass of the product.	Operate	155.	10- 1	49.	49.	20.
3	*Critical Operation:	01/01/94	223	60.	79.5	79.5	20.
					5.	5.	1.
5.1.6	Operate physical dimensions of boule.	Operate	155.	10- 1	49.	49.	10.
3	*Critical Operation:	01/01/94	223	60.	79.5	79.5	10.
					5.	5.	1.
5.1.7	Operate the cutting aand polishing unit to slice sample wafer from boule.	Operate	155.	10- 1	49.	49.	40.
3	*Critical Operation:	01/01/94	223	60.	79.5	79.5	40.
					5.	84.	1.
5.1.8	View and photograph wafers.	View	10.	10- 1	49.	49.	10.
3	*Critical Operation:	01/01/94	224	60.	79.5	79.5	10.
					2.	84.	1.

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Functional Flow Timeline

Experieamt Name:Large Bridgman . Material is:GaAs and HgCdTeworth: 100.00/per gram

Step Number / Skill	Description of Operation	Key Word / When Req.	Mass of Item Moved (kg) / Path	Required Acceleration (g/go) / Frequency (hz)	Start Position X (cm) / Y (cm) / Z (cm)	End Posistion X (cm) / Y (cm) / Z (cm)	Step Time / Crew Time / Move Time
5.1.9	Operate the poliching unit to polish wafers.	Operate	0.05	10-1	49.	49.	40.
					79.5	79.5	40.
3	*Critical Operation:	01/01/94	224	60.	43.	43.	1.
5.1:10	View and photograph wafer using microscope system.	View	0.05	10 1	49.	49.	40.
					79.5	79.5	40.
3	*Critical Operation:	01/01/94	224	60.	2.	2.	1.
5.1:11	Operate the etching equipment to etch wafer.	Operate	0.05	10-1	49.	49.	30.
					79.5	79.5	30.
3	*Critical Operation:	01/01/94	224	60.	2.	2.	1.
5.1:12	View and photograph wafer using microscope system.	View	10.	10 1	49.	49.	40.
					79.5	79.5	40.
3	*Critical Operation:	01/01/94	224	60.	2.	2.	1.
5.1:13	Repeat 5.1:11 and 5.1:12 as required.	Repeat	10.	10-1	49.	49.	70.
					79.5	79.5	70.
3	*Critical Operation:	01/01/94	223	60.	0.	0.	2.
5.2	Operate equipment to characterize wafer crystal structure.	Operate	0.	10-1	49.	49.	0
					79.5	79.5	0
3	*Critical Operation:	01/01/94	221	60.	0.	0.	0.
5.2.1	Operate X-ray system to analyze the wafers crystal structure(topography).	Operate	0.05	10-1	49.	49.	180.
					79.5	79.5	180.
3	*Critical Operation:	01/01/94	223	60.	43.	43.	1.
5.2.2	Operate the elecrtral conductivity probe to analyze the wafers structure.	Operate	0.05	10-1	49.	49.	20.
					79.5	79.5	20.
3	*Critical Operation:	01/01/94	223	60.	43.	43.	1.
6.1	Operate the FTIR to analyze the crystral.	Operate	0.05	10-1	49.	49.	40.
					79.5	79.5	40.
3	*Critical Operation:	01/01/98	223	60.	43.	43.	1.

UNBIS FACILITY

Functional Flow Timeline

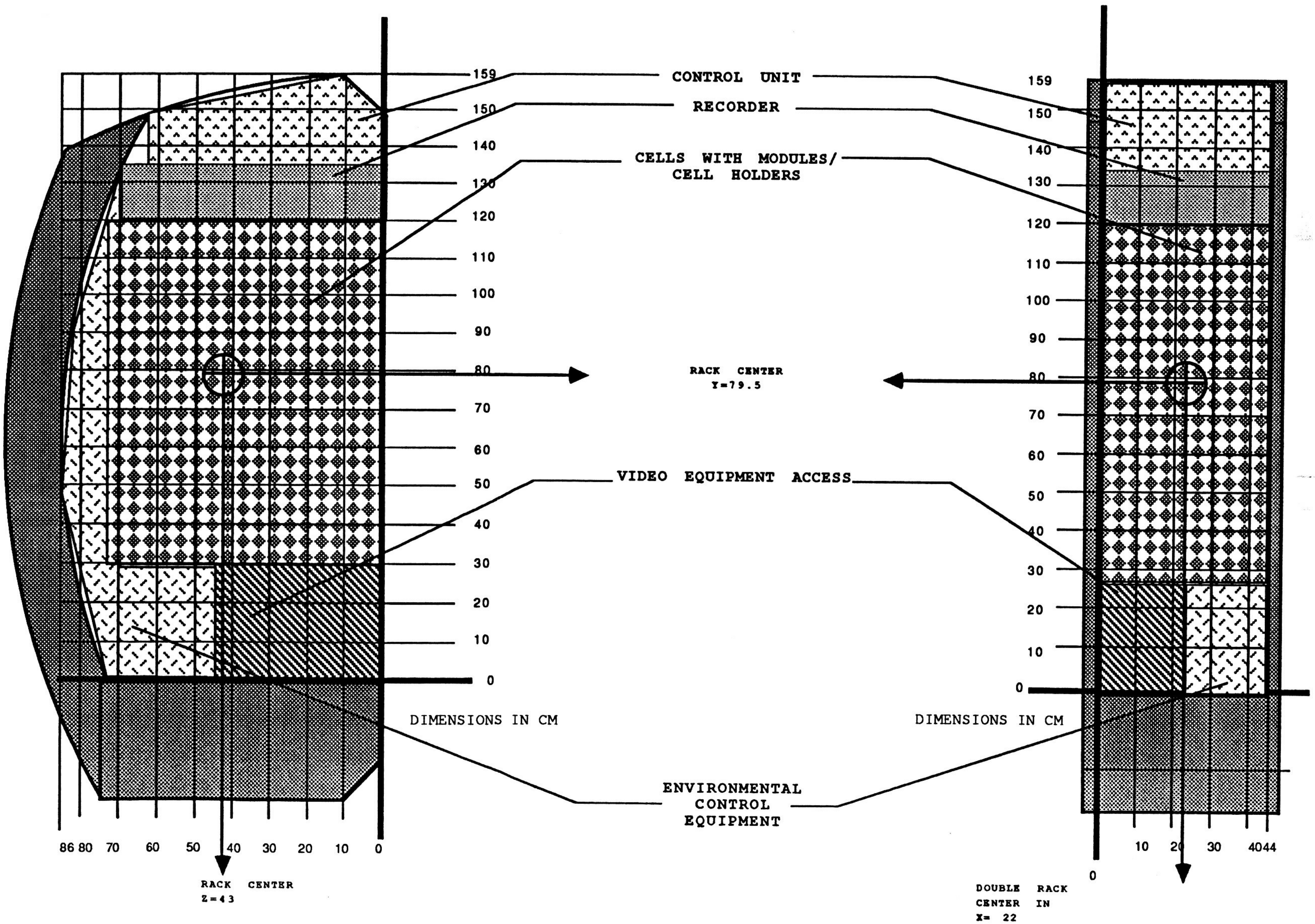
Experiemnt Name:Large Bridgman Material is:GaAs and HgCdTeworth: 100.00/per gram

Step Number	Skill	Description of Operation	Key Word	When Req.	Mass of Item Moved (kg)	Path	Required Acceleration (g/go)	Frequency (hz)	Start Position X (cm)	Start Position Y (cm)	Start Position Z (cm)	End Position X (cm)	End Position Y (cm)	End Position Z (cm)	Step Time	Crew Time	Move Time
6.2	3	Operate the Hall probe to analyze the wafer. *Critical Operation:	Operate	01/01/98	0.05	223	10- 1	60.	49.	79.5	43.	49.	79.5	43.	40.	40.	1.
7.1	4	Secure and store products. *Critical Operation:	Secure	01/01/94	155.	223	10- 1	60.	49.	79.5	0.	49.	79.5	0.	30.	30.	15.
7.2	4	Review post experiment data. *Critical Operation:	Review	01/01/94	0.	221	10- 1	60.	49.	79.5	0.	49.	79.5	0.	-0-	-0-	0.
7.2.1	4	Review data and reduce as required. *Critical Operation:	Review	01/01/94	0.	221	10- 1	60.	49.	79.5	0.	49.	79.5	0.	30.	30.	0.
7.2.2	4	Review data and correlate experimental parameters to results. *Critical Operation:	Review	01/01/94	0.	221	10- 1	60.	49.	79.5	0.	49.	79.5	0.	30.	30.	0.
7.2.3	4	Review data and select next run parameters. *Critical Operation:	Review	01/01/94	0.	221	10- 1	60.	49.	79.5	0.	49.	79.5	0.	60.	60.	0.
8.1	4	Clean equipment as needed. *Critical Operation:	Clean	01/01/94	1635.	224	10- 1	60.	0.	30.	-43.	200.	30.	-43.	30.	30.	15.
8.2	4	Secure equipment as needed. *Critical Operation:	Secure	01/01/94	1635.	224	10- 1	60.	107.	79.5	0.	107.	79.5	0.	90.	90.	45.

*Critical Operation parameters:
A = Acceletation: B=Both Accel. and Time: O = Other Parameters: T = Time

Totals:Run Time - 11027.
Crew Time- 3864.
Move Time- 548.

9.3.2 PROTEIN CRYSTAL GROWTH FACILITY



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** Functional Flow Timeline ***

Experiemnt Name:Protein Crystal Growth   Material is:Proteins   worth:1000.00/per gram

Step Number / Skill	Description of Operation	Key Word / When Req.	Mass of Item Moved (kg) / Path	Required Acceleration (g/go) / Frequency (hz)	Start Position X (cm) / Y (cm) / Z (cm)	End Posistion X (cm) / Y (cm) / Z (cm)	Step Time / Crew Time / Move Time
2.0	Secure facility rack to lab.	Secure	0.	10 1	22.	22.	-0-
					79.5	79.5	-0-
4	*Critical Operation:	01/01/94	111	60.	0.	0.	0.
2.1	Transport equipment from log mogule to the lab.	Transport	0.	10 1	22.	22.	-0-
					79.5	79.5	-0-
4	*Critical Operation:	01/01/94	111	60.	0.	0.	0.
2.1.1	Secure equipment in facility rack.	Secure	52.	10 1	22.	22.	60.
					79.5	79.5	60.
4	*Critical Operation:	01/01/94	114	60.	0.	43.	30.
2.1.2	Secure facility rack to lab.	Secure	120.	10 1	22.	22.	30.
					79.5	0.	30.
4	*Critical Operation:	01/01/94	122	60.	0.	86.	15.
3.0	Review experiment procedure.	Review	0.	10 1	22.	22.	-0-
					79.5	79.5	-0-
3	*Critical Operation:	01/01/94	221	60.	0.	0.	0.
3.1	Review experiment procedure.	Review	0.	10 1	22.	22.	-0-
					79.5	79.5	-0-
3	*Critical Operation:	01/01/94	221	60.	0.	0.	0.
3.1.1	Review experiment proceedure.	Review	0.	10 1	22.	22.	30.
					79.5	79.5	30.
3	*Critical Operation:	01/01/94	221	60.	0.	0.	0.
3.1.2	Insert growth modules with selected proteins.	Insert	10.	10 1	22.	22.	90.
					79.5	79.5	90.
2	*Critical Operation:	01/01/94	224	60.	70.	0.	30.
3.2	Verify system.	Verify	0.	10 1	22.	22.	-0-
					79.5	79.5	-0
3	*Critical Operation:	01/01/94	221	60.	0.	0.	0.

** Functional Flow Timeline **

Experiemnt Name:Protein Crystal Growth   Material is:Proteins   worth:1000.00/per gram

Step Number / Skill	Description of Operation	Key Word / When Req.	Mass of Item Moved (kg) / Path	Required Acceleration (g/go) / Frequency (hz)	Start Position X (cm) / Y (cm) / Z (cm)	End Posistion X (cm) / Y (cm) / Z (cm)	Step Time / Crew Time / Move Time
3.2.1	Verify all connections and fittings.	Verify	0.	10- 1	22.	22.	30.
					79.5	0.	30.
3	*Critical Operation:	01/01/94	224	60.	0.	86.	0.
3.2.2	Turn on facility.	Turn on	0.	10- 1	10.	10.	1.
					140.	141.	1.
3	*Critical Operation:	01/01/94	224	60.	0.	0.	0.
3.2.3	Run master controller sys. integrity test program.	Run	0.	10- 1	20.	20.	10.
					140.	141.	2.
2	*Critical Operation:	01/01/94	224	60.	0.	0.	0.
4.0	Run.	Run	0.	10- 2	22.	22.	-0-
					79.5	79.5	-0-
2	*Critical Operation:	01/01/94	221	60.	0.	0.	0.
4.1	Run facility as programmed.	Run	0.	10- 2	22.	22.	-0-
					79.5	79.5	-0-
2	*Critical Operation:	01/01/94	221	60.	0.	0.	0.
4.1.1	Insert crystal growth facility with selected proteins.	Insert	18.	10- 4	22.	22.	10.
					79.5	79.5	10.
1	*Critical Operation:	01/01/94	223	0.001	70.	0.	5.
4.1.2	Transmit data to facility.	Transmit	0.	10- 4	22.	22.	10.
					79.5	79.5	10.
1	*Critical Operation:	01/01/94	221	0.001	0.	0.	0.
4.1.3	Run facility and allow sample to equilibrate.	Run	0.	10- 4	22.	22.	90.
					79.5	79.5	0.
1	*Critical Operation:	01/01/94	224	0.001	0.	0.	0.
4.1.4	Turn on data recorder.	Turn on	0.	10 4	10.	10.	1.
					130.	131.	1.
1	*Critical Operation:	01/01/94	224	0.001	0.	0.	1.

UNBIS FACILITY

Functional Flow Timeline

Experieant Name:Protein Crystal Growth — Material is:Proteins — worth:1000.00/per gram

Step Number / Skill	Description of Operation	Key Word / When Req.	Mass of Item Moved (kg) / Path	Required Acceleration (g/go) / Frequency (hz)	Start Position X (cm) / Y (cm) / Z (cm)	End Posistion X (cm) / Y (cm) / Z (cm)	Step Time / Crew Time / Move Time
4.1.5 1	Run facility as programmed. *Critical Operation:	Run 01/01/94	0. 221	10 4 0.001	22. 79.5 0.	22. 79.5 0.	3. 3. 0.
4.1.6 1	View and record observations. *Critical Operation:	View 01/01/94	0. 224	10 4 0.001	22. 79.5 -70.	22. 79.5 70.	14400. 50. 0.
4.1.7 1	Turn-off data recorders. *Critical Operation:	Turn-off 01/01/94	0. 224	10 4 0.001	10. 131. 0.	10. 130. 0.	60. 2. 1.
4.1.8 1	Turn-off controller. *Critical Operation:	Turn off 01/01/94	0. 224	10 4 0.001	20. 141. 0.	20. 140. 0.	1. 1. 1.
5.0 1	Run IOC level characterization. *Critical Operation:	Run 01/01/94	0. 221	10 4 0.001	22. 79.5 0.	22. 79.5 0.	-0- -0- 0.
5.1 1	Verify product. *Critical Operation:	Verify 01/01/94	0. 221	10 4 0.001	22. 79.5 0.	22. 79.5 0.	-0 -0- 0.
5.1.1 1	Remove sample. *Critical Operation:	Remove 01/01/94	10. 223	10 4 0.001	22. 79.5 0.	22. 79.5 -70.	5. 5. 5.
5.1.2 1	View and examine individual growth modules cells. *Critical Operation:	View 01/01/94	0. 224	10 4 0.001	22. 79.5 43.	22. 79.5 43.	15. 15. 1.
5.1.3 1	Review crystals for diffraction analysis. *Critical Operation:	Review 01/01/94	0.00001 224	10 4 0.001	22. 79.5 0.	22. 79.5 0.	45. 45. 0.

Functional Flow Timeline

Experieant Name:Protein Crystal Growth Material is:Proteins worth:1000.00/per gram

Step Number / Skill	Description of Operation	Key Word / When Req.	Mass of Item Moved (kg) / Path	Required Acceleration (g/go) / Frequency (hz)	Start Position X (cm) / Y (cm) / Z (cm)	End Posistion X (cm) / Y (cm) / Z (cm)	Step Time / Crew Time / Move Time
5.1.4	Operate x-ray system.	Operate	0.	10-4	22.	22.	200.
					79.5	79.5	20.
1		01/01/94	223	0.001			
	*Critical Operation:				0.	0.	1.
5.1.5	Review crystals for detailed analysis.	Review	0.	10-4	22.	22.	120.
					79.5	79.5	120.
1		01/01/94	223	0.001			
	*Critical Operation:				0.	0.	5.
5.1.6	Operate x-ray system.	Operate	0.	10-4	22.	22.	1620.
					79.5	79.5	200.
1		01/01/94	223	0.001			
	*Critical Operation:				0.	0.	5.
5.1.7	Transmit data to Earth.	Transmit	0.	10-4	22.	22.	20.
					79.5	79.5	20.
1		01/01/94	221	0.001			
	*Critical Operation:				0.	0.	0.
6.0	Run growth characterization.	Run	0.	10-1	22.	22.	-0-
					79.5	79.5	-0-
5		01/01/98	221	60.			
	*Critical Operation:				0.	0.	0.
6.1	No additional characterization required.	n/a	0.	10-1	22.	22.	-0-
					79.5	79.5	-0-
5		01/01/98	221	60.			
	*Critical Operation:				0.	0.	0.
7.0	Review data as required.	Review	0.	10-4	22.	22.	-0-
					79.5	79.5	-0-
1		01/01/94	221	0.001			
	*Critical Operation:				0.	0.	0.
7.1	Operate facility to prepare growth modules for seeded crystals.	Operate	0.	10-4	22.	22.	-0-
					79.5	79.5	-0-
1		01/01/94	221	0.001			
	*Critical Operation:				0.	0.	0.
7.1.1	View and select seed crystals.	View	0.000001	10-4	22.	22.	30.
					79.5	79.5	30.
1		01/01/94	224	0.001			
	*Critical Operation:				0.	0.	1.

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Functional Flow Timeline

Experieant Name:Protein Crystal Growth   Material is:Proteins   worth:1000.00/per gram

Step Number Skill	Description of Operation	Key Word When Req.	Mass of Item Moved (kg) Path	Required Acceleration (g/go) Frequency (hz)	Start Position X (cm) Y (cm) Z (cm)	End Posistion X (cm) Y (cm) Z (cm)	Step Time Crew Time Move Time
7.1.2 1	Insert sample into growth modules. *Critical Operation:	Insert 01/01/94	0.00001 224	10 4 0.001	22. 79.5 0.	22. 79.5 0.	20. 20. 10.
7.1.3 1	Move protein solution into seeded growth cells. *Critical Operation:	Move 01/01/94	10. 224	10- 4 0.001	22. 79.5 0.	22. 79.5 0.	60. 60. 30.
7.2 1	Assemble crystal growth trays. *Critical Operation:	Assemble 01/01/94	0. 221	10- 4 0.001	22. 79.5 0.	22. 79.5 0.	-0- -0- 0.
7.2.1 1	Secure seeded growth modules. *Critical Operation:	Secure 01/01/94	10. 224	10- 4 0.001	22. 79.5 0.	22. 79.5 0.	30. 30. 0.
7.2.2 1	Insert growth modules to be re-run. *Critical Operation:	Insert 01/01/94	18. 223	10- 4 0.001	22. 79.5 -70.	22. 79.5 0.	10. 10. 0.
7.3 1	Repeat process run and analysis procedures. *Critical Operation:	Repeat 01/01/94	18. 224	10- 4 0.001	22. 79.5 0.	22. 79.5 0.	20160. 100. 0.
8.0 3	Clean equipment as needed. *Critical Operation:	Clean 01/01/94	0. 221	10- 1 60.	22. 79.5 0.	22. 79.5 0.	-0- -0- 0.
8.1 3	Clean and sterilize equipment as needed. *Critical Operation:	Clean 01/01/94	52. 224	10 1 60.	22. 79.5 0.	22. 79.5 0.	10. 10. 5.
8.2 3	Clean equipment as needed. *Critical Operation:	Clean 01/01/94	52. 224	10 - 1 60.	22. 79.5 0.	22. 79.5 0.	10. 10. 5.

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** Functional Flow Timeline **

Experiemnt Name:Protein Crystal Growth

Material is:Proteins worth:1000.00/per gram

Step Number / Skill	Description of Operation	Key Word / When Req.	Mass of Item Moved (kg) / Path	Required Acceleration (g/go) / Frequency (hz)	Start Position X (cm) / Y (cm) / Z (cm)	End Posistion X (cm) / Y (cm) / Z (cm)	Step Time / Crew Time / Move Time
8.3	Remove wastes and unreturned solutions.	Remove	10.	10 · 1	22.	22.	10.
					79.5	79.5	10.
3	*Critical Operation:	01/01/94	224	60.	0.	0.	5.

Totals:Run Time 48218.
Crew Time 4889.
Move Time 704.

*Critical Operation parameters:
A = Acceletation: B=Both Accel. and Time: O = Other Parameters: T = Time

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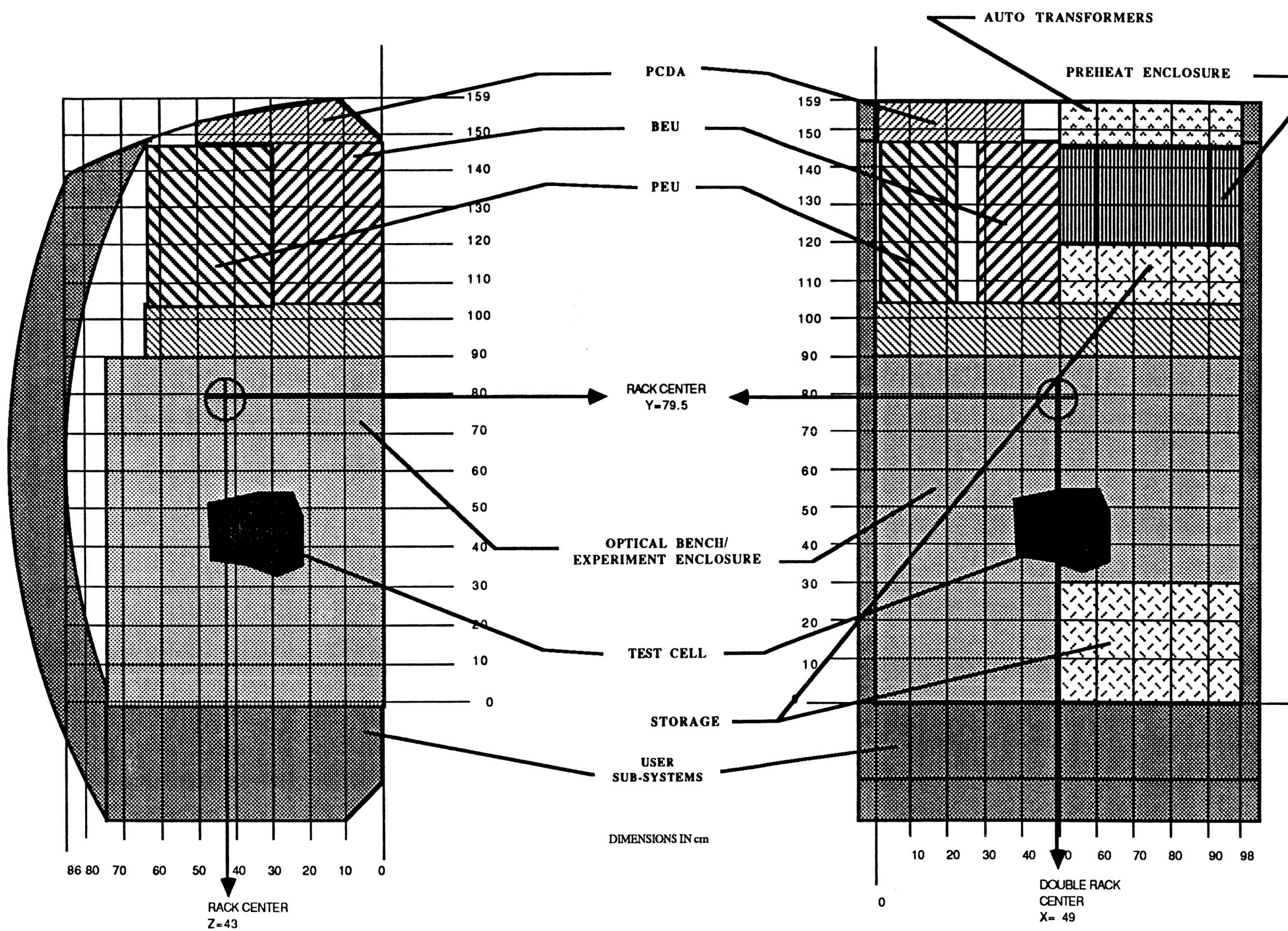
9.3.3 FLUID PHYSICS FACILITY RACK LAYOUT



Functional Flow Timeline

Experiment Name:Fluid Physics   Material is:TGS   worth: $30.00/per gram

Step Number	Skill	Description of Operation	Key Word	When Req.	Mass of Item Moved (kg)	Path	Required Acceleration (g/go)	Frequency (hz)	Start Position X (cm)	Start Position Y (cm)	Start Position Z (cm)	End Position X (cm)	End Position Y (cm)	End Position Z (cm)	Step Time	Crew Time	Move Time
2.0	4	Secure facility rack to lab. *Critical Operation:	Secure	01/01/94	0.	111	10- 1	60.	49.	79.5	0.	49.	79.5	0.	-0-	-0-	0.
2.1	4	Transport equipment from log module to the lab. *Critical Operation:	Transport	01/01/94	0.	111	10- 1	60.	49.	79.5	0.	49.	79.5	0.	-0-	-0-	0.
2.1.1	4	Secure equipment in facility rack. *Critical Operation:	Secure	01/01/94	143.	114	10- 1	60.	49.	79.5	0.	49.	79.5	0.	30.	30.	15.
2.1.2	4	Secure facility rack to lab. *Critical Operation:	Secure	01/01/94	440.	123	10- 1	60.	49.	79.5	0.	49.	0.	86.	30.	30.	15.
3.0	4	Review experiment procedure. *Critical Operation:	Review	01/01/94	0.	221	10- 1	60.	49.	79.5	0.	49.	79.5	0.	-0-	-0-	0.
3.1	4	Review experiment procedure. *Critical Operation:	Review	01/01/94	0.	221	10- 1	60.	49.	79.5	0.	49.	79.5	0.	-0-	-0-	0.
3.1.1	3	Review experiment procedure. *Critical Operation:	Review	01/01/94	0.	221	10- 1	60.	49.	79.5	0.	49.	79.5	0.	30.	30.	0.
3.1.2	2	Insert sample. *Critical Operation:	Insert	01/01/94	36.	224	10- 1	60.	80.	15.	30.	80.	132.	20.	20.	20.	10.
3.1.3	3	Verify all connections and fittings. *Critical Operation:	Verify	01/01/94	0.	224	10 1	60.	49.	79.5	0.	49.	0.	86.	20.	20.	5.

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** Functional Flow Timeline **

Experiemnt Name:Fluid Physics   Material is:TGS   worth: $30.00/per gram

Step Number	Skill	Description of Operation	Key Word	When Req.	Mass of Item Moved (kg)	Path	Required Acceleration (g/go)	Frequency (hz)	Start Position X (cm)	Start Position Y (cm)	Start Position Z (cm)	End Posistion X (cm)	End Posistion Y (cm)	End Posistion Z (cm)	Step Time	Crew Time	Move Time
3.2	3	Verify system. *Critical Operation:	Verify	01/01/94	0.	221	10- 1	60.	49.	79.5	0.	49.	79.5	0.	-0-	-0-	0.
3.2.1	3	Turn-on facility. *Critical Operation:	Turn-on	01/01/94	0.	224	10- 1	60.	40.	100.	0.	40.	101.	0.	1.	1.	1.
3.2.2	3	Run master controller sys. integrity test program. *Critical Operation:	Run	01/01/94	0.	224	10 1	60.	40.	102.	0.	40.	103.	0.	10.	10.	1.
4.0	3	Run. *Critical Operation:	Run	01/01/94	0.	221	10- 2	60.	49.	79.5	0.	49.	79.5	0.	-0	-0-	0.
4.1	3	Run facility as programmed. *Critical Operation:	Run	01/01/94	0.	221	10- 2	60.	49.	79.5	0.	49.	79.5	0.	-0	-0-	0.
4.1.1	3	Transmit data to facility. *Critical Operation:	Transmit	01/01/94	0.	224	10- 2	60.	50.	100.	0.	50.	101.	0.	10.	10.	0.
4.1.2	3	Turn-on data recorder. *Critical Operation:	Turn-on	01/01/94	0.	224	10- 2	60.	60.	100.	0.	60.	101.	0.	5.	5.	1.
4.1.3	2	Vent and purge sting cap. *Critical Operation:	Vent	01/01/94	0.	224	10- 2	60.	80.	100.	0.	80.	100.5	0.	10.	10.	1.
4.1.4	1	Run facility and allow sample to equilibrate. *Critical Operation:	Run	01/01/94	0.	221	10- 4	0.001	49.	79.5	0.	49.	79.5	0.	10.	10.	0.

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Functional Flow Timeline

Experiemnt Name:Fluid Physics   Material is:TGS   worth: $30.00/per gram

Step Number / Skill	Description of Operation	Key Word / When Req.	Mass of Item Moved (kg) / Path	Required Acceleration (g/go) / Frequency (hz)	Start Position X (cm) / Y (cm) / Z (cm)	End Posistion X (cm) / Y (cm) / Z (cm)	Step Time / Crew Time / Move Time
4.1.5	View and record observations.	View	0.	10- 4	49.	49.	1440.
					79.5	79.5	60.
1	*Critical Operation:	01/01/94	221	0.001	0.	0.	0.
4.2	Run end.	Run	0.	10- 4	49.	49.	-0-
					79.5	79.5	-0-
1	*Critical Operation:	01/01/94	221	0.001	0.	0.	0.
4.2.1	Run facility and allow sample to cool.	Run	0.	10- 4	49.	49.	10.
					79.5	79.5	10.
1	*Critical Operation:	01/01/94	221	0.001	0.	0.	0.
4.2.2	Turn-off data recorders.	Turn-off	0.	10- 2	60.	60.	1.
					101.	100.	1.
3	*Critical Operation:	01/01/94	224	60.	0.	0.	1.
4.2.3	Turn-off controller.	Turn-off	0.	10 2	40.	40.	2.
					101.	100.	2.
3	*Critical Operation:	01/01/94	224	60.	0.	0.	2.
5.0	Run IOC level characterization.	Run	0.	10- 1	49.	49.	-0-
					79.5	79.5	-0-
3	*Critical Operation:	01/01/94	221	60.	0.	0.	0.
5.1	Verify product.	Verify	0.	10- 1	49.	49.	-0-
					79.5	79.5	-0-
3	*Critical Operation:	01/01/94	221	60.	0.	0.	0.
5.1.1	Remove spent solution and store for disposal.	Remove	1.75	10- 1	49.	49.	30.
					40.	40.	30.
3	*Critical Operation:	01/01/94	224	60.	30.	0.	1.
5.1.2	Remove holder assembly.	Remove	36.	10 1	49.	49.	20.
					40.	60.	20.
3	*Critical Operation:	01/01/94	224	60.	0.	0.	1.

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Functional Flow Timeline

Experieent Name:Fluid Physics | Material is:TGS | worth: $30.00/per gram

Step Number / Skill	Description of Operation	Key Word / When Req.	Mass of Item Moved (kg). / Path	Required Acceleration (g/go) / Frequency (hz)	Start Position X (cm) / Y (cm) / Z (cm)	End Posistion X (cm) / Y (cm) / Z (cm)	Step Time / Crew Time / Move Time
5.1.3	Clean and dry crystal.	Clean	0.5	10- 1	49.	49.	20.
					79.5	79.5	20.
3	*Critical Operation:	01/01/94	223	60.	0.	0.	5.
5.1.4	Review video data.	Review	0.	10- 1	49.	49.	20.
					79.5	79.5	20.
3	*Critical Operation:	01/01/94	221	60.	0.	0.	0.
6.0	Run growth characterization.	Run	0.	10- 1	49.	49.	-0-
					79.5	79.5	0-
3	*Critical Operation:	01/01/98	221	60.	0.	0.	0.
6.1	No additional characterization required.	n/a	0.	10- 1	49.	49.	-0-
					79.5	79.5	-0-
3	*Critical Operation:	01/01/98	221	60.	0.	0.	0.
7.0	Review data as required.	Review	0.	10- 1	49.	49.	-0-
					79.5	79.5	-0-
3	*Critical Operation:	01/01/94	221	60.	0.	0.	0.
7.1	Secure samples into shipping containers.	Secure	0.5	10- 1	49.	49.	30.
					79.5	79.5	30.
3	*Critical Operation:	01/01/94	212	60.	0.	0.	15.
7.2	Verify post experiment data analysis.	Verify	0.	10- 1	49.	49.	-0-
					79.5	79.5	-0-
3	*Critical Operation:	01/01/94	221	60.	0.	0.	0.
7.2.1	Review data as required.	Review	0.	10- 1	49.	49.	30.
					79.5	79.5	30.
3	*Critical Operation:	01/01/94	221	60.	0.	0.	0.
7.2.2	Verify correlation between experimental parameters and results.	Verify	0.	10- 1	49.	49.	60.
					79.5	79.5	60.
3	*Critical Operation:	01/01/94	221	60.	0.	0.	0.

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UNBIS FACILITY

** Functional Flow Timeline **

Experiemnt Name:Fluid Physics — Material is:TGS — worth: $30.00/per gram

Step Number / Skill	Description of Operation	Key Word / When Req.	Mass of Item Moved (kg) / Path	Required Acceleration (g/go) / Frequency (hz)	Start Position X (cm) / Y (cm) / Z (cm)	End Posistion X (cm) / Y (cm) / Z (cm)	Step Time / Crew Time / Move Time
7.2.3	Review next run parameters.	Review	0.	10 1	49.	49.	30.
					79.5	79.5	30.
3	*Critical Operation:	01/01/94	221	60.	0.	0.	0.
8.0	Clean equipment as needed.	Clean	0.	10 1	49.	49.	-0-
					79.5	79.5	-0-
3	*Critical Operation:	01/01/94	221	60.	0.	0.	0.
8.1	Clean equipment as needed.	Clean	143.	10 1	49.	49.	30.
					79.5	79.5	30.
3	*Critical Operation:	01/01/94	224	60.	0.	0.	15.
8.2	Secure equipment as needed.	Secure	36.	10 1	49.	49.	30.
					79.5	79.5	30.
3	*Critical Operation:	01/01/94	224	60.	0.	0.	15.

*Critical Operation parameters:
A = Acceletation: B=Both Accel. and Time: O = Other Parameters: T = Time

Totals:Run Time - 7413.
Crew Time - 1893.
Move Time - 361.

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APPENDIX 9.4

PREDICTED MICROSTEPPING

ROBOT ACCELERATION

APPENDIX 9.4 MATHEMATICAL ANALYSIS OF MOTION

Two methods were used to estimate the motion of the robot manipulator. **The first method** uses data taken from the LVDT measurements. Figure 9.4.1 shows displacement data from a 0.0002 radian displacement of the robot base with the robot arm in the straight up position. The constant slope portion of the curve represents a constant velocity of 0.01 inches per second. The inset figure shows the elbow of the curve in greater detail. This elbow represents the LVDT measurement of the robot arm going from zero velocity, no dispacement versus time, to a constant velocity, or a constant displacement versus time. The curve of the elbow thus represents the acceleration phase which is described mathematically by:

$$a = \Delta v/\Delta t$$
$$= (.01 \text{ in/s} - 0)/0.011 \text{ s}$$
$$= (0.9091 \text{ in/s}^2)(1g/32.174 \text{ fps}^2)(1 \text{ ft}/12\text{in})$$
$$a = \mathbf{0.00235\ g}$$

The measured value for the same conditions was **0.0009 g.**

This was with the arm in the straight up position. Measurements were made with the arm rotated 90° at joint J1 (see robot drawing). Assuming that the robot controller commands joint motion independent of arm orientation or geometry, it is possible to predict the end of arm accelerations from the base motion measurement. So, for the commanded motion of 0.0002 radians for the base, the torque, T should be the same for each geometrical configuration. The formula for the pure rotation is $T = I \times Ø$, so

$T_1=I_1 \times Ø_1=$ Torque for the base motor with the arm straight up;
$T_2=I_2 \times Ø_2=$ Torque for the base motor with the arm rotated 90° @ J1.

$Ø_1$ Calculation:

Using Figure 9.4-2, the formula for $Ø_1$ is $Ø_1= (0.878 \times a_m)/r$, the predicted value for a_m was previously calculated as 0.00235 g and the r length is 6.265 inches. Therefore,
$Ø_1 = (0.878 \times 0.00235 \text{ g})/6.265 \text{ inch}$
$Ø_1 = 0.000329 \text{ g/inch}$

From the mass table, $I_1 = 102.88$ slug-in^2 and $I_2 = 252.59$ slug-in^2.

Since $T_1 = T_2$, $I_1 \times Ø_1 = I_2 \times Ø_2$ and

$$Ø_2 = (I_1 \times Ø_1)/I_2$$
$$Ø_2 = (102.88 \times 0.000239 \text{ g/in})/253.59$$
$$Ø_2 = 0.000134 \text{ g/inch}$$

At the end of the arm, the accelerometer was mounted to measure the pure tangential acceleration, which is described by

$$a_t = Ø_2 \times r$$
$$a_t = (0.000134 \text{ g/in.})(30.81 \text{ in.})$$
$$\mathbf{a_t = 0.0041 \text{ g}}$$

The measured acceleration at the end of the arm is **0.0096 g.**

The Second Method to predict robot accelerations was used for the end of arm measurement. If the angular displacement and the time of displacement are known, a constant angular acceleration can be predicted if starting at zero velocity. The formula is:

$$Ø = 1/2 \times Ø \times t^2$$
$$Ø = (2 \times Ø) / t^2$$

Assume that the total radian displacement accelerates for half the distance and then decelerates for the remainder of the movement. The acceleration distance is 0.0001 radian and the time for that acceleration is measured from Figure 9.4-3 as 0.035 seconds. Therefore,

$$Ø = (2 \times 0.0001) /(0.035)^2$$
$$Ø = 0.1633 \text{ rad/s}$$

Again, since the measured acceleration is tangential,

$$a_t = (0.1633 \text{ rad/s})(30.81 \text{ in.})(1 \text{ g}/32.174 \text{ fps}^2)(1 \text{ ft}/12 \text{ in})$$
$$\mathbf{a_t = 0.0130 \text{ g}}$$

The measured value is **0.0096 g.**

Summary: the two methods shown above provide a reasonable approximation of the acceleration to be expected for robot arm operating at low speed and with very small displacement.

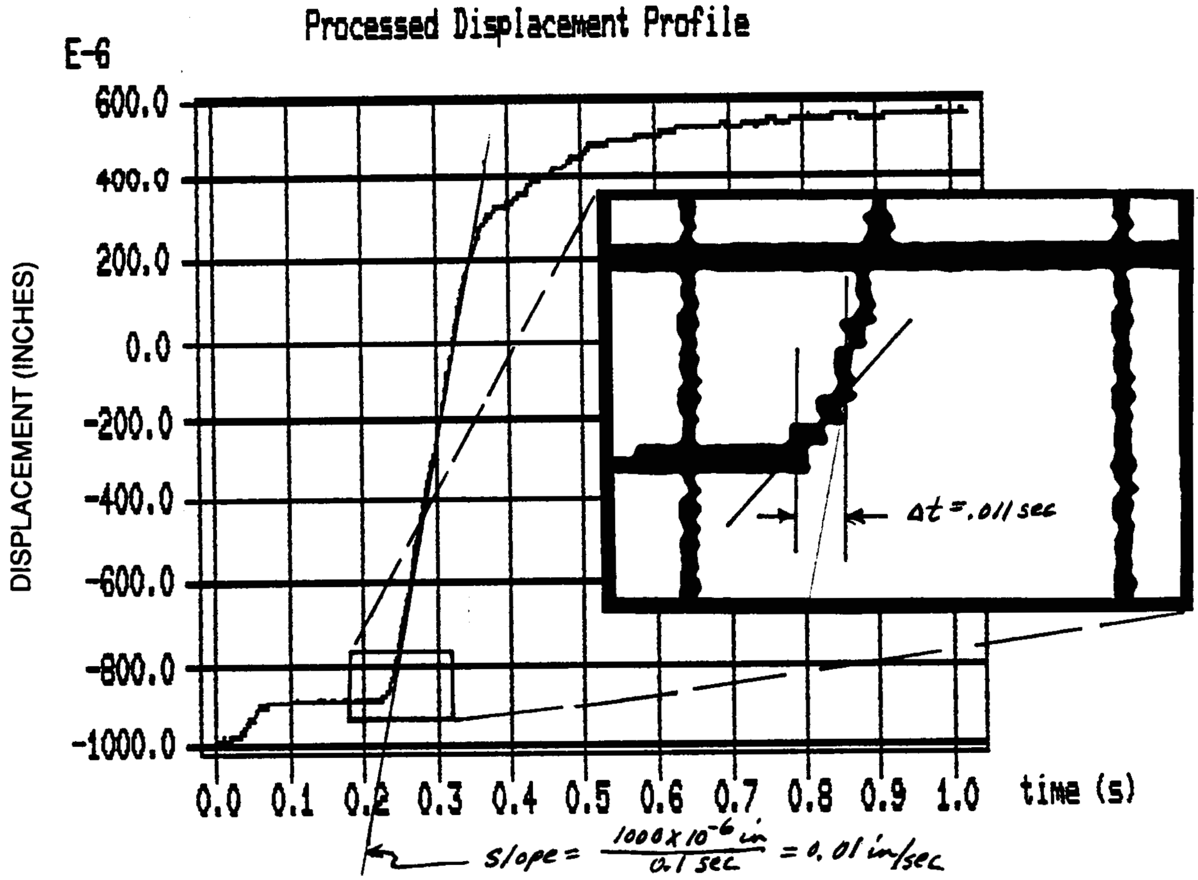
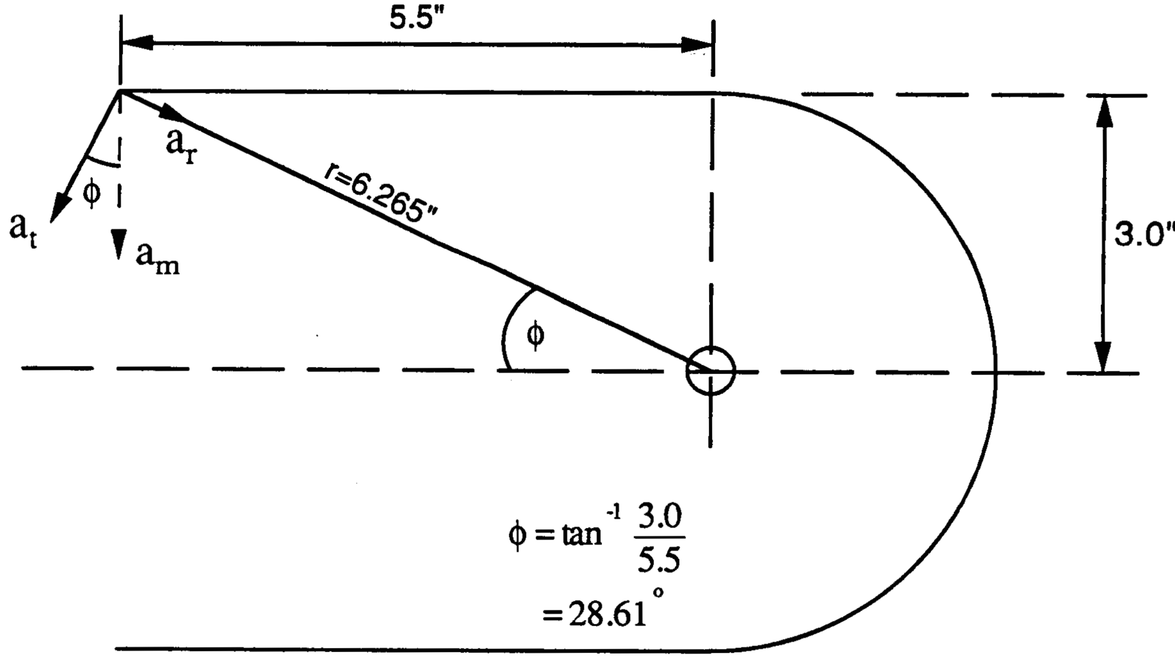


FIGURE 9.4-1. LVDT MEASURED ACCELERATION DETERMINATION



$$a_n = a_m \sin\phi - .479\, a_m = \dot{\theta}^2 r$$

$$a_t = a_m \cos\phi - .878\, a_m = \ddot{\theta}\, r$$

FIGURE 9.4-2. FORCE AND ACCELERATION VECTORS - PLAN VIEW

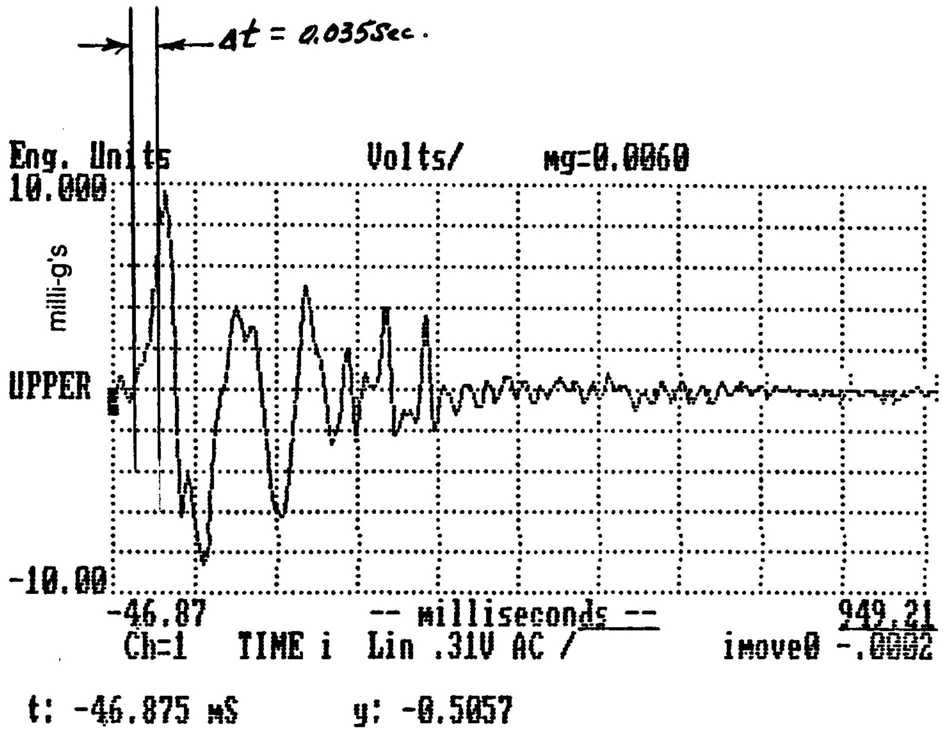


FIGURE 9.4-3. ACCELEROMETER MEASURED "INSTANTANEOUS" ACCELERATION DETERMINATION

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APPENDIX 9.5

INTELLEDEX 660 ROBOT DYNAMICS

(LVDT MEASURED)

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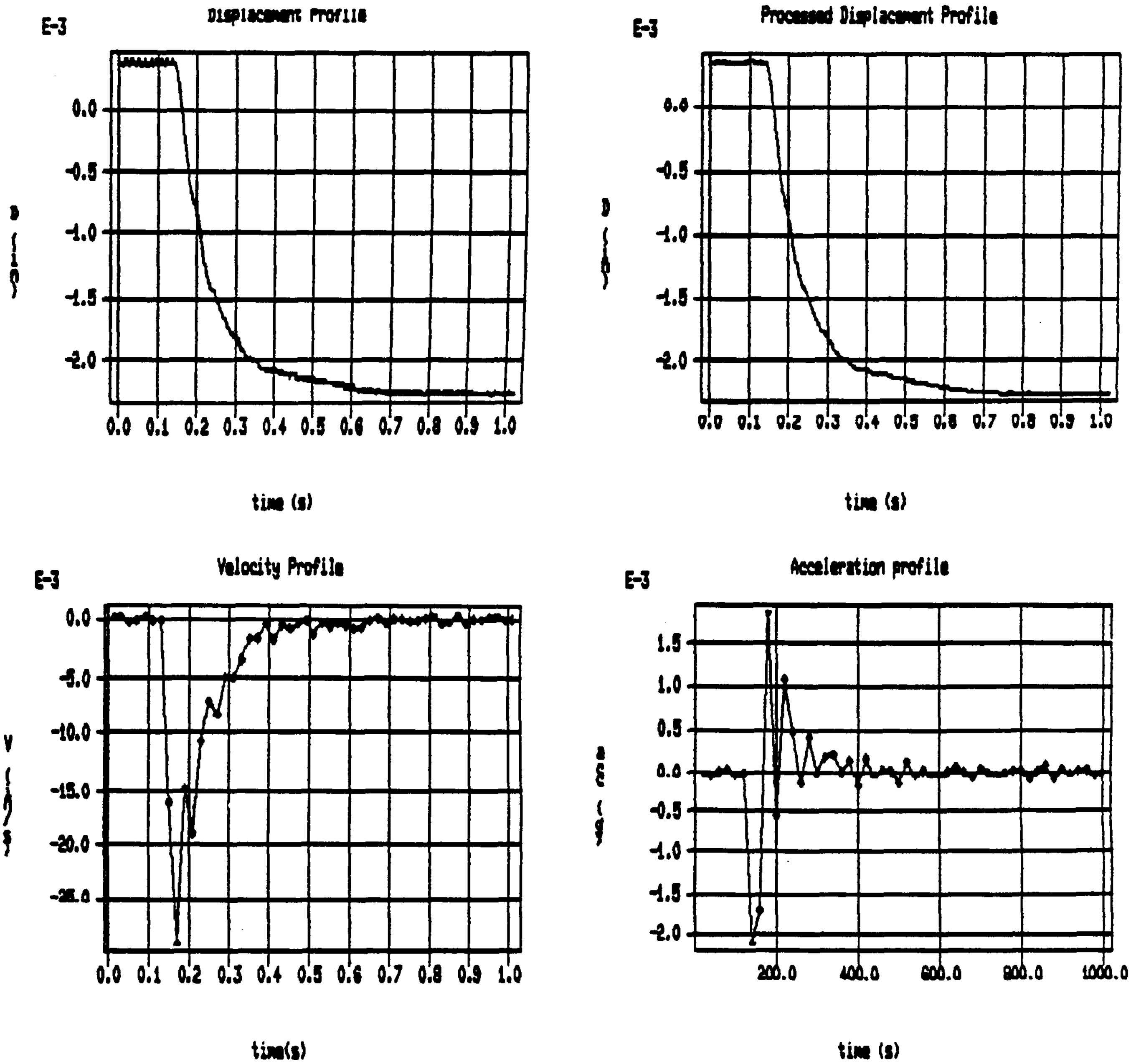
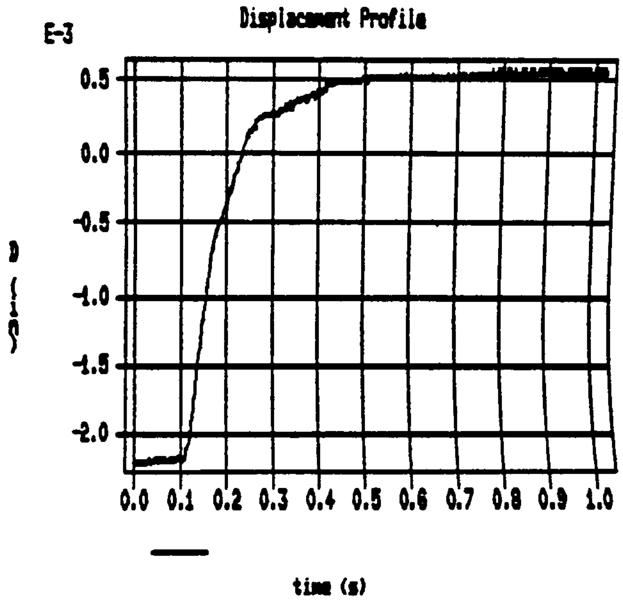
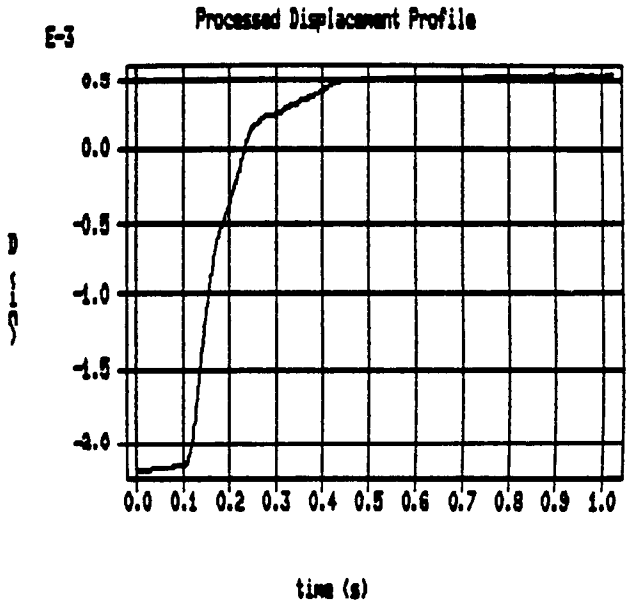
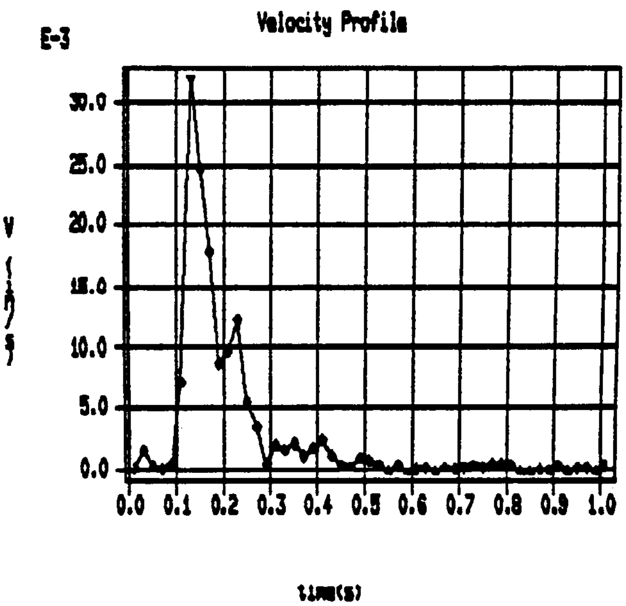
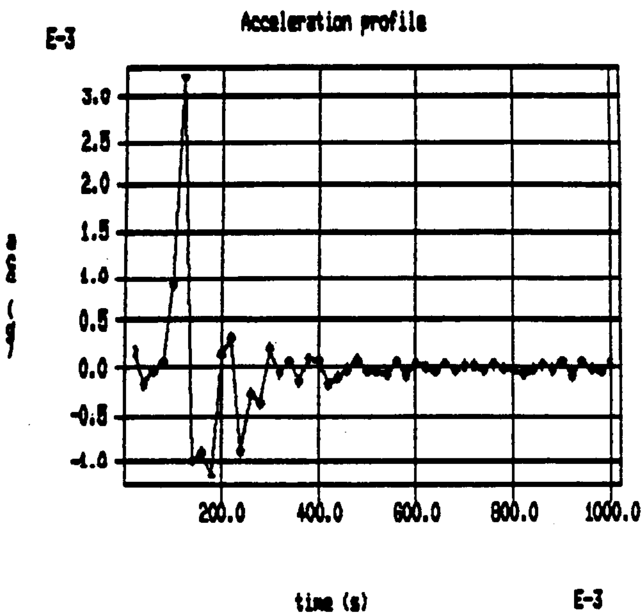


IMOVE0	+0.0005
CASE	I
SPEED	(0, 0, 0)
MAXSPEED	0

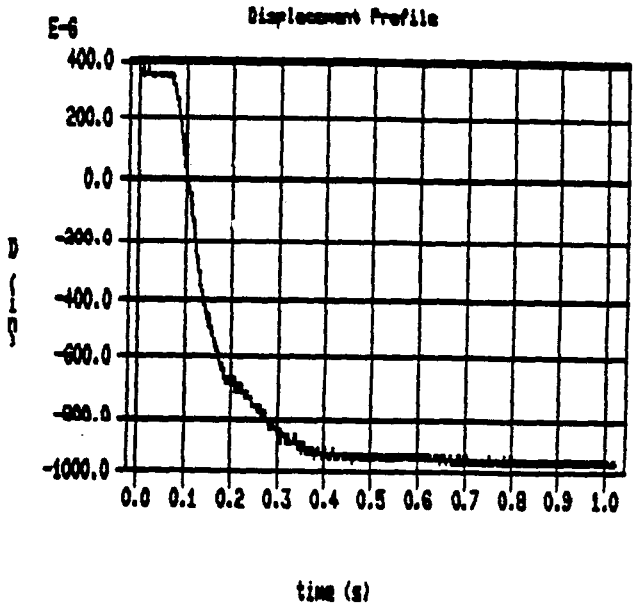


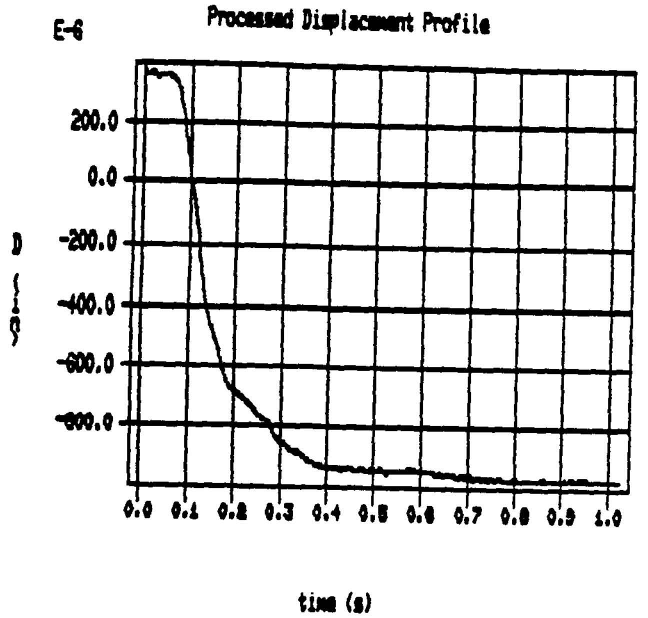


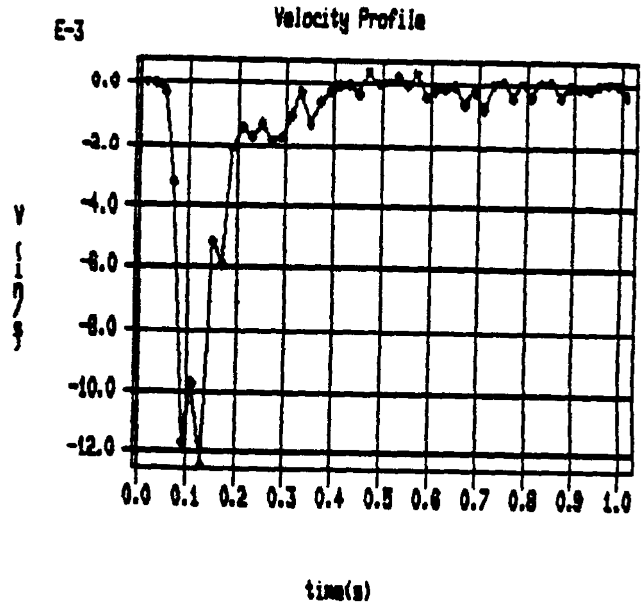


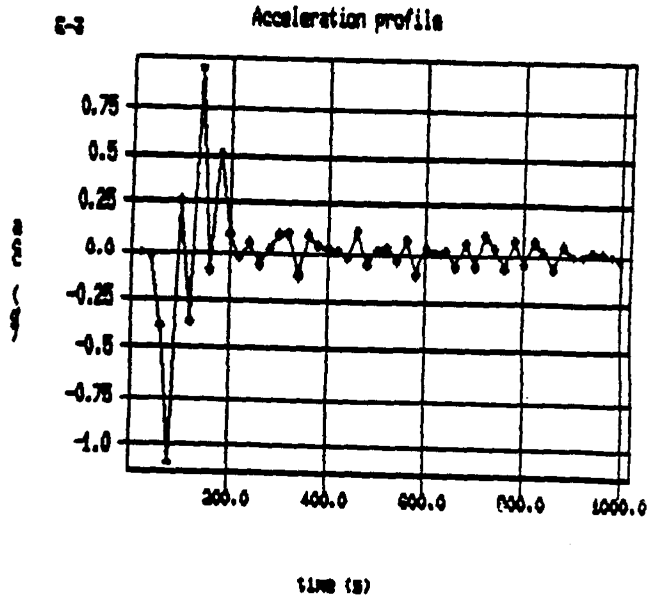


IMOVE0	-0.0005
CASE	I
SPEED	(0, 0, 0)
MAXSPEED	0

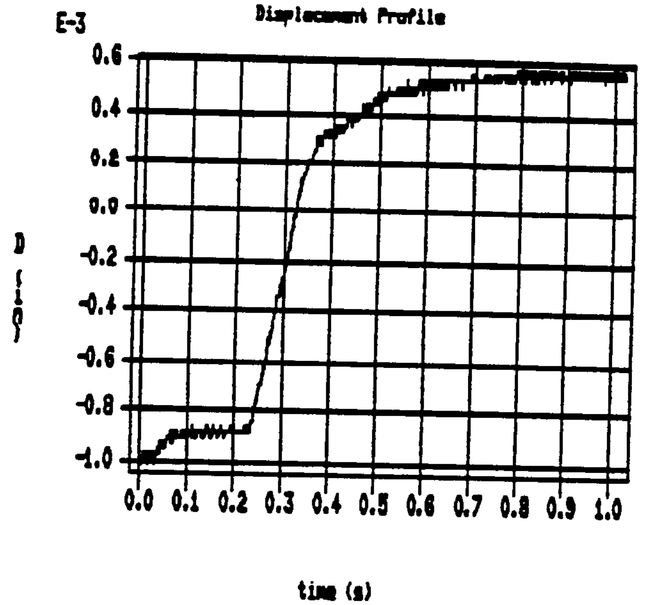


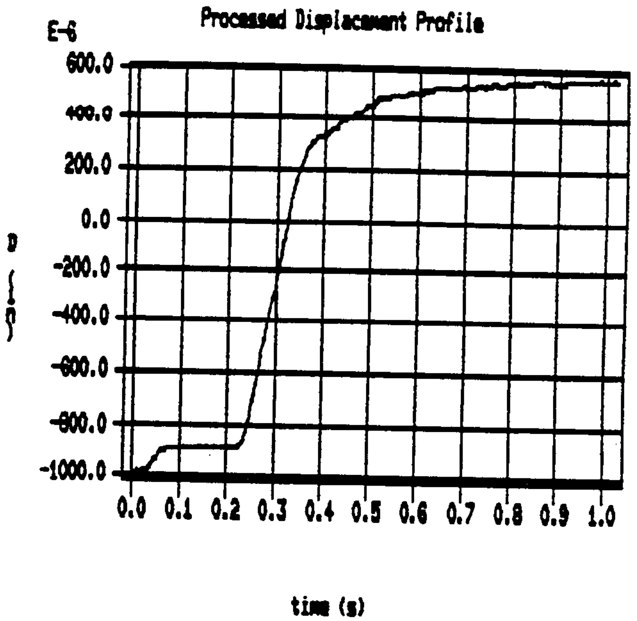


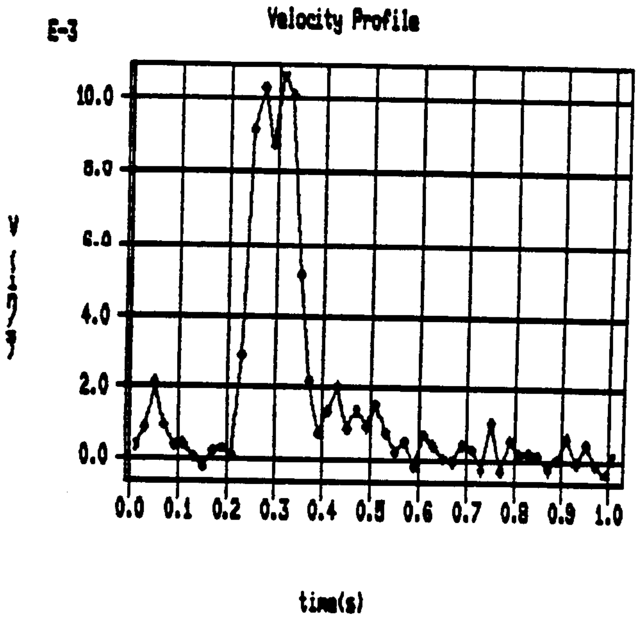


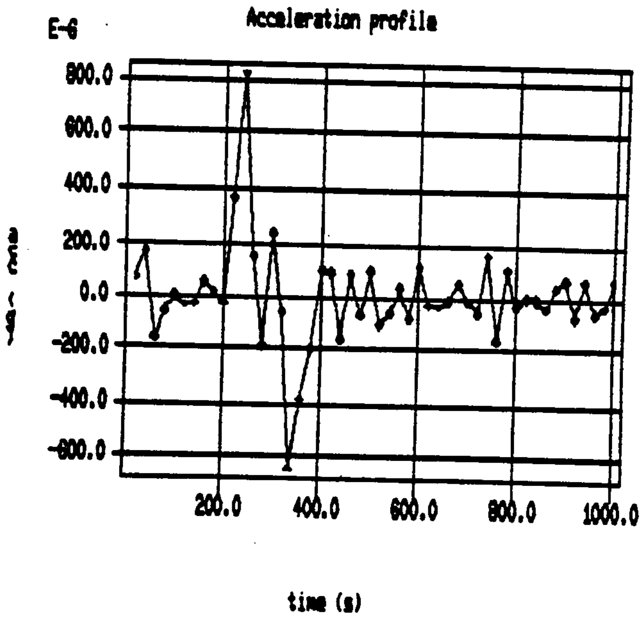


IMOVE0 +0.0002
CASE I
SPEED (0, 0, 0)
MAXSPEED 0

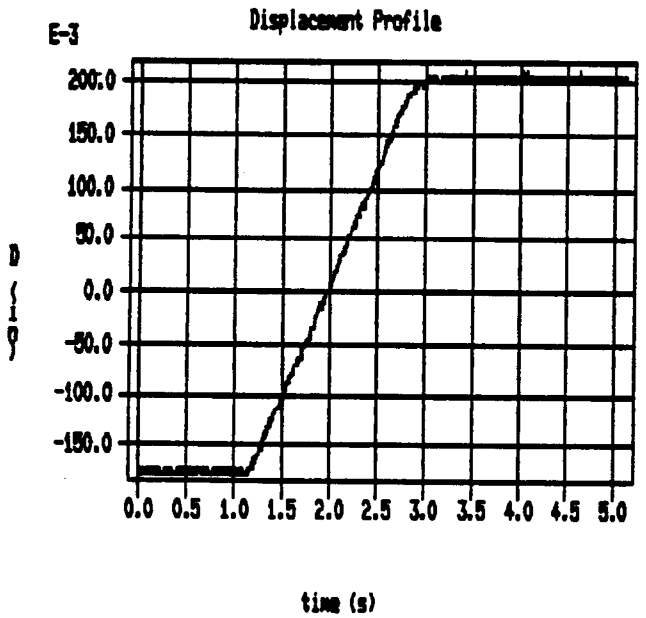


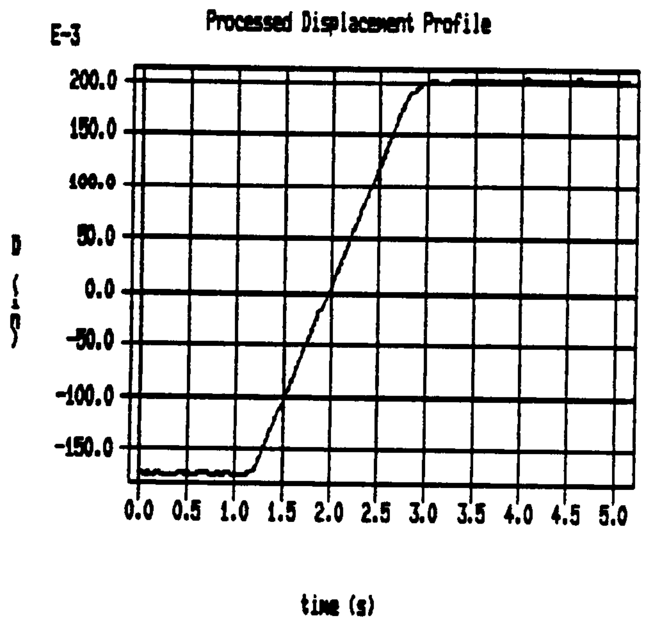


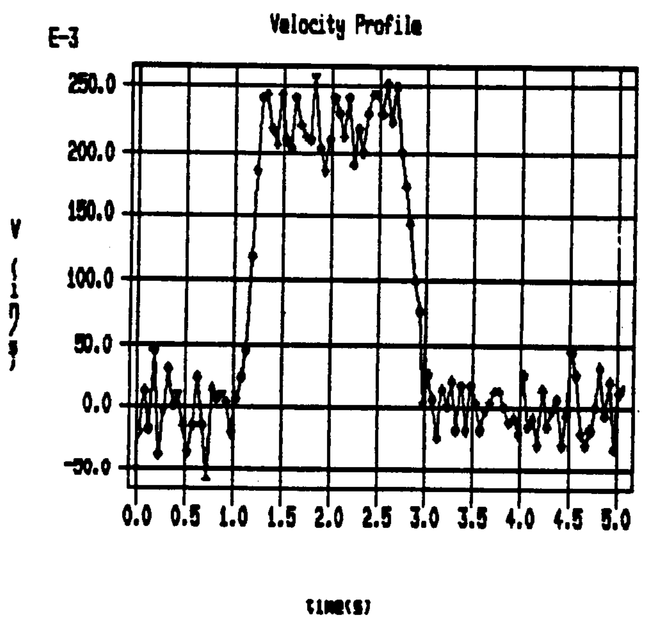


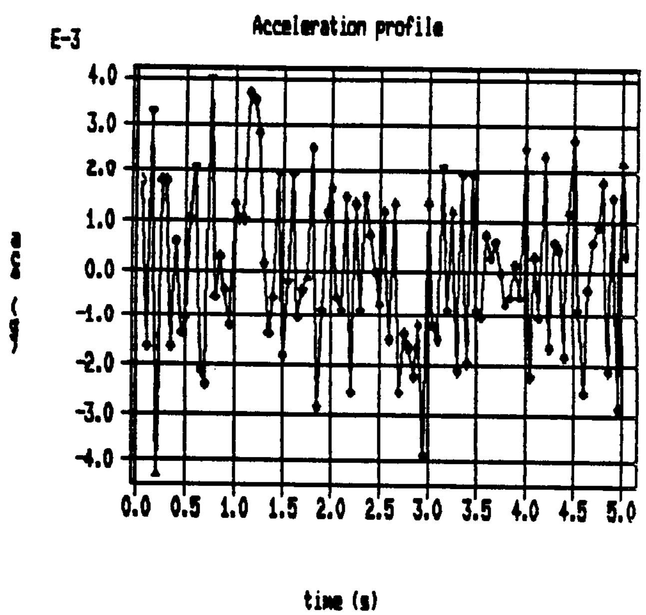


IMOVE0	-0.0002
CASE	I
SPEED	(0, 0, 0)
MAXSPEED	0

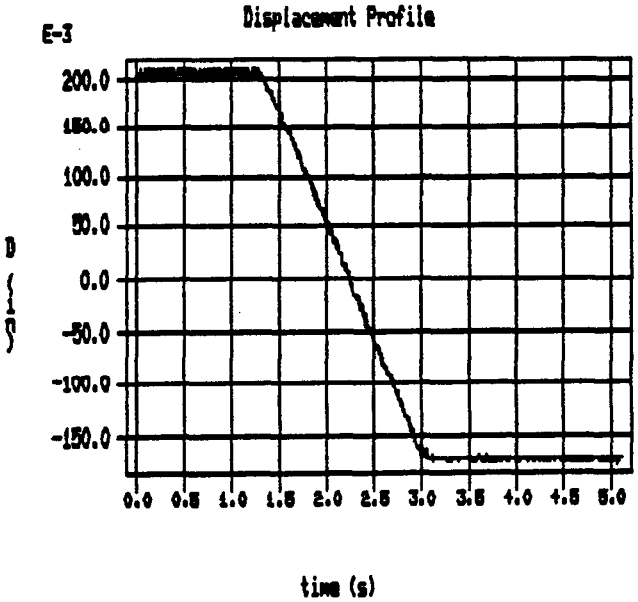


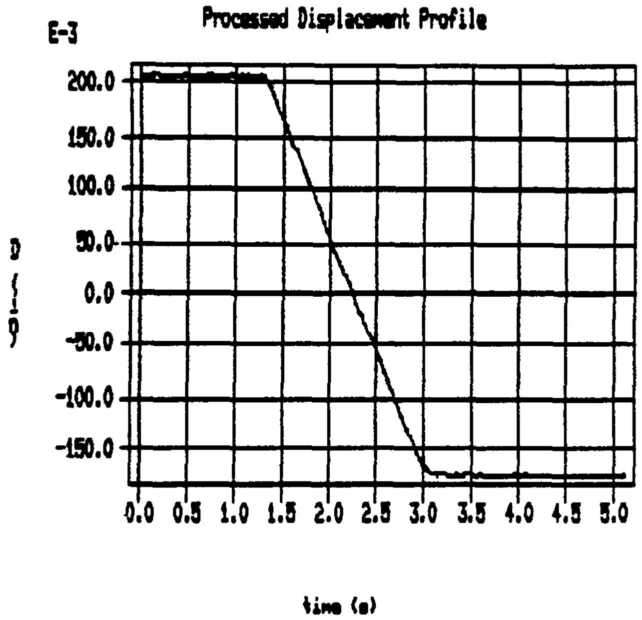


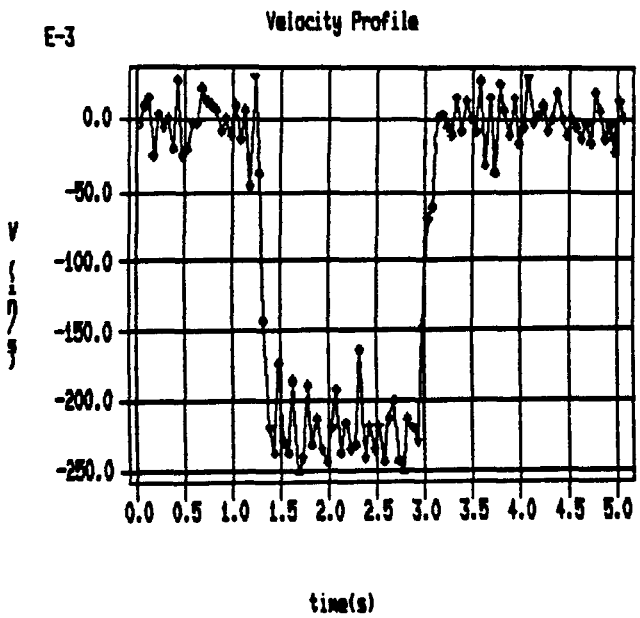


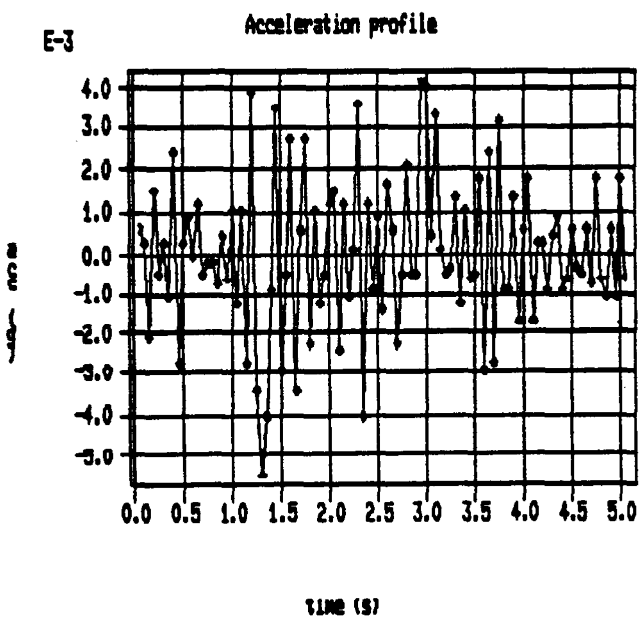


IMOVE0	-0.05
CASE	I
SPEED	(0, 0, 0)
MAXSPEED	0







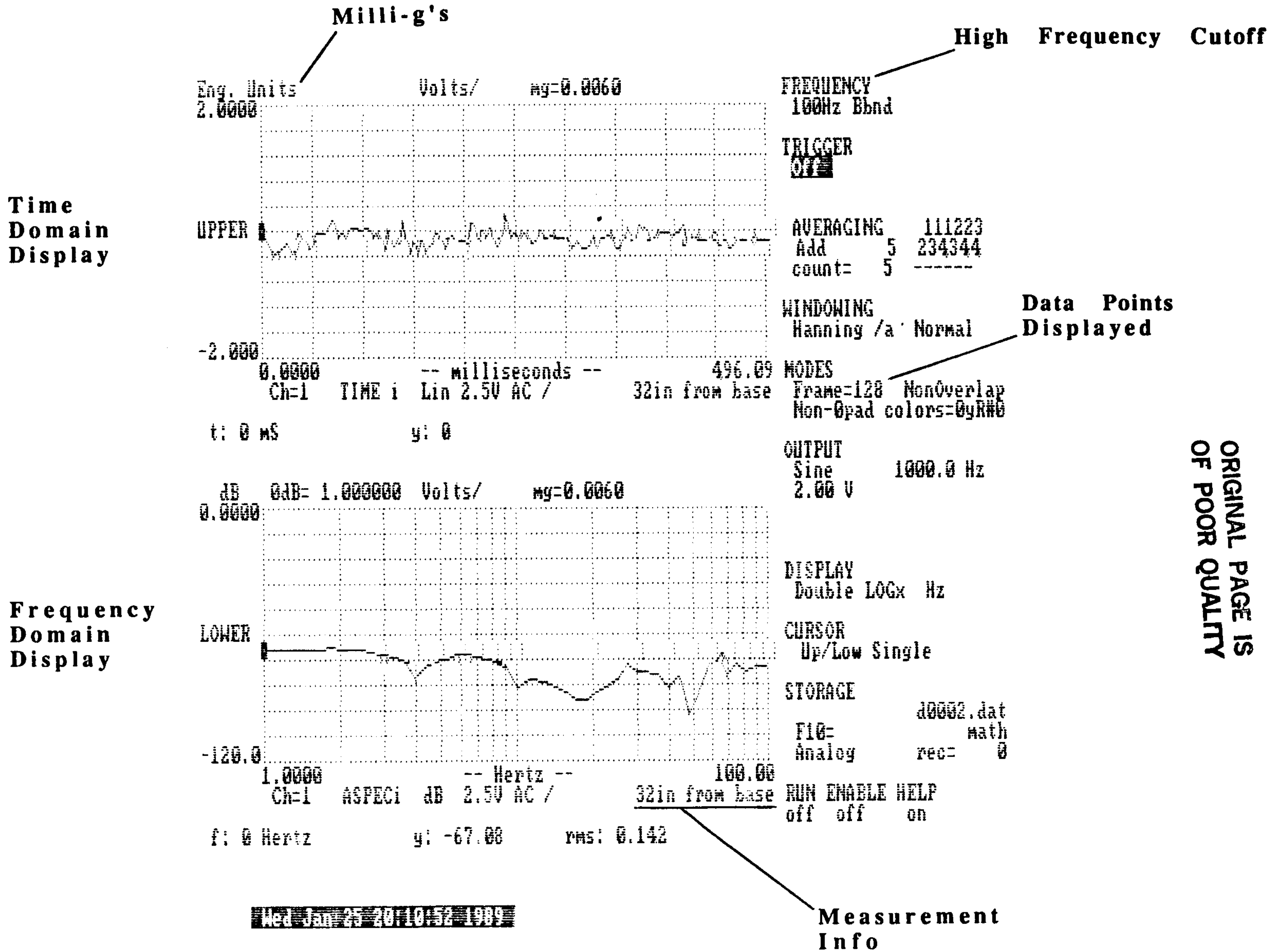


IMOVE0 +0.05
CASE I
SPEED (0, 0, 0)
MAXSPEED 0

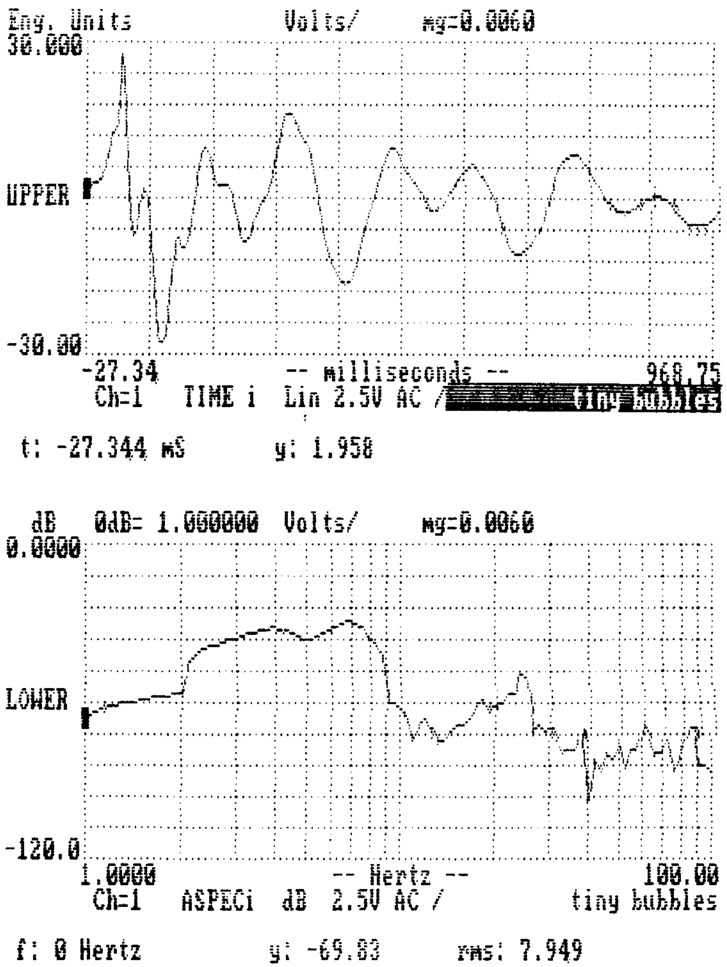
APPENDIX 9.6

ROBOT AND HUMAN DYNAMICS

(ACCELEROMETER MEASURED)

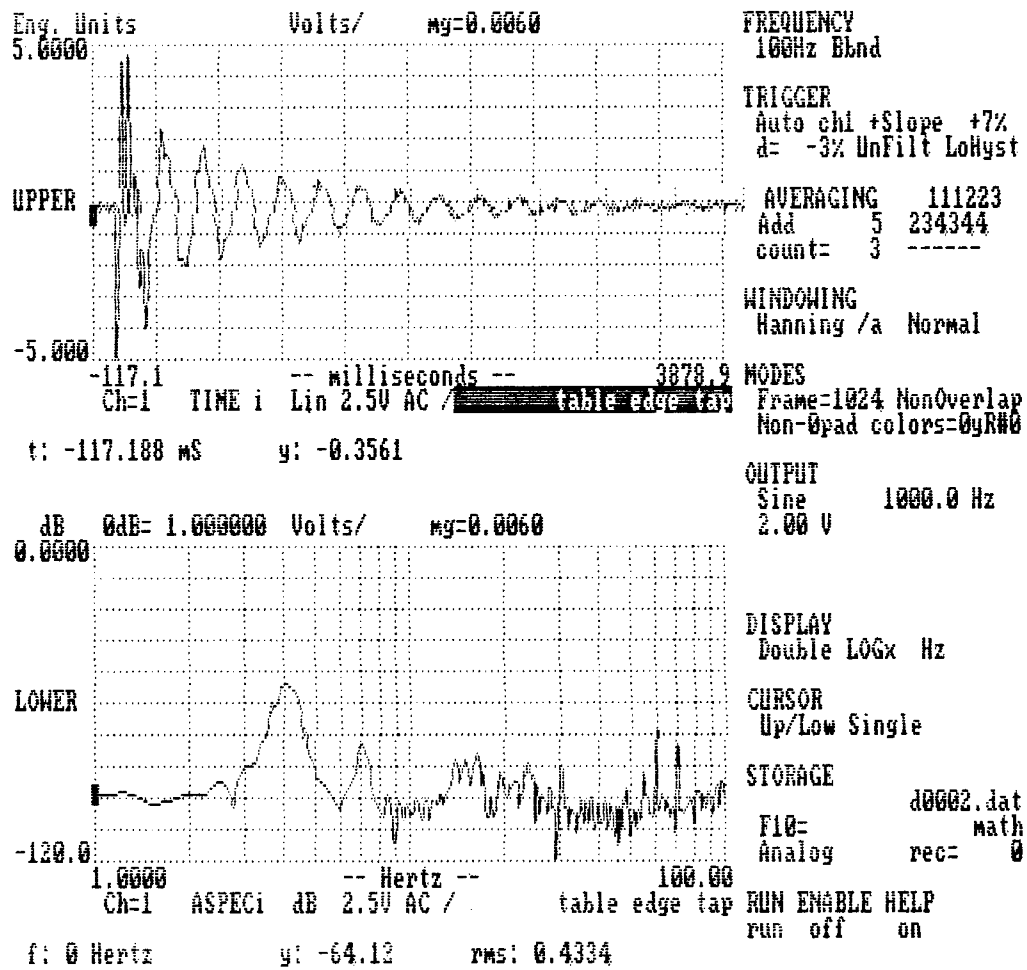


9.6.1 Background On Table 32"
From Robot Base



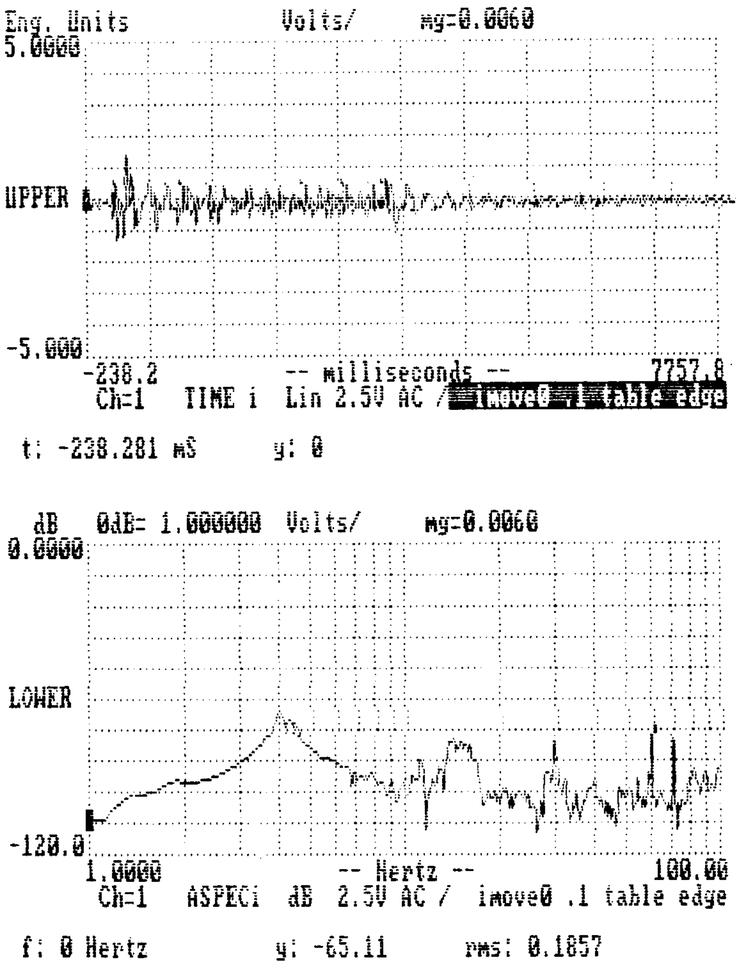
Wed Jan 25 20:19:20 1989

9.6.2 Table Edge Slight (<1/16") Lift And Drop



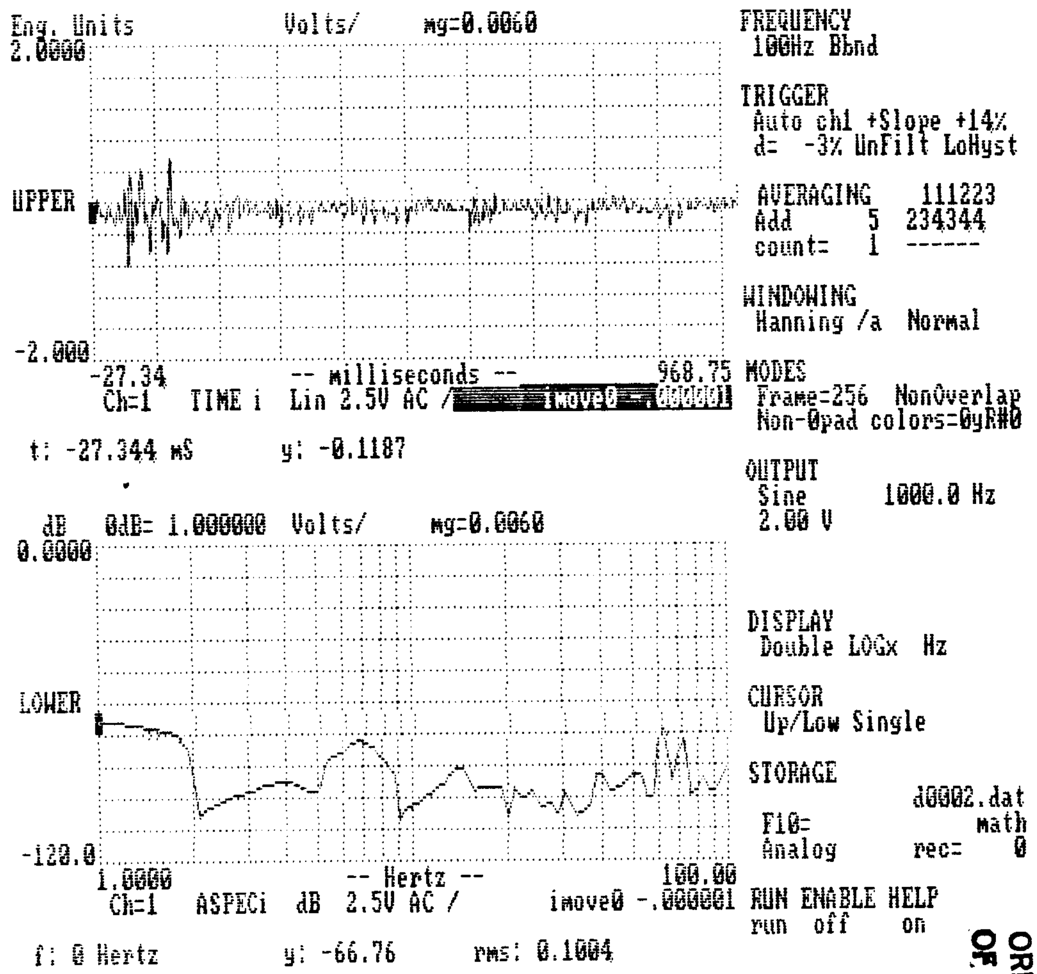
Wed Jan 25 20:32:16 1989

9.6.3 Tap On Table, Edge Mounted Accelerometer



Wed Jan 25 20:34:10 1989

9.6.4 Robot Motion (0.1 Radian) Detected On Table Edge



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9.6.5 Robot Base Measured Microstep Acceleration

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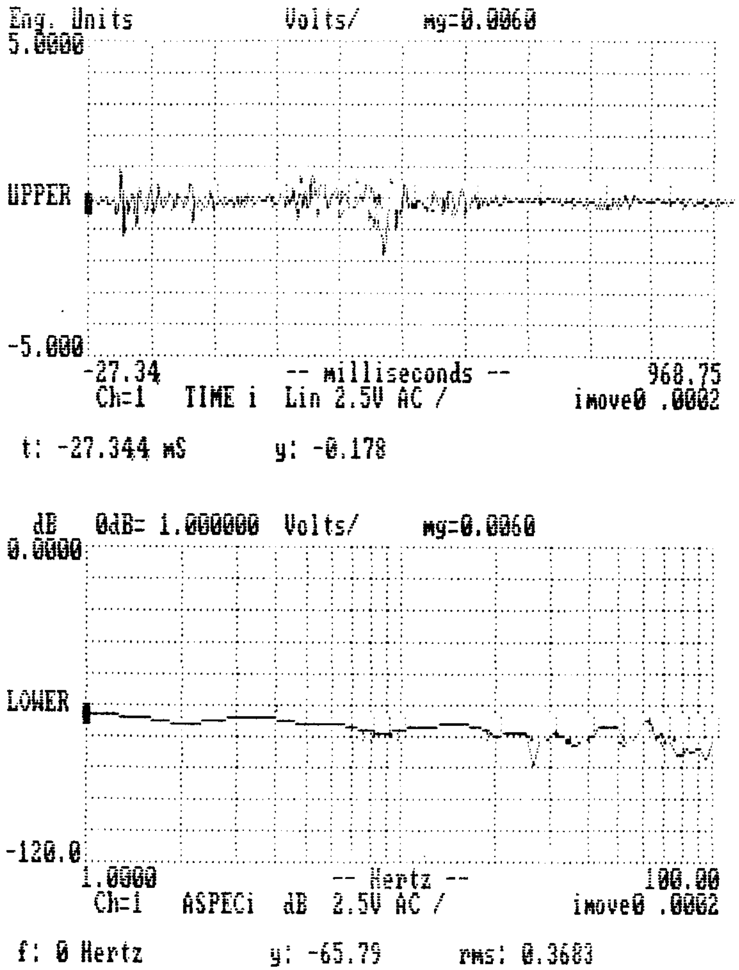
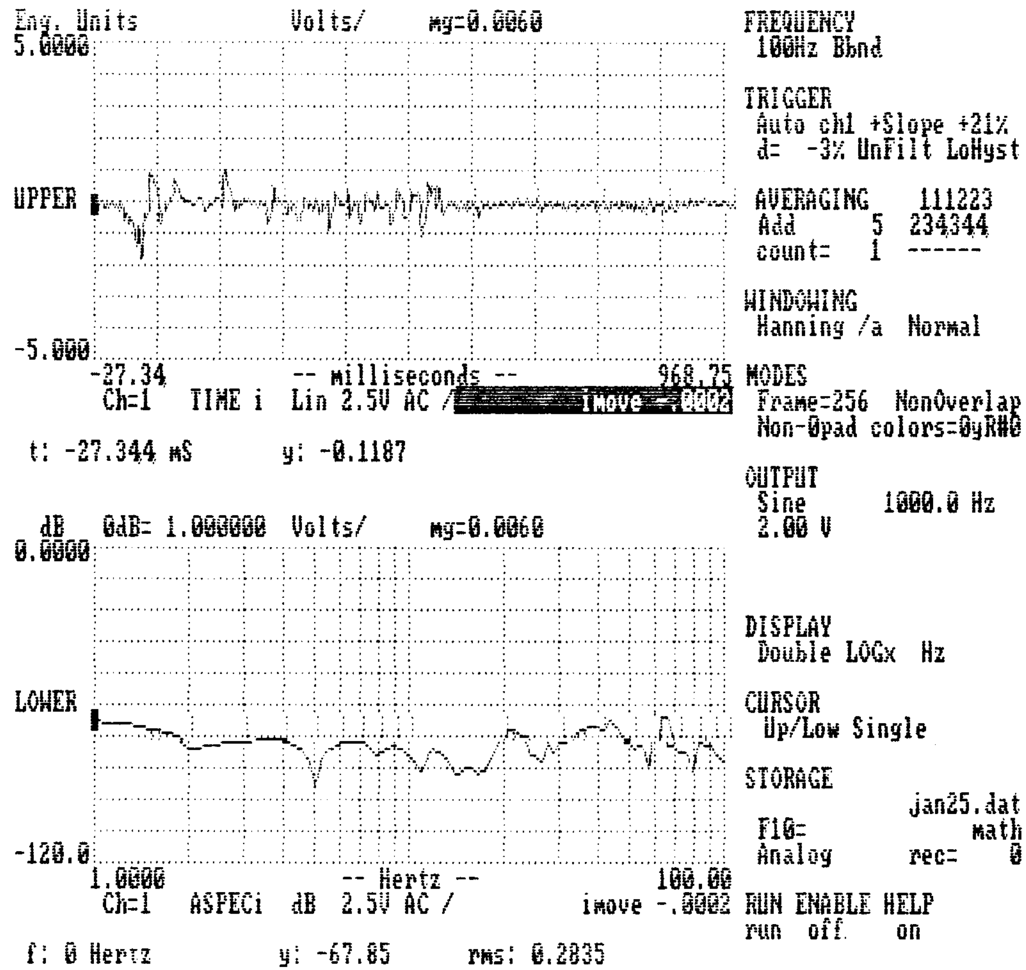


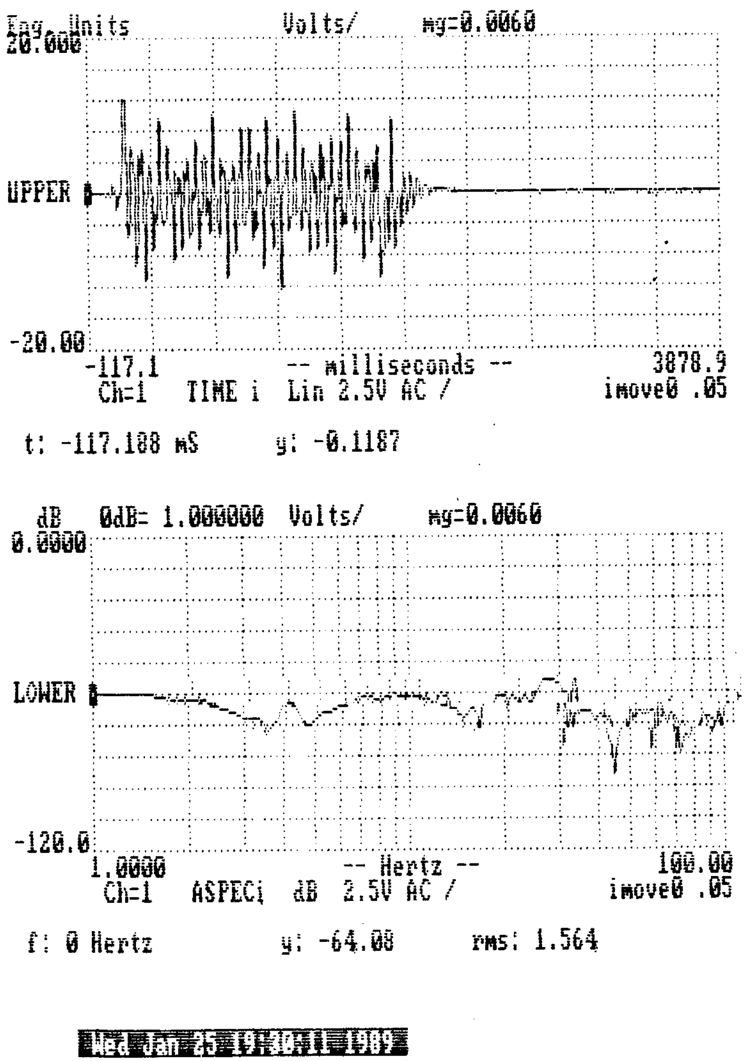
Wed Jan 25 19:15:50 1989

9.6.6 Robot Base Measured Minor Motion (+0.0002 Radian)

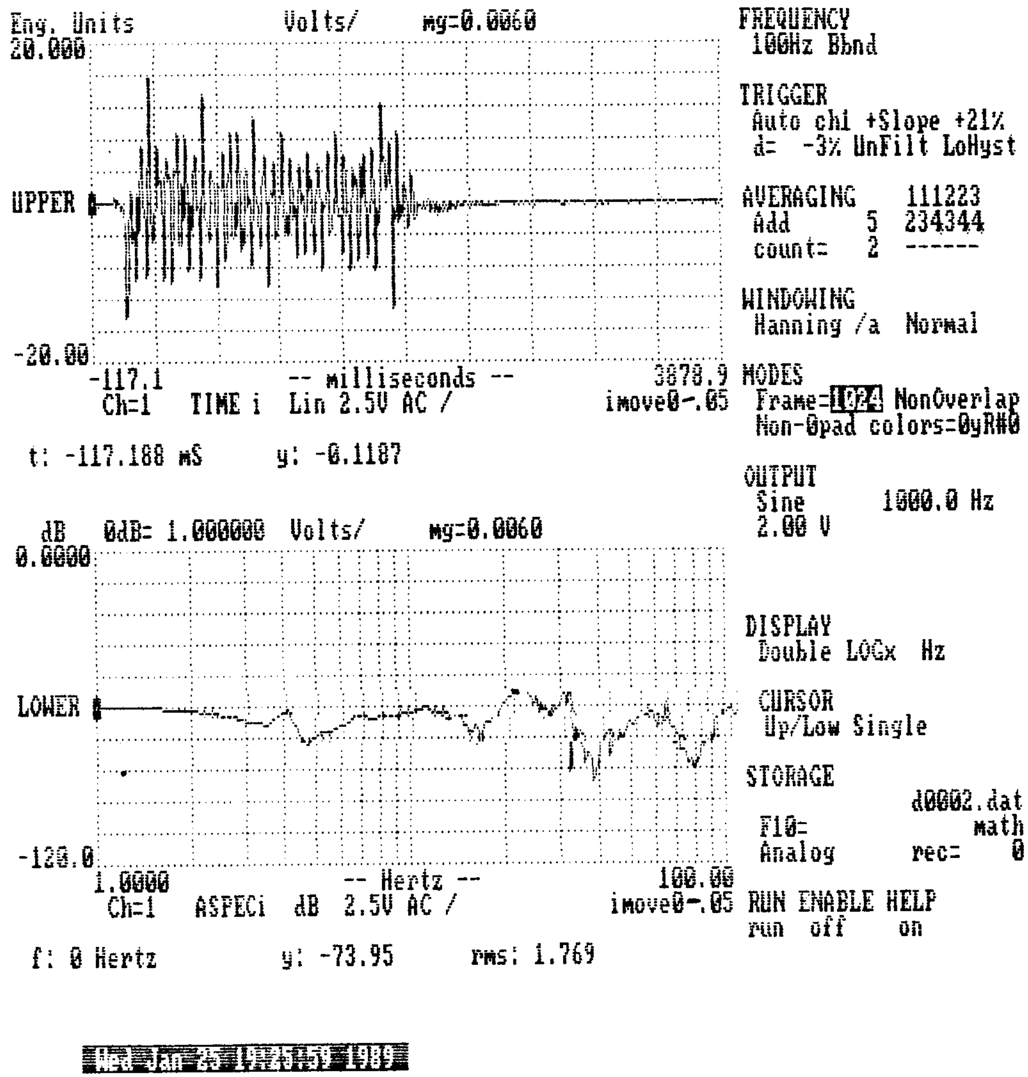


Wed Jan 25 18:43:48 1989

9.6.7 Robot Base Measured Minor Motion (-0.0002 Radian)



9.6.8 Robot Base Measured Major Motion (+0.05 Radian)



9.6.9 Robot Base Measured Major Motion (-0.05 Radian)

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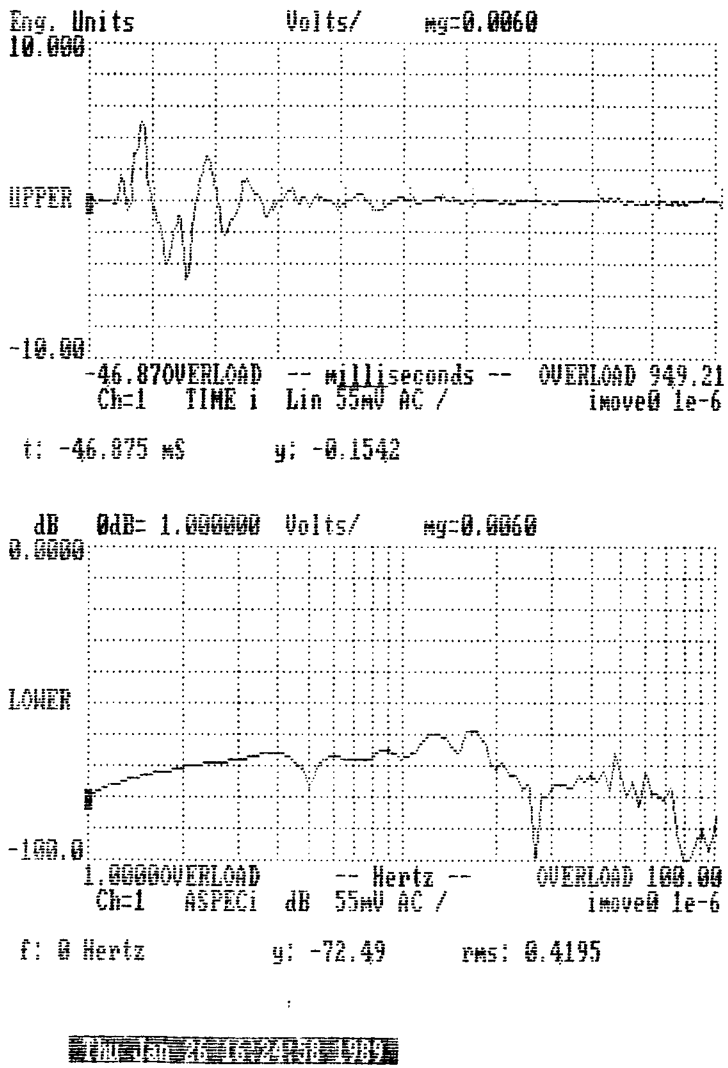
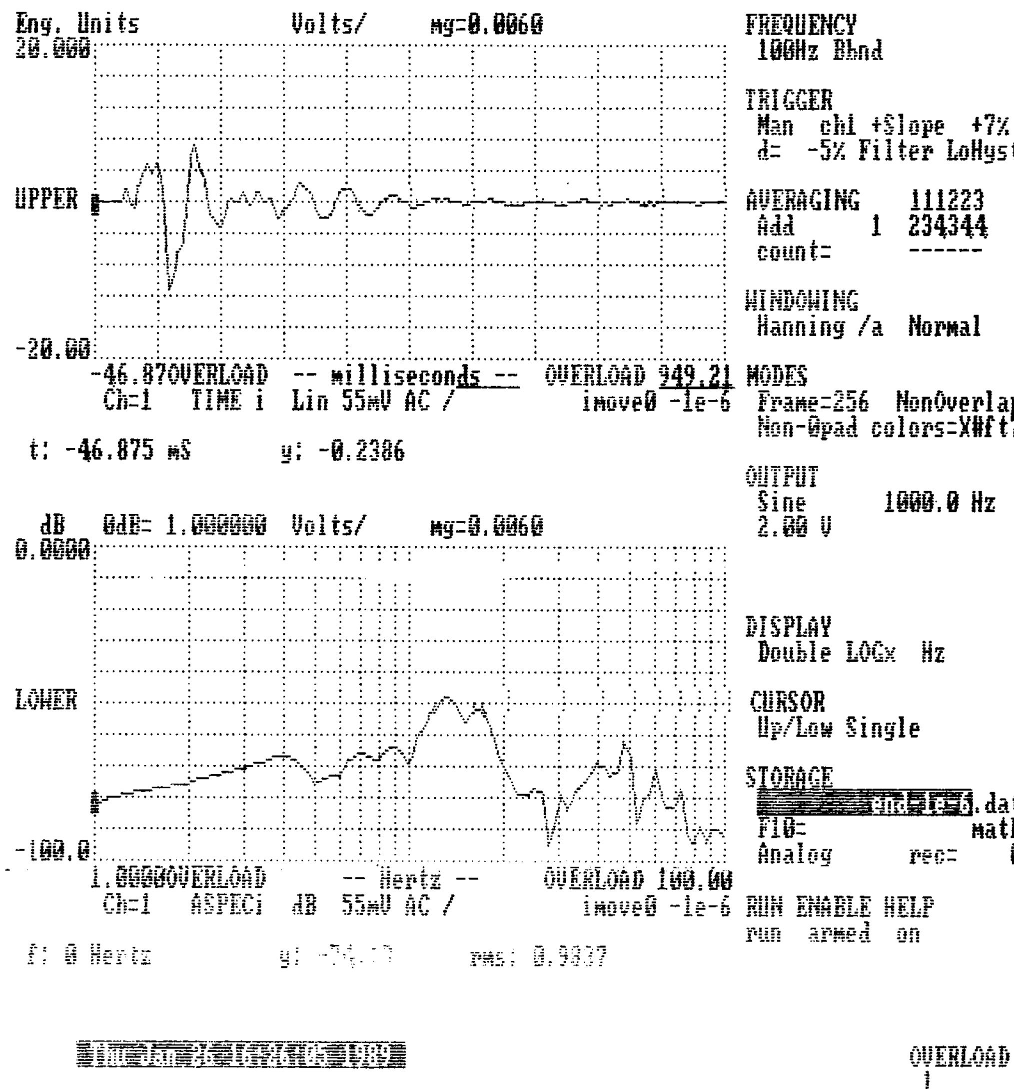
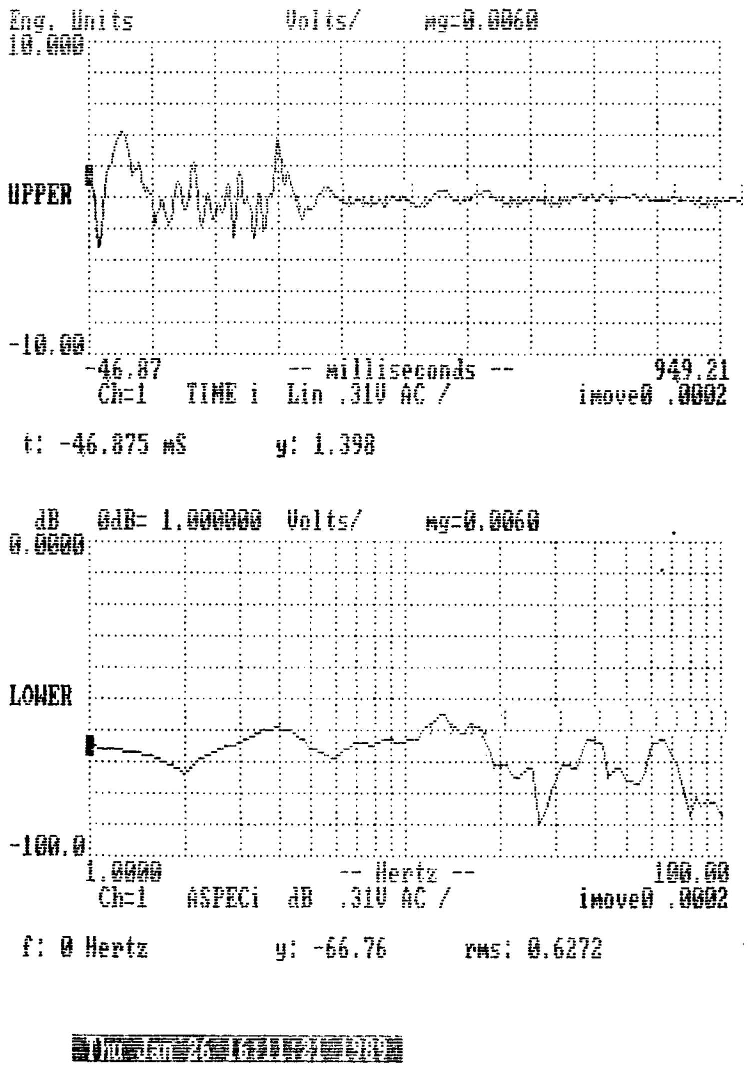


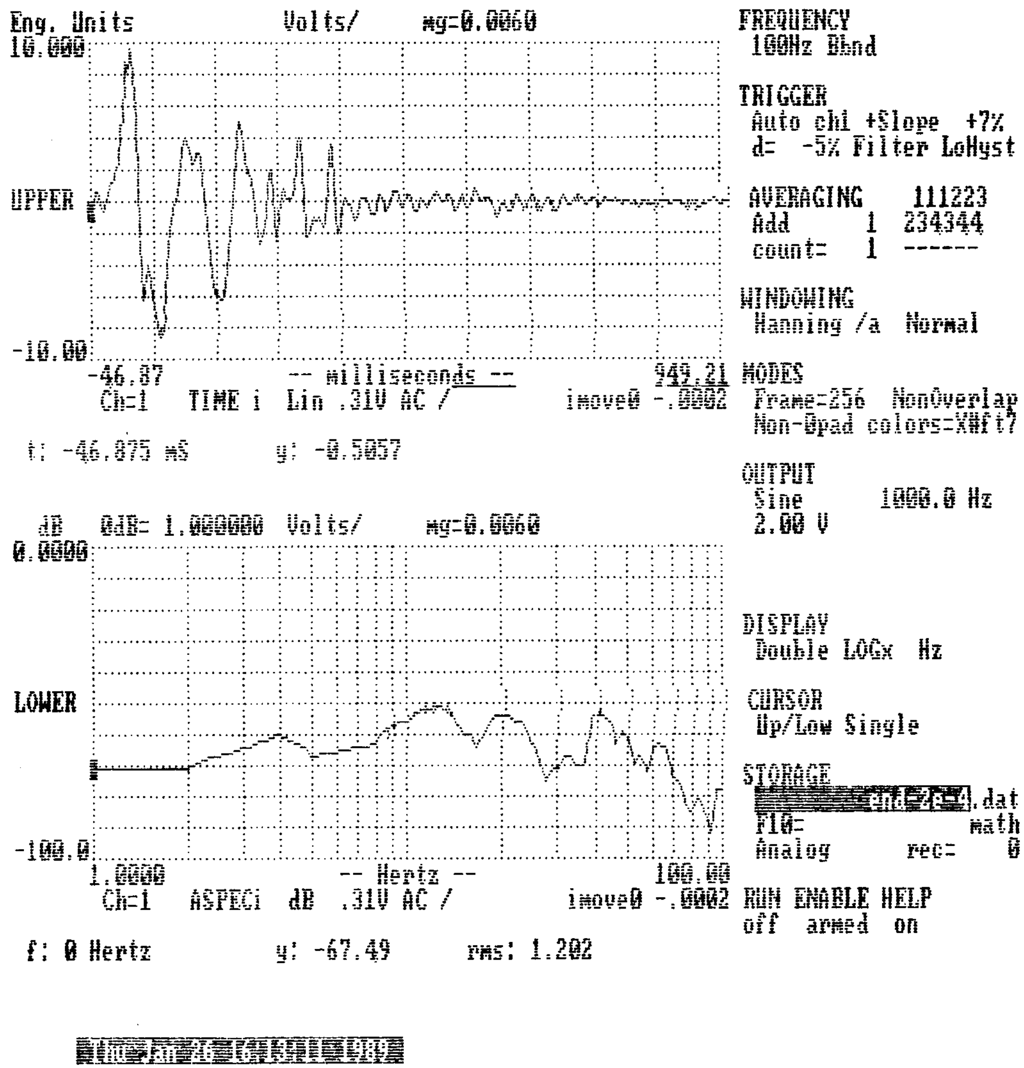
9.6.10 End Effector Measured (+) Microstep Robot Base Motion



9.6.11 End Effector Measured (-) Microstep Robot Base Motion



9.6.12 End Effector (x) Measured Minor Motion (+0.0002 Radian)



9.6.13 End Effector (x) Measured Minor Motion (-0.0002 Radian)

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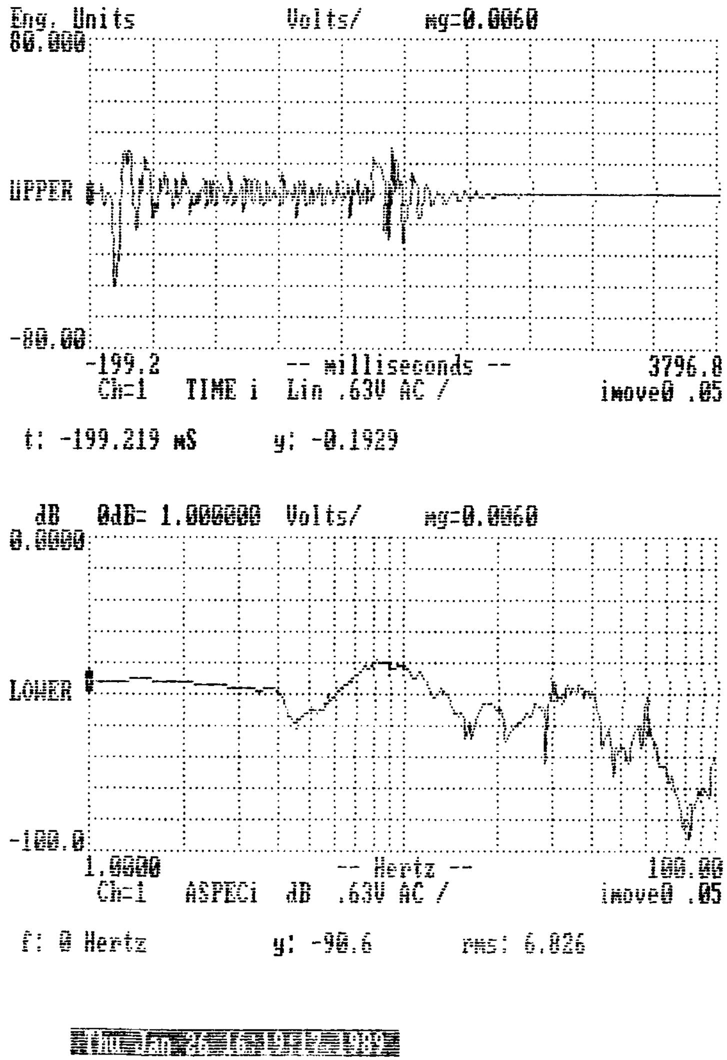
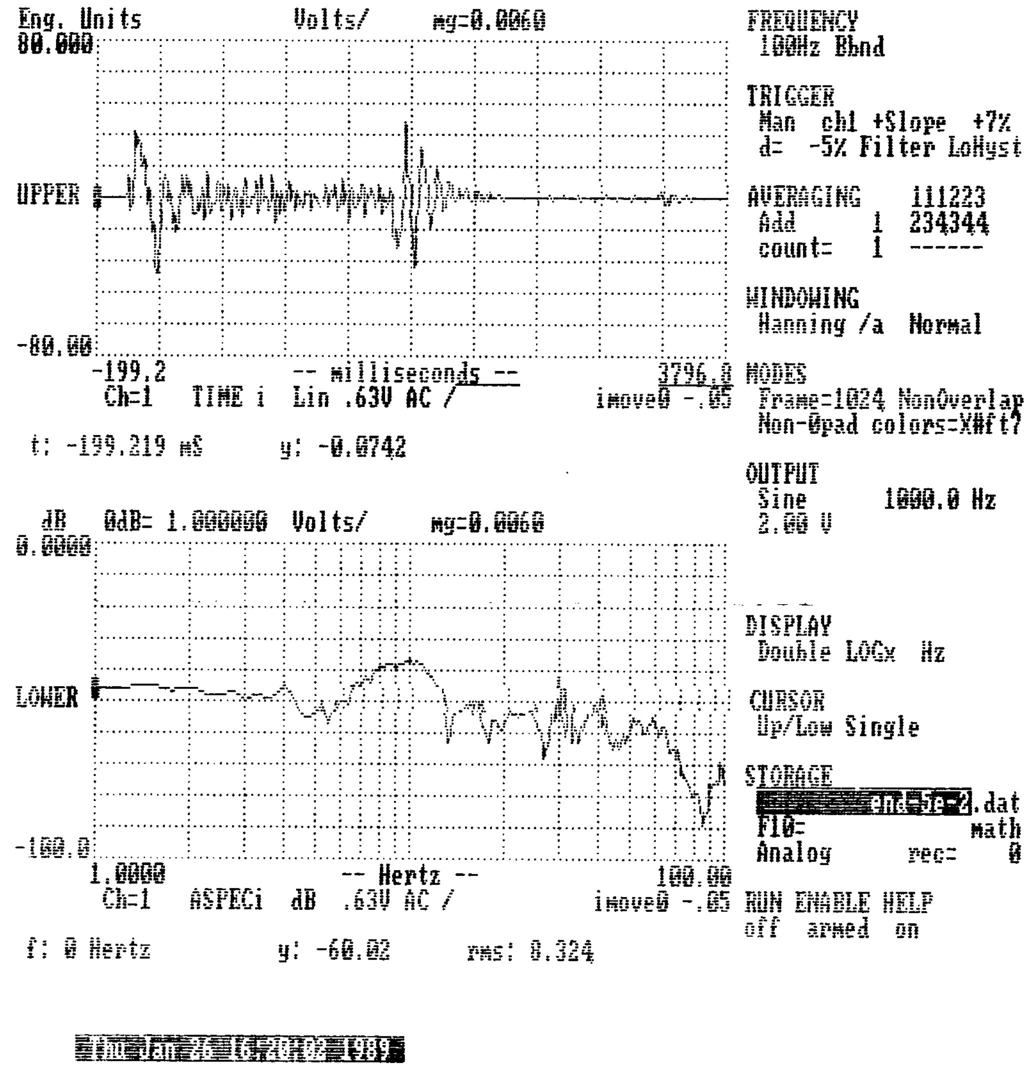
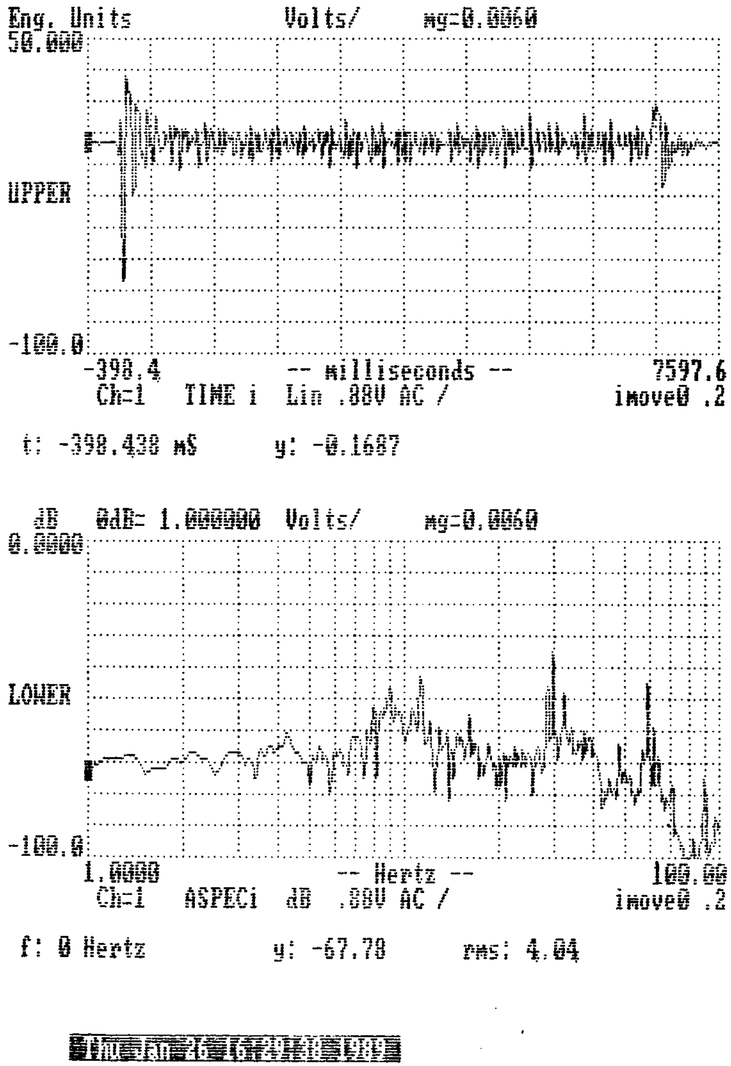


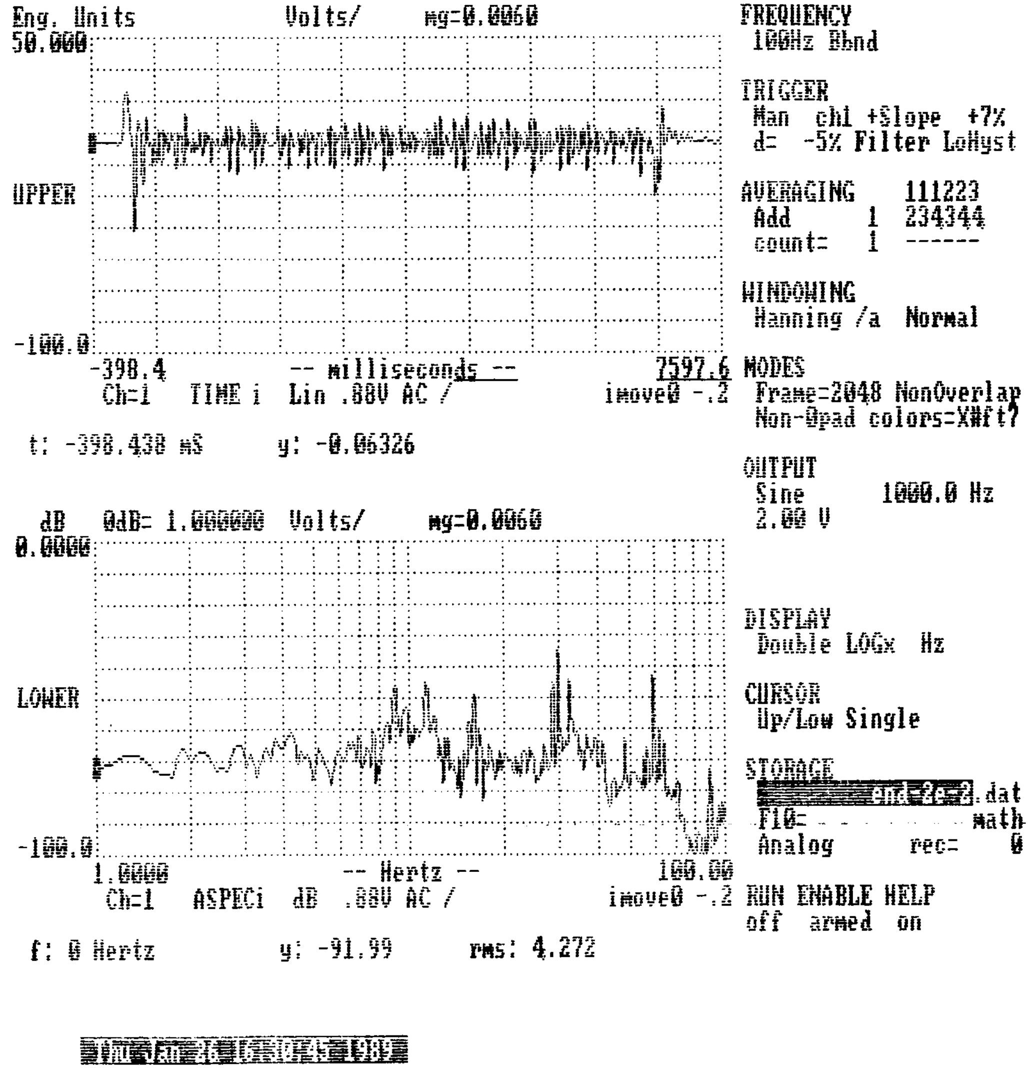
9.6.14 End Effector (x) Measured Major Motion (+0.05 Radian)



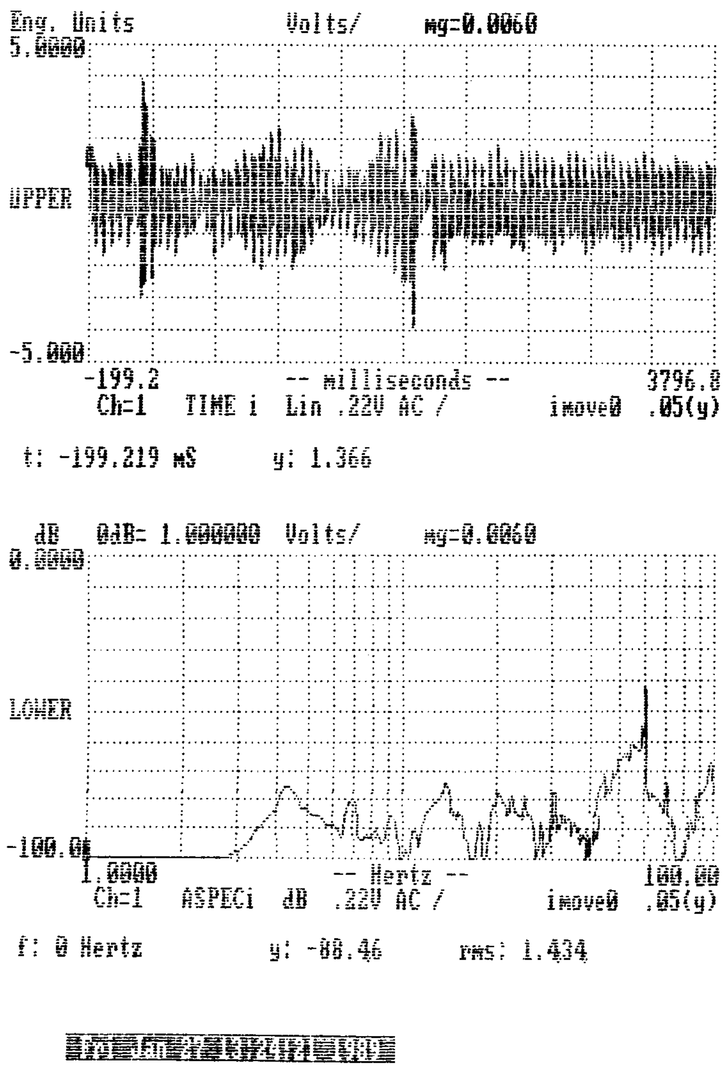
9.6.15 End Effector (x) Measured Major Motion (-0.05 Radian)



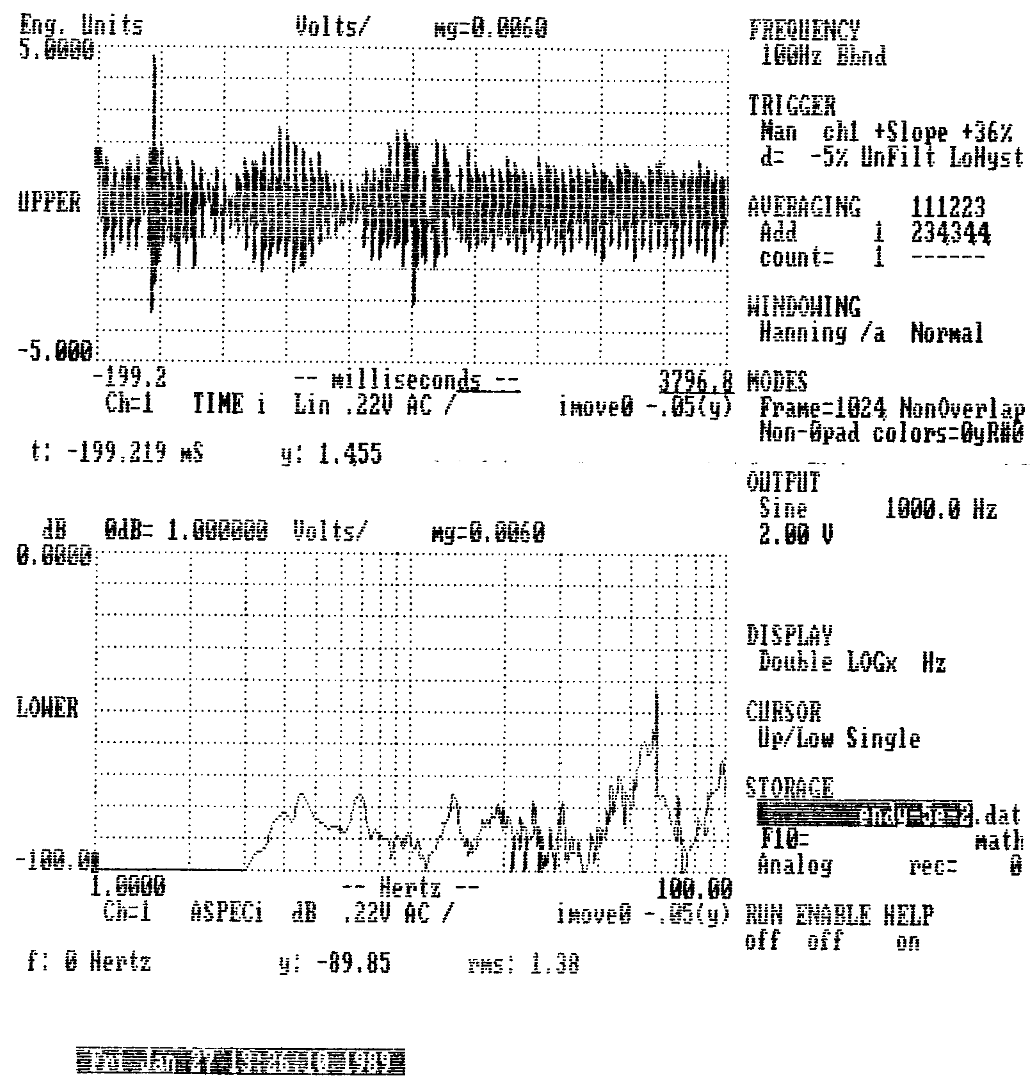
9.6.16 Very Large Base Motion (+0.2 Radian
End Effector (x) Measured



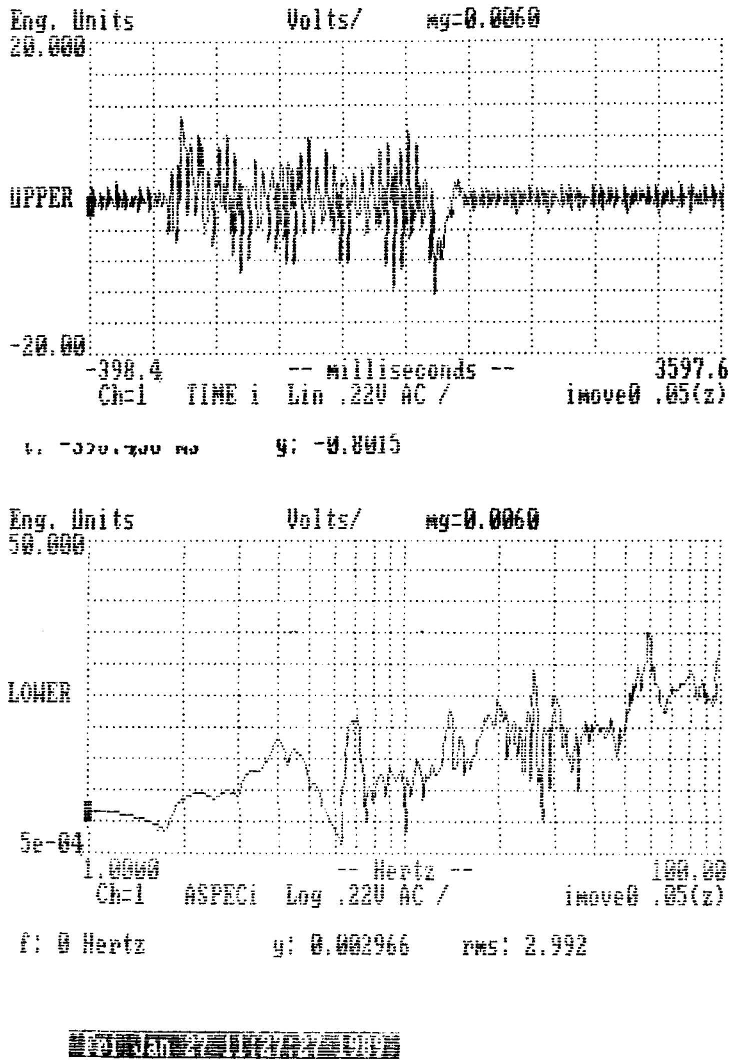
9.6.17 Very Large Base Motion (-0.2 Radian)
End Effector (x) Measured



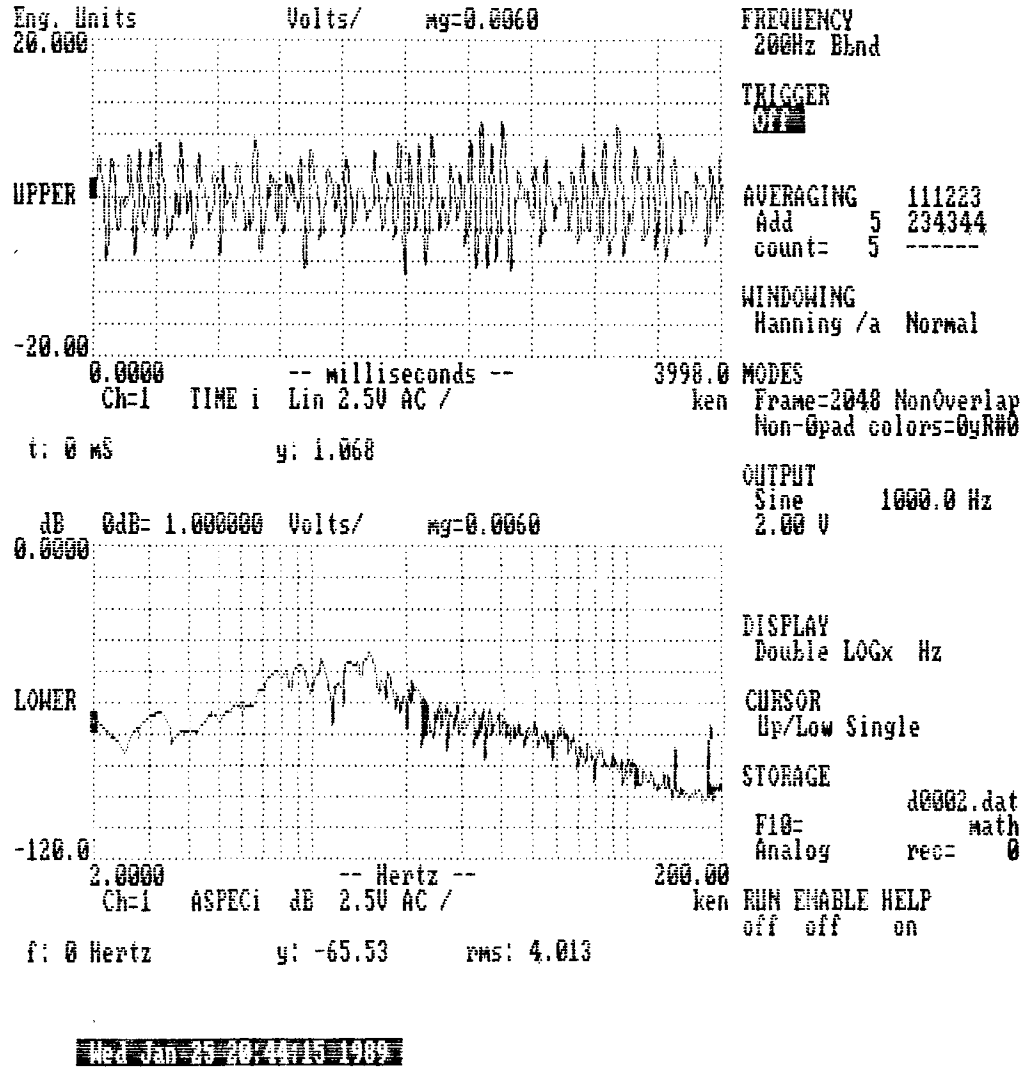
9.6.18 End Effector (y) Measured Major Motion (+0.05 Radian) NOTE: Higher Background



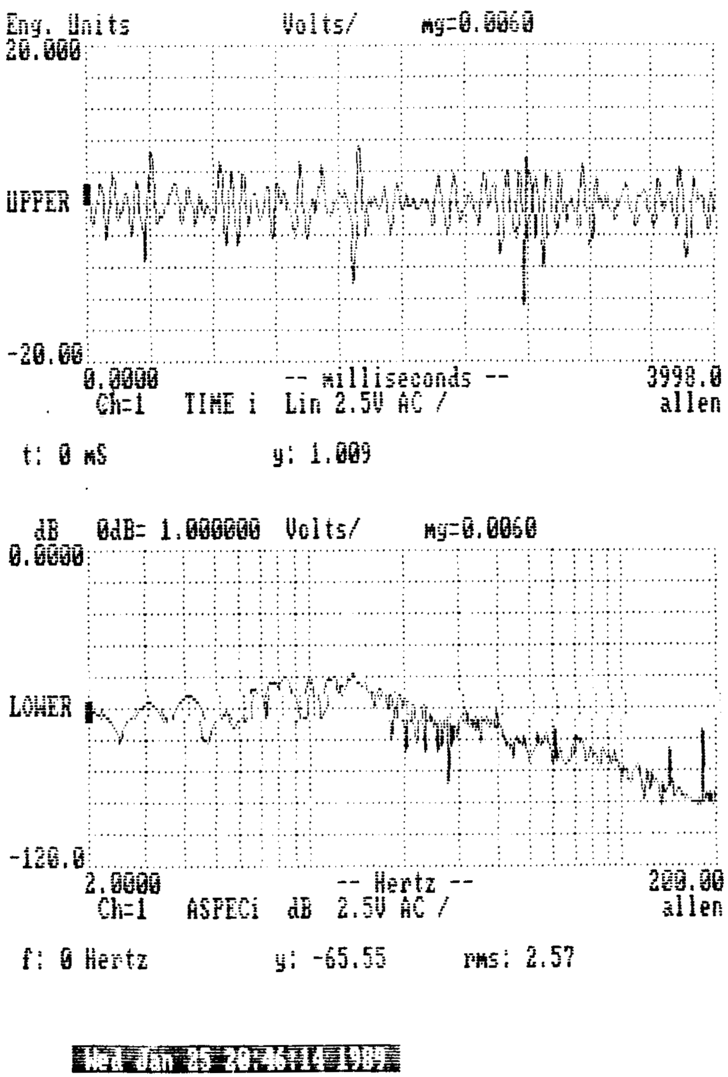
9.6.19 End Effector (y) Measured Major Motion (-0.05 Radian) NOTE: Higher Background



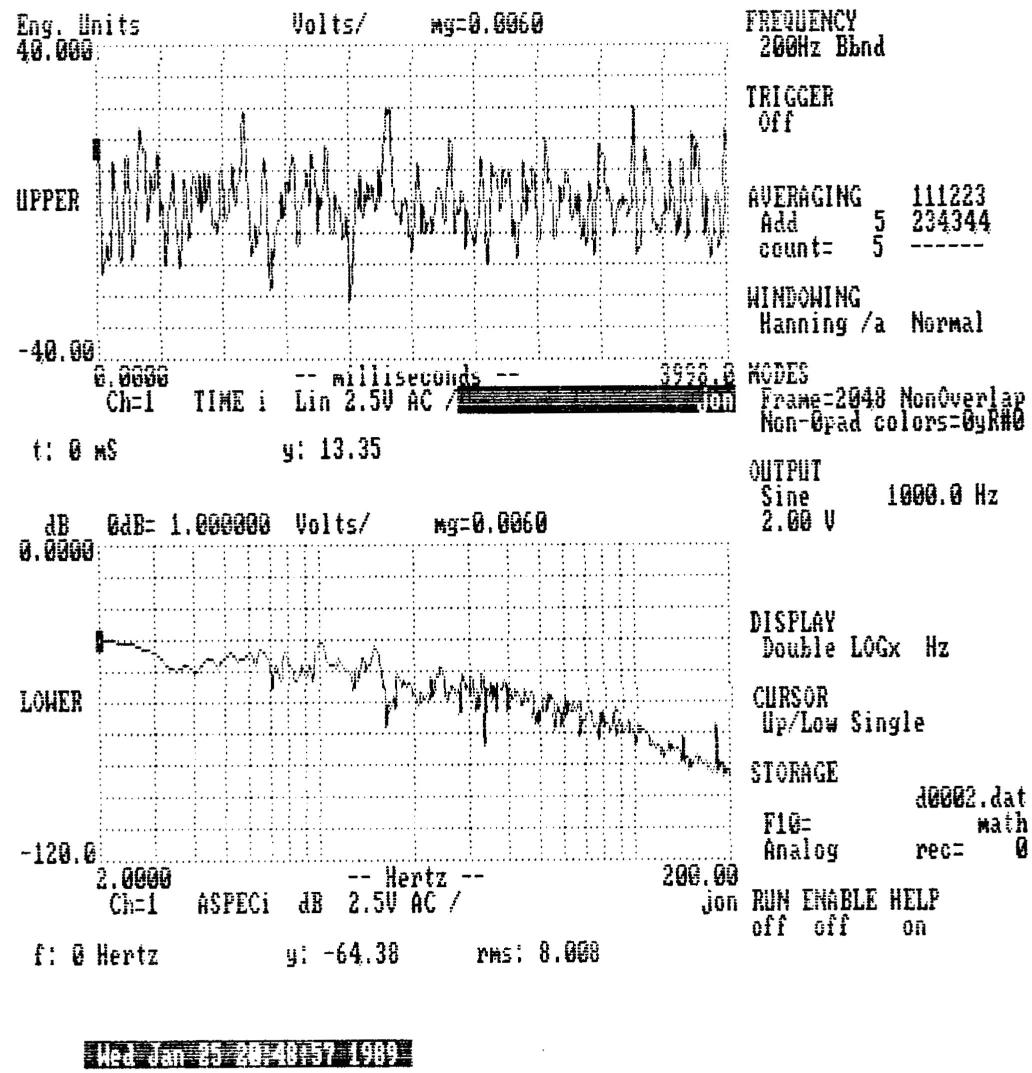
9.6.20 End Effector (z) Measured Major Motion (+0.05 Radian)



9.6.21 Accelerometer Held Vertically By Human Hand (K) With Arm & Wrist Support



9.6.22 Accelerometer Held Vertically By Human Hand (A) With Arm & Wrist Support



9.6.23 Accelerometer Held Vertically By Human Hand (J) With Arm Extended

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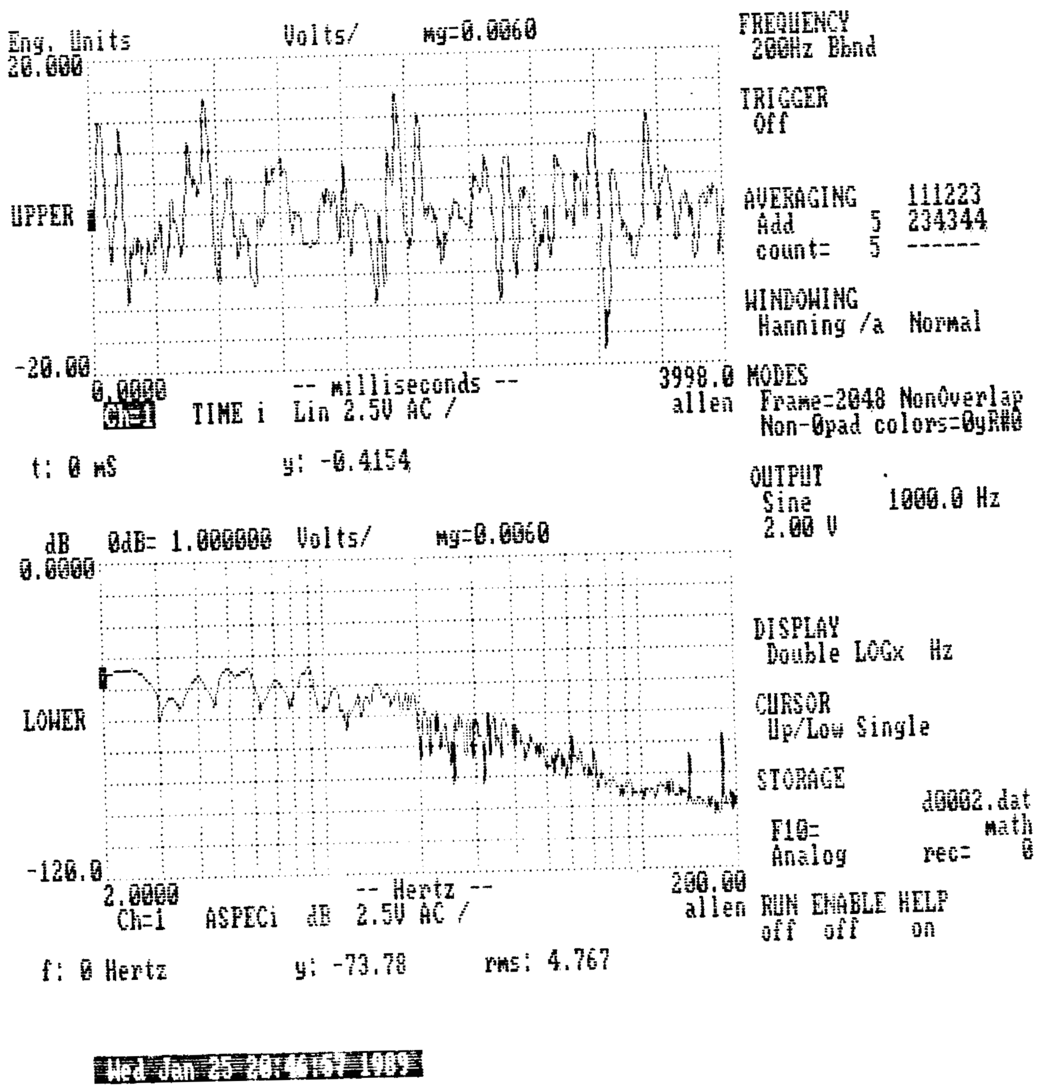

9.6.24 Accelerometer Held Vertically By Human Hand (A) With Arm Extended

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APPENDIX 9.7

COMPARISON OF END-EFFECTORS

AND MANIPULATORS

Vendor Assessment Results - Technical literature was obtained from 24 robot vendors. Two vendors manufactured anthropomorphic robots that were within the volume constraints imposed by the U S Laboratory module and were studied in depth. The vendors included Unimation (PUMA) and Intelledex (Model 660). The former unit uses direct current servomotors while the latter uses permanent magnet stepper motors. Discussions were also held with vendors of state-of-the-art end effectors to ascertain potential application to microgravity manipulation.

SUMMARY OF VENDOR ASSESSMENT

VENDOR	DEVICE	COMPONENTS
Unimation	PUMA Anthropomorphic Robot	Major Axes: Electrocraft Model E19-2 Servomotors, Peak Torque 5.5 N-m Minor Axes: Magnetic Technology No. 1937D-150 Servomotor Peak Torque 50 oz-in
Intelledex	Model 660 Anthropomorphic Robot	Major Axes: Superior Electric Model MO93FD409 Stepper Motor Peak Torque 450 oz-in Minor Axes: Clifton Precision Models 23SHAS42FG/H173 and 23SHBL51BU/H230 Steppers
Telerobotics	Model 100/30 Programmable Two-Finger End Effector	2 Servomotors in parallel 2 Encoders Resolution: 0.00025 in. Accuracy: ±0.004 in. Repeatability: ±0.0005 in.
Lord Corporation	LTS 210 Programmable Two-Finger End Effector	2 Stepper Motor

APPENDIX 9.7

END-EFFECTOR COMPARISON

The following end-effector preliminary specifications were developed for evaluation and comparison of robot system capabilities.

1. SINGLE ARM

1.1. TWO FINGER END EFFECTOR:

1.1.1. HARDWARE:

The gripper system includes a two finger parallel operating gripper with pressure sensing elements arranged to accurately measure closure force on objects gripped. Incremental closure capability is to be included with position sensing elements arranged to accurately measure position of fingers at all times. The gripper unit should include other positive 'capture' confirmation of object gripped including optical and/or encoder feedback.

This system will include a torque sensor to indicate torque and direction of forces with reference to base of end effector.

A quick change feature for in-process change out of end-effector and/or fingers will be built in.

All electronic controls necessary for signal conditioning to interface the end-effector with the manipulator arm and its respective control and monitoring hardware will be included.

The accuracy, repeatability, speed and physical dimension/mass requirements and limitations are to be specified as required.

1.1.2. SOFTWARE:

All software modules required to drive the end-effector, including additions and modifications of primary manipulator software package will be provided.

The system includes end-effector pressure sensor, gripper dimensional opening, and end-effector torque sensor data acquisition and control with primary manipulator system interface.

1.2. THREE FINGER END-EFFECTOR:

1.2.1 HARDWARE:

This gripper system is a three finger gripper with a minimal configuration of two variable fingers opposed by one fixed base finger. The three finger elements are to include a minimum of a single digit but not more than two digits, with variable closure and pressure sensing capability.

The gripper system is to include a quick change feature to allow change out of the end-effector and may include capability to change out fingers only on the end-effector.

This system includes end-effector pressure sensing between digits, gripper dimensional spacing between digits, and torque relative to base of end-effector.

All electronic power and signal control and conditioning hardware necessary to interface the end-effector with the manipulator arm and its respective control and monitoring hardware will be provided.

The required accuracy, repeatability, speed and physical dimensions/ mass requirements and limitations will be met as specified.

1.2.2 SOFTWARE:

All software modules required to drive the end-effector, including modifications and additions to primary manipulator software package will be provided.

Thesoftware system will include necessary data acquisition and processing of sensor data to provide real time information of position and acceleration/pressure states of the end effector.

1.3 DEXTEROUS END-EFFECTOR:

1.3.1. HARDWARE:

The dexterous end-effector will consist of a minimum of three fingers with three digits per finger. The end-effector will be arranged such that two fingers are in a variable configuration structure with an opposing finger.

Individual digit positioning, torque sensing, acceleration sensing (in all required axis) and control capability as required by uG constraints will be provided.

A tool changing feature is not required but preferred in order to provide end-effector redundancy and flexibility.

Control, power interfacing and support hardware will allow interfacing to the manipulator system. A teleoperator pendant (i.e. may be a glove) system for operator training and real time (and predictive control) is to be provided (see software below.)

1.3.2. SOFTWARE:

All software required to support the end effector is to be provided. It will include teach/learn routines to allow training, recording and playback of movements via the teleoperator pendant system.

The software provided will also include routines necessary to interface the end-effector to the manipulator operating system, vision system, and the predictive display/ control system. The software package will include all modifications and enhancements required for real time dexterous end effector operation.

The software package will include all necessary routines to allow operation in the specified micro-g or milli-g range necessary for proper process control.

2. DUAL ARM

2.1. Combination of 2 Finger and 3 Finger End-Effectors

2.1.1. HARDWARE:

This gripper is composed of one each two finger and one each three finger end-effectors as described in 1.1.1. and 1.2.1. above.

A universal tool changer is required for interchangeability and redundancy/backup.

2.1.2. SOFTWARE:

The software package to support these end-effectors will include the software modules as described in 1.1.2 and 1.2.2 above, with additional routines as described:

Multi-arm anti-collision software with interface to predictive software of dual manipulator arms.

Software modules to allow hierarchical control in a leader/ follower or prime/secondary manipulator arrangement.

2.2. Combination of 2 Finger and Dexterous End Effector

2.2.1. HARDWARE:

This arrangement of end-effectors will include one two finger and one three finger dexterous end effectors as described in 1.1.1. and 1.3.1. above.

The system will include a universal tool changing capability on the two finger (non dexterous) end effector.

2.2.2. SOFTWARE:

The software system will consist of modules as described in 1.1.2 and 1.3.2 above with additional modules as follows:

Multi-arm anti-collision software with interface to predictive software of dual manipulator arms.

Software modules to allow hierarchical control in leader/follower arrangement.

2.3. Three Finger and Dexterous End Effector

2.3.1. HARDWARE:

This end-effector configuration will consist of one three finger and one three finger dexterous end effector as described in 1.2.1. and 1.3.1. above. A universal tool changer is required for interchangeability and redundancy/backup.

2.3.2. SOFTWARE:

The software package will consist of the software modules as described in 1.3.2 and 1.3.3 above as well as the following modules:

Multi-arm anti-collision software with interface to predictive software of dual manipulator arms.

Software modules to allow hierarchical control in leader/follower arrangement.

MANIPULATOR COMPARISON

3. SINGLE ARM

3.1 HARDWARE:

The single fixed base robot manipulator includes an anthropo-morphic manipulator with 6 degrees of freedom (not including end-effector) that is capable of manipulating up to 30 k.g. within a LEVEL I u-Gravity range (i.e. 10-3 to 10-5 G at> 1 Hz.).

The manipulator unit will be designed to support and manipulate a fully instrumented end-effector of any of the previously specified types: Two-Finger, Three-Finger, or Dexterous. The accuracy, repeatability, speed and physical dimension/mass requirements and limitations are to be specified as required. A quick change feature for in-process change out of end effectors will be provided.

3.2 SOFTWARE:

All software modules required to drive the manipulator arm including minor additions and modifications of primary manipulator software package to interface with the end-effector will be provided. (note: major interface support for this effort will fall within the end-effector provision.)

Software required for predictive display and control as well as integration of pendant controller (i.e. glove type for dexterous end-effector) is to be provided.

4.1 DUAL ARM:

4.1.1. HARDWARE:

The dual arm robot manipulator includes two anthropomorphic manipulators as specified in Paragraph I. above. Manipulators are to be arranged such that they may operate either in tandem on the same task, or individually on separate tasks. The manipulator units will be designed to support and manipulate any of the specified end effectors with provision to prevent arm-collision.

The two arms will be designed to operate in primary /auxiliary mode (i.e. leader/follower) but will be reversible and redundant in design and functionality with end effector exchangability for enhanced redundancy.

4.1.2. SOFTWARE:

All software modules defined in Paragraph. I. will be provided. All required software modules necessary to allow operation in primary/secondary modes and required to prevent dual arm collision will be provided. Pendant operation of both arms simultaneously via teleoperator control (including predictive control capability) will be provided in the software system.

APPENDIX 9.8

ROBOTIC MANIPULATION

TIME SAVINGS BENEFITS ANALYSIS

MANIPULATIVE TASK TIME SAVINGS WITH ROBOTICS: LARGE BRIDGMAN FURNACE

STEP NO.	STEP NAME:	G-REQUIREMENT: MICRO-G	MILLI-G	MANIP TIME	GND. OPN.	* ONE HANDED ROBOT * TWO FINGER	THREE FINGER	DEXT. GRIP.	* TWO HANDED ROBOT * 2 & 3 FINGER	2 FING. & DEXT.
3.0	RUN PREPARATION									
	Load furnace.	X	X	30	0	0	30	30	30	30
	Seal furnace.	X	X	30	0	30	30	30	30	30
	Check all connections and seals.	X	X	20	0	20	20	20	20	20
	Power up processor facility.	N/A GND	X	0	1	0	0	0	0	0
	Run master controller system test program.	N/A GND	X	0	2	0	0	0	0	0
4.0	RUN									
	Input processing parameters.	X GND	X	0	10	0	0	0	0	0
	Furnace and sample heat-up.	X	X	0	5	0	0	0	0	0
	Sample soak	X	X	0	30	0	0	0	0	0
	Crystal growth.	-	X	0	15	0	0	0	0	0
	Cool-down of furnace.	X	X	0	20	0	0	0	0	0
	End run.	N/A	N/A	0	0	0	0	0	0	0
	Disassemble furnace as required to remove module.	X	X	120	0	120	120	120	120	120
	Remove ampoule from heater module.	X	X	20	0	0	20	20	20	20
	Power down controller.	X	X	1	0	1	1	1	1	1
5.0	IOC LEVEL CHARACTERIZATION									
	Photograph boule through wall of ampoule.	X	X	10	0	0	0	10	10	10
	Remove boule from ampoule.	X	X	30	0	30	30	30	30	30
	Etch growth residue from product.	X	X	30	0	30	30	30	30	30
	Photograph product.	X	X	10	0	0	0	10	10	10
	* Measure mass of boule.	X	X	20	0	0	0	0	0	0
	Measure physical dimensions of boule.	X	X	10	0	0	0	0	10	10
	* Slice sample wafer from boule.	X	X	40	0	0	0	0	0	0
	Photograph wafers.	X	X	10	0	0	0	10	10	10
	* Polish wafers.	X	X	40	0	0	0	0	0	0
	View and photograph wafer using microscope system.	X	X	40	0	0	0	40	40	40
	Etch wafer.	X	X	30	0	30	30	30	30	30
	View and photograph wafer using microscope system.	X	X	40	0	0	0	40	40	40
	Repeat process as required	X	X	140	0	140	140	140	140	140
	Analyze wafer using x-ray system (topography).	X	X	180	0	180	180	180	180	180
	Analyze wafer w/an electrical conductivity probe.	X	X	20	0	20	20	20	20	20
6.0	GROWTH CHARACTERIZATION									
	Analyze wafer using FTIR.	X	X	40	0	40	40	40	40	40
	Analyze wafer using a Hall probe.	X	X	40	0	40	40	40	40	40
7.0	ANALYSIS									
	Package and store products.	N/A	N/A	30	0	0	0	0	30	30
	Reduce data as required.	N/A GND	N/A GND	0	30	0	0	0	0	0
	Correlate experimental parameters to results.	N/A GND	N/A GND	0	30	0	0	0	0	0
	Select next run parameters.	N/A GND	N/A GND	0	60	0	0	0	0	0
8.0	CLEAN EQUIPMENT									
	Clean equipment as needed.	N/A	N/A	30	0	0	0	30	30	30
	Stow equipment as needed.	N/A	N/A	90	0	0	0	90	90	90
	TOTAL MINUTES PER CYCLE (EQUIVALENT MANUAL/CREW TIME)			1101	203	681	731	961	1001	1001
	PERCENTAGE OF ON-STATION STEPS PERFORMED BY ROBOT			-	-	62	66	87	91	91

NOTE 1:ROBOT TIME IS INITITALLY 2 X SHOWN.

NOTE 2:PREPARATION (TRANSPORT AND INSTALL) IS NOT INCLUDED AS IT IS A ONE TIME VALUE AND NOT REPRESENTATIVE OF A NORMAL PRODUCTION CYCLE. (STEPS 1.0 AND 2.0 IN PREVIOUS EDITIONS OF THIS TABLE)

NOTE 3:ADVANCED CAPABILITIES ARE UNDER STUDY WHICH MAY ALLOW ADITION OF THESE STEPS USING DEXTEROUS MULTI-ARM OR SECONDARY ROBOTIC SYSTEM (I.E. GLOVE BOX MOUNTED MICROROBOTIC SYSTEM)

MANIPULATIVE TASK TIME SAVINGS WITH ROBOTICS: FLUID PHYSICS

STEP NO.	STEP NAME:	G-REQUIREMENT MICRO-G	MILLI-G	MANIP TIME	GND. OPN.	* ONE HANDED ROBOT * TWO FINGER	THREE FINGER	DEXT. GRIP.	* TWO HANDED ROBOT * 2 & 3 FINGER	2 FING. & DEXT.
3.0	RUN PREPARATION									
	Review production procedures.	N/A GND	GND	30	0	0	0	0	0	0
	Install sample fluid.	X	X	20	0	0	30	30	30	30
	Check all connections and fittings.	X-GND	X-GND	20	0	30	30	30	30	30
	Load sample into facility.	X	X	10	0	20	20	20	20	20
3.2	VERIFY SYSTEM									
	Power up facility.	X-GND	X-GND	10	0	20	20	20	20	20
	Run master controller system integrity program.	X-GND	X-GND	0	1	0	0	0	0	0
4.0	RUN PROCESS									
	Input process parameters.	N/A GND	N/A GND	0	10	0	0	0	0	0
	Initiate programmed run.	N/A GND	N/A GND	0	5	0	0	0	0	0
	Start data recorders.	N/A GND	N/A GND	0	5	0	0	0	0	0
	Purge sting cap.	X	X	10	0	0	0	0	0	0
	* Observe process and make adjustments as necessary.	X GND	X GND	0	120	0	0	0	0	0
	* Cool facility and sample.	X GND	X GND	10	0	0	0	0	0	0
	Stop data recorders.	X GND	X GND	1	0	1	1	1	1	1
	Power down facility.	N/A GND	N/A GND	2	0	2	2	2	2	2
5.0	IOC LEVEL CHARACTERIZATION									
	Drain spent solution and store for disposal.	X	X	30	0	0	30	30	30	30
	Remove holder assembly.	X	X	20	0	20	20	20	20	20
	Wash and dry crystal.	X	X	20	0	20	20	20	20	20
	Review video data.	N/A GND	N/A GND	0	20	0	0	0	0	0
7.0	ANALYSIS									
	Package product for return to earth.	X	X	30	0	0	0	30	30	30
	Reduce data as required.	N/A GND	N/A GND	0	30	0	0	0	0	0
	Correlate results to process parameters.	N/A GND	N/A GND	0	60	0	0	0	0	0
	Select next run parameters.	N/A GND	N/A GND	0	30	0	0	0	0	0
8.0	CLEAN EQUIPMENT									
	Clean apparatus as needed.	X	X	30	0	0	0	30	30	30
	Stow equipment as needed.	X	X	30	0	0	0	0	30	30
	TOTAL MINUTES PER CYCLE (EQUIVALENT MANUAL/CREW TIME)			273	281	113	173	233	263	263
	PERCENTAGE OF ON-STATION STEPS PERFORMED BY ROBOT			-	-	41	63	85	96	96

NOTE: SEE COMMENTS UNDER SECTION II-2A.

. MANIPULATIVE TASK TIME SAVINGS WITH ROBOTICS: PROTEIN CRYSTAL GROWTH

	STEP DESC.	G-REQUIREMENT: MICRO-G	MILLI-G	MANIP TIME	GND. OPN.	* ONE HANDED ROBOT * TWO FINGER	THREE FINGER	DEXT. GRIP.	* TWO HANDED ROBOT * 2 & 3 FINGER	2 FING. & DEXT.
3.0	RUN PREPARATION									
	Load growth modules with selected proteins	X	X	90	0	90	90	90	90	90
	Check all connections and fittings	X GND	X GND	30	0	30	30	30	30	30
	Power up crystal growth facility	X GND	X GND	0	1	0	0	0	0	0
	Run master controller sys. integrity test	X GND	X GND	0	2	0	0	0	0	0
4.0	RUN									
	Load crystal growth facil. with selected proteins	X	X	10	0	10	10	10	10	10
	Input processing parameters	X GND	X GND	0	10	0	0	0	0	0
	Start data recorder	N/A GND	N/A GND	0	1	0	0	0	0	0
	Initiate programmed temperature profile	N/A GND	N/A GND	0	3	0	0	0	0	0
	Monitor crystal growth	-	X	0	60	0	0	0	0	0
	Stop data recorders and cool system	X GND	X GND	0	5	0	0	5	5	5
	Power down crystal growth facility	N/A GND	N/A GND	0	1	0	0	0	0	0
5.0	IIOC LEVEL CHARACTERIZATION									
	Remove selected crystal growth modules from facil	-	X	5	0	5	5	5	5	5
	Visually examine individual growth module cells	-	X	0	15	0	0	0	0	0
	Select crystals for diffraction analysis	-	X	12	24	0	0	0	0	0
	Perform prelim X-Ray diffraction analysis	-	X	15	0	0	15	15	15	15
	Select crystals for detailed analysis	-	X	120	0	0	120	120	120	120
	Perform detailed X-Ray diffraction analysis	-	X	240	0	0	240	240	240	240
7.0	ANALYSIS									
	Select seed crystals	-	X	12	48	0	12	12	12	12
	Place seed crystals into growth modules	-	X	20	0	0	20	20	20	20
	Transfer protein solution into seeded growth cells	-	X	60	0	0	60	60	60	60
	Load seeded growth modules	-	X	30	0	0	30	30	30	30
	Load growth modules to be re-run	-	X	10	0	0	10	10	10	10
	Place crystal growth trays into facility	X	X	10	0	0	10	10	10	10
	Repeat process run and analysis procedures	X	X	140	0	0	140	140	140	140
8.0	CLEAN EQUIPMENT									
	Sterilize equipment as necessary	X	X	10	0	0	10	10	10	10
	Rinse out crystal growth facility	X	X	10	0	0	10	10	10	10
	Clean filtration equipment	X	X	10	0	0	10	10	10	10
	Dispose of wastes and unreturned solutions	X	X	10	0	0	10	10	10	10
	TOTAL MINUTES PER CYCLE (EQUIVALENT MANUAL/CREW TIME)			844	170	135	832	837	837	837
	PERCENTAGE OF ON-STATION STEPS PERFORMED BY ROBOT			-	-	16	99	99	99	99

* SEE NOTES UNDER SECTION II-2A.

APPENDIX 9.9

COST COMPARISON:

END-EFFECTORS
AND MANIPULATORS

APPENDIX 9.9
COST COMPARISON: END EFFECTORS AND MANIPULATORS
HARDWARE AND SOFTWARE REQUIREMENTS

ITEM:	INDUSTRIAL K$	FLIGHT MOD. K$	FLIGHT QUAL. K$	TOTAL K$
MANIPULATOR				
SINGLE ARM:				
HARDWARE	75	300	200	575
SOFTWARE	75	200	150	425
SUB-TOTAL	150	500	350	1000
DUAL ARM:				
HARDWARE	225	900	300	1425
SOFTWARE	300	300	250	850
SUB-TOTAL	525	1200	550	2275
GRIPPER				
SINGLE ARM:				
TWO FINGER				
HARDWARE	20	80	180	280
SOFTWARE	55	138	188	380
SUB-TOTAL	75	218	368	660
THREE FINGER				
HARDWARE	35	158	258	450
SOFTWARE	195	488	538	1220
SUB-TOTAL	230	645	795	1670
DEXTEROUS				
HARDWARE	105	525	675	1305
SOFTWARE	875	1750	1850	4475
SUB-TOTAL	980	2275	2525	5780
DUAL ARM:				
TWO FINGER & THREE FINGER				
HARDWARE	55	220	420	695
SOFTWARE	400	1600	1750	3750
SUB-TOTAL	455	1820	2170	4445
TWO FINGER DEXTEROUS				
HARDWARE	128	640	890	1658
SOFTWARE	1130	4520	4720	10370
SUB-TOTAL	1258	5160	5610	12028

NOTE : COST SHOWN INCLUDES INTERFACING HARDWARE AND SOFTWARE

APPENDIX 9.10

ROBOT SYSTEM

EVALUATION FACTORS

APPENDIX 9.10 ROBOT SYSTEM EVALUATION FACTORS

A. COMPARISON OF ROBOT SYSTEMS:

The robot systems evaluated in task III have been compared by analyzing their relative merits in each of a broad range of relevant categories. The comparative capability of each robot system to accomplish tasks in relation to resources used was the primary basis for evaluation. The total of all scores indicates the robot system relative effectivity or merit.

B. ROBOT CONFIGURATIONS EVALUATED:

The robotic configuration concepts analyzed are:

1.1. Single Arm Two Finger End-Effector.
1.2. Single Arm Three Finger End-Effector.
1.3. Single Arm Dexterous End-Effector.
1.4. Dual Arm Two Finger End-Effector.
1.5. Dual Arm Three Finger End-Effector.
1.6. Dual Arm Dexterous End-Effector.

C. DESCRIPTION OF CATEGORIES:

The primary factors used to evaluate the trade options for these six robot configurations are as follows:

1. RESOURCES CONSUMED BY SYSTEM: Shared Resources include Power, Data Management, Thermal Control, Video and Communications, and Crew Time. The score for the robot system being analyzed is a number representing the relative 'loading' on resources. For example, the two arm dexterous robot can perform more tasks and needs much less crew assistance in accomplishing tasks than does a more primitive one arm two finger robot system.

2. CREW SET UP TIME: Estimated man days required to set up the robot and monitor calibration is given. Set up time includes equipment unpacking, placement and intializing. Station certification of free flying mobile units is assumed. Relative scoring is given, with the least time required for set-up given the highest score.

3. MAINTENANCE TIME: The Maintenance score is based on the complexity of the robot system and a related maintenance training time required to prepare the crew and ground personnel to manage the system.

4. HOUSEKEEPING: The capability of the Robot to perform the mundane and repetitive tasks associated with clean up, retreaving and storing equipment (and tools), and ability to provide general crew assistance is rated. The crew time saved by this assistance is the primary rating consideration.

5. TELESCIENCE: This figure is based on the results of the study of 3 Experiments in reports 10 - 12 (UNBIS.) Based on the average of these tasks, a percentage of tasks that can be accomplished by the robot type has been calculated. The score is based on the amount of tasks that can be accomplished by the specified robot system.

6. COMPLETION TIME: This figure is an estimated time required by the robot system to accomplish a task in comparison to a human or crew member. Though it is assumed that initial robot task time will be twice that of a crew member, it is also assumed that after experienced operation the robot time will approach crew time. Part of the added task time is due to communications delay between the Sapace Station and earth based telerobotic consoles. Since the more dexterous robot systems have the ability to perform tasks more quickly with fewer interim and/or crew-assisted steps, it is assumed that their more efficient movements will reduce task time.

7. REDUNDANCY: The degree to which the robot system can be defaulted to a back-up scenario if a sub-system fails is the redundancy of the system. A two armed robot has a much higher redundancy factor since one manipulator can continue to serve even though task rate may drop to one half or less. A single manipulator arm has some redundancy if it can change its end effector for example via a quick tool-change feature.

8. RELIABILITY: The reliability of the robot is the overall integrity of mechanical, electrical, audio, video and computational sub-systems. The more capable robot systems are considered more reliable due to their auxiliary communications capabilities, additional redundancy and back up sub-systems.

9. REPEATABILITY: The ability of the robot to repeat motions and routines consistently from one cyle to the next is considered the overall repeatability of that system. This includes dimensional repeatability as well as timing.

10. ACCURACY: The ability of the robot to precisely position its end effector and tool point to the task at hand.

11. SAFETY: Safety will be built into every robot system, with multiple safety checks and multi-level hierarchial safety sensing and control. All systems will have thoroughly designed and tested safety systems.

12. TASK RECOVERABILITY: Task recoverability is a term denoting a degree of robotic flexibility, or the ability to recover operations during a task. For example, if a tool slips from an end effector, the robot may be directed to re-grasp it. If the end effector misses the 'on-switch' during a first attempt, it is directed to try again. The more capable robot (multi-arm and/or dexterous) will be able to recover more easily, more naturally, and more quickly - thus rating a higher score.

13. LOW GRAVITY COMPATIBILITY: The robots capability to perform adequately within the low gravitational disturbance level. Higher levels of dexterity and redundant manipulators will enhance compatibility with process requirements within the U.S. Lab.

14. COST : The cost of the robot systems studied ranges from $3M estimate for a single arm two finger system to the $16M for the two arm dexterous system. (re: Report #12, Study of UNBIS for Robotic Systems in MMPF, Octover 13, 1988.) Costs include flight cost, ground support cost and training cost to support the robot system.

15. TECHNOLOGY DEVELOPMENT: The value of the robot in space for Research and Development data collection and evaluation purposes is noted. The importance to furtherance of Automation and Robotics for future space missions is graded. This value also represents a level of support to the National Space Policy which emphasizes intensive Research and Development in Automation and Robotics in space. (ATAC Progress Report #6, June 15, 1988; NASA Tech. Memorandum 100989.)

16. REACTIONLESS CAPABILITY: The overall impact of the robot on improving operations in performing experiments and production in low gravity is scored. The more capable robot systems can perform more of the operation steps with less impact on the process. It is assumed that each robot system is optimally designed for minimum robotic impact on the micro-gravity environment. Kinematic redundancy will be designed in to allow automatic reaction (inertial) compensation. Mechanical, electrical and control techniques will be designed in to optimize smoothness, eliminate backlash, provide back-drivability, and provide over-torque protection.

17. TRADE OPTION RAW SCORE: This is the sum of the robot system's individual category ratings. This score is a relative number used for comparison of robot systems adequacy in meeting conceptual specifications only (not a valuation in terms of dollars.)

APPENDIX 9.11

TRADE OPTION EVALUATIONS

1. SINGLE ARM TWO FINGER
2. SINGLE ARM THREE FINGER
3. SINGLE ARM DEXTEROUS
4. DUAL ARM TWO FINGER
5. DUAL ARM THREE FINGER
6. DUAL ARM DEXTEROUS

APPENDIX 9.11

TRADE OPTION #1: SINGLE ARM TWO FINGER

CATEGORY	PARAMETER (UNITS)	QUANTITY A	OPTIMUM SYSTEM B	WEIGHTING FACTOR C	RESULTANT RAW SCORE R	
RESOURCES CONSUMED BY SYSTEM: (31%)	POWER (KW)	0.8	1.0	8.0	0.50	R=(1-A/B) x C x .31
	DATA STORAGE (KB)	50.0	100.0	7.0	1.09	"
	VIDEO/COMM (KB/S)	50.0	100.0	7.0	1.09	"
	THERMAL (KW)	0.8	1.0	6.0	0.37	"
	VOLUME (CUFT)	12.0	20.0	3.0	0.37	"
	MASS/ORBIT (LB)	250.0	500.0	3.0	0.47	"
	UP/DOWNLINK (KB/S)	50.0	100.0	4.0	0.62	"
	CREW TIME SETUP (M-DAY)	2.0	5.0	3.0	0.56	"
	CREW TIME MAINT. (M-DAY/MO)	1.0	2.0	9.0	1.40	"
SYSTEM PERFORMANCE: (% COMPARED TO HUMAN) (44%)	HOUSEKEEPING	45.0	95.0	6.0	1.25	R=(A/B) x C x .44
	TELESCIENCE	40.0	95.0	8.0	1.48	"
	COMPLETION TIME	200.0	100.0	5.0	1.10	R=(B/A) x C x .44
	REDUNDANCY	20.0	100.0	6.0	0.53	R=(A/B) x C x .44
	RELIABILITY	90.0	100.0	8.0	3.17	"
	REPEATIBILITY	90.0	100.0	7.0	2.77	"
	ACCURACY	85.0	100.0	7.0	2.62	"
	SAFETY: VOLUME	100.0	100.0	7.0	3.08	"
	SAFETY: CREW EMERG	30.0	50.0	6.0	1.58	"
	TASK RECOVERABILITY	20.0	90.0	6.0	0.59	"
	LOW GRAV. COMPAT.	80.0	200.0	6.0	1.06	"
COST & OTHER FACTORS: (25%)	DDT&E ($M)	3.0	16.0	3.0	0.61	R=(1-A/B) x C x .25
	FLIGHT COST (K$/MO)	15.0	19.2	3.0	0.16	"
	GND SUPPORT COST (K$/MO)	20.0	33.3	3.0	0.30	"
	TRAINING COST (K$/MO)	10.0	17.0	3.0	0.31	"
	TECHNOLOGY DEVELOPMENT (%)	20.0	99.0	5.0	0.25	R=(A/B) x C x .25
	REACTIONLESS CAPABILITY	45.0	95.0	5.0	0.59	"
	TRADE OPTION RAW SCORE				27.9	

NORMALIZED SCORE = 27.9 /35.6 x 100% = 78%

TRADE OPTION #2: SINGLE ARM THREE FINGER

CATEGORY	PARAMETER (UNITS)	QUANTITY A	OPTIMUM SYSTEM B	WEIGHTING FACTOR C	RESULTANT RAW SCORE R	
RESOURCES CONSUMED BY SYSTEM: (31%)	POWER (KW)	0.8	1.0	8.0	0.50	R=(1-A/B) x C x .31
	DATA STORAGE (KB)	55.0	100.0	7.0	0.98	"
	VIDEO/COMM (KB/S)	55.0	100.0	7.0	0.98	"
	THERMAL (KW)	0.8	1.0	6.0	0.37	"
	VOLUME (CUFT)	12.0	20.0	3.0	0.37	"
	MASS/ORBIT (LB)	250.0	500.0	3.0	0.47	"
	UP/DOWNLINK (KB/S)	55.0	100.0	4.0	0.56	"
	CREW TIME SETUP (M-DAY)	2.0	5.0	3.0	0.56	"
	CREW TIME MAINT. (M-DAY/MO)	1.2	2.0	9.0	1.12	"
SYSTEM PERFORMANCE: (% COMPARED TO HUMAN) (44%)	HOUSEKEEPING	75.0	95.0	6.0	2.08	R=(A/B) x C x .44
	TELESCIENCE	70.0	95.0	8.0	2.59	"
	COMPLETION TIME	175.0	100.0	5.0	1.26	R=(B/A) x C x .44
	REDUNDANCY	30.0	100.0	6.0	0.79	R=(A/B) x C x .44
	RELIABILITY	90.0	100.0	8.0	3.17	"
	REPEATIBILITY	90.0	100.0	7.0	2.77	"
	ACCURACY	90.0	100.0	7.0	2.77	"
	SAFETY: VOLUME	100.0	100.0	7.0	3.08	"
	SAFETY: CREW EMERG	30.0	50.0	6.0	1.58	"
	TASK RECOVERABILITY	35.0	90.0	6.0	1.03	"
	LOW GRAV. COMPAT.	90.0	200.0	6.0	1.19	"
COST & OTHER FACTORS: (25%)	DDT&E ($M)	3.7	16.0	3.0	0.58	R=(1-A/B) x C x .25
	FLIGHT COST (K$/MO)	16.0	19.2	3.0	0.13	"
	GND SUPPORT COST (K$/MO)	20.0	33.3	3.0	0.30	"
	TRAINING COST (K$/MO)	12.0	17.0	3.0	0.22	"
	TECHNOLOGY DEVELOPMENT (%)	25.0	99.0	5.0	0.32	R=(A/B) x C x .25
	REACTIONLESS CAPABILITY	50.0	95.0	5.0	0.66	"
		TRADE OPTION RAW SCORE			30.4	

NORMALIZED SCORE = 30.4 /35.6 x 100% = 85%

TRADE OPTION #3: SINGLE ARM DEXTEROUS

CATEGORY	PARAMETER (UNITS)	QUANTITY	OPTIMUM SYSTEM	WEIGHTING FACTOR	RESULTANT RAW SCORE	
		A	B	C	R	
RESOURCES CONSUMED BY SYSTEM: (31%)	POWER (KW)	0.9	1.0	8.0	0.25	R=(1-A/B) x C x .31
	DATA STORAGE (KB)	75.0	100.0	7.0	0.54	"
	VIDEO/COMM (KB/S)	75.0	100.0	7.0	0.54	"
	THERMAL (KW)	0.9	1.0	6.0	0.19	"
	VOLUME (CUFT)	12.0	20.0	3.0	0.37	"
	MASS/ORBIT (LB)	275.0	500.0	3.0	0.42	"
	UP/DOWNLINK (KB/S)	75.0	100.0	4.0	0.31	"
	CREW TIME SETUP (M-DAY)	3.0	5.0	3.0	0.37	"
	CREW TIME MAINT. (M-DAY/MO)	1.0	2.0	9.0	1.40	"
SYSTEM PERFORMANCE: (% COMPARED TO HUMAN) (44%)	HOUSEKEEPING	90.0	95.0	6.0	2.50	R=(A/B) x C x .44
	TELESCIENCE	85.0	95.0	8.0	3.15	"
	COMPLETION TIME	165.0	100.0	5.0	1.33	R=(B/A) x C x .44
	REDUNDANCY	35.0	100.0	6.0	0.92	R=(A/B) x C x .44
	RELIABILITY	90.0	100.0	8.0	3.17	"
	REPEATIBILITY	93.0	100.0	7.0	2.86	"
	ACCURACY	93.0	100.0	7.0	2.86	"
	SAFETY: VOLUME	100.0	100.0	7.0	3.08	"
	SAFETY: CREW EMERG	35.0	50.0	6.0	1.85	"
	TASK RECOVERABILITY	65.0	90.0	6.0	1.91	"
	LOW GRAV. COMPAT.	100.0	200.0	6.0	1.32	"
COST & OTHER FACTORS: (25%)	DDT&E ($M)	7.8	16.0	3.0	0.38	R=(1-A/B) x C x .25
	FLIGHT COST (K$/MO)	17.0	19.2	3.0	0.09	"
	GND SUPPORT COST (K$/MO)	25.0	33.3	3.0	0.19	"
	TRAINING COST (K$/MO)	15.0	17.0	3.0	0.09	"
	TECHNOLOGY DEVELOPMENT (%)	45.0	99.0	5.0	0.57	R=(A/B) x C x .25
	REACTIONLESS CAPABILITY	85.0	95.0	5.0	1.12	"
	TRADE OPTION RAW SCORE				31.8	

NORMALIZED SCORE = 31.8 /35.6 x 100% = 89%

TRADE OPTION #4: DUAL ARM TWO FINGER

CATEGORY	PARAMETER (UNITS)	QUANTITY A	OPTIMUM SYSTEM B	WEIGHTING FACTOR C	RESULTANT RAW SCORE R	
RESOURCES CONSUMED BY SYSTEM:	POWER (KW)	0.9	1.0	8.0	0.25	R=(1-A/B) x C x .31
	DATA STORAGE (KB)	80.0	100.0	7.0	0.43	"
(31%)	VIDEO/COMM (KB/S)	80.0	100.0	7.0	0.43	"
	THERMAL (KW)	0.9	1.0	6.0	0.19	"
	VOLUME (CUFT)	18.0	20.0	3.0	0.09	"
	MASS/ORBIT (LB)	400.0	500.0	3.0	0.19	"
	UP/DOWNLINK (KB/S)	80.0	100.0	4.0	0.25	"
	CREW TIME SETUP (M-DAY)	3.0	5.0	3.0	0.37	"
	CREW TIME MAINT. (M-DAY/MO)	1.5	2.0	9.0	0.70	"
SYSTEM PERFORMANCE: (% COMPARED TO HUMAN)	HOUSEKEEPING	92.0	95.0	6.0	2.56	R=(A/B) x C x .44
	TELESCIENCE	90.0	95.0	8.0	3.33	"
(44%)	COMPLETION TIME	125.0	100.0	5.0	1.76	R=(B/A) x C x .44
	REDUNDANCY	95.0	100.0	6.0	2.51	R=(A/B) x C x .44
	RELIABILITY	95.0	100.0	8.0	3.34	"
	REPEATIBILITY	91.0	100.0	7.0	2.80	"
	ACCURACY	91.0	100.0	7.0	2.80	"
	SAFETY: VOLUME	100.0	100.0	7.0	3.08	"
	SAFETY: CREW EMERG	40.0	50.0	6.0	2.11	"
	TASK RECOVERABILITY	80.0	90.0	6.0	2.35	"
	LOW GRAV. COMPAT.	110.0	200.0	6.0	1.45	"
COST & OTHER FACTORS:	DDT&E ($M)	8.0	16.0	3.0	0.38	R=(1-A/B) x C x .25
	FLIGHT COST (K$/MO)	17.0	19.2	3.0	0.09	"
(25%)	GND SUPPORT COST (K$/MO)	22.0	33.3	3.0	0.25	"
	TRAINING COST (K$/MO)	12.0	17.0	3.0	0.22	"
	TECHNOLOGY DEVELOPMENT (%)	40.0	99.0	5.0	0.51	R=(A/B) x C x .25
	REACTIONLESS CAPABILITY	70.0	95.0	5.0	0.92	"

TRADE OPTION RAW SCORE : 33.4

NORMALIZED SCORE = 33.4 /35.6 x 100% = 94%

TRADE OPTION #5: DUAL ARM THREE FINGER

CATEGORY	PARAMETER (UNITS)	QUANTITY	OPTIMUM SYSTEM	WEIGHTING FACTOR	RESULTANT RAW SCORE	
		A	B	C	R	
RESOURCES CONSUMED BY SYSTEM: (31%)	POWER (KW)	0.9	1.0	8.0	0.25	R=(1-A/B) x C x .31
	DATA STORAGE (KB)	85.0	100.0	7.0	0.33	"
	VIDEO/COMM (KB/S)	85.0	100.0	7.0	0.33	"
	THERMAL (KW)	0.9	1.0	6.0	0.19	"
	VOLUME (CUFT)	18.0	20.0	3.0	0.09	"
	MASS/ORBIT (LB)	425.0	500.0	3.0	0.14	"
	UP/DOWNLINK (KB/S)	85.0	100.0	4.0	0.19	"
	CREW TIME SETUP (M-DAY)	3.0	5.0	3.0	0.37	"
	CREW TIME MAINT. (M-DAY/MO)	2.0	2.0	9.0	0.00	"
SYSTEM PERFORMANCE: (% COMPARED TO HUMAN) (44%)	HOUSEKEEPING	95.0	95.0	6.0	2.64	R=(A/B) x C x .44
	TELESCIENCE	94.0	95.0	8.0	3.48	"
	COMPLETION TIME	120.0	100.0	5.0	1.83	R=(B/A) x C x .44
	REDUNDANCY	90.0	100.0	6.0	2.38	R=(A/B) x C x .44
	RELIABILITY	95.0	100.0	8.0	3.34	"
	REPEATIBILITY	95.0	100.0	7.0	2.93	"
	ACCURACY	95.0	100.0	7.0	2.93	"
	SAFETY: VOLUME	100.0	100.0	7.0	3.08	"
	SAFETY: CREW EMERG	45.0	50.0	6.0	2.38	"
	TASK RECOVERABILITY	85.0	90.0	6.0	2.49	"
	LOW GRAV. COMPAT.	120.0	200.0	6.0	1.58	"
COST & OTHER FACTORS: (25%)	DDT&E ($M)	8.5	16.0	3.0	0.35	R=(1-A/B) x C x .25
	FLIGHT COST (K$/MO)	18.0	19.2	3.0	0.05	"
	GND SUPPORT COST (K$/MO)	25.0	33.3	3.0	0.19	"
	TRAINING COST (K$/MO)	15.0	17.0	3.0	0.09	"
	TECHNOLOGY DEVELOPMENT (%)	75.0	99.0	5.0	0.95	R=(A/B) x C x .25
	REACTIONLESS CAPABILITY	90.0	95.0	5.0	1.18	"
			TRADE OPTION RAW SCORE		33.7	

NORMALIZED SCORE = 33.7 /35.6 x 100% = 95%

TRADE OPTION #6: DUAL ARM DEXTEROUS

CATEGORY	PARAMETER (UNITS)	QUANTITY A	OPTIMUM SYSTEM B	WEIGHTING FACTOR C	RESULTANT RAW SCORE R	
RESOURCES CONSUMED BY SYSTEM: (31%)	POWER (KW)	1.0	1.0	8.0	0.00	R=(1-A/B) x C x .31
	DATA STORAGE (KB)	100.0	100.0	7.0	0.00	"
	VIDEO/COMM (KB/S)	100.0	100.0	7.0	0.00	"
	THERMAL (KW)	1.0	1.0	6.0	0.00	"
	VOLUME (CUFT)	20.0	20.0	3.0	0.00	"
	MASS/ORBIT (LB)	500.0	500.0	3.0	0.00	"
	UP/DOWNLINK (KB/S)	100.0	100.0	4.0	0.00	"
	CREW TIME SETUP (M-DAY)	5.0	5.0	3.0	0.00	"
	CREW TIME MAINT. (M-DAY/MO)	1.0	2.0	9.0	1.40	"
SYSTEM PERFORMANCE: (% COMPARED TO HUMAN) (44%)	HOUSEKEEPING	95.0	95.0	6.0	2.64	R=(A/B) x C x .44
	TELESCIENCE	95.0	95.0	8.0	3.52	"
	COMPLETION TIME	100.0	100.0	5.0	2.20	R=(B/A) x C x .44
	REDUNDANCY	100.0	100.0	6.0	2.64	R=(A/B) x C x .44
	RELIABILITY	100.0	100.0	8.0	3.52	"
	REPEATIBILITY	100.0	100.0	7.0	3.08	"
	ACCURACY	100.0	100.0	7.0	3.08	"
	SAFETY: VOLUME	100.0	100.0	7.0	3.08	"
	SAFETY: CREW EMERG	50.0	50.0	6.0	2.64	"
	TASK RECOVERABILITY	90.0	90.0	6.0	2.64	"
	LOW GRAV. COMPAT.	200.0	200.0	6.0	2.64	"
COST & OTHER FACTORS: (25%)	DDT&E ($M)	16.0	16.0	3.0	0.00	R=(1-A/B) x C x .25
	FLIGHT COST (K$/MO)	19.2	19.2	3.0	0.00	"
	GND SUPPORT COST (K$/MO)	33.3	33.3	3.0	0.00	"
	TRAINING COST (K$/MO)	17.0	17.0	3.0	0.00	"
	TECHNOLOGY DEVELOPMENT (%)	99.0	99.0	5.0	1.25	R=(A/B) x C x .25
	REACTIONLESS CAPABILITY	95.0	95.0	5.0	1.25	"
	TRADE OPTION RAW SCORE				35.6	

NORMALIZED SCORE = 35.6 /35.6 x 100% = 100%

APPENDIX 9.12

PRELIMINARY INTERFACING REQUIREMENTS

Preliminary interfacing requirements for a reactionless microgravity manipulation system in the MMPF are being prepared in sufficient detail to serve as an input for manipulator system conceptual design, addressing the design factors as follows:

a. Experiments/Processes
b. Facility
c. Physical
d. Control
e. Safety
f. Internal/External
g. Housekeeping

The following is a preliminary review of these important interfacing requirements.

a. Experiments/Processes:

The robot system must be able to perform its tasks without disturbance of the specified acceleration environment, whether Level I (milli-G) or Level II (micro-G.) This requires the design and installation of torque and acceleration monitoring devices on the robot base and force/pressure monitoring devices on the manipulator arm and end-effectors. The robot system must also be able to autonomously carry out preprogrammed tasks with safety, reliability and repeatibility. Teach-pendent modes provide for flexibilty, which is the ability to modify operations based on new knowledge gained. These needs drive the requirements for a highly reliable ground-based telerobotics control system, with the ability to include the experimenter in the loop for process/experiment optimization.

b. Facility:

A major consideration is that the Multi-User work stations and equipment as well as the user-specific equipment must be operable by either crew-member (human) or robotic system. Emphasis is towards anthropomorphic function, that is - towards robotic emulation of human motions and scales of forces in order to minimize special robotic fixturing. Hand rails can; however, include optically encoded information useable by the robot for navigation without any change in form or function.

The Space Station subsystems provide adequate power, data/comm., video, lighting, and thermal control for the robotic systems we are evaluating. Slow-scan video is being investigated for reducing data requirements in robotics applications.

Motive power requirements (i.e. electrical) are kept to a minimum. Efficient drive motors and control schemes should be used. Power transmission cables and control cables - if used - must be durable, well protected, unobtrusive, and easily replaceable. If batteries are used in mobile base configurations, methods of recharging must be accounted for.

Infrared and R.F. links should be considered in order to eliminate communciations cables. Power interface to the USL should be by compatible interface connectors.

c. Physical: The physical dimensions and constraints of the robotic system must take into consideration the following concerns:

1. The robot must be designed with overall physical dimensions not exceeding that of a double rack in order to insure its transportability through the Space Station. It is preferrable that the robot be retractable into a small envelope for transportation, temporary storage and/or 'parking'. The weight of the robot should be minimized to reduce payload transportation requirements as well as to optimize operation (reduce reaction forces) within the low-G environment.

2. The robot must have a manipulative reach from its mobile base to perform all assigned tasks. It is desirable that the design include additional degrees of freedom in the manipulator to permit multiple modes of approach to the work piece and thereby make optimized trajectories for minimum G-disturbances.

3. The robot should have smooth and backdrivable power transmission. The system must have 'mechanical break-away' features as further described under the Safety section. This feature insures that the robot can be overpowered even in the unlikely event of multiple failure of the robot control system and the safety system.

Mechanical ratings of torque and force (for individual joints and combinations of joints) must not exceed that of a level to be determined as 'safe'. Maximum allowable operating torque and pressure (breakaway limits) should be adjustable.

D. Control:

Control includes ground based teleoperator control with predictive display and with user/experimenter input on an advisory basis. Control must be available to the crew at their discretion.

The Control system should include a hierarchial computer operating system that will allow evolution of on-station robotics operations towards higher level knowledge based expert system control capability.

The control system should be designed with voice control. Speech recognition and speech synthesis will allow crew-member concentration of the task at hand and minimize distractions.

E. Safety:

The robot must be designed to include multi-level safety detection and shut-down elements. The robot must be stoppable by either ground-based teleoperators or crew members. The safety sensors should include torque sensing, ultrasonic obstacle detection, proximity detectors (thermal and/or capacitive field), optical detectors, and annunciators. All sensors must be cleared of obstruction for resumed operation of the robot.

Safety interfacing should include interface with voice control systems so that the robot can be shut down by verbal command. Safety annunciation should include voice proximity annunciation and some level of visual alerts (perhaps a small flashing light activates during major robot translations).

All robotic operations must be constrained to operate within an envelope governable by specific safety rules and safety limits. This is achievable via setting maximum torque capacities in the mechanical system. It is also desireable to apply 'dead-man-switching' control methods such that if control is lost or out of specification conditions are encountered. For example, temporary loss of power or loss of teleoperator communciations must place the robot into shutdown mode. This toggling of the robotic systems to a shut down mode must be recoverable via crew or ground station.

Robotic systems must be 'instantly dismissable' or mechanically and electrically disengageable such that any robotic system can be instantly stopped during an emergency, or any other reason determined necessary by the crew-member.

The robot control system should include an independent safety computer to provide real-time monitoring and reporting on safety issues. This system should include diagnostic features to monitor and report on robot control and communications integrity. In addition, 'object retention and control' must be monitored to insure that objects being manipulated are monitored during translation. The safety computer should include an independent capability to shut down robot operation.

f. Internal/External:

The robotic system must be designed such that external events and requirements are accounted for. The robot should be secured when external operations occur, such as when station keeping attitude thrusters are fired, a shuttle is docked , etc. The robot system design should allow a 'parking' feature to minimize robotic profile and presence within the LAB when it is not needed.

g. Housekeeping

Robots will be used to accomplish the mundane and repetitive tasks, leaving the crew to work on non-routine matters.

The robot system should include the ability to perform housekeeping tasks such as routine facility inspection, cleanup, equipment storage (put-away), and equipment inventory.

In the category of facility inspection, the robot can provide the mobile platform on which to mount additional environmental sensors, such as gas analyzers, leak detectors, temperature sensors and light sensors.

APPENDIX 9.13 ACRONYMS

ARAMIS	Automation, Robotics and Machine Intelligence System
ARMS	Anthropomorphic Realtime Manipulator Simulation
DMS	Data Management System
DOF	Degree of Freedom
ERD	Experiment Requirements Document
FES	Fluids Experiment System
FTS	Flight Telerobotic Servicer
GAS	Get-Away Special
GFFC	Geophysical Fluid Flow Cell
GPPF	Gravitational Plant Physiology Facility
IIA	Instrument Intetrface Agreement
I/O	Input/Output
IML-1	International Microgravity Laboratory One
IRD	Interface Requirements Document
JEM	Japanese Experiment Module
LaRC	Langley Research Center
LEMS	Laboratory Experiment ˜anipulator System
LeRC	Lewis Research Center
MEPF	Multiple Experiment Processing Facility
MICG	Mercury Iodide Crystal Growth
MIT	Massachusetts Institute of Technology
MMPF	Microgravity and Materials Processing Facility
MPESS	Multi-Purpose Experiment Support Structure
MSC	Mobile Servicing Center
MSL	Materials Science Laboratory
O&IA	Operations and Integration Agreement
OMV	Orbital Maneuvering Vehicle
PAYPLAN	Payload Production Planning Program, Payback Planning and Analysis
PCG	Protein Crystal Growth
PMC	Permanently Manned Configuration
PMIC	Payload Missions Integration Contract
PRICE	Parametric Review of Information for Costing and Evaluation Program
RMMS	Reactionless Microgravity Manipulator System

RMS	Remote Manipulator System
RUR	Requirements Update Review
SOW	Statement of Work
SS	Space Station
SSPVU	Space Station Pressurized Volume Utilization
TBE	Teledyne Brown Engineering
TDRSS	Tracking and Data Relay Satellite System
THURIS	The Human Role in Space
TLEM	Teleoperated Laboratory Experiment Manipulator
TLEMS	Telerobotic Laboratory Experiment Manipulator Simulator
UNBIS	User Needs, Benefits, and Integration Study
USL	United States Laboratory
VCGS	Vapor Crystal Growth System

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